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SYMPOSIUM 6

COASTAL ZONE SEDIMENTATION

EFFECTS OF SEDIMENTATION ON COASTAL ZONE ORGANISMS

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ABSTRACT

Some direct and indirect effects of sedimentation on coastal zone organisms are identified and discussed with respect to future increases in exploitation of coastal zone mineral resources (sand and gravel mining, oil and gas extraction), construction, dumping (sewage sludge, dredged material, demolition debris), and dredging. The potential biological effects of particulate organic and inorganic material which has been suspended, resuspended and deposited in the coastal zone will depend at least upon (1) concentration, (2) composition (mineral types, particle sizes and shapes, (3) sorbed minerals, toxins, or other associated substances, and (4) tolerances of the organisms. Tolerance limits (sensitivities) of organisms to sedimentation can differ with respect to trophic level, life stage, feeding mechanisms, habitat preference (mid-water interface, shoal water, open water) and duration of exposure. At coastal zone sites selected for sedimentation changes, an appropriate basis for preproject decision making could be provided by identification of the most sensitive biological components (important species and life stages) and an adequate knowledge of local conditions.

INTRODUCTION

At no time has any single unit of the earth's surface presented to man an environmental challenge of such magnitude as that of the "coastal zone." Indeed, we have yet to define the coastal zone with sufficient accuracy to please all workers in the physical and natural sciences; perhaps this will never occur, even though a satisfactory definition is a prerequisite for effective management of coastal zone resources and conservation of coastal ecosystems.

The resources of nearshore waters are staggering even today; in the near future even more resources will become available as technology begins to approach need. Presently near-coastal waters provide to us directly: (1) protein (fish and shellfish), (2) fossil fuels (oil and gas), (3) minerals (sand and gravel, phosphorite), (4) mineral ores (copper, magnesium), (5) dump space (sewage, dredge spoil, etc.), (6) water, (7) salt, and (8) recreation.

The indirect contributions of coastal waters are seldom thought of, and far less tangible. These are life processes of the coastal waters of the world which are major factors in maintaining the earth's "rebreather" units in operation. They include absorption of atmospheric carbon dioxide by sea water and the photosynthetic release of oxygen by algae in coastal waters, two mechanisms largely responsible for the existence of terrestrial life.

Sedimentation processes have been in operation since the appearance of liquid water on the earth's surface and represent an aspect of the natural "separation process" responsible for natural differentiation of matter in aquatic systems (Stumm and Morgan, 1970). It is safe to assume that the phenomenon of sedimentation presaged the appearance of life by hundreds of millions of years and that the entirety of organic evolution has proceeded in the presence of sedimentary particles in the suspended and deposited state. There is little reason to believe that sediments form any less an important feature in the history of organic evolution than other physical environmental factors such as inorganic nutrients, sunlight, thermal regimes, and the colligative properties of water.

Among the physical determinants of "environment," sediments are unique in their relationships to the biota due to their ability to behave simultaneously as a substrate for living organisms, modifiers of the chemical, thermal and photic environments and as translators of major geologic, meteorologic, and oceanographic phenomena which, may otherwise never affect biological processes to any noticeable extent. The intimate relationship of sediments with the biota in coastal zone habitats has generated characteristics of sediments and sedimentation which have been useful

in deducing the climatology and biogeography of certain areas throughout geologic time, and which make possible today the location of mineral resources of biogenic origin, such as oil and natural gas deposits.

Sediments, or, more properly, sedimentary materials, may be divided readily into two classes with respect to an interface with biological systems: suspended sediments, that class of particulate material which by virtue of physical factors remain suspended in the water; and deposited sediments, that class of particulate material which cannot be maintained in the suspended state in a given body of water. Each class of sedimentary material plays a significant role in the ecological relationships of the coastal zone and each of the two classes is affected significantly by human activities. One may conclude, therefore, that man's activities in the coastal zone will very likely have an effect on the coastal zone by virtue of impact on suspended and deposited sediments. The overriding considerations regarding this impact are: 1) to evaluate the extent to which its magnitude and persistence will affect the integrity of coastal zone ecosystems and; 2) to determine whether we can term localized effects "acceptable" as a proportion of the system in space and time.

The distribution of suspended and deposited sedimentary particles of varying sizes depends upon the physical/chemical and hydraulic characteristics of the specific system with which one is dealing. The prime factors in relation to the coastal zone are velocity, turbulence and salinity. These factors may differ substantially between brackish waters and waters typical of lower estuaries and the marine environment. Thus, a great deal of complexity is injected into considerations of the effects of sedimentation in the coastal zone since habitats having different physical/chemical parameters should, rightfully, be included in a discussion of the coastal zone environment.

SEDIMENTATION IN THE COASTAL ZONE

It is relatively simple to establish a physical or chemical definition of the coastal zone environment. One may use as an outer limit the continental edge, the depth contour of 200m quite conveniently, since

waters beyond this limit are generally far less affected by major coastal processes (Tait and DeSanto, 1972). The inshore margin, however, is a more difficult limit to define. We propose here a definition of the coastal zone strictly for biological purposes, realizing full well that we may be in contradiction of definitions adhered to by oceanographers and geologists. We shall treat the coastal zone as:

The complex of ecosystems common to the waters and substrate shoreward of the 200m depth contour and incorporating estuaries and other semi-enclosed waters to the defined limit of mixopolyhaline waters (~ 18 o/oo) at mean-high water.

By this definition we include, purposefully, lower estuarine zones, the intertidal zones of sandy and rocky beaches and salt marsh communities essential to the function of marine and estuarine littoral communities (Teal, 1962; Keefe, 1972; Moore, 1958).

It is within this zone that the majority of dredging, mining, dumping and exploration is taking place (see Hood, (ed.) 1971). With the apparent exception of dumping operations, an activity which is not restricted by the depth of water in which it is performed, one can predict that most of man's future activities in the marine environment will also be limited to the "coastal zone" (Hood and McRoy, 1971; Bigler and Winslow, 1969).

The majority of natural sediment input to the coastal zone is fine particulate material (Sharma, 1971; Holeman, 1968). In recent times the engineering activities of man have become an important factor in sedimentary additions to the sea. By means of dumping (including incinerated wastes, sewage sludge, acid waste, dredge spoil, etc.) the input of solids to the seas has increased (Gross, 1970a, b; Sherk, 1972). In certain instances, such as in the vicinity of industrial and urban centers, the dumping of waste represents the largest source of sediments entering certain ocean areas (Gross, 1970a). The size distribution of natural sediments derived from rivers is rather limited, ranging from fine sands to clay-sized particles. The majority of coarse natural sedimentary material in the coastal zone such as commercially valuable sand and gravel deposits, may be traced to glacial activity and

local erosional phenomena during and prior to the Pleistocene.

The deposition of suspended particles in estuarine systems is dependent upon water velocity and salinity. The settling of particles in relation to velocity is dependent upon the effective settling diameter of particles in suspension, a parameter which is increased in high salinity environments by flocculation of the finely divided particles. This results in moderate-to-well sorted sediments of clay-silt sized particles in protected backwater areas and silt-fine sand particles in river channels. At the mouths of estuaries where ocean current and wave activities may increase one generally observes unstable fine-to-coarse sand bottoms distributed between offshore bars and beaches. Their movement is dependent upon currents and storm activity.

The turbidity of coastal waters decreases rapidly with distance from shore as land-derived particles settle or are diluted by increasing volumes of water. Thus, one can envision in the "coastal zone" distinct areas in which the biota are affected by sediments and the process of sedimentation in a vastly different manner. Inshore areas and estuaries are turbid zones wherein alluvial input, turbulence, tides, storms and currents interact to maintain a relatively high concentration of finely divided solids in the water column. Offshore zones of greater depth are far less turbid (Okubu, 1971). This has resulted, via the process of natural selection, in inshore organisms capable of existing in turbid conditions and offshore organisms adapted to a less turbid environment of a more stable nature.

The results of man's activities in the marine environment has been the direct or indirect disruption of the process of sedimentation, the generation of high levels of turbidity and the alteration of sediment chemistry (Sherk, 1971). The various categories of man's engineering activities fall conveniently within either the nearshore, turbid sector or the offshore sector of the coastal zone. We shall now examine some activities (e.g. dredging and dumping) which alter sedimentation, increase turbidity and change sediment chemistry and their effects on coastal zone organisms.

SEDIMENTATION EFFECTS

The majority of dredging operations which are undertaken in the U.S. and other seafaring nations are maintenance operations designed to restore shipping channels, turning basins and ocean inlets to depth by removal of finely divided solids (U.S. Army Engineers, 1971).

Maintenance dredging operations may generate substantial concentrations of solids by suspension and dispersion of fine particles that have not been lifted to the surface in the vicinity of the dredge. Maintenance dredging also increases turbidity by disposal. Water disposal results in resuspension of all the material as well as significant changes in the chemical nature of the sediments dredged and the water in which disposal takes place (Masch and Espey, 1967; CBL, 1970). The extent to which changes in water quality take place and the nature of those changes depends upon sorbed materials resident in the dredged material (Sherk, 1971; National Marine Fisheries Service, 1972; CBL, 1970) which may include radionuclides, toxic metals, pesticides, petrochemicals and other materials (see e.g. Bender, 1971; Rashid, 1974; Rudd and Herman, 1972).

Upland disposal generally results in little resuspension of waste, but reintroduces to the aquatic environment quantities of leachate which may represent a deviation from ambient water quality.

Most literature on the effects of sedimentation in the coastal zone concentrates on estuaries and relates to the impact of dredging on estuarine and near-coastal fishes (see bibliographies by Sherk and Cronin, 1970; Condon, 1973). Long-term studies with sufficient support to attack the biological, chemical and physical interactions of dredging effects on estuarine organisms are rare.

Examination of the effects of suspended and deposited sediments in the estuarine environment requires: 1) an understanding of the natural physical forces that control estuarine sedimentation; 2) sufficient data on biological responses to evaluate the impact in an ecological context and; 3) foresight to anticipate future dysfunction of the ecosystem. Extrapolation of conclusions regarding the effects of sediments on estuarine

organisms to the coastal zone as a whole may be possible in some cases in the context of available data.

PHYTOPLANKTON:

Increased turbidity is generally considered "unaesthetic" although in estuaries high turbidity indicates the estuary is performing its function.

Estuaries support high levels of primary productivity. Turbid waters have less light penetrating to a given depth than clear sea water (Jerlov, 1970). One might conclude, therefore, that to reduce turbidity would be to increase productivity, and that increased turbidity would be destructive of production in estuaries. It has been demonstrated that increased suspended solids decrease rates of photosynthesis under experimental conditions (Sherk, O'Connor and Neumann, in press). But to conclude that the production of algae is decreased by a decreased light caused by dredging or construction activities is little more than confirmation of phyecological studies a century old. Under more realistic conditions one finds synergistic factors operational; increased turbidity may also indicate more nutrients in a nutrient limited system (Sherk, 1972) as happens in many lakes and coastal environments. One must ask whether the duration of decreased light penetration is significant to the community; what chemical changes occur during a dredging or dumping operation; is the system in question dependent upon photosynthesis for maintaining biota; is the turbidity beneficial to systems downstream?

Recent research indicates that engineering activities which disrupt estuarine sediments have little or no measureable effect on primary producers. During the productive, growing season most temperate algae are inhibited by strong sunlight and estuarine algae have a pronounced ability to adapt or acclimate to "shade" conditions (Stross and Stottlemeyer, 1965). In fact, some estuarine environments may not be dependent upon photosynthesis for support.

A consideration of physical and chemical factors however forces one to look toward the culmination of seemingly nonconservative physical events in the process of sediment resuspension and redposition. Sedi-

ments are sinks for substances of natural and anthropogenic origin which are harmful: toxic minerals (radiochemicals, metal ions, mutagens); pesticides; petrochemicals; etc. Many of these substances become incorporated into sediments by chemical adsorption. Their resuspension could initiate the process of bioconcentration and food-chain magnification which has resulted in numerous human health scares in recent years.

PRIMARY CONSUMERS

The primary producers in the near-shore and estuarine sectors of the coastal zone are major constituents of the parameter referred to as "turbidity" (McCluney, 1975; Jerlov, 1970). Let us now consider sedimentation on turbidity effects on the herbivore community.

Herbivores may take many forms: foragers such as the rasping snails, fishes, anthropods and ciliated protozoans; benthic and burrowing deposit and suspension feeders (e.g. barnacles, clams, oysters); and planktonic suspension feeders such as the innumerable species of copepods, cladocerans, rotifers, salps and others. Most of these organisms and many unnamed herbivores have a common feature that increases their vulnerability to sediment-generating activities: that is they feed on particles and their choice of food is based on particle-size rather than nutritional value.

One might question the adaptive value of this mechanism of filter-feeding, but when one views the filtering capacity of suspension-feeders in relation to their available food the strategy is apparent. They filter small particles, generally smaller than the size of typical flocculates of inorganic suspended materials ($\sim 63\mu$) which form in saline waters. Smaller particles of organic detritus which remain suspended in lower estuaries and in the coastal zone may be filtered; however these particles are suitable for nutritional purposes due to their organic nature. It has been estimated that for some coastal-zone copepod species organic detritus may provide up to 97% of their food at certain times (Raymont, 1963).

Engineering activities may affect the biology of suspension-feeders by suspending concentrations of energy-poor particulates which would defeat the purpose of

sophisticated size-selective filtering apparatuses. The potential for impact must be evaluated in the context of the ecology of the affected zone. For example, in turbid estuarine systems organisms may regulate feeding activities in relation to the extremes of environmental factors, including suspended sediments: clams and oysters can "clam-up" when suspended solids are too high; oysters can excrete pseudofeces consisting of "unacceptable" particles; certain species of copepods can adjust filtration rates in relation to concentrations of suspended solids (Frost, 1975).

Marine organisms from less turbid environments may not be able to vary their activities in relation to suspended solids concentrations. Sherk, O'Connor and Neumann (in press) found that comparison of particle filtration rates between two calanoid copepods differed greatly. Eurytemora affinis responded to increased concentrations of particles with increased rates of filtration. Acartia tonsa did not respond to the increased particle levels. Ecologically these species are characteristically found in environments which differ, among other factors, in turbidity (Jeffries, 1967). E. affinis increased filtration in suspended solids, a response which may be interpreted as a mechanism to increase food ingestion during high turbidity or to maintain their rate of ingestion of energy-rich particles when mineral solid turbidity is high (O'Connor and Sherk, in press). A. tonsa on the other hand is found in less turbid environments. In such an environment one might not expect turbidity responses to have developed. Thus, A. tonsa may exhibit a greater sensitivity to sediments than E. affinis.

Studies to document the effects of sedimentation on zooplankton have predicted little or no measureable impact due to dredging and spoiling (Sherk, O'Connor and Neumann, in press; CBL, 1970), dumping (National Marine Fisheries Service, 1972) and mining (Quirk, Lawler and Matusky Engineers, 1974). This lack of predicted impact is related to the rapid settling of re-suspended particulates.

Foresight dictates that the potential problem not be minimized, however, for the outstanding characteristic of a finely divided solid is its sorptive capacity,

which makes each particle a potential vector for contaminants when substances capable of sorption are mixed with suspended or deposited sediments. Under conditions where release from adsorption of potentially toxic materials is likely if the chemical environment is changed drastically (such as in resuspension of deposited sediments) substantial areas of the coastal zone may be affected in a deleterious manner.

BENTHIC ORGANISMS

Benthic organisms make use of deposited sediments as a habitat, a substrate and a source of nutrition. There are recognized three distinct groups of benthic organisms, each making different use of bottom sediments: epifauna, which inhabit the mud-water interface, infauna, which burrow in the sediments, and meiofauna, generally microscopic organisms which inhabit the interstices of the sedimentary deposits.

Most benthic organisms are dependent upon the stability of sediments and show adaptations of behaviour and physiology specific to the natural disturbances common to their preferred habitat. Such adaptations take the form of the ability to reach the mud-water surface after burial, the ability to function anaerobically during sediment stress and the ability to physically alter the nature of the sediments deposited upon them.

The benthic infauna and sedentary epifauna are mostly incapable of extended horizontal motion and, thus, are subject to the direct impact of sedimentation. The impact of sediment removal upon such organisms is complete: destruction of the habitat and, generally, transportation elsewhere. The impact of dumping is virtually complete: by placing new sediments atop an established community the function of all but those organisms capable of swimming or rapid upward burrowing is disrupted.

