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ENVIRONMENTAL EFFECTS OF HYDRAULIC DREDGING IN ESTUARIES

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NOTE

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ABSTRACT

Hydraulic channel and shell dredging and open water spoil disposal have little significant immediate effect on water quality in Alabama estuaries. Almost all of the sediment discharged by dredges settles very rapidly and is transported by gravity along the bottom as a separate flocculated density layer and potentially harmful components of the mud are not dissolved into the water. There is a limited, temporary reduction in benthic organisms in areas affected by dredging. Spoil piles from channel dredges can indirectly affect the ecology and usefulness of estuaries by interferring with water circulation and altering salinity. The basic hydrological concepts which determine the effects of dredging should be applicable in other areas. Extensive regulations apparently are not necessary to protect water quality in open water dredging situations but spoil disposal practices from channel dredges must be reconsidered and appropriate new disposal plans developed.

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INTRODUCTION

Hydraulic dredging is one of the most noticeable, controversial and significant activities of man in estuaries. Among the many uses of estuaries including fishing, industrial sites, recreation and waste disposal, these water bodies have long been used for navigation and as a site for mineral recovery. Dredging has been necessary for the development of almost all of those activities and will be necessary for them to continue. The question has now arisen whether dredging and open water spoil disposal as it has been done in the past is compatible with some of the other water uses because of possible physical alterations, secondary pollution or other harmful effects. Multiple water use is indeed one of the more important environmental problems and the effect one activity has on another has become increasingly significant. Because of its conspicious character, the possible harmful effects of hydraulic dredging on the environment has caused more public arousal than any other estuarine activity with few possible exceptions. Sufficient information on the effects of dredging has not been available to allow those concerned to evaluate the problem comprehensively. Recent environmental and water quality considerations have made it apparent that more knowledge is needed by those involved in the practice and its regulation.

The objectives of this study were to determine the immediate and long term physical, chemical and biological effects of hydraulic dredging and open water spoil disposal in estuaries with particular emphasis on Mobile Bay, Alabama. This was done by field studies of sediment transport and water quality around active dredges including shell dredges, a ship channel maintenance dredge and an intracoastal waterway maintenance dredge. The impacts of these operations were interpreted in relation to how ambient and natural or background conditions were altered. Existing conditions of water and sediment quality were determined throughout Alabama estuaries and partially compared to numerous other estuaries along the Gulf of Mexico. Literature on the effects of dredging and open water spoil disposal and other germane studies were reviewed. A main objective of this study was to review the question and define important concepts that govern how dredges may affect water quality in order to provide a basis for interpreting study results and to supply a framework for further investigation.

Definition of the Problem

Hydraulic dredging is of major importance to the commerce and economy of all coastal regions in the United States. Water transportation is dependent upon channel construction and maintenance by the U. S. Army Corps of Engineers who currently dredge approximately 373 million cubic yards of spoil annually in the U. S., of which 164 million cubic yards is along the Gulf Coast (Mobile District, pers. comm.). Large industrial complexes are dependent on dredging for access to the sea and intracoastal transport of raw materials and manufactured products.

Buried shell is one of the more important natural resources found in estuaries. Industrial demand for this almost pure source of calcium carbonate is great and several major industries are dependent upon it. Limestone cannot presently be substituted economically for shell for industrial uses in coastal areas (Kerr, 1967; Hill and Masch, 1969). Private companies annually dredge about $30 million worth of unprocessed clam and oyster shells from Gulf Coast estuaries and the resource makes a substantial contribution to the economy of many coastal areas. In addition, royalty from shell dredging contributes about $3 million each year to conservation activities in the Gulf States (May, 1971). Shells from this source are extensively used for cultch on public oyster beds in many states and the practice has greatly increased oyster production. Effectual management of public and private oyster reefs is largely dependent on planting dredged shells in Alabama as well as in other states since no satisfactory substitute is available in the volumes used.

Hydraulic channel dredging and shell dredging make use of essentially the same equipment although there are distinctions in operations. Channel dredges construct or maintain navigation channels. Maintenance of existing channels contracted to private firms presently makes up most of their activity. In this operation, recent alluvium and water are pumped from the bottom of the channel and the spoil is discharged by pipeline some distance away from the channel. Shell dredges operate outside of channels in the open estuary on a practically continuous basis. Dredged material is screened and washed to remove the shell. The discharge, composed mostly of original bottom material, is returned overboard in the immediate vicinity of the dredge and usually over the hole from which it was taken.

Concern about dredging has been mainly local until the past few years. In most cases the major concern has been whether or not dredging was destroying oysters. Recent federal actions placed considerable national emphasis on the environmental aspects of spoil disposal and other discharges into navigable waters. Although individual states generally adopt and enforce their own water quality standards, the authority is basically national since state water quality standards must comply with federal guidelines. There is presently a problem of what operational or quality standards should be applied to dredging and spoil disposal and whether the same criteria can be applied nationwide.

The major problem related to dredging is whether changes in circulation and water depth and the discharge of mud and water back overboard detrimentally affect the aquatic environment or man's use of it. In addition to natural mud components, a large portion of municipal and industrial wastes and other pollutants discharged into waterways end up in the estuaries. Consequently, a portion of these become deposited in the bottom sediment and may become concentrated over a period of time to levels many times higher than those in the overlying water. Theoretically, there may be a possibility of secondary pollution by resuspension of these materials.

Estuarine sediments are effective traps for many organic and inorganic materials because of sorption and ionic processes. Among these constituents are several which can influence water quality if dissolved into the water, some harmful, some beneficial and some insignificant. Some of these materials have a potential to degrade water quality and can be damaging or toxic to marine life. Some of these chemicals can become highly concentrated by aquatic organisms which in turn render them unfit for consumption by other animals, including man.

In addition to potential chemical and biological effects, dredging and open water spoil disposal may have significant physical effects on estuarine waters. Deep channels alter previously existing salinty regimes by allowing sea water to penetrate further into estuaries. Spoil piles in open water interfere with small boat navigation and normal water circulation and mixing. Spoil from dredges may discolor the water, interfere with primary productivity, rearrange bottom sediments and cover benthic organisms. There is some concern that modifications of estuaries and the physical presence of an active dredge may affect wildlife and aesthetic values.

From the positive position, many benefits occur from dredging. The concern for environmental degradation and the vital economic nature of this activity make an understanding of the effects of dredging essential. It should be accepted that dredging in some form must be continued and that the most realistic approach to the problem is to understand the effects of the practice fully before trying to apply expensive restrictions on the dredging industry and those dependent upon it. Placing proper emphasis on what dredging does and what it does not do is an important step in insuring that dredging is done with the least harm and that regulatory policies are realistic from both environmental and economic standpoints.

In dredging studies the physical, chemical and biological aspects should be clearly defined. It should be recognized that changes in the physical or chemical properties of water which may affect aquatic organisms are generally more convenient to measure precisely in the field than monitoring the effects on organisms directly. The problem of the effects of dredging should be approached by determining, (1) the physical and chemical character of the surrounding water and the bottom materials to be dredged, (2) the extent to which dredging and spoil deposition physically and chemically alter water quality, and (3) the effects of dredging practices on aquatic communities. These objectives should be approached by determining the direct or immediate effects and the indirect or consequential effects. The significance of these effects should be interpreted by comparison with the effects caused by natural conditions. The extent and the duration of effects should also be weighed in perspective to the entire ecosystem.

Regulation of Dredging

Channel Dredging

Construction and maintenance of navigation channels has historically been under the jurisdiction of the U. S. Army Corps of Engineers. Corps of Engineer permits are required for all private dredging in navigable waters and public notices are issued on almost all projects. An Environmental Impact Statement is required for most Corps projects and some private projects. In reviewing permit requests the U. S. Environmental Protection Agency has jurisdiction over water quality and the U. S. Bureau of Sport Fisheries and Wildlife and the National Marine Fisheries Service consider effects on fish and wildlife. State agencies comment on these aspects before permits are issued. Responsibilities of various agencies are basically defined by Federal law although judicial and executive rulings sometime influence dredging projects. On occassions, criteria are established by Federal agencies by the issuance of guidelines. In addition to federal permits, channel dredging projects require a local sponsor to provide spoil sites. This is usually done by port authorities, industries, or local or state governments.

Numerous publications are available from the Corps of Engineers which describe their individual projects or district activities. A nationwide evaluation of dredging projects is currently underway at the Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi.

Shell Dredging

The shell dredging industry in the Gulf States has been reviewed in Texas by Kerr (1967) and Hill and Masch (1969), in Louisiana by Louisiana Wild Life and Fisheries Commission (1968), in Mississippi by Gunter (1969) and in Alabama by May (1971). A resume of the entire Gulf Coast industry is being prepared by Robert H. Arndt of the U. S. Bureau of Mines. Each Gulf state regulates dredging through a permit or contract lease system. Leases are either exclusive or nonexclusive. Alabama, Louisiana and Mississippi operate under an exclusive lease system and regulation is by contractural agreement. Texas has a nonexclusive lease program while Florida has both exclusive and nonexclusive leasing.

Rules and regulatory procedures vary between states and within states at different times but all provide for control of dredging operations to insure that damage is not done to other natural resources. Dredging operations are either limited to a fixed distance from oyster reefs, monitored when in the proximity of reefs to prevent damage, or are not allowed where oysters are cultivated. Distances from bridges, shorelines and navigation channels are frequently stipulated. In addition, the U. S. Army Corps of Engineers issues permits for shell dredging after evaluating effects on navigation, esthetics, recreation, fish and wildlife and discharge of effluents into navigable waterways which must be in compliance with state and federal water quality standards. State legislatures sometimes impose restrictions on dredging. In most shell dredging operations the regulatory authority and responsibility is the function of a state conservation agency.

LITERATURE REVIEW

There are several nontechnical references to dredging which are of historical interest, some as early as the nineteenth century. Although dredging has had a long history there have been relatively few studies carried out on the environmental effects of dredging until the past few years.

Gunter (1938) was the first to cite the benefits of using dredged oyster shell for cultch material.

Lunz (1938; 1942) investigated dredging of the intracoastal waterway in South Carolina and in Florida. He determined that oysters were not harmed by high turbidity or spoil from dredging unless they were actually buried and smothered. He found that mud in high concentrations was not toxic to oysters and that spawning and spat setting were not affected by the operations.

Wilson (1950) studied the effects of shell dredging in Copano Bay, Texas. He found that suspended solids of 33 to 58 g/l may be found near the discharge of a suction dredge and that suspended material caused by the dredge dissipated rapidly. The heavier material such as larger shell fragments and coarser sand was deposited in the immediate vicinity of the discharge. Turbidity from the dredge which was above background levels extended out to 300 to 900 feet on most occasions. On one occasion suspended material above background levels was found 1,800 feet from the dredge. He stated that the direction of movement of suspended material was in the direction of the current and that the amount which moved away from the dredge decreased with distance. Material transported beyond 900 feet was very slight. In other directions, no suspended material was detected beyond 600 feet from the dredge. A considerable amount of the material placed in suspension settled in to the cut from which it was taken. He subjected oysters in laboratory aquaria to very high concentrations of suspended silt and stated that if such levels were maintained in the water for a long period it would be detrimental to oysters. He found no correlation between amount of spat set and distance from the dredge or with amount of suspended material in aquaria. He said dredging may be beneficial to oyster production by building firm spoil piles which catch spat and produce oysters and by digging deeper areas thereby facilitating water circulation in shallow bays.

Ingle (1952) and Ingle, Ceurvels and Leinecker (1955) studied shell dredging in Mobile Bay, Alabama. In the first paper, damage to fish and motile crustaceans was not observed even within 75 to 150 feet of an active dredge. Shellfish suspended from the dredge were unharmed. Silting effects were observed on bottom out to a distance of 150 to 1,200 feet from the discharge. He suggested that dredging stirs up organic detritus which may be beneficial to shellfish and crustaceans and mentioned that shrimp were apparently more abundant in waters muddied by dredging. In the second paper the authors were concerned with inorganic and organic nutrients, carbohydrates, fats and proteins contained in the muds. An attempt was made to determine if muds contained toxic components and if mud in suspension was harmful to fish life. No toxicity, including hydrogen sulfide, was found but high mud concentrations killed fish held in tanks by clogging their gills. Fishes were thought to avoid these high concentrations and to be unaffected in the open bay. High turbidity created by dredges was limited to a small area in the vicinity of the discharge.

Hutton et al. (1956) studied Boca Ciega Bay, Florida with special reference to dredging and filling. Conditions resulting from dredging and filling were harmful to most plant and animal life although under certain conditions there was some evidence that dredging operations were beneficial to echinoderms, ascidians and sponges. Land fills from dredging were damaging to sport and commercial fishing and recreation.

Viosca (1958) felt that fish and shrimp congregated near dredges in Louisiana and that dredging was beneficial. He attributed this to the dredges stirring up food and nutrients.

Breuer (1962) reported that major ecological changes resulted from channel dredge spoil in South Bay, Texas due to progressive closure of passes and hinderance of water circulation by spoil deposition. Because of these changes commercial and sport fishing in the bay were reduced to insignificance. However, dredging of an intracoastal canal into the lower Laguna Madre eliminated periodic fish kills resulting from hypersalinity.

Engle (1962) wrote a review of shell dredging and discussed the pros and cons of proposed shell dredging in North Carolina. He pointed out that monetary and oyster rehabilitation benefits are accrued from shell dredging and that the question of exploitation of this valuable buried shell natural resource required a thoughtful and unemotional approach.

Hellier and Kornicker (1962) did a before, during and after study of sedimentation from a hydraulic channel dredge in Redfish Bay, Texas. They did not measure the dredging directly but attempted to measure silt deposition by placing colored gravel chips on bottom at various distances from the operation. The gravel was put out at least 9 months before dredging and core samples were taken before dredging, 1 week and 18 months after dredging. They reported 22 to 27 cm of sediment deposition within one-half mile on the dredge but effects at greater distances were negligible. They felt little sediment sorting occurred during dredging.

Mackin (1962) studied canal dredging in Louisiana. He found that silt was carried a maximum of 1,300 feet and that at distances greater than a few hundred feet, turbidities did not exceed those attained at times under natural conditions. He calculated that only about one percent of the spoil was transported away from the immediate vicinity of the discharge. Fine material was lost in the natural turbidities at distances over 1,000 feet and had the same effect on the environment as the materials put in suspension by natural conditions. Turbidities produced by shrimp trawlers were not excessive but they were greater than those produced by the dredge at distances of 300 feet from the spoil discharge. Turbidity levels outside the influence of direct spoil deposit did not harm oysters. He considered it unlikely that dredge spoil would significantly reduce dissolved oxygen and stated that the factors which control silt deposition had not been properly considered in previous studies.

Odum and Wilson (1962) studied dredging of an intracoastal channel near Redfish Bay, Texas and found that respiration exceeded photosynthesis in the dredge tailings, possibly because of organic matter in the dredged sediments. Photosynthesis was not diminished much during or after dredging as compared with data from a previous year and the additional respiration due to extra organic matter did not apparently interfere with normal production. They hypothesized that high production and dense grass found after dredging may have resulted from release of nutrients.

Odum (1963) measured chlorophyll A and diurnal oxygen production over grass beds in Redfish Bay, Texas before and after the dredging of an intracoastal canal. The cause was uncertain but he found productivity temporarily decreased and an imbalance of respiration over photosynthesis which may have been associated with dredge silt in the spring. The following year he found growth to be exceptional and suggested that nutrients released by dredging may have been the cause.

McCoy and Johnston (no date) studied sedimentation of soils collected from proposed shell dredging sites in Albermarle Sound, North Carolina. They considered a chlorinity content of 19.5 ppt as full strength sea water and suspended soils in 0, 5, 10, 15 and 25 percent of this concentration. They used transmitted light to measure sedimentation under calm conditions and in a wind tunnel. They found that the mud settled faster in salt water than in de-ionized water and that a 14 mph wind would keep sediment in a jar suspended. On this basis they concluded that sediments disturbed by a dredging operation can be expected to settle in salty water during low or no wind velocity and become resuspended by winds of approximately 14 mph or greater, thereby creating an "accumulated turbidity" which could detrimentally affect an aquatic habitat.

White (1966) did laboratory experiments on the formation and movement of dredge sediments as density currents in a 40-foot long by 1-foot deep by 4-inch flume. He found that the formation of density layers depended primarily on the concentration of suspended sediment allowed to build up at the source. Water currents tend to prohibit the formation of density flows by turbulent mixing and by sweeping the sediment away before it builds up a sufficient concentration for layer formation. Currents promote movement of density layers only slightly by interfacial shear. Density layers were observed to flow against the current and uphill. Gravity is the primary force which controls movement of the density layers. Dikes and trenches were used to promote deposition of sediment from density flows in the experiments.

Harrison (1967) reviewed the effects of dredging and associated spoil disposal in lower Chesapeake Bay. Spoil dumped from a hopper dredge appeared to have only a transitory effect on the populations of infauna and epifauna. Resettlement of benthic organisms in both the areas of dredging and spoiling was very rapid. Animal collections taken in the spoil area one month after dredging showed a marked decrease in numbers of animals and species. Recovery of the infaunal population was relatively complete after six months. It was found important to differentiate between transitory high populations of juveniles at certain seasons and normal faunal distributional patterns when attempting to assess the effects of dredging or spoil deposition on benthic organisms by means of before and after faunal surveys. He also monitored deposition of sediment on oyster grounds 0.8 to 2.0 miles from a dredging site before and/after dredging. The changes in bottom level he observed were due to natural sedimentation rather than dredge spoil.