The data accumulated to date would suggest that the impact of sediment-generating activities on benthic organisms is transitory, having the immediate effect of near-complete disruption followed by rapid recovery of most populations, generally on the order of one-to-two years (First, 1970, Saila, Pratt and Polgar, 1972; CBL, 1970; Sherk, 1971, 1972). Recovery phenomena are, how-

ever, very much restricted to areas having nearby unaffected populations to provide individuals for repopulation and to areas where dredging and/or dumping operations do not uncover or deposit sediments with high levels of toxicity (Gross, 1970b, National Marine Fisheries Service, 1972; Sherk, 1971).

FISH

Exposure to suspended solids may affect fishes and fisheries adversely (EIFAC Working Party on Water Quality Criteria for European Fish 1964, Rogers, 1969; Sherk, O'Connor, Neumann, Prince and Wood, 1974). Effects range from extensive mortality at high concentrations of suspended solids (Sherk, et al., 1974; Rogers, 1969; Wallen, 1951) to changes in hematological parameters after prolonged exposure to low concentrations (Sherk et al., 1974). In most instances mortality and sublethal responses have been attributed to interference with gill function by clogging (Wallen, 1951; Ellis, 1936, 1937) or to disruption of the respiratory epithelium (Herbert and Merkens, 1961).

Investigators of siltation-induced fish mortality hypothesized that fishes died from suffocation, as evidenced by their silt-laden gills and the gaping mouths and opercula of dead and moribund organisms (Ellis, 1936, 1937). Histological studies have demonstrated that for a number of species (Rainbow trout; Southgate, 1962; brown trout; Herbert and Merkens, 1961; Herbert et al., 1961; white perch; O'Connor and Sherk, 1975) exposure to finely divided mineral solids caused appreciable damage to gill structure, including epithelial hyperplasia, fusion of secondary lamellae, edema and excessive proliferation of mucus cells. Hematologic responses of white perch to suspended solids (increased hematocrit, red cell count and hemoglobin) parallels those of fishes in hypoxic environments (Ostroumova, 1964; Prosser, Barr, Pinc and Lauer, 1957).

In general, the sensitivity of fishes exposed to suspended solids varied in relation to the activity level of the species tested; with typically active fishes (white perch, striped bass, bay anchovy, bluefish, rainbow trout, brown trout) showing greater sensitivity than less active species such as cunner, hogchoker and toadfish (Herbert and Merkens, 1961; EIFAC, 1964; Rogers,

1969; Saila, Pratt and Polgar, 1972; Sherk, et al., 1974

CONCLUSIONS

Physical alterations in estuaries and offshore dumping have obvious local effects (habitat, destruction and smothering) on aquatic organisms. Even so, the basic relationships between physical and chemical aspects of suspended and deposited sedimentary material and the responses of estuarine marine organisms are poorly understood, although there has tended to be general agreement that "abnormal" amounts of particulate material in suspension or settling on the bottom can effect aquatic organisms both directly and indirectly, by mortality or decreased yield.

Clearly, tolerable suspended sediment levels or ranges and their associated substances should accomodate the most sensitive life stages of biologically important species in areas (sites) of high biological value (major benthic resources, nursery and spawning areas). The present state of knowledge dictates that these critical organisms must be determined for each site and proposed environmental modification. However, data are difficult to compare because of different methods and approaches. In addition, the observed responses of organisms may not be due to turbidity or total suspended sediments concentrations, but to the number of particles, their densities, sizes, shapes, heights, presence and types of organic matter, and sorptive properties of the particles. Consequently, values such as ton/day, milligrams/meter, JTU or extinction values which may be hydrologically satisfactory from a water quality standpoint, may be insignificant from the standpoint of biological effects.

What is needed is additional comprehension of coastal biological systems. Very little information exists concerning the magnitude of biological change resulting from excessive sedimentation during environmental modifications for dredging and disposal or dumping activities. This additional information would provide a partial basis for the guidance of efforts to minimize damage and enhance desirable features of coastal zone systems.

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CHEMICAL AND BIOLOGICAL MOBILIZATION OF HEAVY METALS FROM ESTUARINE SEDIMENTS

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ABSTRACT

The recent emphasis on estuarine pollution has culminated in a series of Federally funded research programs to identify the mechanisms involved in the movement of heavy metals from the sediment reservoir into the biosphere. The U. S. Army Corps of Engineers, San Francisco District, as part of its Dredge Disposal Study is conducting experiments both in the laboratory and the field to evaluate the possible influence of dredging operations on mobilization of heavy metals and their ultimate uptake and accumulation by estuarine biota. Investigations have shown that cadmium, lead, zinc, and copper can be emitted from resuspended San Francisco Bay sediments under oxygen rich conditions. Biological investigations have shown that dissolved heavy metals ions can be accumulated during low salinity periods and desorbed as the salinity increases. Field studies have shown that estuarine organisms will accumulate heavy metals during periods of high urban runoff. Heavy metals may be taken up and accumulated by organisms following dredging activities via chemical reactions in the water column causing increased ambient concentrations or by ingesting and breaking down organic matter containing metals.

INTRODUCTION

One of the characteristics of living cells is their ability to take up elements from a solution against a gradient in concentration. This is perhaps most obvious for marine organisms, especially for algae, which obtain all their nutrients directly from sea water. Passive uptake of ions or simple diffusion is one pathway for element concentration. Living cytoplasm functions as an efficient cation (positively charged ion) exchanger and much less as an anion (negatively charged ion) exchanger. There are relatively few basic groups (mostly substituted ammonium ions) which function as ion exchangers in cytoplasm. Also, there is a potential difference of 50-80 millivolts between the inside and the outside of algal cells, with the outer surface being positive. This corroborates the preponderance of anionic polymers inside the cell. The main features of uptake of ions by cells can be accounted for by assuming that another process operates apart from simple diffusion. This process is called active uptake and is closely linked with metabolic processes inside the cell. The metabolic processes provide the energy necessary for uptake against a concentration gradient, but the exact mechanism is still a subject of dispute. One function is clearly the maintenance of the concentration of immobile anions in the cell. Active uptake has a larger temperature coefficient than uptake by diffusion; a rise in temperature of 10 degrees increases the rates of adsorption by 100 percent and by 20 percent, respectively.

This type of uptake requires the presence of a source of energy and also oxygen. It is particularly important for anions such as nitrate, sulphate, bicarbonate and phosphate (i.e., nutrients) which are rapidly consumed by the metabolic reactions of the cell. Thus, most nutrients are concentrated via the active uptake process. Other trace elements are typically incorporated into tissue fluids via passive uptake; however, certain elements are selectively concentrated only by specific organisms. Some of the elements are important for respiration or other metabolic processes; the purpose of others is unknown.

Heavy metals have the potential for killing organisms, impairing their reproductive capacities (thus adversely affecting future generations), and poisoning their tissues such that their meat is inedible to other species, including man. Incorporation of heavy metals into an organism's tissue is, among other things, dependent on the availability of a source of trace elements for uptake. Recently, dredged material has received a great deal of attention as a potential source of these trace elements because of the cation accumulator characteristic of many dredged sediments. To address this question as to the significance of dredged sediments as a direct source of heavy metal contamination of estuarine organisms, the San Francisco District has performed both chemical and biological studies. The studies were designed to investigate the location of selected heavy metals in association with San Francisco Bay sediments, the sorption-desorption characteristics of these metals, and laboratory/field experiments to investigate uptake of heavy metals by indigenous species during a dredging operation.

CHEMICAL AND BIOLOGICAL MECHANISMS

Little is known about the kinetics of the accumulation of heavy metals on and/or in sediment particulates, and their incorporation in and release from animal tissues. More is known about the mechanisms of element-sediment interaction and organism uptake and accumulation. The following is a discussion of mechanisms, not kinetics.

The most accessible elemental fractions of disturbed sediments to organisms are the interstitial waters and ion exchange fractions. These fractions contain only a minor portion of the total heavy metal burden of the sediments (Serne and Mercer, 1975) but could be the most biologically significant. The interstitial water metal concentrations are primarily dependent on the Eh and pH of the in situ sediment and the exchange reactions occurring under these conditions. When the sediments are resuspended during dredging operations, the interstitial waters can be dispersed and diluted by the over-lying waters almost immediately. The disassociated metal ions would be free to complex with both inorganic and organic ligands or for passive uptake by organisms.

The next most available source of metals is from ion-exchange sites. The sediment particle's ability to participate in exchange reactions arises from the fact that their surfaces, rather than being neutral, bear negative electrostatic charges. Postma (1967) suggested this negative charge may be explained by: (1) residual valences (broken bonds at particle edges; (2) substitutions within the crystalline lattice structure; (3) preferential adsorption of anions, especially hydroxyl ions. Broken bonds around the edges

of the silica-alumina units of the particle would give rise to unsatisfied charges, which would be balanced by adsorbed cations. The broken bonds would tend to be on noncleavage surfaces and therefore on the vertical planes. The number of broken bonds and hence the exchange capacity due to this cause would increase as the particle size decreases. Also lattice distortions would tend to increase broken bonds, and the exchange capacity would be expected to increase as the degree of crystallinity decreased.

Substitutions within the lattice structure of trivalent aluminum for quadrivalent silicon in the tetrahedral sheet and of ions of lower valence, particularly magnesium, for trivalent aluminum in the octahedral sheet result in unbalanced charges in the structural units of some clay minerals. Exchangeable cations resulting from lattice substitution are to be found mostly on the basal cleavage surfaces. Since the charges resulting from substitution in the octahedral sheet would act through a greater distance than the charges resulting from substitutions in the tetrahedral sheet, it would be expected that cations held because of the latter substitutions would be bonded by a stronger force than those held by forces resulting from substitutions in the octahedral sheet. In some cases, cations held by forces due to substitutions of aluminum for silicon seem to be substantially nonexchangeable.

When the clay mineral with its negatively charged surface is immersed in the estuarine environment, there is a tendency for the dissolved cations to be attracted by Coulombic forces to the surface. The number of cations required to neutralize the surface charge depends upon the number of excess anions, broken bonds and substitutions in the alumino-silicate skeleton and is referred to as the "cation exchange capacity" of the mineral. In the clay minerals, replacements in the octahedral layer are probably the major substitutions causing cation-exchange capacity (Grim, 1953). Commonly the cation exchange capacity in San Francisco Bay sediments ranges from 10.6 to 35.2 meq/100g (Serne and Mercer, 1975).

Many factors influence these exchange reactions in the estuarine environment. These factors not only affect which cation in the solution may enter the crystal structure and replace a stoichiometric equivalent of another ion but the rate of this exchange as well. They may be separated into physical and chemical factors.

The physical factors of the environment appear to be the major controlling component of the exchange reactions (Lee, 1970). The factors can be separated into the hydrodynamics of the system and the mixing of the sediments. In the estuary the hydrodynamics are primarily effected by the tides but additionally commercial shipping and, to some extent, pleasure boating can cause mixing of the water. These currents in the overlying waters tend to transport leached materials away from the sediments or an effluent outfall allowing concentration dependent exchange reactions to proceed. The amount of mixing that occurs in the sediments cannot only determine the rate of exchange but also determine the depth of sediment that may ultimately become involved in ion exchange reactions.

The chemical factors can be separated into the relative concentration of the various ions, the concentration of positive charge possessed by the dissolved ion, the total ionic strength of the solution and finally the specific interactions between certain ions and certain alumino-silicate clay minerals (Nelson, 1962).

The factor of first importance is the relative concentration of the various ions in solution. Concentration is the driving force that allows the ions to compete successfully for the negative exchange sites on the surface of the mineral. As the relative concentration of an ion in solution decreases, its ability to compete successfully for the exchange sites also decreases. Thus the proportion of exchange sites occupied by the ion should decrease.

Sea water contains several important cations. On an equivalent basis, sodium is the most abundant. Magnesium is the next most prominent, and calcium and potassium are relatively low in concentration.

The second factor is the relative concentration of positive charge possessed by the dissolved ion. The more highly concentrated is its positive charge, the more it can successfully compete for the negative sites. In terms of Coulombic forces this is because a small, highly charged ion can get closer to the source of negative charge than can a large ion of relatively low charge. However, a phenomena of aqueous chemistry has an important affect in the competition. Ions in solution are hydrated, i.e., surrounded by a number of water molecules held very tightly as a "hydration sphere" (Krone, 1963). The ion and its hydration sphere participate in exchange reactions as a unit. The more favorable the ratio of hydrated radius to charge, the more favorable the chances for the ion to successfully compete for the exchange sites.

The third factor is the total ionic strength of the solution, irrespective of the relative concentration of the individual ions. In dilute solutions there is a tendency for monovalent cations to compete less successfully than divalent or trivalent ions for exchange sites. This factor reflects the change in chemical activity of the ions with dilution. At very low salinities the divalent cations Mg^{++} and Ca^{++} , should dominate the exchange sites while at progressively higher salinities the monovalent Na^+ and K^+ ions progressively replace them.

Heavy metal cations participate in these reactions to a greater or lesser extent particularly during the transition of particles from freshwater to saline waters (Kharker et al, 1968). Ion exchange site extractions of selected Bay sediments indicated that 3.2 percent of the total copper, 1.8 percent of the total cadmium, 0.9 percent of the total lead, 1.4 percent of the total zinc and 19.3 percent of the total manganese may be contained on these sites (Serne and Mercer, 1975). The possible release of these metals via replacement during resuspension would elevate ambient water concentrations making the metals availability to organisms greater for some period of time.

Most primitive animals, unicellular protozoa, etc., take up ions from solution by diffusion. Multicellular invertebrate animals can be divided into two groups as far as uptake is concerned, those with impermeable skins and those without. Invertebrates with impermeable skins are the most numerous of terrestrial organisms. Their skin is coated with a layer of wax except for small pores which admit air. Their principal representatives come from the arachnid (spiders, ticks, etc.) and insect groups. These organisms take up ions exclusively by mouth, in their food. Invertebrates with permeable skins, including the majority of marine invertebrates (e.g., coelenterates, annelids, molluscs and echinoderms), have soft bodies through which ions can diffuse freely. In such cases the body fluid or blood is very similar to sea water in chemical composition, but the cells themselves maintain a high concentration of potassium, phosphate, etc., by actively excreting sodium and chlorine. The gills of molluscs are coated with a layer of carbohydrate sulphates which may function as ion-exchangers. The gills of marine Crustacea, which have hard impermeable carapaces, are fully permeable to water and salts.

In molluscs, the suspended fine and coarse particles are taken into the body differentially according to size by filter feeding, and digested differentially also according to size. Small particles of the size that enter the mouth are carried by delicate cilia on the ridges of the stomach to the digestive diverticulae while particles of a larger size enter the grooves of the stomach and are borne by more massive cilia to the intestine. In the intestine, the larger particles form fecal pellets which are then extruded through the anus. The finer suspended particles taken in during feeding probably contribute significantly to the nutrition of the animal. The cations adsorbed on particulates may be released and adsorbed in the digestive tract of molluscs.

Deposit feeders (i.e., various polychaetes, amphipods, etc.) ingest sediment directly without sorting. The cations associated with exchange sites could be displaced during oxidation processes occurring in the gut and the metals transferred into the intestinal lining by passive uptake. As previously mentioned some metals are accumulated to very high concentrations in invertebrates and thus are probably being incorporated into tissues by active transport. The kinetics and biochemistry of these uptake reactions is still very nebulous.

CHEMICAL REACTIONS

Dredged sediments may contain high concentrations of contaminants; however, the question arises as to what percentage of the total concentration will be available for immediate release upon disturbance. Most metals exist in several forms which differ in toxicity and availability.

Sorptive behavior and oxidation-reduction potential (redox) reactions of various chemical contaminants that occur with sediments during dredging and aquatic disposal and after redeposition, govern to a large extent the distribution of chemical constituents among various available and nonavailable forms. These contaminants may exist in various forms and reside in different

fractions of the sediment, making them more or less available to the water column and, thus, a potential water quality hazard. The heavy metals in the sediment may be found in the soluble form, exchangeable form, in the carbonate mineral phase, easily reducible form, or may be found with interactions with organic and sulfide fractions, associated with a moderately reducible iron oxide or hydroxide, or present in the intricate lattice structure of clay and silicate minerals.

Particulate organic materials present in sediments can act as strong scavengers. Organic materials such as humic and fluvic acids and detergents containing the functional groups hydroxyl, carboxyl, sulfhydryl and amino acids show significant sorption capacities. In seawater the presence of divalent cations can cause the precipitation of metal fulvates and humates with possible co-precipitation of trace elements (Williams, et al, 1974).

Among the metal species in various geochemical fractions of sediment, the fractions in the interstitial waters and water soluble phase can be immediately available for biological uptake upon resuspension of sediments. However, these fractions represent only an extremely small part of the potentially available portion--the non-residual fraction. This non-residual fraction, consisting of trace metals from land source pollution and marine derivation, in contrast to that derived from the crystalline structure of minerals, has magnitudes ranging from a low of 1.4 percent for copper to a high of 98 percent for cadmium (Serne and Mercer, 1975). The residual phase, which contains the greatest percent of most contaminants, is probably not available for biological uptake.

During dredging and disposal activities, trace metals in the sediment are brought into direct contact with the water column for some period of time. Because the trace metals are found at much greater concentrations in the sediment than in the water column, the contact time during dispersion and settling could result in their release and availability for biological uptake. Depending on the water depth, mixing, and sediment characteristics, contact time between the disturbed sediments and water column will vary.

A sudden release of low levels of some trace metals into the water column upon addition of dredged material to seawater has been observed in laboratory studies (Chen et al, 1975; Serne and Mercer, 1975). This is followed by a subsequent removal of metals from solution; either gradually, as would often be found in slightly reducing environments, or rapidly under oxidizing environments. The initial release of trace metals is most likely due to the dilution of interstitial waters, dissolution of the solid phase through complex formation, and release from the exchangeable phase (Chen et al, 1975).

Turbulent mixing at any Bay disposal site during the introduction and settling of the dredged material promotes the release and diffusion of metals from the enriched interstitial water found in reduced sediments. Upon release and exposure to oxygen many reactions occur. Metal species can be readsorbed to organic matter, hydrous iron and manganese oxides; form precipitates or complex compounds. The presence of active redox species such as carbon, nitrogen, oxygen, iron, manganese, and sulfur play predominant roles in regulating the soluble metal concentrations in the water column.

Oxidation-reduction potential, salinity, agitation time, solids-to-solution ration, and type of sediment are considered to be the most important factors determining the release of trace metals to the water column during disposal of dredged material. During sorption-desorption laboratory experiments with dredged sediment from San Francisco Bay oxidation-reduction potential was demonstrated to have the greatest effect on the fate of trace metals (Serne and Mercer, 1975). The results of the experiments are summarized below.

Oxidizing conditions. Under oxidizing conditions more copper, cadmium, lead, and zinc were released to the water column than under reducing conditions. However, more iron was released to the water column under reducing conditions. The release of mercury was not significantly affected by either oxidizing or reducing conditions.

Salinity. At higher salinities more cadmium, copper and zinc were released to the water column under oxidizing conditions and more iron under reducing conditions. The release of lead and mercury was not significantly affected by different salinity conditions either under oxidizing or reducing conditions.

Agitation time. Under oxidizing conditions more cadmium, copper, and zinc were released with a greater duration in agitation time.

Solids-to-solution ratio. With an increase in the solids content in the sediment-seawater mixture, more zinc and iron were released under both oxidizing and reducing conditions.

Remembering that typical water column concentrations are usually in the sub-parts per billion, a comparison between elutriate values and original water concentrations can be made. The release of trace metals (Cd, Cu, Pb and Zn) under oxygen rich conditions in general increased the water column concentration 30-200 percent. Ratios of elutriate to original water concentrations in general ranged from 1.3 to 2.0. The iron release was substantial under reducing conditions with ratios of elutriate to original waters ranging from 50 to 3000. This phenomenon should be very uncommon in San Francisco Bay because the water column is not normally oxygen deficient. Under the usual oxygen rich conditions in the Bay, iron ratios of elutriate to original water concentrations ranged from 2 to 4.

Another environmental parameter which was found to effect the elutriate concentration of heavy metals was salinity. For zinc, cadmium and copper, significantly higher concentrations of these metals were found in solution as the salinity increased from 1 ppt. to 15 ppt. and 29 ppt.

BIOLOGICAL REACTIONS

To investigate biological reactions, dredging operations in Mare Island Strait in northern San Francisco Bay were examined between September 1973 and May 1974 to determine whether these operations release toxic heavy metals from the dredged sediments, resulting in elevated concentrations of these metals in adjacent sediments and invertebrate populations (Anderlini et al, 1975).

Concentrations of the metals silver, arsenic, cadmium, copper, mercury, nickel, lead, selenium and zinc were monitored prior to, during and after two

dredging periods. Metal concentrations were measured in sediments, and the native invertebrates Macoma balthica, Neanthes succinea, Ampelisca milleri, Mytilus edulis and Ischadium demissum. Mytilus edulis transplanted into Mare Island Strait from Tomales Bay, a relatively undisturbed area on the California coast, were also monitored. Samples were collected at stations established immediately adjacent to the dredge zone, and at stations located outside of the area exposed to dredging activity.

Changes in the mean metal concentrations in sediments and invertebrates during the study period were relatively small, considerably less than an order of magnitude. Mean metal concentrations in sediments and benthic invertebrates changed by less than a factor of two and changes in metal levels in M. edulis were no greater than a factor of three.

The two dredging periods coincided with the two heaviest rainfalls of the year, and the resultant freshwater runoff caused significant changes in the salinity and particulate load in Mare Island Strait. It was, therefore, not possible to determine whether changes in metal concentrations at stations within the dredge zone were caused by either dredging or rainfall phenomena. However, changes in metal levels at stations outside of the dredge zone were of comparable magnitude and direction to those exposed to dredging activity. If the observed increases had been resultant from dredging, a gradient should have been apparent in the results as distance from the area of intense activity increased. No such gradient was apparent. Thus this leads to the hypothesis that the observed increases could have been the result of the rainfall washing pollutants into the channel from the adjacent town of Vallejo. URS Research Company (1974) estimated the total amount of certain pollutants washed off Vallejo streets annually. They estimated that 1.9 thousand pounds of copper, 520 thousand pounds of iron, 43 thousand pounds of lead and 8.7 thousand pounds of zinc would be removed in the form of runoff. Further, the pollutants would not be washed off uniformly, but rather vary with the time between major storms and with the intensity of rainfall. It is probable that the first storm of the fall (the period when the first dredging operation occurred) would wash off more pollutants than any succeeding storm because of the typical lengthy dry period in the San Francisco area which precedes the first storm. This is reflected in the data by a greater organism uptake during the first period than the second.

Uptake and accumulation of the chloride salts of silver, cadmium, copper, lead, and mercury by the clam Macoma balthica, were examined in a laboratory study (Anderlini et al, 1975). Exposure to three concentrations ($X + 2.5$ ppb, $X + 5.0$ ppb, and $X + 10.0$ ppb - where X is the concentration of the diluting water) of these metals under three salinity regimes (5 ppt., 12.5 ppt., and 25 ppt.), demonstrated uptake above pre-exposure levels and that the higher concentrations and lower salinities were associated with the greatest accumulations. Desorption was found to be greatest when M. balthica was exposed to water with the highest salinity. Using these laboratory results, it seems that the uptake observed during the field operations could very well be the result of salinity reductions and metal concentrations increases caused by urban runoff.

BIOLOGICAL RESPONSES TO DREDGING

Uptake of heavy metals by marine organisms has been substantiated. The part that resuspension of heavy metal contaminated sediments by dredging plays in this transfer is still nebulous. Based on the work by Serne and Mercer (1975) and Chen *et al* (1975) transfer via desorption to the water is insignificant compared to the loading induced by municipal-industrial effluents or urban runoff. The possible importance of the highly acid chemical environment in the organism's stomach upon clay minerals or organic molecules which have chelated or complexed trace elements is uncertain. The selective extraction schemes used by these same two investigators indicate that for the animal to free these elements from the atomic lattice of clay minerals, its gut would have to be made of materials more acid resistant than they are presently believed to be. However, gut acidity would probably be sufficient to break down most organic compounds (humic or fulvic acids, etc.) which typically have scavenged any available heavy metals. These materials are produced as breakdown or by-products of metabolic activities. The humic and fulvic acids are derived from herbaceous matter which degrades under bacteriological attack. Other organic molecules capable of complexing come from organisms' excretions, terrestrial detritus, and municipal-industrial discharges. These materials move through the water column until they are removed by ingestion or flocculation/aggregation and settling. During the period in the water column, the molecules will bond with other molecules or ions depending on respective charges. If ingested, the molecular chain or network will be broken down and the elements incorporated into the body fluids via passive or active uptake or will be voided. The elements taken up can be used in the cellular operations, stored or ejected after a period of time. Those elements that are stored can be concentrated to such a degree as to be toxic to the organism itself or to other organisms which might eat it. The exact level at which elements are toxic varies between species and even between individuals within the same species. If the organic compound settles before ingestion by filter feeders, it can be ingested by deposit feeders and the same gut processes, more or less, occur. If it is not ingested by macro-organisms, it will be attacked by benthic micro-organisms. These forms, principally bacteria, can break down the organic molecule, release the elements for future chemical reactions or uptake by organisms. Thus, when dredging and disposal operations occur, these organic complexes, sometimes partially broken down, are resuspended and again made available to various pelagic and filter-feeding organisms, and upon redeposition are available to the deposit feeding organisms in the area influenced by disposal.

CONCLUSION

Heavy metals have the potential for killing organisms, impairing their reproductive capacities (thus adversely affecting future generations), and poisoning their tissues such that their meat is inedible to other species, including man. Transfer of toxicants from sediments to organisms can occur either by ingestion or cutaneous absorption. Interstitial waters of the sediments are often enriched with certain heavy metals and thus are available for passive uptake by burrowing organisms. Resuspension of sediments under oxidized conditions can cause releases of low concentrations of some metals. The deposit feeders or mud-eaters can take up heavy metals as well as other toxicants, such as

pesticides or polychlorinated biphenyls, by ingesting these materials in association with mineral or organic matter. Thus, heavy metals may be taken up and accumulated by organisms following dredging and disposal activities via chemical reactions in the water column causing increased ambient concentrations or by ingesting and breaking down organic matter containing metals.

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SEDIMENT TRANSPORT IN THE COASTAL ZONE

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ABSTRACT

The results of research on initiation of motion and sediment transport in unsteady oscillatory flow from a research program underway at Massachusetts Institute of Technology are summarized. The results show the Shields criterion for initiation of sediment motion in steady flow to hold also for unsteady, oscillatory flow when the Shields parameter is based on the maximum bottom shear stress. A quasi-steady application of the Einstein-Brown sediment transport relationship is shown to yield a fairly good representation of experimental data on sediment transport in oscillatory flow. The relationship is then modified for application to sediment transport by waves and currents and an example is given from a computer application for sediment transport in the vicinity of a semi-infinite breakwater subject to a spatially varying wave and current field, in which the maximum wave orbital velocity, $u_b = 1.15$ m/sec (3.8 ft/sec), is considerably larger than the current velocity, $U = 0.15$ m/sec (0.5 ft/sec). The results are presented in a topographical map showing areas of scour and accretion of the order 2 cm/day (0.78 in) at a maximum.

INTRODUCTION

The transport of sediment in the coastal environment results from the complex action of forces on the ocean bottom caused by the interaction of waves and currents. When the wave motion is large enough to initiate movement of the bottom sediments, but the bottom force generated by the current alone is below that required for the onset of motion, the wave may, to the first order, be considered as a stirring mechanism making sediment available for transport by the current. If higher order effects are considered a net transport can result from wave induced currents, wave asymmetry, bottom slope or the effects of a porous bed. In the case where a current of significantly larger magnitude than that required for initiation of motion is combined with a large wave very little is known about what the resulting coupling of forces are. In the following paper only the first order effects of a wave motion with a small current superimposed are considered.

To avoid any confusion in the paper it should be made clear at this point that the following discussion is limited to cohesionless sediments under the influence of well behaved waves, i.e., away from the region of wave breaking. Thus we are limited to regions where the wave motion is predictable and the orbital velocities considerably larger than the currents present. The conditions are ideally satisfied by the region outside the surf zone along the continental shelf.

The results presented here are a necessarily brief account of the research conducted at R. M. Parsons Laboratory at Massachusetts Institute of Technology during the past two years. Further details of the study may be found in a forthcoming report and journal articles.

INITIATION OF SEDIMENT MOTION

The obvious starting point in studying sediment transport is to determine when the sediment actually starts to move. In a steady current, Shields criterion is a widely accepted measure of the onset of sediment movement on a flat bed. Under purely oscillatory, unsteady flow conditions, Madsen and Grant (1975a,b) show that the Shields criteria still applies when Shields parameter is based on the maximum shear stress, i.e.,

$$\Psi_m = \frac{\tau_{om}}{\rho g (S-1) d} \quad (1)$$

where ρ is the density of water, g is the acceleration of gravity, S is the specific gravity of the sediment and d is the sediment diameter. τ_{om} is the maximum bottom shear stress due to the wave, which is given by Jonsson (1966) as

$$\tau_{om} = \frac{1}{2} \rho f_w u_b^2 \quad (2)$$

where u_b is the maximum orbital velocity at the bottom and f_w is the wave friction factor. When the value of Ψ_m exceeds a critical value, Ψ_c , sediment motion occurs. This critical value is a function of the boundary Reynolds number defined in a Shields curve, thus making it possible, in a completely general sense, to determine when sediment will start to move given the sediment diameter, the specific gravity and the water temperature.

Since the bed generally will exhibit ripples, rather than being flat, the practical importance of the Shields criterion is somewhat limited. Its main importance lies in the fact that it establishes the importance of the Shields parameter, Eq. 1, in quantifying the fluid-sediment interaction. In this respect it should be noted that the experiments on initiation of sediment movement analyzed by Madsen and Grant (1975b) were obtained using quite different experimental procedures. The data of Bagnold (1946) were obtained by oscillating a tray in still water, whereas the data of Rance and Warren (1968) were obtained in an oscillating water tunnel. The similarity of these results obtained using different experimental techniques not only indicates the minimal effects of unsteadiness but may also be taken as an indication of the equivalence of the two experimental techniques.

RATE OF SEDIMENT TRANSPORT IN AN OSCILLATORY FLOW

Once a general criterion for the initiation of sediment movement

has been established, the next logical step is to determine the rate at which sediment is being transported once the critical value of Shields parameter is exceeded. In unidirectional steady flow a number of empirical sediment transport relationships relating the value of the transport rate to the value of Shields parameter are available. In oscillatory, unsteady flow it is important to realize that a net sediment transport arises as the (possibly small) difference between the (possibly large) amounts of sediment being transported back and forth. This points out that it is important first to quantify the rate of which sediment moves forward (and backward) in a purely sinusoidal flow. This problem has been studied extensively at the University of California at Berkeley by Einstein and co-workers and an account of this work is given by Einstein (1972). The Berkeley experiments which determined the average rate at which sediment was being transported without accounting for the direction of transport were performed by oscillating a tray in still fluid.

The Berkeley data was re-analyzed by Madsen and Grant (1975c) using the non-dimensional parameters originally suggested by Einstein (1950) for the analysis of sediment transport in steady flow, i.e., using the Shields parameter, Eq. 1 and a non-dimensional transport parameter.

$$\bar{\Phi} = \frac{\bar{q}_s}{wd} \quad (3)$$

in which $\bar{q}_s$ is the average volume transport rate of sediment per unit width; w is the fall velocity of an equivalent spherical particle of sediment and the overbar indicates that the time average is used.

From a plot of $\bar{\Phi}$ versus $\bar{\Psi}$ (Madsen and Grant, 1975c) a definite relationship emerges. This relationship is

$$\bar{\Phi} = c \bar{\Psi}^3 \quad (4)$$

where c is a constant.