Masch and Espey (1967) studied shell dredging in Galveston Bay, Texas using an engineering approach. Shell dredges resuspended considerable quantities of sediment which formed density layers near the bottom. These layers were formed when dredge wash waters contained high concentrations of fine sediments with more than about 80 percent by weight of particles in the silt and clay size range of which 50 percent were of the clay size. These sediments tended to flocculate into density layers when the concentration was greater than about 10 g/l. Dredges operating in sands were not expected to produce such density flows. The movement of density layers are controlled to a large extent by gravity and the layers are capable of moving in directions other than that indicated by either bottom or surface currents. Movement by gravity and tidal action is possible until the layers are consolidated to concentrations of about 175 g/l. They stated that oyster reef topography may play an important role in the movement and settlement of these layers. Reefs protruding above the bay bottom tend to deflect or resuspend density currents and are not as susceptable to sediment deposition as surrounding areas. Old dredge cuts and trenches can be used to control and trap dredge sediments moving as density layers. Control of dredging operations cannot be based solely on a distance limit but must, in each individual case, consider type and amount of overburden sediments, number of dredges to work in the area, and local conditions of reef topography and bottom currents. If dredging is controlled in a prescribed manner it can be done very near live oyster reefs and exposed shell with no damage. Considerable data on dredging operations were given.

The U. S. Army Corps of Engineers (1967) conducted a water quality investigation during dredging of highly polluted Chickasaw Creek, a tributary of the Mobile River, Alabama, near its mouth and entrance into Mobile Bay. They found dissolved oxygen was depressed in the recently dredged area 100 feet behind the pipeline dredge when compared with an area 100 feet ahead of the dredge due to samples being taken at different depths and suspension of sludge undergoing anaerobic decomposition which exerted an oxygen demand on the water. They said that this was only temporary and that water quality after dredging was improved. Dissolved oxygen before dredging was 0.3 ppm and after dredging was 1.3 ppm. No changes in the other parameters studied appeared to result from dredging with the exception of an increase in suspended solids.

Geological and biological studies of dredging were done by the Virginia Institute of Marine Science (1967) in Chesapeake Bay. Sedimentological data from bottom cores were given as they may apply to disposal of spoil. Studies of benthic fauna before and after dredging showed a population reduction of aerobic fauna followed by a dramatic increase by the following summer. It was concluded that spoil deposited in deep estuarine areas has an immediate but not a lasting effect on benthic fauna.

Biggs (1968) published an interim report from Cronin et al. (1970) Chesapeake Bay studies of the environmental effects of overboard spoil disposal. He concluded that overboard spoil disposal increased turbidity over an area of 4 to 5 km^2 around the discharge site and spoil material deposited on the bottom covered an area at least five times that of the defined disposal area. Total phosphorus and nitrogen were increased 50 to 100 times ambient levels in the immediate vicinity of the disposal point.

Brown and Clark (1968) observed that dissolved oxygen was lowered by a clam shell dragline in a polluted tidal waterway between New York and New Jersey.

An interim report from the Cronin et al. (1970) study was also published on the biological effects of spoil disposal in Chesapeake Bay by Flemer et al. (1968). They collected considerable background data and samples at the dredging site. They observed no gross effects from disposal of fine materials on microscopic plants and animals in the water nor on the eggs and larvae of fish, nor on adult fish held in cages near the outfall or caught near the area. Some bottom animals were smothered over a wide area and significant loss occurred. Some benthic invertebrates survived deposition and certain species began repopulation soon after deposition.

Taylor and Saloman (1968) described how extensive dredging and filling in Boca Ciega Bay, Florida has degraded water quality and adversely influenced plant and animal production. A total of 3,500 acres of estuarine areas worth $1.4 million annually have been physically eliminated by development of the coastal area for residential use.

The U. S. Army Corps of Engineers (1968) found that hydraulic dredging in Bon Secour Bay, Alabama had no effect on nearby oysters. By use of silt traps they determined silt was transported 1,200 feet from the discharge and that the dredging operation, when compared to weather, was an insignificant contributor to the overall sediment movement in the bay.

Gunter (1969) reviewed shell dredging in Gulf estuaries from a geological, biological and historical standpoint. He discussed the effects of dead shell dredging and stated he was convinced that the antagonism towards the exploitation of this valuable resource was not in the best interests of the states involved or the nation. He surmised that shell dredging did little harm and that there is a vast lack of understanding about the operation. He cited numerous instances where the use of buried shells for cultch has greatly increased oyster production in the Gulf States.

Murawski (1969) studied the fitness of holes left by dredges for finfish habitat. About 55 percent of the holes had dissolved oxygen or hydrogen sulfide conditions in their bottom waters that could not sustain healthy fish life. About 60 percent of the holes lacked bottom invertebrates. Although he did not recommend creating stagnant or semistagnant holes, he said some were of benefit because fish concentrated in them in the winter because warm water of the fall months was retained in the depressions.

Servizi, Gordon and Martens (1969) studied sediments which were to be dredged from Bellingham Harbor in relation to the salmon fishery in Washington. The sediments consisted of pulp fibers high in volatile solids (27 percent) and hydrogen sulfide and were devoid of normal benthic marine life. When the sediment was mixed with water it was lethal to salmon smolts at concentrations above 1 percent from initial hydrogen sulfide levels of 2.3 ppm. Because of toxic hydrogen sulfide, high oxygen demand and because the time of air exposure during transport to the disposal site on barges was not thought to be adequate to eliminate hydrogen sulfide, they recommended that the spoil be disposed of on land. The authors were concerned about turbidity created by any type of disposal since natural turbidity there averaged 2.6 ppm and did not exceed 4 ppm.

Sherk and Cronin (1970) compiled an annotated bibliography on the effects of suspended and deposited sediments on estuarine organisms which contains many useful references.

Sykes and Hall (1970) surveyed the benthic mollusks in dredged and undredged portions of Boca Ciega Bay, Florida. Species were fewer in number and variety in the soft sediments in dredged canals than in the predominantly sand and shell sediments in undredged areas.

Taylor, Hall and Salomon (1970) studied benthic mollusks and sediments in Hillsborough Bay, Florida. They stated that dredging and pollution now control the ecology of the bay. The diversity and abundance of mollusks were affected by bottom conditions which were influenced in varying degrees by domestic and industrial pollution and dredging.

Cronin et al. (1970) studied the gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. The study projects consisted of geology and hydrography, phytoplankton, benthos, zooplankton, adult fish and their eggs and larvae. The final report of the study summarizes individual reports in each discipline. Fine sediments released as a semiliquid by a channel dredge increased turbidity over an area of 1.5 to 1.9 square miles around the disposal site. Over most of the area the suspended sediment load was within the range of natural variation observed, but at a different season from observed natural maxima. Suspended sediments in the top 10 feet of water were carried in a tide-related plume to a maximum distance of about 3.1 miles but virtually disappeared within two hours after pumping ceased. Total phosphate and nitrogen were increased in the immediate vicinity of the discharge 50 to 1,000 times ambient levels, but limited field experiments did not show any detectable effects on photosynthesis by phytoplankton. Little or no oxygen sag occurred except near the discharge site. Dissolved oxygen decreased from 10 ppm to 9 ppm within the first 2,000 feet down current of the discharge. At least one foot of spoil material was deposited on an area five times or more as large as that of the defined disposal site. Approximately 12 percent of the deposited sediment disappeared from the spoil pile within 150 days. No gross effects of dredging or spoil disposal were observed on phytoplankton primary productivity, zooplankton, adult fish or their eggs and larvae. There was a reduction of about 70 percent in the average number of benthic individuals per square yard and about 65 percent in the benthic biomass in the spoil disposal area accompanied by a marked reduction in the number of species present. After one and one-half years numerical abundance, biomass and species diversity had recovered to approximately the levels before dredging. Individual species varied greatly in susceptibility to damage and in recovery patterns. An erratic series of species fluctuations occurred at the site of dredging in the channel. After one year the channel had about the same number of individuals as before dredging but not as many species were present. The sediments were not known to contain any highly toxic metals, oils, or other deleterious materials. It was recommended that quantitative laboratory studies be done on the effects of sediments on important estuarine species to investigate effects not ascertainable by field methods. It was further recommended that sites considered for future dredging and disposal should receive individual consideration in relation to ecological impacts, drawing both upon related research in other areas and from adequate knowledge of local conditions.

Briggs and O'Connor (1971) studied the effects of channel dredging and filling on fish populations in shallow estuarine waters of New York. Seine hauls were made over naturally vegetated bottoms and sand-filled bottoms created by the deposition of spoil from dredges. Of 40 fish species recorded, 23 clearly preferred one bottom type over the other. Most species preferred the naturally vegetated bottoms.

Corliss and Trent (1971) compared phytoplankton production between an undredged marsh area, a bay area and an adjacent marsh area altered by channelization, bulkheading and filling. Average gross carbon production in the altered area (canals) was 8 percent higher than in the marsh and 48 percent higher than in the bay. Gross and net production were significantly higher in the canals and marsh than in the bay but differences between the canals and marsh were not significant.