The results on initiation of motion indicated that quasi-steady application of steady flow relationships may be applicable in unsteady flow. This is further supported by the resemblance of Eq. 4 to the Einstein-Brown sediment transport relationship for steady flow (Brown, 1950). The Einstein-Brown relationship applied in a quasi-steady manner can be written

$$\Phi(t) = 40\Psi(t)^3 \quad (5)$$

where $\Phi(t)$ and $\Psi(t)$ are the instantaneous values of the transport parameter, Eq. 3, and the Shields parameter, respectively. The instantaneous value of the Shields parameter is taken as

$$\Psi(t) = \frac{\frac{1}{2} \rho f_w u(t) |u(t)|}{\rho g (S-1) d} \quad (6)$$

in which $u(t)$ is the instantaneous near-bottom velocity and f_w is the wave friction factor based on the value of the maximum wave velocity. The absolute value sign on the velocity preserves the direction.

For sinusoidal oscillations such as in the Berkeley experiments

$$u(t) = u_b \cos \omega t \quad (7)$$

in which ω is the angular frequency $2\pi/T$ and T is the wave period. When equations 6 and 7 are substituted into equation 5, the resulting expression may be time averaged over the portion of the wave cycle when transport occurs in either the negative or in the positive direction. For the case of transport occurring throughout the wave cycle (effectively $\Psi_m > 2\Psi_c$) the expression becomes

$$\Phi = 12.5 \Psi_m^3 \quad (8)$$

As transport occurs over a smaller portion of time during the wave cycle, the curve gradually falls off. The resulting computed curve is shown in Fig. 1 and is seen to be in excellent agreement with the data of Manohar (1955).

Up to this point, nothing has been said about the roughness used to evaluate the wave friction factor. Drawing again on the approach used in steady unidirectional flow by Einstein (1950) the boundary resistance can be divided into a skin friction component and a form drag component accounting for the presence of bed forms. The skin friction component depends on the grain roughness and is considered responsible for sediment transport. The friction factor used in the analysis of the data presented in Fig. 1 was therefore taken from Jonsson's (1966) wave friction factor diagram corresponding to a boundary roughness equal to the grain diameter whether or not bed forms were present.

Thus a quasi-steady application of the Einstein-Brown sediment transport relationship has been shown to yield a fairly good representation of experimental data on sediment transport rates in oscillatory flow. It is therefore concluded that Eq. 5 may be adopted as the basis for further study of sediment transport in the coastal zone.

SEDIMENT TRANSPORT BY WAVES AND CURRENTS

For a purely sinusoidal motion it is obvious that the net transport predicted by Eq. 5 would be zero since the time average over one wave cycle is zero, but as indicated previously a net transport can result due to the presence of a current even if the current by itself

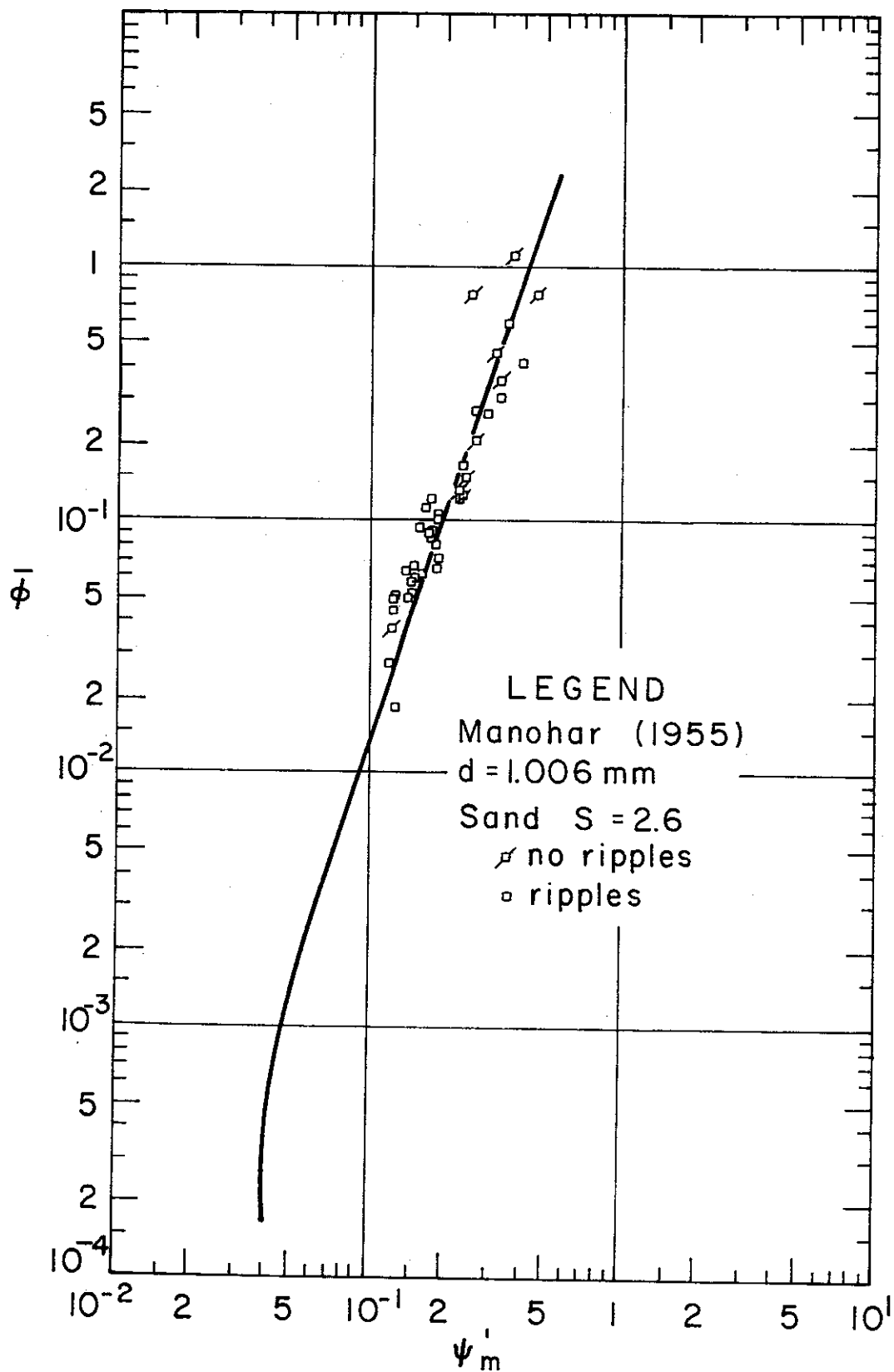


Figure 1: Empirical Relationship for the Average Rate of Sediment Transport in Oscillatory Flow.

is insufficient to initiate sediment motion.

To the authors' knowledge, the only experimental results dealing with sediment transport by waves and a weak current were obtained by Inman and Bowen (1963). They measured sand transport due to waves with a superimposed current travelling over a horizontal sand bed in a wave flume. Sand was collected in traps at opposite ends of the flume. Because wave conditions varied along the flume due to the dissipation of wave energy, a correction was applied so that the amount of sand collected in each trap would represent that amount which would have been collected had the wave conditions at the center of the flume existed at each trap. The results from eight experiments performed exhibit some rather peculiar behavior. Thus, part of the data seem to indicate a decrease in sediment transport although the current velocity is increasing and in one run the net transport is in the opposite direction of the wave and current direction. The reversed transport can be shown to be dependent on the fact that Inman and Bowen assumed the rate of sediment transport to be proportional to the maximum wave velocity cubed when making their corrections. In fact, by applying the correction using our experimentally substantiated transport relationship, Eq. 5, which shows the transport to depend on the wave velocity to the sixth power, the transport does not reverse. Inman and Bowen noted the presence of a reflected wave in their experiments but did not determine its magnitude. To properly correct the collected sand for the variation in wave conditions over the flume this reflected wave should have been accounted for. This was not done nor is sufficient information included in the paper to accomplish this. As a consequence the authors feel that this study does not shed much light on the phenomena of sediment transport by waves and currents.

The remainder of the paper describes the application of Eq. 5, to the determination of topographical changes due to a spatially varying wave and current field. To apply Eq. 5, it is necessary to know the instantaneous value of the bottom shear stress. This knowledge of the bottom shear stress resulting from the combined action of waves and currents is, however, incomplete so the results obtained can be considered only qualitative. Formally we may, however, take

$$\vec{\tau}_o(t) = 1/2 f_{wc} \rho |\vec{V}(t)| \vec{V}(t) \quad (9)$$

where $\vec{\tau}_o(t)$ is the time varying bottom shear stress now being considered a vector, f_{wc} is an appropriate friction factor for waves and currents and $\vec{V}$ is the instantaneous velocity vector

$$\vec{V}(t) = \vec{u}(t) + \vec{U} \quad (10)$$

in which $\vec{u}(t)$ is the wave velocity and $\vec{U}$ is the current velocity vector. The expression for τ_o is to be introduced in Eq. 5 which written in vector form reads

$$\vec{\tau}(t) = 40\vec{\tau}^3(t) = 40 \left(\frac{|\vec{\tau}_o(t)|}{\rho g(S-1)d} \right)^3 \frac{\vec{V}(t)}{|\vec{V}(t)|} \quad (11)$$

Following Jonsson (1966) we take the friction factor

$$f_{wc} = \frac{|\vec{U}|f_c + |\vec{u}(t)|f_w}{|\vec{U}| + |\vec{u}(t)|} \quad (12)$$

where f_c is the friction factor corresponding to a pure current. This formula has the feature of being correct in the limits of only waves or only currents, but it should be noted that it has only limited experimental support. Then with the above formulation, if the velocities are known, the problem is solveable.

As an example the case of sediment transport in the vicinity of a semi-infinite breakwater is considered. Due to the present lack of knowledge about the interaction of waves and currents of comparable magnitudes cited above, the example treats an incident wave with a velocity amplitude $u_p = 1.5$ m/sec (3.8 ft/sec) considerably larger than the current, $U = .15$ m/sec (0.5 ft/sec). For this situation the wave primarily determines the sediment transport capacity of the waves and the current.

The solution to the problem of the free surface oscillations associated with the diffraction of waves around a semi-infinite breakwater is given by Penny and Price (1952). From their solution the wave motion may be interpreted to consist of an incident wave, a reflected wave and scattered waves associated with the incident and reflected waves. The incident and reflected waves are plane waves described by linear theory and the scattered waves are cylindrical waves propagating essentially radially away from the breakwater tip. The amplitudes of the appropriate wave components are evaluated at a given point and linear wave theory is used to express the near-bottom velocities associated with each component. The various components are added vectorially with the direction of the scattered wave assumed to be radial. Thus the term $\vec{u}(t)$ is determined. The current, $\vec{U}$, is for this simple example taken as parallel to the breakwater and the water depth h is taken as a constant as is assumed in the diffraction theory. Thus, for given incident wave characteristics and reflective properties of the breakwater it is possible to obtain values for the velocity $\vec{V}$ in Eq. 10.

In the example illustrated here the water depth is taken as 15.2 m (50 ft), the incident wave height is 3.05 m (10 ft), the wave period is 10 seconds, the specific gravity of the sediment is 2.65 and the sediment diameter is .45 mm. The wavelength, f_w , f_c , the fall velocity w , and the critical value of Shields parameter are evaluated internally in the program. At every point in a grid system 10 wavelengths in each direction parallel and perpendicular to the breakwater measured from the tip and at quarter wavelength spacing the program evaluates the

critical value of the Shields parameter and determines if motion occurs. If motion occurs the program numerically integrates the transport, Eq. 11, over that portion of the wave cycle when $|\psi(t)| > \psi_c$ and calculates the time averaged net transport vector

$$\vec{q}_{net} = (q_{net,x}, q_{net,y}) \quad (13)$$

The resulting values of transport are spatially averaged between each grid point and these average values are substituted into the sediment continuity equation to yield the time rate of elevation change

$$\frac{\partial \eta}{\partial t} = \frac{1}{1-n} \left(\frac{\partial q_{net,x}}{\partial x} + \frac{\partial q_{net,y}}{\partial y} \right) \quad (14)$$

where η is the bottom elevation at any point, n is the porosity and $\partial q_{net,x}/\partial x$, $\partial q_{net,y}/\partial y$ are the gradients of the averaged net transport rate in the x and y directions, respectively.

Figs. 2 and 3 show the resulting regions of scour and accretion for the computer run described above. To understand what is presented in Fig. 3, it is instructive to look at Fig. 2 which shows the variation of the rate of change in bottom elevation a distance of two wavelengths behind the breakwater, along with the variation in the diffraction co-

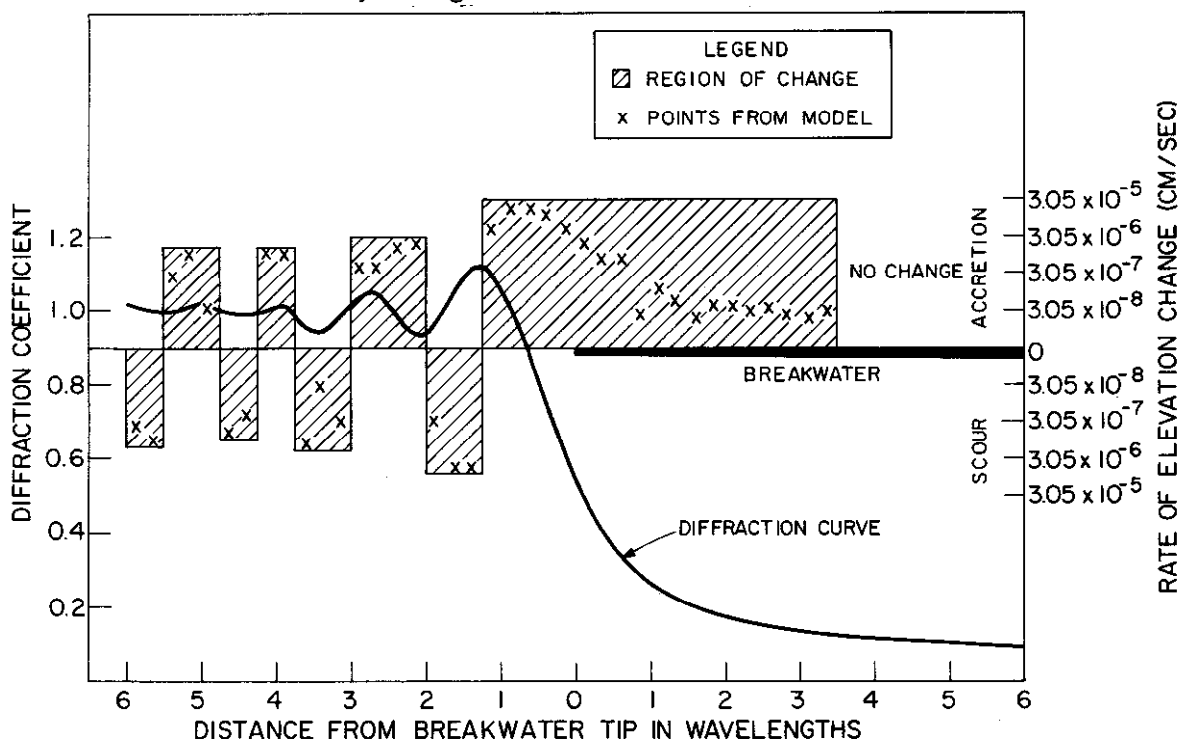


Figure 2: Diffraction Coefficient and Areas of Erosion and Accretion Two Wavelengths Behind Breakwater.