Godcharles (1971) studied the effects of harvesting live clams with a small hydraulic dredge on benthic communities in Florida estuaries. The dredge cut an 18-inch deep by three feet wide trench to recover the clams. The dredge uprooted all vegetation and the dredge tracts remained visible from one to 86 days. Some spots remained soft for over 500 days. After more than a year no recolonization of sea grasses occurred in any dredged area. No increase of clam set was detected. No pelagic faunal variations were found between dredged and control plots at any time after dredging and benthic plug samples revealed no marked faunal differences except at one station. He recommended that dredging for clams be prohibited in grass areas but that it should be allowed on other substrates where little if any damage occurs.

O'Neal and Sceva (1971) investigated the effects of dredging on water quality in Washington. They concluded that the disturbance of bottom material by pipeline and grapple dredging and the discharge of spoil materials can significantly reduce dissolved oxygen levels, cover or smother bottom organisms, and release toxic compounds in localized areas. Open water disposal from a pipeline dredge produced little or no change in surface water quality. Oxygen was zero in the mudflow near bottom. The chief visible effect from pipeline dredging was the turbidity plume created by spoil disposal. They observed the submarine mudflow around an open water dredge discharge and partially described its properties. Emptying of hopper dredges created little visible effect on water quality. They discussed retention of spoil by diking. They observed that the settling rate of sediments is more rapid in salt water than in fresh water and felt that development of a healthy benthic community is inhibited when volatile solids content of bottom sediments was 10 percent or higher. They recommended adoption of guidelines based on sediment criteria for determining acceptability of sediments for dredging and recommended restrictions on where and how dredging and spoil disposal can be done.

The U. S. Army Corps of Engineers (1971) issued a preliminary report on dredging studies of in San Francisco Bay. Dredge material from the main ship channel was not polluted according to Environmental Protection Agency criteria with the exception of zinc which exceeded the 50 ppm standard in two of five samples. Water quality data collected during the study were insufficient to analyze the impact of dredging and disposal operations but generally they indicated little harm to water quality or benthos.

Bardarik, Alden and Shema (no date) studied the effects of sand and gravel dredging on aquatic life at three dredging sites on the upper Allegheny River in 1971. They found no effect on riffle benthos or fishes. There was a limited increase in suspended solids but the pH, alkalinity, specific conductance, biochemical oxygen demand, nitrate, ammonia, and dissolved oxygen were unaltered by the dredging operations.

Gustafson (1972) supplied data from pilot laboratory studies and discussed the fallacies connected with turbidity and resuspension of sediments by dredging. He stated recent regulatory actions concerning dredging were taken in ignorance of the effects of turbidity and in spite of the fact that turbidity created by winds and tides dwarf those of man's activities. Suspended clays attract bacteria and remove from the water; oils, pesticides, sewage products (except nitrates), and metals. He demonstrated the probability that metals adsorbed to clays are not released when clays are resuspended and that organic molecules are not liberated in amounts sufficient to cause ecological concern. Pilot experiments to determine whether metals could be digested off the clay by clams were inconclusive but he felt they were not. Several beneficial effects of turbidity in addition to adsorption were presented.

Oleszkiewicz and Krenkel (1972) studied the effects of sand and gravel dredging in the Ohio River. They concluded that the physical, chemical and biological characteristics of the river were not altered to a significant degree by dredging and that other environmental effects were negligible or non-existent. The only increased water quality parameters were turbidity and suspended solids.

Stickney (1972) studied the effects of intracoastal waterway dredging on ichthyofauna and benthic macroinvertebrates in a Georgia river estuary. No effects of dredging could be demonstrated on motile organisms capable of being captured by otter trawling. The patterns of seasonal occurrence and dominance of specific organisms appeared to be consistent regardless of whether or not dredging occurred in the area sampled. Control stations often showed more variability in diversity during the period immediately before, during and after dredging than did the experimental stations.

Windom (1972) evaluated environmental changes resulting from dredging activities in a salt marsh estuarine environment of the southeastern Atlantic Coast. He investigated the chemical response of salt marsh sediments to the deposition of dredged materials and the water quality response to the dredging and deposition of sediment. He tentatively concluded that in natural and relatively unpolluted areas dredging has no significant effect on water quality whether diked or undiked confinement techniques are used. Water quality impairment caused by dredging activities in polluted areas in marine environments does not necessarily bear any simple relation to the composition of the sediments. In order to evaluate the possible effects on water quality of dredging in a particular area specific information must be obtained in that area. No general criteria can be set up for dredging in marine waters until a significant variety of dredging situations has been studied in order to have broad experience in possible water quality effects due to dredging activities. The time that the water mixed with the dredged material is allowed to stay in an enclosed spoil area will greatly influence the quality of the effluent from the spoil bank. Dredging of "polluted" sediments does not necessarily impair water quality in estuarine environments.

Yeaple, Feick and Horne (1972) simulated dredging operations by dipping a tablespoon in small aquaria. They added 100 ppm to 185 ppm mercury as $HgCl_2$ to the sediments and found that mercury increased in the water after stirring. They stated that some mercury will undoubtedly be released during a dredging operation. They discussed the chemistry of mercury especially as influenced by the oxidation-reduction systems and recommended that if excessive concentrations are encountered the bottom be treated with binding agents before or after dredging to hold the mercury in the sediment.

Gunter (in press) discussed the use of dead reef shell and its relation to estuarine conservation. He refuted public objections to shell dredging and stated that the operations vary from innocuous to highly beneficial. After pointing out the invalidity of objections, he said people opposed to dredging on those grounds should be taught carefully and patiently and, for the time being, for the general welfare of everyone involved they should be ignored.

PRESENT STATE OF KNOWLEDGE

Some of the previous studies supply important information about the effects of hydraulic dredging and spoil disposal and others do not. Many studies have not given proper consideration to the basic principles which influence or determine the effects of dredging. The interrelationship between the physical, chemical and biological considerations has not always been properly emphasized and many findings are inconsistant. As a consequence, some of these studies are misleading. The conditions under which Yeaple, Feick and Horne (1972) experimented with mercury release do not apply fully to most actual open water dredging situations. The concentrations they used are very much higher than has been found in open estuaries. However, their discussion on chemistry is informative and such laboratory experiments will eventually contribute to knowledge on dredging if all conditions associated with or produced by dredge discharges are considered. Some such experiments were outlined by Gustafson (1972). Some studies have drawn conclusions about the effects of dredging which were not supported by their data. For instance, O'Neal and Sceva (1971) supplied very little data on the effects of dredge discharges in open water or in diked areas but rather sampled around the dredges and in undredged sediments. They stated there were no significant water quality problems associated with dredging alone and that most of the problems arise in the spoil disposal operations.

However, they made little distinction between the two and took only one sample from a diked spoil disposal overflow for limited analyses. They took several samples of sediment for chemical analyses before an open water spoil disposal project but they ran only turbidity (JTU) and dissolved oxygen in the disposal site. They collected no data on release of toxic compounds or destruction of bottom organisms nor did they find significantly reduced dissolved oxygen values outside of the mudflow. Their conclusions and recommendations, however, do not reflect this.

Several investigations of suspended material from dredges have given little or no consideration to the important processes of flocculation and density currents. Consequently, some investigators have mistakenly stressed that current direction and velocity determines the distance spoil will be carried away from a dredge. Silt traps and some measure of turbidity have been used in many studies to measure conditions which have little application to the overall process of spoil dispersion. Sometimes only surface water samples were taken in an erroneous concept that the visible plume and dilution were representative of the entire sedimentation process.

A major concern about open water dredging and spoil disposal is whether or not it adversely affects the biota and some studies have been done on the direct effects on benthic and pelagic plants and animals. It has been shown that no serious effects occur to nektonic organisms and that benthic animals soon repopulate dredged areas. Mobile Bay and other turbid estuaries of the Gulf contain few if any rooted plants in open water so the destruction of grass beds does not usually present a problem. Oysters, of course, are killed if dredged up or buried. However, the approach to determining the effect of dredging on aquatic organisms has often been over simplified. Although there has been a lot of concern expressed, little has been done previously to determine whether or not high concentrations of potentially deleterious chemicals in the mud are actually released into the water and made available for uptake by aquatic organisms. If dredges are to cause other than physical effects on aquatic organisms it will be done by altering the quality of the water either immediately or with time.

Consideration of processes which regulate the exchange of chemicals between mud and water has frequently been neglected in dredging studies. Because of this, the effects of dredging on water quality and biota have not always been properly defined. Some emphasis has been placed on physical alterations but even so, there are few data on the long-term physical effects of spoil piles on water circulation and other ecological parameters. Changes in salinity and water circulation by channel dredging and spoil disposal have been generally overlooked because of difficulty of measurement and a lack of historical information for comparison.

It is of basic importance to the understanding of open water spoil disposal that the movement and fate of sediment suspended by dredges be considered in terms of how it chemically and physically alters water quality and thereby directly or indirectly affects aquatic biota. Fortunately, several studies have been done which, although they do not pertain directly to dredging, are of considerable use in evaluating the effects of dredging on the aquatic environment.