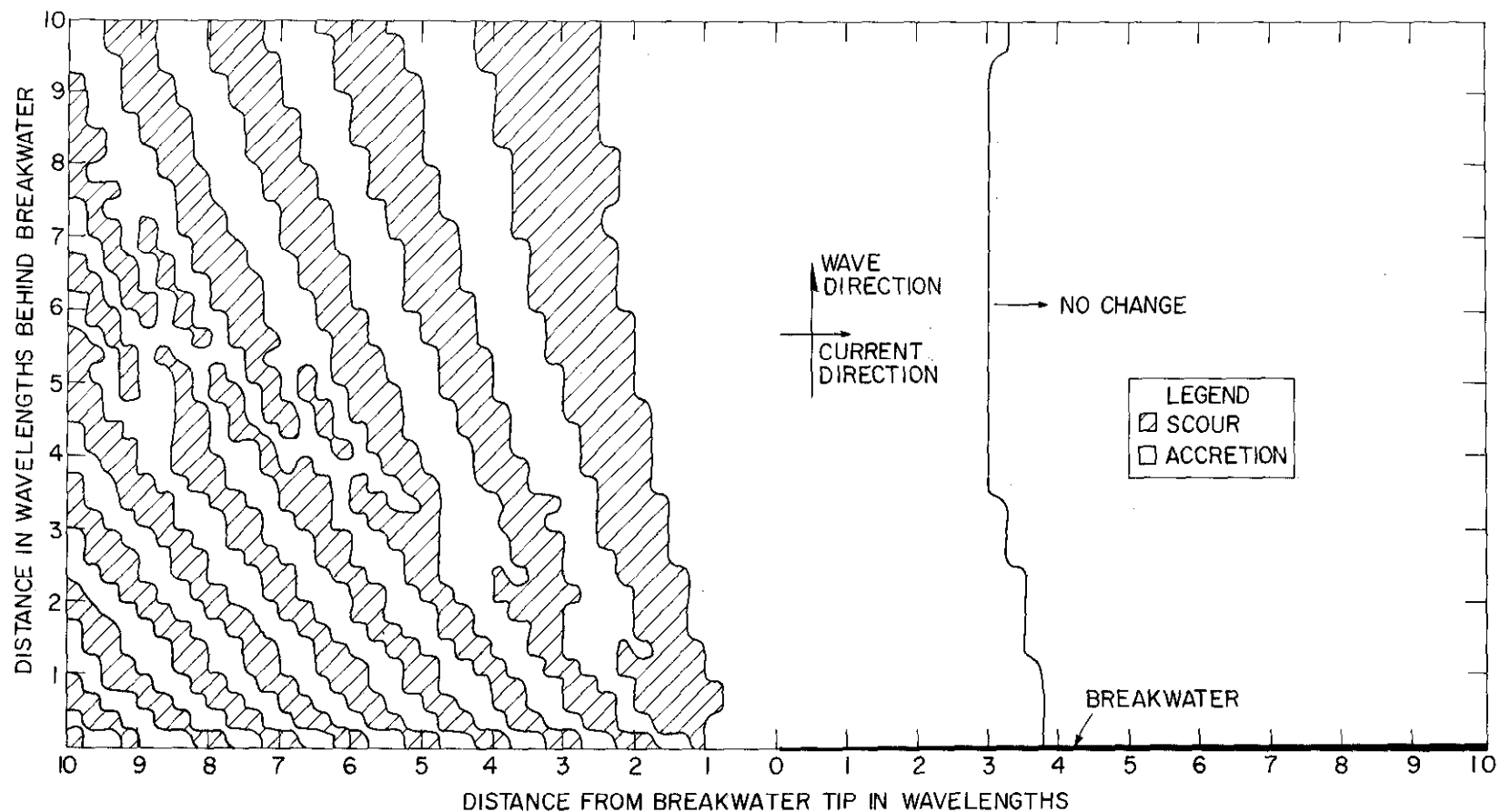


Figure 3: Topographical Relief Map Showing Regions of Scour and Accretion Behind Semi-Infinite Breakwater with a Normally Incident Wave and a Superimposed Current Parallel to the Breakwater.

efficient along this line. The important point demonstrated by this figure is the relationship between the location of relative maxima and minima on the diffraction curve with regions of scour and accretion. For example, between two wave lengths and one and one-half wavelengths to the left of the breakwater tip, a region of scour occurs. In this region the diffraction coefficient is increasing in the direction of the current causing progressively more sediment to be in motion and therefore available for transport by the current, as the tip of the breakwater is approached. From the sediment continuity equation, Eq. 14, it is evident that more sediment therefore will be transported out of than into each grid square. As the diffraction curve levels out, the gradient in the rate of elevation change also levels out. At about one wavelength to the left of the breakwater tip the diffraction curve starts to decrease in slope and an area of accretion is found which also follows the gradient in the diffraction curve. Finally, no transport occurs after approximately three and one-half wavelengths to the right of the breakwater tip. This point corresponds to a value of Shields parameter for the combined action of waves and current which is below the critical value of Shields parameter.

Any transect parallel to the breakwater in Fig. 3 will continue to exhibit the type of behavior illustrated by Fig. 2. The regions of deposition and accretion spread out with distance from the back of the breakwater and at the same time gradually decrease in magnitude as the influence of the scattered wave decreases. The results presented in Fig. 3 show only the region behind the breakwater due to the fact that the grid spacing used was too coarse to get adequate resolution in the standing wave region in front of the breakwater. The topographical changes in this region can be determined with more expense by using a smaller grid size.

The numerical values for the rate of elevation changes per day for the fairly severe wave conditions are of the order 1 cm (0.4 in) to 3 cm (1.2 in) in the region near the breakwater tip. This example using one wave height and direction is obviously not physically realistic, as these wave and current conditions would be expected to vary over the duration of a storm and it should be noted that the model is capable of accounting for this type of variation.

CONCLUSION

The results presented for the example of a semi-infinite breakwater are of a qualitative nature and indicate regions where loss of sand or buildup of sand can be expected. Further research into the bottom shear stress associated with the combined action of waves and currents is necessary before quantitative results from the above procedure can be accepted with confidence.

The application of the sediment transport model is only possible when the bottom shear stress can be evaluated. The ability to treat higher order wave effects, wave asymmetry, mass transport or bottom

slope can be incorporated into the model only when their effects on bottom shear stress and sediment transport are known. Research designed to try to incorporate some of these effects into the quantitative analysis of the net sediment transport rate associated with the combined action of waves and currents are presently being pursued at MIT and will be reported upon in future publications.

ACKNOWLEDGMENT

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SEDIMENT DISPERSAL IN WESTERN LAKE MICHIGAN NEAR TWO CREEKS, WISCONSIN,
AND
THE INFLUENCE OF AN INDUSTRIAL COOLING WATER DISCHARGE

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ABSTRACT

The sedimentary regime in Lake Michigan between Two Rivers and Two Creeks, Wisconsin was investigated during four field seasons, 1971-1974. The area was selected because a shoreline industrial cooling water discharge became operational in 1971. Sediment transport patterns, including natural short-term variabilities, were defined. Alterations in the near-shore deposition patterns were noted near the cooling water discharge.

The offshore sedimentary regime is composed of four types of sediment. Desiccated red clay of Valderan age (Pleistocene) is exposed, with little or no overlying recent sediment, primarily in nearshore waters in the northern half of the study area. Rocky gravels and gravelly sand predominantly occupy a lobate zone in the intermediate depths in the northern sector. Sand, mainly in the fine sand class, dominates the southern portion of the area, from the shoreline to depths exceeding 30 m (100 ft.) and extends northward in a band east of the rocky gravels and gravelly sands. Muddy sands are found beneath the deepest waters and in intermittent patches elsewhere. As indicated by the increase in sorting and decrease in grain size, the net transport of sediments offshore is north to south through the study area. Along the shoreline, the transport direction periodically reverses, but the net transport is from north to south. Pleistocene drift deposits form bluffs at the back-beach north of Two Creeks and act as a source for the modern sediments.

An anomalous zone of sand deposition was established along the shoreline to the north, in front of, and to the south of the cooling water outfall during the first years of plant operation. This sand patch was characterized by well sorted, very fine sand at its outer edges, grading to poorer sorted, coarser sediment directly lakeward of the outfall. Subsequent sampling has shown no further changes in the sediment deposition patterns near the outfall.

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INTRODUCTION

The coastlines of the Great Lakes and the oceans are attractive sites for industrial facilities requiring large volumes of cooling water, particularly nuclear and fossil-fueled power plants. Competition for use of the coastal zone is growing, and the effects of industrial discharges on the environment and multiple use potential of the coastal zone is an ever-increasing concern. While cooling water discharges interact with several elements of the environment--including temperature distribution and fisheries--this investigation studied the interaction of a cooling water discharge with the sedimentary regime. Annual variability of regional sediment distribution was mapped in order to interpret sediment transport patterns and the influence of a cooling water discharge. The problem centered on the nature of man-induced changes in patterns of natural sediment dispersal, erosion and deposition as a result of water jetted perpendicularly into the lake at the shoreline.

The study area was in western Lake Michigan between Two Rivers and Two Creeks, Wisconsin. Two nuclear power plants are located along this shoreline; one was operational during the study period. Both plants have once-through lake water cooling systems. The operational plant discharges cooling water through twin flumes, jetted nearly perpendicularly to the shoreline.

Several applications of this study can be identified. Used as a parameter of outfall design, sediment transport information can forestall deposition in the outfall area, and if nearby, the intake area. Erosion of the natural shoreline may be prevented, thereby removing later requirements for shoreline protection devices. Finally, environmental impact can be assessed. Thus, the problem of changes in patterns of sedimentation resulting from a new sediment transport mechanism, or a barrier to natural sediment transfer mechanisms, is of immediate economic and environmental significance.

STUDY AREA

The study area, located in western Lake Michigan off Two Creeks, Wisconsin, extended from the shoreline to 1800 meters (4 nautical miles) lakeward. While Lake Michigan lies near the edge of the Canadian Shield, it is entirely surrounded by Paleozoic bedrock. Glacial material ranges in thickness a few centimeters to 137 m (450 ft), but is typically less than 6 m (20 ft) thick (Thwaites and Bertrand, 1957). Along the shoreline, the back-beach is formed by Pleistocene deposits. South of the power plant, sand ridges are visible south past Rawley Point. North of the power plant and continuing to Kewaunee and beyond, glacial deposits, primarily a red till (the Valders deposit) form a high bluff. Bathymetry of the study area is shown in Figure 1.

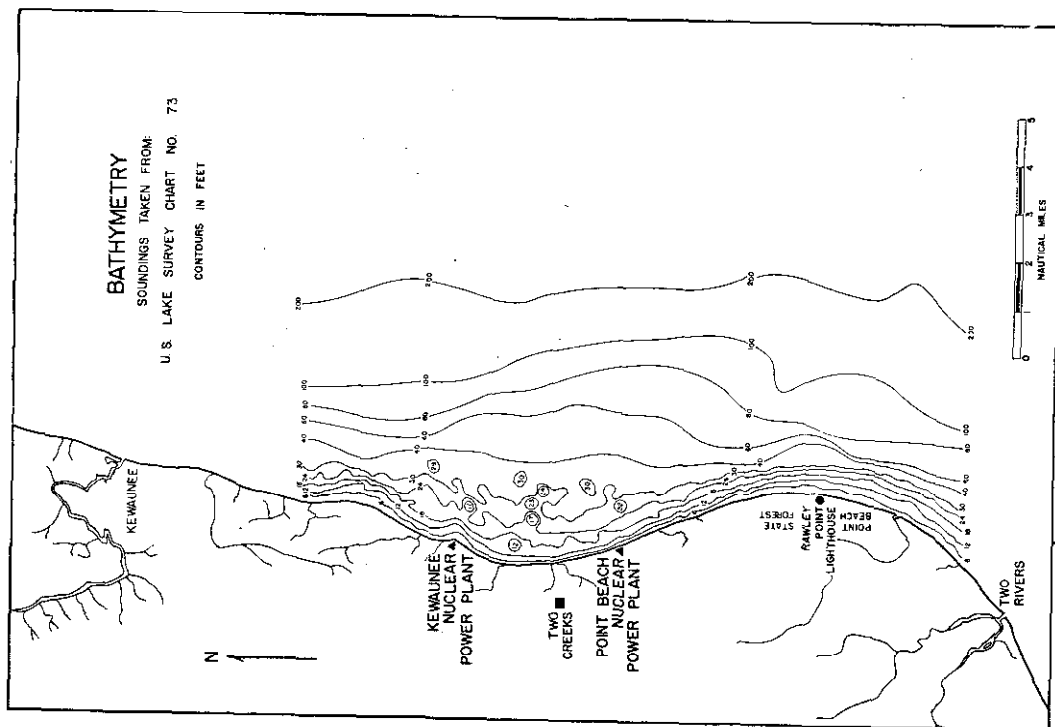


Figure 1.

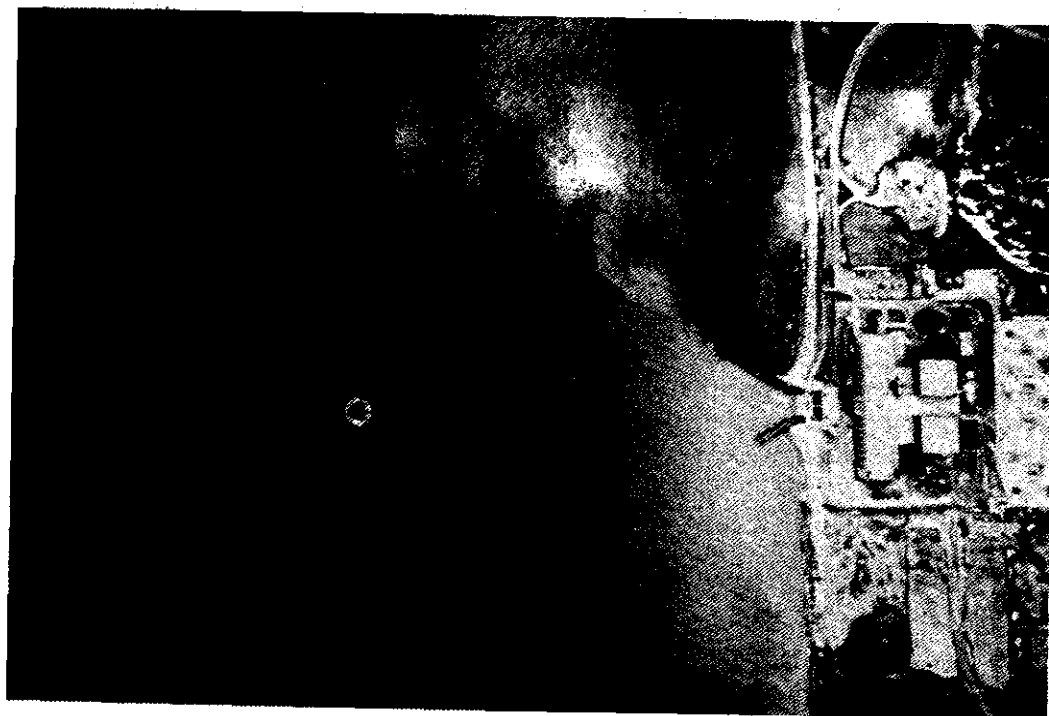


Figure 2.

Cooling water is discharged at the shoreline through twin flume structures. Only the southern flume was in use during the first two years of this study. The interaction of the plume with its receiving water was investigated by a team of Wisconsin Sea Grant physical oceanographers and civil engineers. While cross-sectional form and velocity structure of the plume along a line paralleling its direction of travel are not known in detail, there are indications of its structure from the temperature measurements. It is believed that the plume water sweeps through the entire depth of the water column, and in doing so impinges on the bottom for about one hundred meters (several hundred feet) after leaving the flume. It then begins rising to the surface because of its lesser density than that of the receiving lake water. It is known that the plume water leaves the bottom and begins rising to the surface at varying distances from the end of the outfall structure. Further, it is believed that this distance is on the order of 100 to 150 m (400-500 ft) from the end of the flume.

Aerial photographs, such as the one shown in Figure 2, show the relations at the surface between the turbid littoral receiving water and the clearer plume waters. When this photograph was taken (April, 1972), the littoral current was moving toward the south. While the littoral current and hence the cooling water plume typically flows toward the south, the direction is reversed on some days.

Changes in the volume of water discharged and changes in the dynamics of the receiving water, such as the opposing force of incoming wave energy, result in variations in the flow velocity of the plume. These velocities range from 27 m/min. (90 ft/min) to 60 m/min. (200 ft/min.).

METHODS

The R/V AQUARIUS, the University of Wisconsin's 12.5 m (41 ft) research vessel, was used as the platform for all sampling. A sampling grid was established in which east-west transects were made at 800 m (1/2 mile) north-south intervals. Transects along which samples were taken at 400 m (1/4 mile) east-west intervals alternated with those in the 800 m (1/2 mile) spacing. Two samplers were used: a Shipek grab sampler and a chain bag rock dredge. The Shipek, a spring-loaded sampler, used initially at each station, retrieved samples from the top 10 cm (4 inches) in sand bottoms varying to a surface scrape in stiff clays. Where the initial grab sampling indicated a rocky bottom, a chain bag dredge was used. All samples were placed in plastic bags for transfer to the laboratory.