METHODS

Analytical procedures used were those described by the Environmental Protection Agency (1971) and Taras (1971). Except for suspended solids and some of the phosphorus analyses, most of the laboratory analyses were done by the Environmental Protection Agency, Athens, Georgia; the Corps of Engineers, Mobile, Alabama and Waterways Experiment Station, Vicksburg, Mississippi; and Gulf South Research Institute, New Iberia, Louisiana. Total phosphorus was determined by the ascorbic acid method. Dissolved oxygen was measured using a sulfamic acid modification of the Winkler method (Swingle, 1964) and a YSI Model 54 oxygen meter. Technical assistance was provided by the Environmental Protection Agency in taking sediment cores and dredge samples. The study period was from June 1969 through January 1973. The field work was divided into two broad categories; (1) background water and sediment samples, and (2) water and sediment samples around active dredges.

Background Conditions

From June 1969 through November 1969, natural background levels of water quality were established in Mobile Bay, Mississippi Sound and Bon Secour Bay with special emphasis being given turbidity. Also determined were dissolved oxygen, salinity, pH, temperature, wind, and sedimentation using funnel silt traps. Silt traps were found to be unsatisfactory for determining suspended solids or sedimentation rates for the same reasons stated by Masch and Espey (1967). Fifteen fixed stations throughout the estuary were randomly sampled at least once a month from June through September 1969. The general procedure was to sample a group of stations for several days in succession. An average of eight samples were taken at each of the 15 stations during July and August 1969. Samples were taken at 10 stations in the vicinity of the shell dredge for a three-day and an eight-day period in July 1969, and one day in August and November 1969.

During the second phase of the study 14 stations in Mobile Bay were sampled weekly from March 1971 through July 1971 for salinity, temperature, dissolved oxygen, turbidity and suspended solids. Extensive dissolved oxygen data were gathered throughout Mobile Bay from June 1971 through September 1971. Bottom cores of sediments for chemical analyses were taken in October 1971 at 15 locations in Mobile Bay and water samples were taken at 17 stations (Figure 1). Additional surface mud samples and bottom cores were taken in May 1972 for biological, physical and chemical analyses (Figure 2). Three water samples for heavy metal analyses were collected in November 1972.

The bulk of the earlier data and station locations are unpublished (Alabama Marine Resources Division). The purpose of collecting considerable background data was mainly to determine ranges and averages of natural parameters under various conditions in order to make a comparison with conditions resulting from dredging and presentation is limited to such.

Dredge Samples

Three hydraulic dredging operations in Mobile Bay were sampled intermittently from September 1971 until October 1972. The operations sampled represent the predominate types of dredging activities which are responsible for most open water spoil disposal in estuaries. These included an intracoastal waterway maintenance dredge, a ship channel maintenance dredge and a shell dredge (Figure 3). Samples of ambient conditions were taken at locations outside the influence of the dredge at the same time the dredges were sampled. A single sample of the effluent of a shell dredge operating in San Antonio Bay, Texas was taken in February 1972.

The dredging operations in Alabama were usually sampled using a predetermined radial grid pattern (Figure 4). A transet was used to orient the grid in relation to magnetic north and to establish 22.5-degree radii around the discharge. These traverses were established with the discharge stationary and were used as sample lines. The distance of each sample station from the discharge was determined with the dredge in operation by using a Trisponder® 202A automatic distance measuring system. Water samples were taken at the desired depth with a Van Dorn water sampler attached to a cane pole. Samples were collected from a 52-foot, self-propelled spud barge which was stationary while collecting samples. The distance from the discharge, number of traverses and the depth at which samples were taken varied depending on water depth, the kind of dredging operation and the type of analysis to be performed on the samples.

Water samples were taken out to a distance which was obviously beyond the influence of the dredge. The grid pattern was extended in a direction down current from the dredge in some cases for distances up to several miles. This was sometimes done by observing the visible surface plume from an aircraft and establishing stations by radio command to a small surface vessel.

Analyses conducted on the boat during sampling included salinity, temperature, pH, Eh, dissolved oxygen, turbidity, and occasionally carbon dioxide and hydrogen sulfide. Direction and velocity of water current and wind were also recorded. Laboratory analyses of water samples included turbidity, total suspended solids, volatile solids, particle size, heavy metals, total phosphorus and total Kjeldahl nitrogen. Analyses of bottom cores included volatile solids, chemical oxygen demand, biochemical oxygen demand, total Kjeldahl nitrogen, oxidizable nitrogen, organic carbon, oil and grease, heavy metals, pesticides, coliform bacteria, benthic aerobes and in-place density of mud. When appropriate, mud and water samples for chemical analyses were frozen in the field (Taras, 1971).

In addition to samples from Alabama, bottom muds were analyzed for heavy metals from Florida in Tampa Bay, Choctawachee Bay, Apalachicola Bay, Escambia Bay, East Bay Pensacola, West Bay Pensacola; from Mississippi in Mississippi Sound; from Louisiana in Lake Pontchartrain and Atchafalaya Bay; from Texas in Galveston Bay and San Antonio Bay; and from near Costa Blanca, Campache, Mexico. These samples were collected in January and February, 1972.

The channel dredge Orleans was sampled on 24 September 1971. This dredge is owned by Standard Dredging Corp., New Orleans, Louisiana and was operating under contract with the Corps of Engineers. Maintenance dredging amounting to approximately 5 million cubic yards was being done in the Lower Reach of the Mobile Ship Channel near beacon "14" about 18 miles south of the mouth of the Mobile River. The dredge was removing two feet of silt from the bottom of the 40-foot channel and discharging spoil about 2,000 feet west of the channel. The dredge has a pumping capacity of over 34,000 gpm.

The channel dredge Arkansas was sampled on 17 February 1972. The dredge has a capacity of over 20,000 gpm and is owned by Williams-McWilliams, New Orleans, Louisiana. This project consisted of maintenance dredging of approximately 738,000 cubic yards from the Gulf Intracoastal Waterway to a project depth of 12 feet. The dredge was operating under contract with the Corps of Engineers in Bon Secour Bay near beacon "202" and was discharging south of the channel.

The shell dredge Mallard was sampled on 30 September 1971, 3 November 1971, 21 January 1972, 29 March 1972, 11 August 1972, 20 April 1972, 13 October 1972 and 5 January 1973. The dredge is owned by Radcliff Materials, Inc., Mobile, Alabama and operates under contract with the Alabama Department of Conservation and Natural Resources. All but the 1973 dredge samples were taken while the dredge was operating on the west side of the ship channel south of the Hollingers Island Barge Channel in upper Mobile Bay. The dredge had operated in the same general area since November 1970 and moved east of the ship channel in November 1972. The Mallard has a total pumping capacity of 41,000 gpm with a production capacity of over 800 cubic yards of shell per hour (304 cubic yard average) and is one of the largest shell dredges in the world.

HYDROGRAPHY AND SEDIMENTOLOGY OF MOBILE BAY AND SELECTED ESTUARIES

An understanding of how dredging alters natural conditions must be preceded by a consideration of what the natural conditions are and how natural processes affect existing water quality and sediment characteristics.

The general sedimentology of Mobile Bay was studied by Ryan (1969) and other papers containing hydrographic data on Alabama waters were cited by May (1971). The geology of the Alabama coastal plain was reviewed by Carlston (1950) and Copeland (1968). The major source of sediment entering Mobile Bay is the Mobile-Tensaw River System which drains approximately 44,000 square miles. In addition, shore erosion and biological processes contribute considerable amounts of sediment. The bulk of bay sediment is clays and silty clays except near shore where it is mostly sand. The general pattern of stratigraphy and sediment distribution conforms to that of other Gulf bays (Ryan, 1969). The bottom composition is variable with depth which reflects several thousand years of sedimentation processes.

The character of sediment influences the distribution of minerals, organic matter and biota. The chemical properties of sediments are largely determined by the kind and size of particles because of the affinity of clays for many materials. For instance, the cation exchange capability of vermiculite is about 100 times greater than quartz (Nelson, 1962). Consequently, the behavior of different sediments in dredge effluents is different. Although the mineralogy of sediment is of academic interest, the most important points in relating sediment types to dredging is the percentage of clay and silt to sand, and the chemical quality of the sediment to be dredged.

The sediment overburden in areas where shell dredging is done in Mobile Bay varies from predominantly sand to fine clay and silt. Nearer shore, sand predominates while clay and silt fractions make up most of the sediments in deeper water outside the six-foot contour. Within limits, the composition of the overburden is of foremost importance in determining the dispersion and deposition of dredge effluent. When overburden material is composed mostly of larger particles, they are deposited in the immediate vicinity of the discharge. Bits of shell which may make up a large percentage of the discharge and sand larger than 125 microns settle rapidly. Particles less than about 62 microns may be transported in the mud flow but settlement of the larger particles nearer the discharge is apparent as data from a single line of samples indicate (Table 1).

Analyses of Background Bottom Cores

Sediment cores were taken at stations shown in Figures 1 and 2 and analyses are shown in Tables 2 and 3 respectively. It was not a main intent to use these data to show the degree of pollution of the sediments or a lack of it, but rather to provide a framework for interpretating the results of dredge effluent samples. However, none of the sediment components were significantly different than those reported from other bays: volatile solids (Mackin, 1962; White, 1966; Gunter, 1969; Huggett, Bender and Slone, 1971); C.O.D. and organic carbon (Volkmann and Oppenheimer, 1962; Biggs, 1967; Virginia Institute of Marine Science, 1967; O'Neal and Sceva, 1971); pesticides (Butler, Childress, and Wilson, 1970); heavy metals (Windom, 1972). Heavy metals were little different than single sediment samples from other estuaries along the Gulf of Mexico with the possible exception of zinc (Figure 5). These data are interesting but their use for comparison is limited since they are based on single surface samples. Zinc, for instance, ranged from 10 to 184 ppm in Alabama estuarine sediments so it is apparent that additional samples are desirable from other areas. There was no consistant relationship between metallic concentrations and depth of samples in Alabama samples although means of all metals except mercury decreased slightly with depth. Mercury showed a slight increase with depth. Pesticides were either not detected in Alabama or were found at very low levels. Among all detected pesticides, low levels of DDT or its metabolites (less than 0.02 ppm average) were most frequently found in the sediments.

Analyses of Background Water Samples

Results of analyses of water samples collected on 22 October 1971 at the stations shown in Figure 1 are presented in Table 4. Wind varied from 2 to 10 knots during sampling. Total suspended solids averaged 39.6 mg/l and volatile solids were 9.6 mg/l or 24.2 percent. Additional samples were collected for determination of ambient levels of water quality when dredging operations were investigated. Ambient levels are difficult to determine because of the spatial variation in parameters. If samples are taken too far away from the dredge, characteristics such as water depth, salinity, dissolved oxygen, etc. may be different than those which would normally be found at the dredging site.

(a) Heavy Metals

The data indicate an increase in mercury and possibly chromium in the lower part of the estuary (Tables 4 and 5). This trend was also observed for metals in the sediments (Table 2) but the cause is uncertain in both cases. D'Itri (1972) reported natural concentrations of mercury in seawater as ranging from 0.03 to 5.0 ug/kg with a normal mean value near 0.03 ug/kg. He also stated that the anionic complex ions of mercury found in seawater do not appear to adsorb to particulate matter as readily as the cationic forms of mercury found in freshwater. Using levels much higher than that found in Gulf estuaries Feick, Horne and Yeaple (1972) found that addition of salt increased the relative amount of mercury in the water at equilibrium with the sediments by two to five or more orders of magnitude. The effect increased as the mercury burden on the sediment was increased. Huggett, Bender and Slone (1971) suggested that estuarine sediments are more closely related to oceanic than freshwater sediments with respect to mercury concentrations. Wolfe and Rice (1972) suggested that since seawater contains less of most metallic elements than estuarine waters, net loss from the estuary probably results but; if on the other hand, the coastal or estuarine waters contained an excess of uncomplexed organic material, seawater might represent an input of ionic metallic elements which could accumulate in the estuary through sedimentation or other processes. This may be the case in Mobile Bay or it may just be a reflection of a higher rate of sedimentation of clay and organic matter in the lower estuary and a higher solubility in more saline water.

(b) Suspended Solids

Weekly samples at 14 stations in Mobile Bay from December 1970 through July 1971 showed that total suspended solids varied from 2 mg/l to 133 mg/l and averaged 27 mg/l on top and 33 mg/l on bottom. These values fluctuate widely with wind velocity which causes bottom sediments to be resuspended by waves. Volatile solids, which are an index of the organic matter in the water, ranged from 1 to 36 mg/l and averaged 9 mg/l. Volatile solids composed 29 percent of the total suspended solids.

(c) Turbidity

Samples were taken under various conditions of wind and river flow from 14 stations in 1969, 1970 and 1971. Natural turbidity ranged from 1 to 90 JTU with an average of 23. Turbidity could not be accurately correlated with wind velocity or river flow. In a separate study Bault (1972) reported that Mobile Bay averaged 22.3 JTU in 1968 and 1969 with a range of 4 to 250 JTU.

(d) Nutrients

The concentration of selected nutrients in Mobile Bay waters was determined from monthly samples from April 1968 through March 1969 (Bault, 1972). Nitrate-nitrogen ranged from zero to 232 ug/l and averaged 67.3 ug/l. Total phosphorus ranged from about 8 ug/l to 287 ug/l and averaged 77.5 ug/l. Total phosphorus in the bottom waters averaged 91.4 ug/l.

(e) Dissolved Oxygen

Dissolved oxygen was taken throughout the estuary at least once a week from December 1970 through September 1971. Concentrations ranged from zero to 12 mg/l. Samples were taken almost daily in July and August 1971 over all of Mobile Bay. Total oxygen depletion in bottom water was found over large areas in the upper bay from June through September (May, in press). The only deep area in the upper two-thirds of the bay where total oxygen depletion was not found was in a four square mile area around the shell dredge. This was likely due to mixing of the water by the dredge and tender boats.

(f) pH

During the same period, pH from the weekly samples ranged from 6.1 to 8.5 and averaged 7.3. Bault (1972) reported an average pH of 7.0 in 1968 and 1969.

(g) Pesticides

Chlorinated pesticides were either not detected or were found at very low levels in all Mobile Bay water and bottom sediments in 1965 and 1966 (Casper et al., 1969). Total DDT was detected most frequently with a median of less than 0.001 ppm in the water. Other pesticides were either not detected or were found with a median concentration of less than 0.001 ppm. All oyster samples collected in 1968 and 1969 (May, 1971) contained detectable residues of DDT. However, the maximum level of DDT was lower than eight of the 14 other coastal states monitored (Butler, in press).

OBSERVATIONS OF SHELL DREDGING

Ambient Conditions

On 30 September 1971 measured winds were from NE to E at 1 to 8 knots. Tide during the sample period was falling and the current increased from 0.2 knot at 10 degrees to 0.5 knot. Salinity was approximately 7.0 ppt at the surface and 7.5 ppt on bottom. Water temperature averaged 28.0 C at the surface and 27.8 C at the bottom. Dissolved oxygen was 7.5 ppm at the surface and 7.0 ppm on the bottom. pH was about 8.2 at all depths. Ambient levels of total suspended solids taken at right angles to the current direction 1, 2 and 3 miles from the dredge were highly variable but averaged about 7 mg/l on the surface and 12 mg/l near bottom which was about three times lower than the annual average. Volatile solids were 36 and 29 percent on top and bottom, respectively. Water depth was about 10 feet at mean low water and the sediment overburden over the shells ranged from 6 to 9 feet.

On 3 November 1971 measured winds were N 20 to 25 knots with gusts slightly higher. This is approaching the maximum velocity dredges can operate in. Winds in excess of 30 knots blow shells off the conveyor belt of the dredge and create conditions hazardous to operations. The tide was falling during the sample period from 10 degrees at 0.3 knot and 0.2 knot at the surface and bottom, respectively. Salinity was highly variable at all depths due to wind mixing. Bottom salinity ranged from 5 ppt to 25 ppt with a median of 17 ppt. Water temperature averaged 24.5 C at all depths. Bottom dissolved oxygen was about 5.8 ppm. Turbidity was 50 JTU and pH was 7.8 at all depths. Background levels of suspended solids were unusually high even for a windy day. Samples one mile north of the dredge were 156 mg/l on the surface and 196 mg/l on the bottom which was about six times higher than the annual average. Samples near bottom over 2,000 feet west of the dredge averaged about 250 mg/l. Volatile solids were 17 percent.

On 21 January 1972 winds were calm and there was a neaptide. Current was northerly at 0.1 to 0.2 knot. Salinity was 2.3 ppt on the surface and 3.9 ppt on bottom. Temperature was near 11 C at all depths. Dissolved oxygen was 9.0 at the surface and was 8.9 on bottom and pH averaged 7.7 at all depths. Total suspended solids were variable and ranged from 37 to 81 mg/l at all depths. These fairly high suspended solid levels were due to a recent freshet.

Pertinent background information for the other sample periods is reported with the data.

Turbidity

Surface and mid-depth turbidity measured on a very windy day (3 November 1971) did not exceed the ambient of 50 JTU beyond about 400 feet from the discharge in any direction or beyond 200 feet in most directions.

Turbidity measured on a calm day (11 August 1972) at the surface did not exceed 12 JTU at distances beyond 400 feet from the discharge. Samples at mid-depth ranged from 12 to 19 JTU beyond 400 feet. Ambient levels or the annual average turbidity (23 JTU) at these depths were not exceeded at distances beyond 400 feet.

Turbidity was measured down current and downwind on 13 October 1972 with winds NNW at 7 knots at 8:00 A.M. which increased to 13 knots by 2:30 P.M., the end of the sampling period. Samples were taken at approximately mid-depth (5 feet). The tide had been falling 5½ hours before sampling and reached predicted low approximately ½ hour after sampling ended. Ambient turbidity was about 6 to 12 JTU during the first half of the sample period and increased to about 14 to 20 JTU during the latter half. Samples were taken out to 5,000 feet from the discharge but on this particular day the plume was visible for about 5,000 feet beyond this distance. The bay was unusually clear on this day and the plume was exceptionally pronounced visually. Natural levels (90 JTU) were exceeded out to 800 feet from the discharge and ambient and the annual average (23 JTU) were slightly exceeded beyond 5,000 feet (Figure 6). Three adjoining stations had high levels at a distance of 1,500 feet but this was possibly due to disturbance by a passing boat.