Bulk samples were air-dried, then divided using a Humboldt Sample Splitter. The weight of the cut varied with texture; 50-75 grams of sand-sized material ranging up to 200 grams of pebbly or cobble-sand bimodal sediments. U.S. Standard sieves were used for textural analysis. Sieve sizes ranged from -2.0 ϕ (4mm) to 4.0 ϕ (0.062 mm) at one-half mile intervals. For samples composed in part by cobbles, a sieve of 64 mm

(-6.0φ) mesh was added. Statistical moment measures of the grain size distribution as defined by Mc Bride (1971) were calculated by computer. Sediments were also categorized using a system, shown in Figure 3, modified from Folk (1962). Station plots of the statistical measures and sediment classes were contoured by hand.

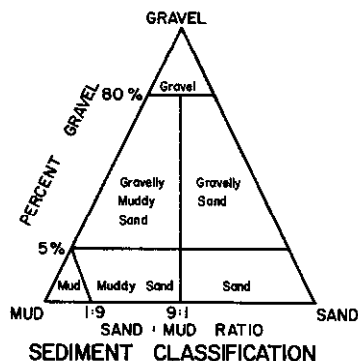


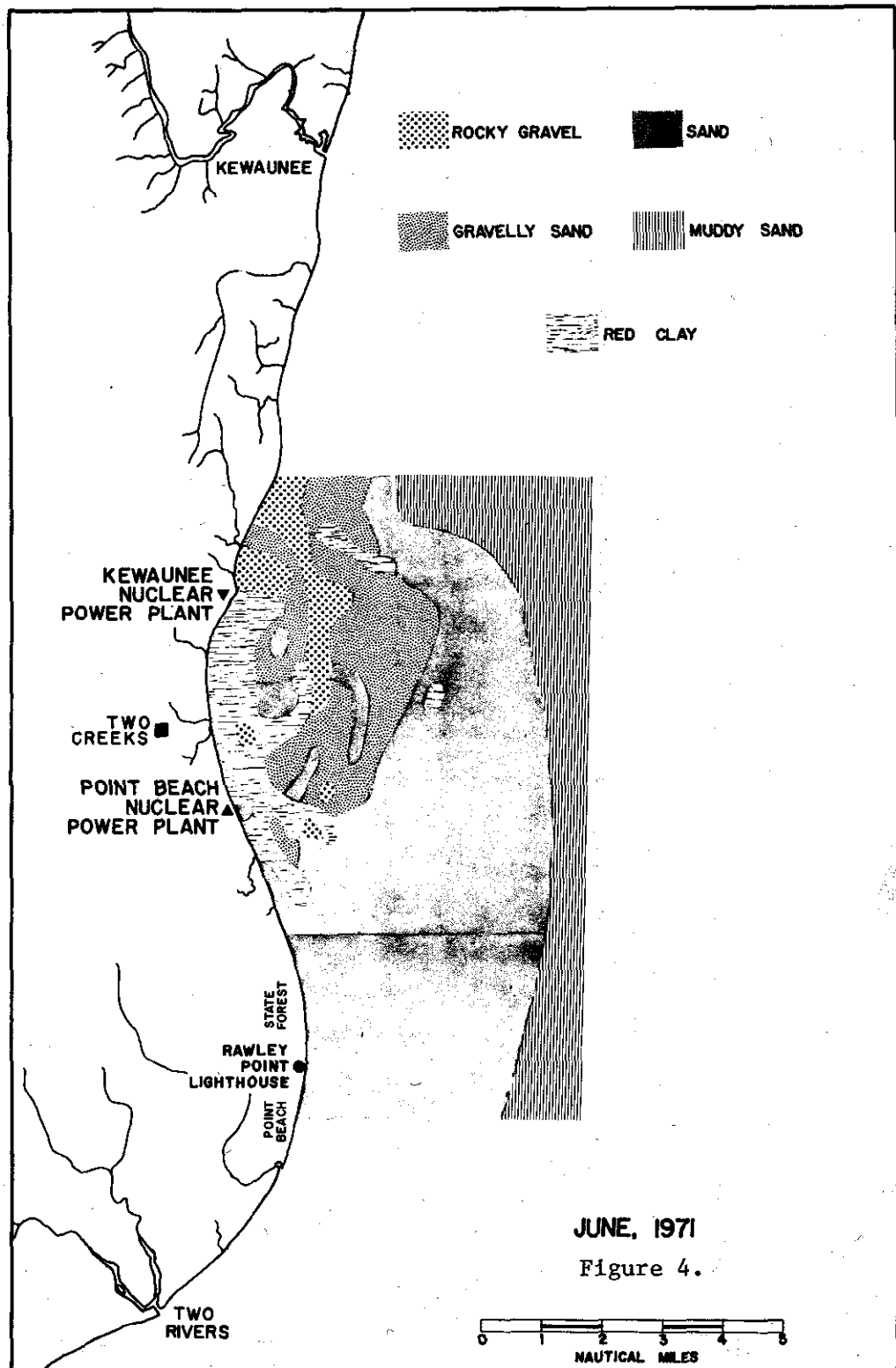
Figure 3.:

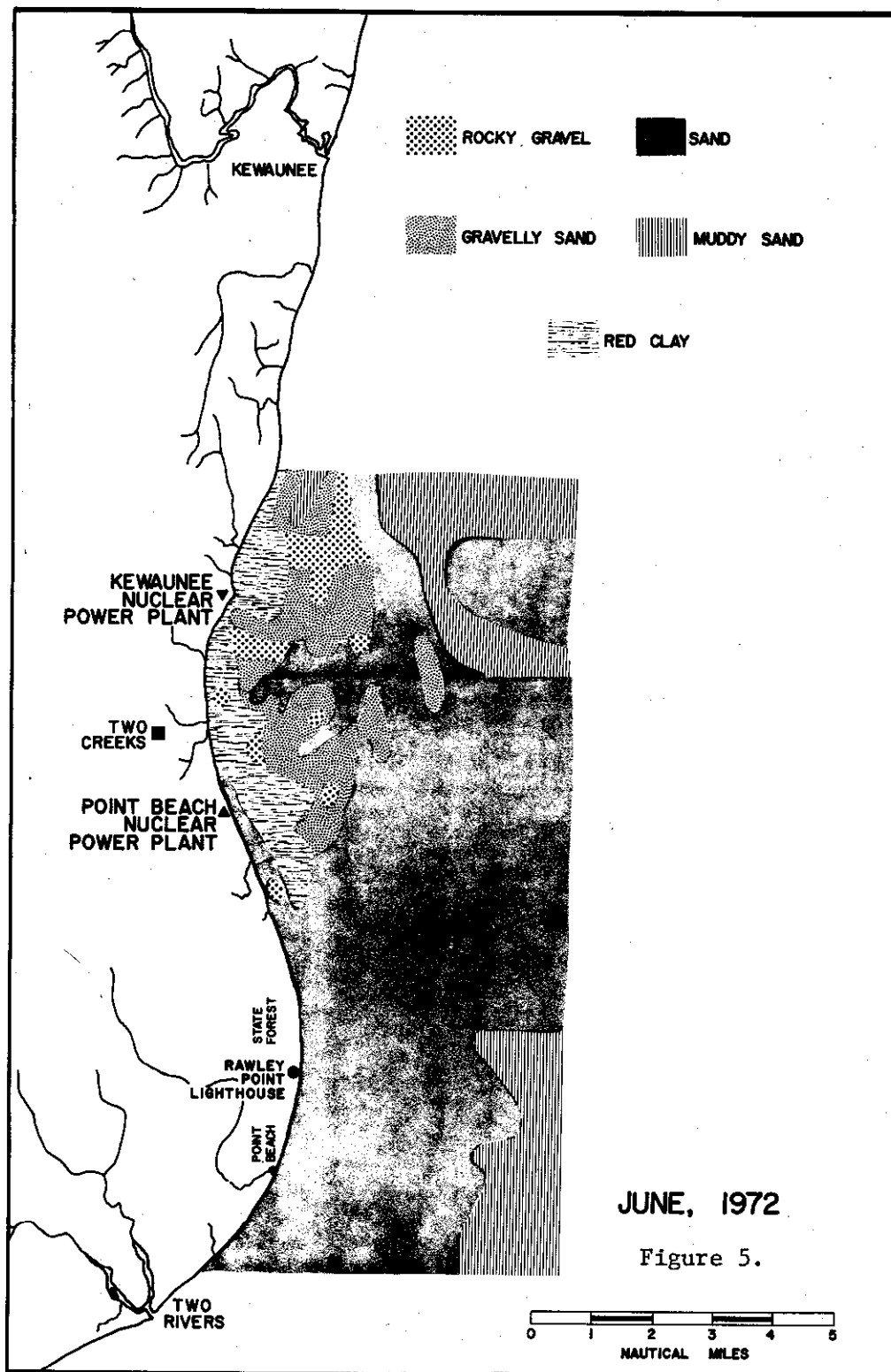
RESULTS

Four types of sediment were found in the study area: (1) a desiccated red clay of Valderan age (Pleistocene), exposed with little or no overlying recent sediment; (2) rocky gravels and gravelly sand; (3) sand, principally in the fine sand class; and (4) muddy sand. Figures 4 and 5 show the sediment distribution patterns in the first two years of this study; the last two years showed little change from these distributions.

The red clay occurs principally in the nearshore areas of the northern part of the study area, paralleling the coast but with lobes extending into intermediate depths. In 1971, patches of red clay were interspersed among the other types of sediment offshore. As reported elsewhere (Kohler and Moore, 1974), the red clay is the same material as the glacial drift which forms bluffs at the back-beach of the northern half of the study area. Frequently during sampling, a small amount of unconsolidated, very fine to medium sand and/or gravel and cobble was found in the samples together with a piece of hard red clay, broken from the surface by cutting edge of the Shipek bucket. This was observed near the boundaries of the "clean" clay with other sediment types. It is believed that the clay is covered in many areas by a veneer of unconsolidated sediments and that the patches of unconsolidated materials thin out at their edges, exposing the underlying red clay.

Rocky gravel and gravelly sand occur in patches, principally in the northern part of the area, typically between areas of "clean" clay and sand. If one views the areas of rocky gravel and gravelly sand as related deposits, it can be seen that there is a lobe of these materials in the intermediate depth offshore area. In 1972, a small patch of rocky gravel occurred nearshore south of the power plant. During sampling, large rocks retrieved from the northern zone appeared to have been partly buried in red clay. This was indicated by a sharp line of demarcation around the rocks, above which the surface was clean and well





washed and below which clay still adhered.

Sand was found in the southern zones and bounding the lakeward edge of the rocky gravel and gravelly sand zone to the north. By 1972, sand was observed in the nearshore areas lakeward of the power plant, where in 1971, "clean" clay had been found. Finally in the offshore and hence deeper waters, muddy sand was found.

Of the statistical measures computed, the dispersion (standard deviation) or sorting is perhaps the most informative in determining transport patterns. The sediments to the north are generally less well-sorted than those further south. In 1971 (Fig. 6), the lobe of coarser, bimodal materials--gravelly sand and sandy gravels--is reflected in the lobe of sorting values greater than 1. Sorting values below 1, both offshore and in the southern zone, reflect the fine sand nature of the surficial sediments. Along the shoreline between Point Beach Power Plant and Rawley Point were well- and very well-sorted fine and very fine sands. In 1972 (Fig. 7), the sorting values displayed an irregular pattern, particularly in the north. It is important to note that, directly in front of the Unit I flume, there was poorly sorted material, grading to better sorted sediments on either side. To the north of the power plant, the irregular pattern of the sorting values reflects the patchiness of the surficial sediments.

DISCUSSION

The study area can be characterized by a combination of relict sediments and recent unconsolidated materials. There is considerable difference in the nature of the unconsolidated materials, with patchy rocky gravel and gravelly sand dominated the northern zone and sand dominating the southern zone. Considering the distribution of the texture and sorting parameter and the theories of sediment movement, the transport of material through the study area can be deduced. From the principle which states that the most mobile sands are those in the fine sand class and that coarser fragments are less subject to transport, a north-to-south movement of sediment is indicated. The widespread occurrence of gravels and gravelly sands in the north and sands in the south bears this out.

The discovery of desiccated red clay along the shore and in scattered patches of the northern sector is central to this idea. While very close to shore, with only a few exceptions, this material was devoid of overlying unconsolidated, transportable sediment; further offshore, veneers of mobile material of varying coarse sediment surrounded by gradations of finer material were found in the intermediate depths of the northern area. That this sediment overlies a red clay basement was evidenced by the scattered clay patches found among this unconsolidated material. A picture emerges of mobile sediment moving from north to south over a surface of red clay, which being desiccated and consolidated, functions somewhat like a bedrock surface. The gravels would then be

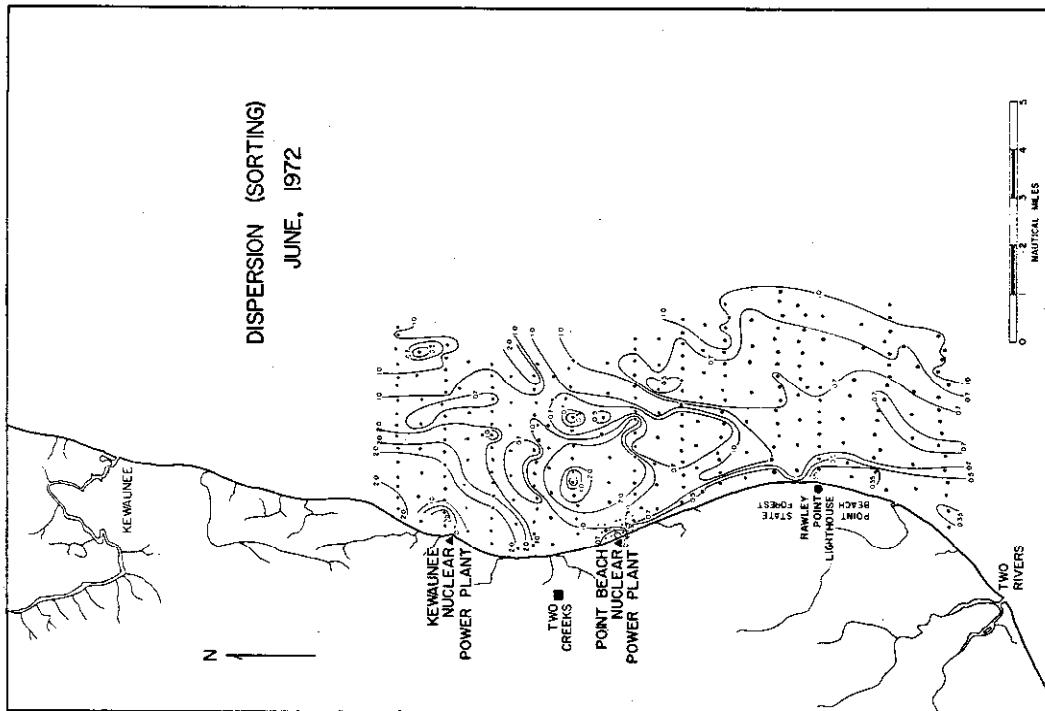


Figure 7.