Under normal conditions, water affected by the dredge cannot move a distance greater than the tidal movement in a 12-hour period since the water mass reverses direction at the end of a tidal cycle. Based on a tidal velocity of 0.3 knot this distance would be 3.6 nautical miles. However, winds and floods are known to have an influence on water movements and this distance is occasionally greater or less.

Suspended Solids

The horizontal distribution of total suspended solids was determined on a relatively calm day (30 September 1971) and on a very windy day (3 November 1971).

On the calm day total suspended solids at the surface were less than 100 mg/l except within 400 feet of the discharge (Figure 7). These levels are frequently exceeded throughout the bay on windy days and during freshets. Ambient levels were exceeded up to 2.800 feet from the dredge but at distances greater than 1,200 feet, the levels were less than the 27 mg/l average for Mobile Bay. The surface readings which were above ambient were within the visible plume which was noticeably affected by current and wind direction.

Total suspended solids at mid-depth were higher and more widely distributed than at the surface (Figure 7). Values over 100 mg/l extended up to 800 feet from the discharge. Ambient concentrations were exceeded out to 2,000 feet in some directions. These data show that most of the dredge effluent settled very rapidly from the upper part of the water column. The combined average of all top and middle samples between 200 and 800 feet from the discharge was 60 mg/l which was only 0.1 percent of the average concentration on the bottom samples at the same distances. Within 100 feet from the discharge the concentration at the surface was reduced 98.5 percent and by 91.0 percent at mid-depth. Over 90 percent of the solids fall to near the bottom immediately under the discharge and about 96 percent within 200 feet. Thus, dilution does not significantly contribute to a decrease in the concentration of suspended solids since sufficient water is not available within the receiving area to allow mixing. Lack of dilution forces the solids in the effluent to fall quickly to the bottom where the fluid mud displaces the bottom part of the water column. This affords little time or opportunity for anything to become dissolved.

Almost all of the mud discharged by the dredge was transported near the bottom as a fluid mud flow in a distinct density layer (Figure 7). Concentrations at first were lower than the discharge. At 100 to 200 feet the mud flow became significantly more concentrated due to consolidation. Concrescence and consolidation were responsible for the greatest concentrations being found on the perimeter of the mud flow. The majority of the mud was unaffected by water currents and was moved by gravity as a density flow. There was no evidence that the mud flow was moved back and forth by the tide. The layer of high density fluid with concentrations above 1,000 mg/l extended a maximum of 1,000 feet from the discharge. The mud flow abruptly ended at its outer edge. Water currents scalp the surface of the mud flow and alluvially disperse solids at relatively low concentrations in a predominantly down current direction in a pattern similar to the shape of the mud flow. Background levels and the bottom annual average of 33 mg/l were exceeded out to a maximum distance of 2,800 feet. Concentrations above 50 mg/l were limited to within a maximum distance of 1,600 feet. Values over 100 mg/l were limited to a maximum of 1,200 feet. Concentrations in the density layer were greater away from the dredge as was the expanse of the mud flow. Little significant silt dispersion was observed outside the density flow except for slight amounts down current from the southern edge.

On the windy day, samples were collected 0.5 and 2 feet above bottom (Figure 8) to observe the effect of wind mixing on the density flow. High concentrations of total suspended solids in the upper samples extended out to 1,600 feet from the dredge. Values over 1,000 mg/l were found out to 2,000 feet. Concentrations in the density layer were greater away from the dredge as was the expanse of the mud flow. Little significant silt dispersion was observed outside the density flow except down current from the southern edge.

Near bottom, most of the total suspended solids were transported as a mud flow in concentrations as high as 22,000 mg/l as far as 1,600 feet from the dredge. The high density area 1,200 feet south of the dredge with concentrations over 1,000 mg/l was over 2,400 feet wide. These concentrations extended out to 2,000 feet from the dredge. Suspended solid concentrations were almost twice as high along an east to west line 1,200 feet south of the dredge as along a north to south line from the discharge out to 1,600 feet.

Background levels were not greatly exceeded beyond 2,000 feet from the dredge under what was near extreme conditions of wind and tidal transport during which dredges can operate in this area. Wind mixing was apparent from salinity and temperature fluctuations and inversions. This had two effects on the mud transport. Wind energy caused the solids to remain in suspension longer and thereby extended the distance traveled before settling. This caused higher concentrations of solids in the mud flow further from the dredge. Wind roiling caused bottom concentrations beyond the mud flow to be higher than background levels for a greater distance. A flocculated density layer with concentrations of 1,000 to 4,000 mg/l was maintained over a larger area than under less windy conditions. This is a reflection of the higher concentrations in the boundaries of the mud flow and a higher energy for suspension.

The vertical distributions of suspended solids taken on a calm day under low salinity conditions at various distances from the dredge discharge are shown in Figures 9 and 10. In Figure 9 the original bottom is about 12 feet deep. The mud flow in the down current direction is observed to be mostly confined to the cut the dredge is operating on and an older cut from a few days earlier. Figure 10 is at a right angle to the current and it can be seen that the character of the mud flow is identical to that shown in Figure 9. It is interesting to note the concentrations at 1,200 feet in Figure 10 when the mud flow was accidently disturbed by prop wash from the sample boat.

Volatile solids remained associated with the clay minerals and were transported in the mud flow proportional to the distribution of inorganic suspended solids (Figures 11 and 12). No evidence was found that these concentrations of volatile solids detrimentally affected water quality. Although the lowest oxygen observations were in the area of highest volatile solid concentrations it is thought to be inconsequential due to the more rapid chemical oxygen demand of reduced inorganic material in the mud flow.

Dissolved Oxygen

Dissolved oxygen was not significantly altered by the dredge except in the mud flow (Figures 13, 14, 15, and 16). Sufficient oxygen was present at the interface of the mud flow and the overlying water to prevent reducing conditions. Dissolved oxygen immediately at the effluent ranged from 1.2 to 8.3 ppm. Outside of dredge cuts the density flow is usually less than 2 feet thick. When it is allowed to settle for several minutes it condenses to a few inches or less. It may be possible for motile aerobic benthic organisms, including mollusks, to migrate to the surface before oxygen concentrations become fatal. This possibility should be considered in future studies since it has been shown that some species survive deposition by dredge effluents (Flemer et al., 1968).

pH

The dredge effluent had no measurable effect on pH even in the discharge. There was a slight indication that pH was raised less than 0.1 unit within 200 feet of the dredge. Production of acids by the oxidation or disassociation of sulphur compounds is of minor concern since most gases apparently escape into the atmosphere or any acids which are formed are buffered by calcium carbonate in the shell washing process. There is sometimes a slight nondescript odor near the dredge which is probably a mixture of gases (methane, sulfur gases, etc.).

Total Phosphorus and Total Kjeldahl Nitrogen

Dredge effluent had a limited effect on nutrient concentrations. I did not find it to be of the magnitude reported by Ingle et al. (1955) or Cronin et al. (1970). When the total phosphorus content of the water was low, the levels were slightly raised within 1,000 feet or less from the dredge (Figures 17 and 18). When the phosphorus levels were higher, the dredge apparently had little effect (Figure 19). There was no great increase in phosphorus and my data support the finding of laboratory researchers (Rochford, 1951; Pomeroy et al., 1965) that the process is apparently concentration dependent and that dissolved phosphorus is at equilibrium with oxidized sediments at approximately 95 ug/l.

Nitrogen in samples collected at stations shown in Figure 19 showed no increase above ambient except for a possible very small increase in the discharge. Most of the samples were lower than background.

Metals

Shell dredge effluent did not dissolve heavy metals into the water and ambient levels were possibly decreased (Figure 20; Table 6). In Table 6 notice the lack of correlation between percent volatile solids and chemical concentrations and that filtered samples and samples with low suspended solids are equal to background.

Pesticides

Because of the fairly recent introduction of pesticides into estuarine areas, they must necessarily be confined to the upper few feet of undisturbed sediment in the zone where they are deposited or transported by burrowing benthic organisms. Hence, the mixing of surface sediments with large volumes of uncontaminated deeper sediments would be expected to lower the relative concentration of pesticides in the redeposited sediment. It was observed that sediment in dredge cuts less than two years old had average total DDT residues 4 to 5 times lower than older cuts or undredged areas and that these dredge cuts possibly accumulated more DDT with age (Table 3).