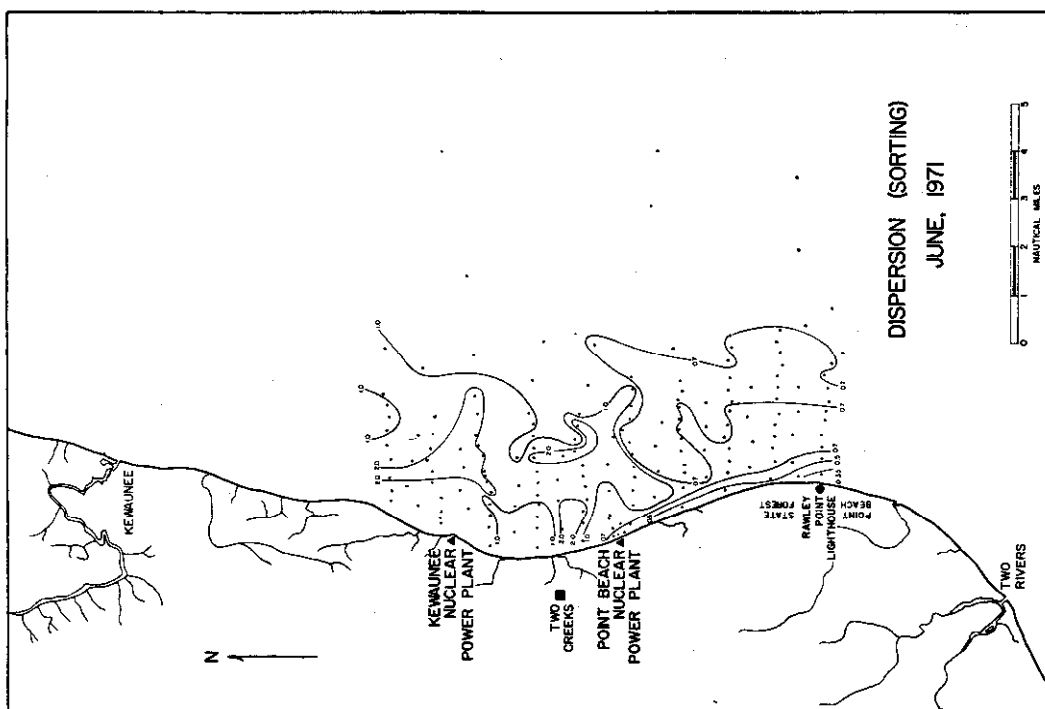


Figure 6.

moved only under high energy conditions in the fluid regime and would roll and slide, rather than be in suspension. The sands found among the gravels are more mobile and no doubt move through the northern part of the study area much more rapidly than the gravel. There are reports in the literature that the Valders deposits extend, on land at least, far south of the study area. Petersen (1967) showed these deposits to continue uninterrupted to the Milwaukee area. Thwaites and Bertrand (1957) published a cross-section along the shore of Lake Michigan near Two Rivers which shows a thick layer of Valders till and clay underlying more recent sand and gravel. These authors also noted that at Rawley Point, well logs indicate "sand with driftwood to a depth of 90 feet." (Ibid., p.876). Given this evidence that the Valders till extends along shore for the entire length of the study area, along with the recovery of similar material offshore, it can be concluded that a clay surface underlies, at varying depths, the recent sediments in the offshore area.

Why, then, does the northern sector of the study area have such different recent sediments than the southern zone? In fact, recent sediments are absent in some areas in the northern zone, particularly in the nearshore waters. And, why, given a north-south transport, does the sand, which is transported through the northern sector, come to rest in the southern zone? The answer lies in the bathymetry and the apparent slope of the clay surface. Recall that the offshore depths decreased much more gradually east of Two Creeks than east of Rawley Point. For instance, whereas the 15 m (50 ft) contour lies less than 1600 m (1 mile) offshore from Rawley Point, off Two Creeks it lies about 5000 m (3 miles) offshore. The shallow depth of the clay surface puts it into a position in the fluid regime where transportation is easily accomplished. As a result, either the clay is swept clean by the moving water or gravels are moved over the clay. Also, sand transported into this area from the north is winnowed out of the gravels to continue its outward transport.

Off Rawley Point, the clay surface dips to a lower level (Thwaites and Bertrand, 1957). The lack of clay bluffs bordering the beach in this area along with the well records attest to this. Because the clay surface is lower, deposition of modern sediments can still occur on top of it. The bathymetry, the depth of the clay surface and the competency profile of the fluid regime controls the zones of transport, erosion and deposition in the study area.

Given these patterns of transportation, erosion and deposition, what major changes have occurred during the period of study? The nearshore areas directly in front of the Point Beach Unit I flume have changed from a "clean" red clay surface with only scattered sand patches to a large, continuous zone of sand. In June 1971, at only three closely-spaced stations were fine and medium sands recovered. Surrounding this sand patch was the clay surface. By June, 1972, a sand patch had been deposited, forming a continuous lobe with the sand zone dominating the southern sector of the study area. The sorting values are poorest just south of the flume, with better sorting to either side.

The growing sand patch in front of the outfalls is a result of interactions between the littoral drift and the cooling water plume. As described above, as the turbid water of the littoral current approaches the upwind edge of the plume, it moves lakeward, covering a wider zone along the shore. It decelerates, and is finally deflected along the upwind edge of the plume. It must be remembered that the plume changes its path of flow and that the littoral current also reverses from time to time. Therefore, the turbid littoral water approaches the upwind plume edge from opposing directions at different times.

In order for sand being carried in suspension to be deposited, the flow and upward turbulent forces must diminish. It is believed that such decreases in the flow velocity and turbulent forces in the littoral current occur at the upwind sides of the plume. Owing to the reversals of the littoral current, sand has been deposited, over a period of time, on both sides of the outfall.

The textural changes found also agree with this proposed mechanism. Very fine, well-sorted sands were found farthest away from the outfall along the shore, grading to coarser poorly sorted material in front of the outfall. As deceleration of the littoral current occurs, the finer material would settle out first. The coarser material in front of the outfall is due to the plume sweeping over the bottom in various paths. As the plume flows over the bottom in an area where previously sand had been deposited, the fine sands are winnowed away and only the coarsest material remains.

CONCLUSIONS

1. The offshore sedimentary regime is composed of four types of sediment. Desiccated red clay of Valderan age (Pleistocene) is exposed, with little or no overlying recent sediment, primarily in the nearshore waters north of Point Beach Nuclear Power Plant. Because this material is of Pleistocene age, it has been identified as a relict sediment. Rocky gravels and gravelly sand predominantly occupy a lobate zone in the intermediate depths north of the power plant. While most of this material is recent, some of the larger rocks were resting within the surface of the Valderan drift and are therefore relict materials. Sand, mainly in the fine sand class, dominates the area south of Point Beach Nuclear Power Plant, from the shoreline to depths exceeding 30 m (100 ft) and extends northward in a band east of the rocky gravels and gravelly sands. Muddy sands are found beneath the deepest waters of the study area and in intermittent patches off Rawley Point.

2. The net transport of sediments offshore is north to south. This was indicated by the increase in sorting and decrease in grain size from north to south through the study area. Along the shoreline, the transport direction reverses, but the net transport is from north to south.

3. The anomalous zone of sand deposition was established along the shoreline to the north, in front of, and to the south of the Unit I cooling water outfall at Point Beach Nuclear Power Plant during the course of the study period. This sand patch is characterized by well sorted, very fine sand at its outer edges, grading to poorer sorted, coarser sediments directly lakeward of the outfall. The unnatural fluid regime resulting from the cooling water discharge is causing a zone of deposition along the shoreline. No significant adverse environmental impact can be attributed to this zone of sand deposition.

ACKNOWLEDGEMENTS

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COASTAL EROSION IN EASTERN LAKE MICHIGAN

by

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ABSTRACT

Rapid and extensive erosion has taken place throughout the eastern coast of Lake Michigan during the past several years (1968-73). The result has been millions of dollars of property loss and damage. Detailed monitoring of 17 beach profiles along nearly 200 miles of the Lake Michigan coast has provided substantial insight into the nature of the erosion and its probable causes.

Rapidly rising lake level caused the beach and adjacent dunes or bluffs to be vulnerable to wave attack. Erosion was quite localized during the first two years of the study and did not become universal until the final year (1972-73). During most times local factors predominate in controlling erosion and/or accretion on the coast. Longshore sand bars, coastal composition and shoreline configuration are most significant.

Erosion is common during the intense storms of late fall just prior to the formation of coastal ice and to a lesser extent just after ice melting in early spring.

Single storms may cause the bulk of the annual erosion at a given site. Rapid recovery of the beach may take place between individual storms however during later fall their frequency is such that recovery is not possible.

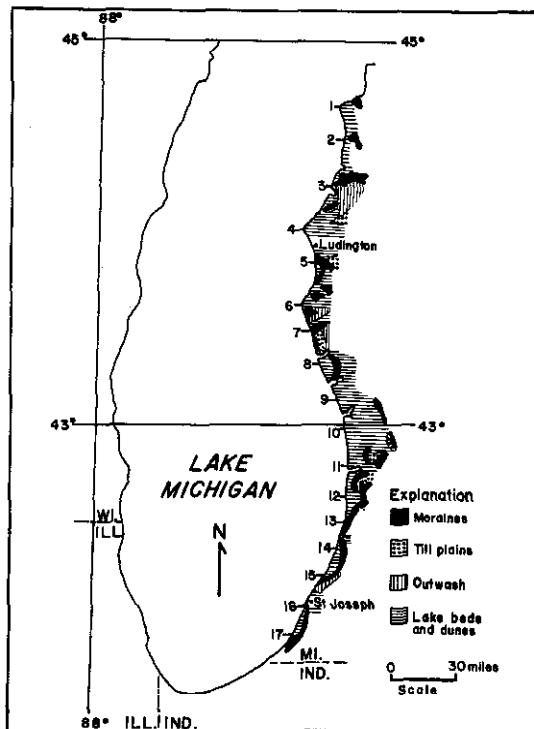


Figure 1 - Location map showing beach locations.

INTRODUCTION

During June of 1968 the author began to systematically monitor three beach locations in southeastern Lake Michigan. These sites were surveyed and beach sediment was collected every two weeks on a year-around basis. After more than a year of collecting these data it became apparent that coastal erosion was increasing and that this was coincident with rather rapid rises in lake level. These factors suggested that a widespread monitoring pro-

gram along the eastern coast of Lake Michigan might serve as the basis for both determining the specific causes of coastal erosion and also for predicting patterns of erosion during periods of future lake level changes.

Beginning in August, 1970 the study was expanded to include 17 locations (Figure 1), sub-equally spaced between Point Betsie on the north and Lakeside, Michigan on the south; a distance of near 200 miles (325 km.) of coast. The beach at each site was profiled and sampled at four-week intervals for a three-year period. Profile changes in the beach and adjacent coasts at each site were compared to weather patterns, shoreline orientation and configuration, composition and morphology of the coast and nearshore topography. Weather data were obtained from the U.S. Weather Bureau (ESSA) located at the Muskegon County Airport. Because of its central location along the eastern coast of Lake Michigan and the absence of any other first order weather stations within the study area, all weather data were compiled from this location. Nearshore topography was determined using fathometer profiles run during August, 1972.

GENERAL COASTAL GEOLOGY AND MORPHOLOGY

The entire coastal area is comprised of Pleistocene glacial drift and reworked drift. The latter may take the form of dunes, lake or estuarine sediments, or beach sediments. No bedrock is exposed along the study area.

Bluffs and terraces landward of the beaches are composed of moraines, till plains, outwash, lake beds and dunes (Figure 1) with the latter being most widespread. The beach and nearshore zone is composed primarily of sand with scattered gravel at most locations, however there are a few sites where gravel is dominant. There are also a few sites where glacial till was temporarily exposed on the lake bottom in the surf zone or on the beach. This, as well as other data (Davis, 1970), indicates that the thickness of the beach sand prism over the Pleistocene "bedrock" is quite thin. Resistivity surveys at several locations have shown the thickness to range from 3 to 10 feet at most of those sites where data are available.

Although the eastern Lake Michigan coast has a general north-south orientation, the orientation of the 17 study sites is from N25W to N43E, a range of 68 degrees. The most prominent large-scale features are Point Betsie, Big Sable Point and Little Sable Point, all of which occur within the northern half of the study area (Figure 1).

The east coast of Lake Michigan is quite variable in composition and morphology. It is possible to find active dunes, stabilized dunes, till bluffs, or lake beds adjacent to the beach throughout the coast. As a result, the determination of a cause or causes for erosion is complicated by the general lack of uniformity of the coast in essentially all respects.

There is one aspect of the coastal morphology however that is rather widespread or at least was so at the initiation of the study. This is a low-lying sand terrace which is located behind the active beach and lakeward of the dunes, bluffs or whatever comprises the coast. The terrace is generally less than 10 feet above lake level and in 1970 its width ranged from a few feet to more than 50 feet along the eastern coast. It is formed during low lake level

periods when there is great accumulation of backbeach sediment. Onshore winds and occasional washover of waves, pile sand in the backbeach zone. This area is quickly stabilized by dune grass and shrubs so that in a period of from a few years to a decade or so the terrace is fully developed and somewhat stabilized. Formation of these terraces is therefore easily accomplished between periods of high lake level. Likewise these terraces are quite susceptible to erosion and may be completely removed during high lake level.

Lake Levels

One of the few variables of this coastal environment which shows significant temporal change but is essentially uniform throughout the study area is lake level. It is evident from nearly a century of data that there is considerable lake level fluctuation on both a long term and short term basis. Long period fluctuations generally range between 9 and 13 years and may have a magnitude of up to 4 feet in the mean annual lake level. This change is the result of fluctuating rainfall within the Michigan-Huron drainage basin and may be quite significant in terms of coastal erosion.

There is also an annual lake level cycle which is fairly predictable and is generally about one foot in magnitude. It is a seasonal fluctuation resulting from changes in the availability of water over a year's duration. Annual high levels are typically in July or August whereas the low is generally in February when there is little or no runoff due to freezing temperatures (Figure 2).

Astronomical tides are not factors in coastal processes because of their low amplitude. Storm surge or storm tides caused by intense weather systems and high winds may cause increase in water level in excess of one foot on eastern Lake Michigan (Fox and Davis, 1970).

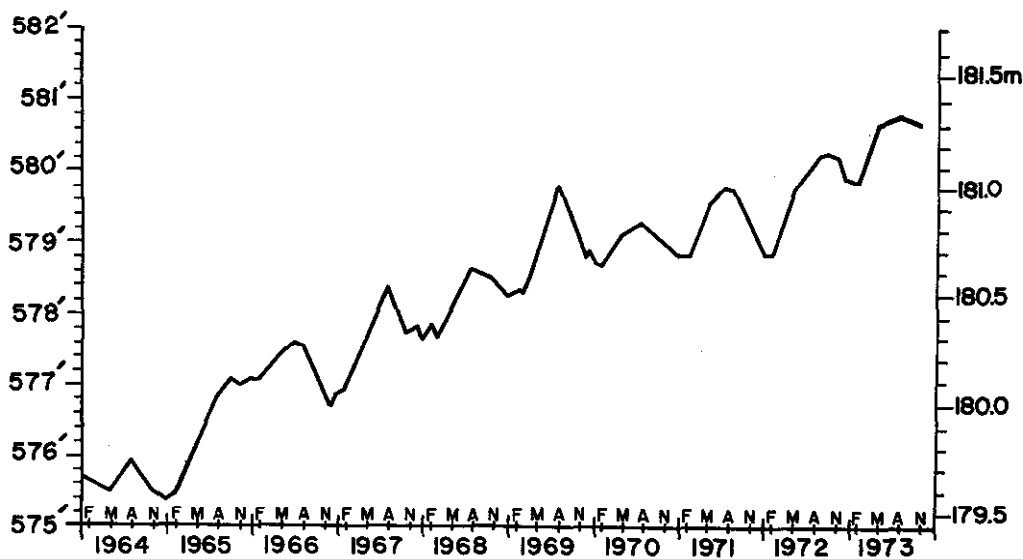


Figure 2 - Lake Michigan levels from 1964 through end of study period.

of sand was removed from a stretch of beach 800 feet long (Fox and Davis, 1970; Davis and Fox, 1971).

Meteorological Data

Weather Patterns

Low pressure systems or cyclones generally move across or to the north of the eastern coast of Lake Michigan during the summer months and they move to the north during the winter. Most intense physical energy is generated by the winter storms because of the generally higher winds than during summer. Late fall through early spring is the time when cyclonic systems pass most frequently (Figure 4). During the three year study there was an average of 40 cyclonic systems that past through the area. This is comparable to the annual average of 43.2 cyclonic systems passing over the Lake Michigan area between 1938 and 1970 (Seibel, 1972).

Because of the general consistency in the total number of storms that passes through the area annually it is apparent that this is not an important variable with respect to the annual or long term periodicity of coastal erosion. Typically, the most intense storms develop during late fall and winter. Because of the ice cover from January through March, the storms during November and December are most effective in coastal erosion. There may also be extremely intense storms during summer but they are not common. One such storm during July, 1969 caused severe erosion on the southeastern coast of Lake Michigan (Fox and Davis, 1970).

Data on wind velocity and direction were obtained from the U. S. Weather Bureau located at the Muskegon County Airport. Wind roses for each of the three study ears show the expected similar patterns with two modes, one from the southwest and one from the northwest. This pattern is similar to that found for a ten-year period from 1960-1969 (Seibel, 1972). Climatological data show that the prevailing winds are those from the southwest and the pre-dominant winds are from the northwest. The latter are generated by the trailing side of the cyclonic system as it passes over the Lake Michigan area.

It is evident that storms are a key factor in coastal erosion and that, as a result, essentially all of the coastal erosion occurs during only a small percentage of the time. Following the method of Seibel (1972), a storm day was designated as any 24 hour period during which the wind velocity has a mean value of 15 mph. During the three-year study period there was a total of 16.7% of all days which fell into this category. It should be noted that there was a nearly exact distribution among each of the three years, but within each year there is an obvious seasonal trend. The period of November through May represents the high energy period with the greatest concentration from January to April (Figure 4). It is also important to note the mean wind direction for storm days lies between the south and north-northwest direction.

Ice and its Effect on the Coast

One of the most important factors in the overall scheme of coastal processes and erosion on the eastern coast of Lake Michigan is the ice that forms on the beach and adjacent nearshore zone. This ice generally begins to accu-

A small ephemeral bar may be present, particularly just after storm conditions or during low energy periods of the summer months. This bar is generally less than 100 feet from the strand line and has less than 3 feet of water over its crest. Commonly the bar will migrate shoreward during low energy conditions and eventually weld to the beach (Davis, et al, 1972).

Most of eastern Lake Michigan contains two longshore bars although one or three are present at some locations. These bars are fairly stable (Davis, and McGeary, 1965) however, they have been shown to move slowly in response to changing lake level conditions (Saylor and Hands, 1970). They are also rather continuous based on aerial photographs and field surveys. The longshore bars are generally rather poorly known in terms of their migration, stability, and storm modifications.

Processes

With the notable exception of significant astronomical tides there is no general difference between beach and nearshore processes operating along eastern Lake Michigan and those on marine coasts (Davis and Fox, 1972; Davis, et al, 1972). Waves and currents form the dominant processes with wind being of only minor significance. Currents are primarily of two types: longshore currents and rip currents. Because of limited fetch in the Great Lakes, swell is not prominent in coastal processes.

There is an apparent cyclic nature to the processes operating along the eastern coast of Lake Michigan with the most prominent underlying cause being that of passing weather systems and in particular, fluctuations in barometric pressure (Fox and Davis, 1970; 1971; 1973). In this latitude, weather systems move in a generally west to east path due to the prevailing westerly winds. As a low pressure system (storm) approaches, the wind is from the southwest in the cyclonic system. This generates waves which approach the coast at an angle open to the north and thus generates northerly flowing longshore currents (Fox and Davis, 1971). As the storm approaches the eastern coast of the lake there is an increase in wind velocity, wave height and longshore current velocity which accompanies the falling barometer. As the center of the storm passes over the coast there is an abrupt change in wind direction due to the flow of air on the trailing side of the cyclone. This produces strong winds from the northwest, and a change in direction of wave approach and longshore current. Immediately after this shift in wind direction, the barometric pressure rises abruptly and this is characteristically the time of most intense physical energy imparted on the coast (Fox and Davis, 1971).

The above described processes occur in a cyclic fashion with a period of 5 to 8 days. Intensity of the physical energy imparted to the beach varies depending upon the change in barometric pressure and the proximity of the cyclonic system to the coast. Typically, storms of late fall and winter are the most intense although summer storms may also be severe (Fox and Davis, 1970).

During storm conditions, winds in excess of 35 mph, breakers of 3 to 4 feet, and longshore currents of 3 feet per second are not uncommon (Fox and Davis, 1970; 1971; 1973). Extremely large quantities of sediment are moved under such conditions. During a summer storm in 1969, nearly 4,000 cu. yds.

During the past decade there has been rather extreme lake level conditions. The all-time low occurred during 1964. Since then there has been an abrupt increase in lake level so that the level reached in 1973 is the second highest in recorded history. The rapid increase and its associated erosion is now coupled with great monetary losses because of the expanding utilization of the coast for private, public and industrial development. As a result, several million dollars have been lost in property damage. Much of this economic disaster could be avoided through wise regulation of coastal zone utilization. It is hoped that this study will be an aid to better utilization of this coast and in the prevention of similar losses during future periods of high water level.

BEACH MORPHOLOGY AND PROCESSES

Morphology

The eastern Lake Michigan coast is characterized by sand dunes and bluffs of glacial drift. Lakeward of these features a low-lying sand terrace is typically developed although this feature may be absent or exist for only a few years from place to place.

Erosion dominates during periods of rising lake level due to the combination of wave activity and encroachment of the strand line into the backbeach zone. This results in alteration of both the shape and the width of the beach with minimal beach development during high level (Figure 3). In fact, there are sites on eastern Lake Michigan which have recently had no beach at all during high energy periods of late fall when storms are common. Erosion reduces the gradient of the foreshore whereas accretion results in a greater inclination. During recent prolonged periods of erosion the foreshore zone may comprise the entire beach.

Beyond the foreshore the profile slopes rather gently to the nearshore area where longshore bars and troughs are typically present (Figure 3). These bars are quite continuous and extend through the eastern Lake Michigan nearshore area; however, their position and depth varies.

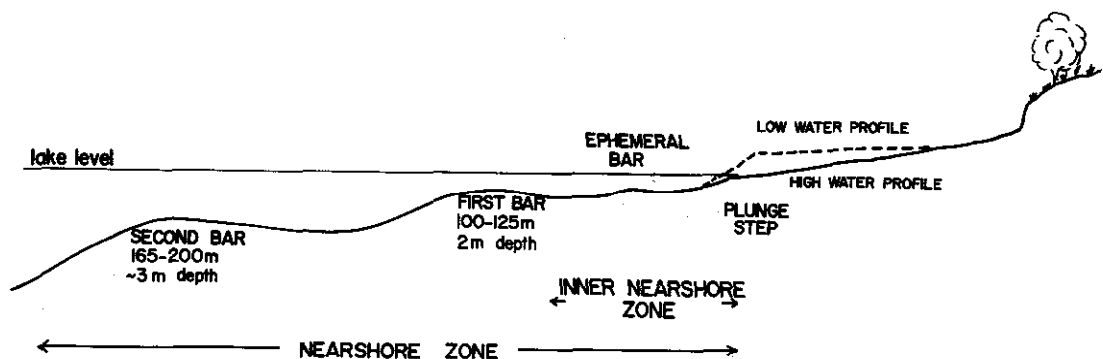


Figure 3 - Generalized beach and nearshore profile for eastern Lake Michigan.

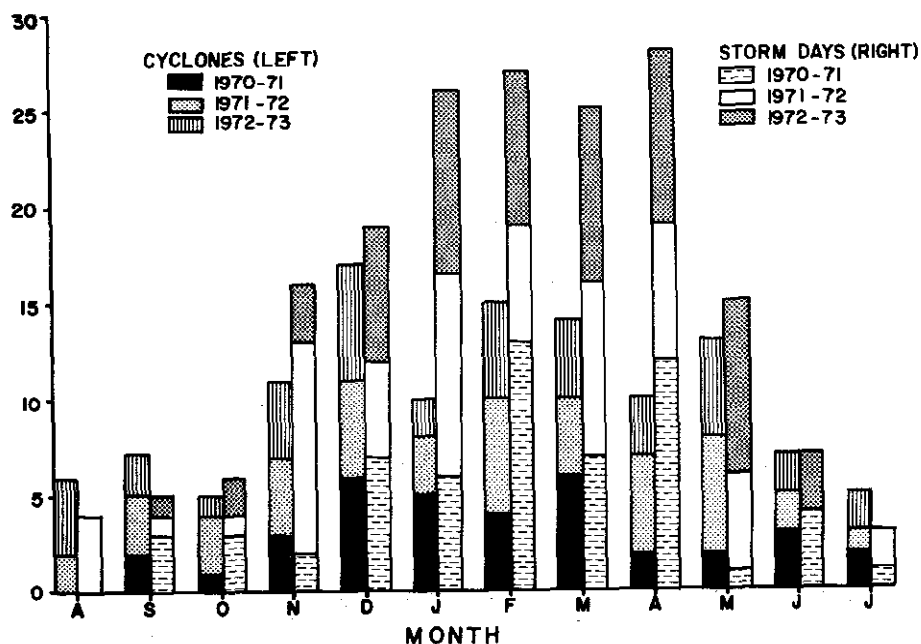


Figure 4 - Monthly occurrence of cyclones and storm days during study period.

mulate in late December. By the first of the year it is well developed and the coast is a "zero energy" coast from the standpoint of coastal processes. This situation prevails until melting which begins in early March and is completed by the end of March or early April. At that time the beach resumes its extremely dynamic nature. The change from a static or ice-protected coast to a completely dynamic one may take place in just a day or two.

The protection afforded by the ice is extremely beneficial inasmuch as it comes at a time when it is needed most. The months of January, February and March combine to have the most storm days of any three month period (Figure 4). The presence of the ice totally negates the storms, however, because ice commonly extends about a quarter- to a half-mile from the shore.

BEACH PROFILE CHANGES

The primary method of monitoring, analyzing, and evaluating beach changes was by means of monthly surveys of the beach and adjacent areas. A profile was surveyed from the dune, bluff or terrace across the beach to the base of the foreshore. In addition to the profile survey, a color photograph was taken at each site during all visits to provide a pictorial history of the changes experienced by each beach. Summarization of the 17 beach sites is based on both the profile surveys and the photographs. In the following discussion, terrace or bluff recession or erosion refers to the amount of lateral retreat of the steep portion of the profile that lies landward of the active beach. The term erosion is used to denote removal of sediment from the profile whereas accretion indicates addition of sediment to the profile.

Discussion of Profile Changes

Although it is difficult to generalize about the changes in beach profiles

there are several factors which are apparent when one looks at the entire spectrum of time and location. There is a general absence in patterns insofar as erosion and accretion are concerned. During the first two years of study this was particularly true, however there was much more uniformity to the erosion during the third year (Figure 5).

Considering only the beach, which is quite fragile and easily changed, it is possible to gain an appreciation for the tremendous temporal and spatial variations. During a four-week sampling interval there is time for a wide range of coastal conditions so that only net changes are recorded during the site visits. These net changes may reflect gradual processes or short term and intense storm activity. In some situations there was storm activity which caused terrace or bluff erosion however the net beach change after the four-week sampling interval was one of accretion. This testifies to the rapid changes that take place on beaches.

A compilation of beach changes at each location over the three years of the study demonstrates the aforementioned variability. Only three of the 38 sampling periods show uniformity in the changes over a four-week interval. In one of these (July, 1971) there were only 7 of the 17 sites that showed change and all exhibited beach erosion. Both of the other two periods (September, 1970 and September, 1972) were during the same month of the year and showed beach erosion at 12 and 17 locations respectively. In December, 1972 only 10 sites were not bound by shore ice and all but two of the 10 showed erosion. These were the only periods of the 38 included in the study that showed any uniformity and all were periods of erosion. The reason for this occurrence in September is apparent. Late summer (August or September) is generally the time of maximum lake level within the annual cycle. As a result, an early fall storm will have an important impact on the coast.

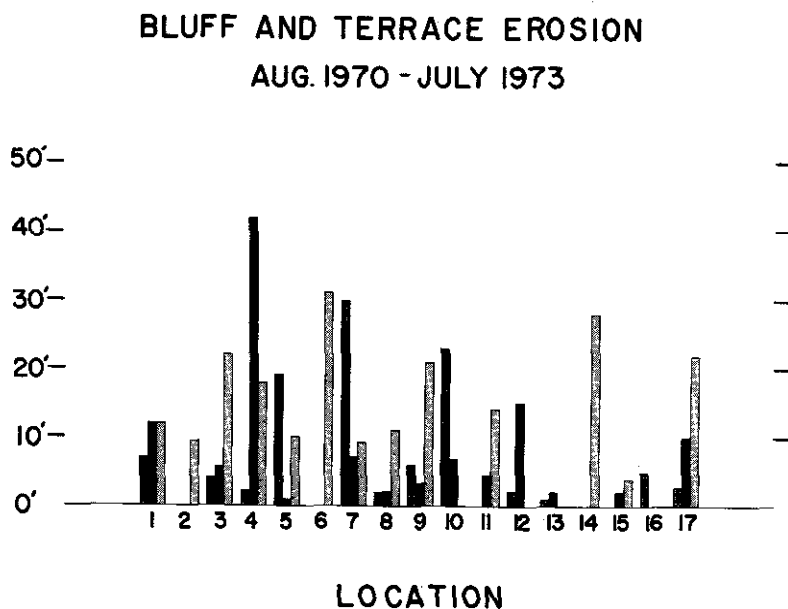


Figure 5 - Summary of bluff and terrace erosion during three-year study period.

There were some periods when substantial portions of the eastern Lake Michigan coast were subjected to the same process. During storm periods in late fall, beach erosion took place across large segments of the coast, typically the southern portion. This was the case in November, 1970 and November, 1971. In December, 1970 and 1972 the northern sector experienced erosion. Although less common, the same generalization is also true for beach accretion. In December, 1970, locations 11-14 experienced a new growth of the beach. A similar situation prevailed during other periods at other sections of the coast.

Sediment Budget

In order to obtain at least a semi-quantitative sediment budget for the sites monitored, the changes in profiles were determined and converted to sediment volumes (Table 1). These annual changes were calculated using the extension of the lake level at the start of the study as a datum. Annual changes were taken from the profiles plotted at the end of each study year. In order to obtain sediment volumes, a width of one foot was used for each profile.

A glance at the profile diagrams or the sediment budget data (Table 1) indicates the great variability alluded to in previous discussions. Although all sites show a net loss over the three-year study there are some which do show net accretion in one-year periods except for the final year during which all sites experienced erosion. In the first year three sites had net accretion as the result of beach growth whereas five locations experienced 100 cu. ft. of sediment loss. The following year three different sites showed a net beach growth and 100 cu. ft. of sediment loss was effected at five locations. Ten of the locations lost 100 cu. ft. of sediment during the final study-year. Only four sites lost less than 100 cu. ft./ft. during the three-year study period.

Table 1 - Annual changes in sediment volume at each location. Units are in cubic feet.

<u>LOCATION</u>	<u>Study year</u>			<u>TOTAL</u>
	<u>1970-71</u>	<u>1971-72</u>	<u>1972-73</u>	
1	-26.0	-128.5	-222.0	-268.5
2	+33.5	-19.0	-42.0	-27.5
3	-103.5	-115.5	-153.0	-372.0
4	-174.5	-395.5	-492.0	-1062.0
5	-149.0	+15.0	-39.5	-173.5
6	+68.5	-66.0	-115.0	-112.5
7	-169.0	-1.5	-18.5	-189.0
8	-10.0	-29.0	-16.5	-55.5
9	-87.5	-52.0	-192.5	-332.9
10	-40.5	-77.0	-9.0	-126.5
11	-24.5	-58.0	-112.5	-195.0
12	-148.0	-14.0	-193.0	-355.0
13	-3.0	+46.0	-59.5	-16.5
14	+14.5	-79.0	-202.5	-261.0
15	-9.0	-140.0	-112.5	-261.5
16	-51.0	+30.5	-62.5	-83.0
17	-14.5	-135.5	-190.0	-340.0

SUMMARY AND CONCLUSIONS

There are a number of summary statements regarding recent coastal changes on eastern Lake Michigan that are appropriate.

1) Coastal erosion is definitely linked to high lake levels however this phenomenon plays a passive role not an active one. Primary evidence for this is the fact that erosion was not ubiquitous during the first two years but it was in the third year when lake level was extremely high. There is evidently a critical level beyond which erosion is universal. This level is apparently about 580.0 feet for eastern Lake Michigan.

2) Local factors predominate in controlling erosion and/or accretion during most conditions. Of these factors the nature of longshore sand bars and coastal composition and configuration appear to be most significant. Natural shoreline local embayments or protuberances are significant and clayey till is extremely resistant to wave attack.

3) Sand terraces behind the active beach have remarkable capabilities of regeneration during periods of low lake level and apparently can form in a decade or two as evidenced by artifacts incorporated in them.

4) Storms are the dominant energy force with the bulk of the coastal erosion taking place in only a small percentage of the total elapsed time. As few as two or three major storms per year can account for the majority of the erosion. By the same token there is extremely rapid recovery of beaches between storms. Only a week or two is necessary in most instances.

5) There are obvious seasonal variations in the coastal processes with late fall and early spring being the periods of greatest energy. Winter ice cover affords excellent protection for the coast.

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