Limited analyses for total DDT around the shell dredge on 5 January 1973 showed that levels in the mud were about 20 to 30 times higher than in the water or dredge discharge (Table 7). No reliable difference was detected between filtered and unfiltered effluent samples. Samples taken at the same depth near bottom during dredging were little or no different than background before the dredge started pumping. Surface and mid-depth samples were somewhat higher but no background samples were taken at those depths for comparison. Variations with depth may have been due to a freshet which was occurring during sampling. All water samples were below the lower range of total DDT reported from throughout the bay by Casper et al. (1969). Little difference in DDT concentration was found between undisturbed bottom one-half mile west of the dredge and the sediment deposited by the dredge on top of the original bottom. DDT in the bottom of a new dredge cut was higher but was well below the average for undisturbed sediments or older cuts in Mobile Bay. All sediment concentrations were below the median DDT concentrations in sediments reported by Casper et al. (1969).

OBSERVATIONS OF CHANNEL DREDGING

Ambient Conditions

When the ship channel dredge Orleans was sampled, measured winds were E at 10 knots shifting to SE. Tide was falling from 20 degrees at 0.1 knot and had been ebbing for 12 hours previous to sampling. Salinity was 10.5 ppt at the surface and 12.0 ppt near bottom. Water temperature was 28.2 C at the surface and 28.0 near bottom. Dissolved oxygen was 7.6 and 6.6 ppm at surface and bottom, respectively. pH was about 8.3 at all depths. Suspended solids were approximately 20 mg/l at the surface and 50 mg/l near bottom at right angles to the current direction over one mile from the dredge. Volatile solids ranged from 20 to 40 percent. JTU were 15 at the surface and mid-depth and 60 near bottom. Water depth was 8 to 11 feet MLW.

The intracoastal dredge Arkansas was sampled when winds were from the west at 0 to 5 knots. The current was from 285 degrees at 0.1 knot on the surface and 0.3 to 0.9 knot from 200 to 255 degrees on bottom. Salinity was 8.0 ppt on the surface and 8.2 on bottom. Water temperature was 14.0 C on the surface and 13.0 C on bottom. Dissolved oxygen was 11.0 ppm on the surface and 10.4 ppm on bottom. pH was 8.2. Suspended solids were 90 mg/l at surface and mid-depth and 72 mg/l on bottom. Volatile solids were 30 percent on the surface and 20 percent at mid-depth and bottom. Water depth was 8 feet.

Turbidity

Turbidity on the surface around the discharge of the Orleans did not exceed 100 JTU beyond 200 feet nor 50 JTU beyond 400 feet. Ambient turbidity (15 JTU) was slightly exceeded out to a distance of 1,200 feet in the down current direction. At mid-depth, values over 100 JTU were limited to a distance of 400 feet and values over 50 JTU extended to a maximum distance of 1,200 feet in one direction but were otherwise confined to within 600 feet.

Suspended Solids

Samples around the ship channel dredge were taken at surface, mid-depth and near bottom (Figure 21). Total suspended solids at the surface slightly exceeded ambient levels out to 1,000 feet from the discharge. Values in excess of 100 mg/l were limited to within 400 feet. The concentration was reduced 92 percent within 100 feet and 98 percent within 200 feet which showed rapid settling. At mid-depth, concentrations over 100 mg/l extended out to 400 feet and values of 50 mg/l extended to a maximum of 1,200 feet from the discharge. Ambient levels were slightly exceeded out to 1,400 feet in some directions.

The majority of the sediment which was not deposited immediately under the discharge of the pipeline was transported near bottom as density flows. Concentrations

10,000 mg/l were found within 400 feet of the discharge. Concentrations over 1,000 mg/l extended out to at least 1,800 feet from the discharge. Ambient levels were exceeded at all bottom stations sampled which were extended out to only 1,800 feet. Sampling was being done on concentric circles by proceeding from one transect to another and was terminated when the dredge quit pumping. Mud transport occurred at concentrations of 100 to 500 mg/l beyond the main density flow and may have extended slightly farther. The recent alluvium being pumped from the bottom of the channel was composed of a higher percentage of smaller particles than typical bottom material. Having been previously sorted by flocculation and disturbance from ships the particles apparently remain suspended longer. This may have resulted in the density flow having a lower viscosity than if original bottom was being pumped. The smaller amount of material being pumped (compared to the shell dredge) was reflected in comparatively lower concentrations at all distances from the discharge especially on the perimeter of the density flow. Another important point is that spoil from the channel dredge was not being deposited into a dredge cut and the fluid mud had no place to go other than to be spread along the bottom.

The effluent from the intracoastal dredge did not exceed ambient concentrations at surface or mid-depth beyond 400 feet or on the bottom beyond 800 feet (Figure 22). This was apparently due to coarse material being pumped and the smaller discharge volume. A comparison of the particle size amoung the three dredge effluents was not made.

Volatile solids in the effluent of both dredges settled very quickly and were transported in the mud flow proportional to the distribution of inorganic suspended solids (Figures 23 and 24). The concentrations around the ship channel dredge were slightly higher and more widespread at the surface than at mid-depth. This indicated that some of the lighter organic particles were suspended near the surface and were transported by wind or water currents.

Dissolved Oxygen

The extent of low oxygen caused by these two dredges was similar to the shell dredge and was limited to the mud density flow near bottom (Figures 25 and 26). There is apparently little difference in the immediate oxygen demand between recently deposited and older sediments.

pH

The pH was slightly lowered in the discharge of both dredges and was somewhat less than ambient out to 200 feet from the ship channel dredge. The maximum reduction in pH was 1.3 units but the average was only about 0.5 which is less than normal diurnal fluctuations. This small and limited change in pH had no measurable effect on other water quality parameters. An increase in acidity may have been due to the oxidation or disassociation of sulphur compounds to form acids since gases in the muds could not escape into the atmosphere until discharged from the end of the pipe.

Total Phosphorus

Analysis for phosphorus was done only on the intracoastal dredge. A single line of samples showed no phosphorus increase in settled samples (Table 8). The possible reduction in total phosphorus suggested by these data and those in Figure 19 ve been due to phosphorus being naturally higher where the background data were collected than it was at the dredge discharge, although a reduction in dissolved phosphorus would not be surprising. Fitzgerald (1970) found that aerobic mud rapidly removed dissolved phosphorus from water.

Metals

Channel dredge effluent did not increase the levels of dissolved heavy metals (Tables 9 and 10). These data are compared to additional samples of shell dredges operating in Alabama and Texas in Table 11.

HYDROLOGICAL DREDGING CONCEPTS

Estuarine Sedimentation

White (1966) and Masch and Espey (1967) were apparently the first to apply the basic concepts of estuarine sedimentology to dredging studies. Little consideration had been given previously to the possibility of flocculation processes, mud flows or density levels resulting from high concentrations of suspended sediments. Since these factors largely control dredge sediment dispersion and deposition, they are fundamental in influencing chemical exchanges and subsequent biological effects. The above authors gave an extensive discussion of estuarine sedimentation concepts which are briefly reviewed here along with other considerations important in understanding the processes of dredge effluent sedimentation and the subsequent effects on water quality.

A large percentage of estuarine sediment is made up of small clay and silt particles which may behave entirely different in suspension than larger particles. When sediment enters the upper part of an estuary or is resuspended by waves or other activities, the coarser particles settle out rapidly in the absence of a suspending force. The finer particles remain in suspension longer. In salt water, even with salinity below 1 ppt, these fine sediments flocculate rapidly and settle out. Before being deposited, however, they sometime form a separate density layer near bottom which is fluid and can remain stationary or be moved about by water currents or other forces. Flocculation is an extremely important process in estuarine sedimentation and is of particular importance in regard to dredge effluents. Ryan (1969) found that Bon Secour Bay and the higher salinity areas of Mobile Bay are silting more rapidly than the upper estuary. This is due in part to flocculation of the waterborne clays nearer the mouth of the estuary. Naturally occurring layers of flocculated silt have been observed in Mississippi Sound and southwestern Mobile Bay, Alabama following flood periods and have been known to smother oysters (May, 1971). Soupy silt has frequently been observed on bottom at other times in many areas of the estuary.

Flocculation, as it applies to sedimentation, is an electrochemical process associated with clay particles in water containing dissolved salts. Flocculation results in clay particles grouping together and thereby settling faster than they would in the absence of this force. The rate of flocculation is determined by the type, size and concentration of particles and the kind and concentration of electrolytes. Mobile Bay sediments flocculate and settle at any salinity in just a few minutes when left undisturbed. As flocculation proceeds, the clay flocs form agglomerates that become large enough to overcome suspending forces and settle toward the bottom. As the concentration become greater due to rapid settling, the settling flocs tend to interfere with one another and there is a decrease in the settling velocity of particles. This hindered settling apparently occurs at concentrations of about 10 g/l and a layer of fluid mud results. These layers of flocculated sediment have sufficient strength to resist the shear and friction forces of the water current and can flow as density currents or mud flows independent of current direction. This is usually accomplished by gravity acting on the fluid. A concentration of approximately 175 g/l is apparently the limiting concentration of the hindered settling phase under undisturbed conditions. Above this concentration the mud layer has consolidated to the point that it is more resistant to movement (Masch and Espey, 1967).

The flocculation process is rapid in discharged dredge effluent due to the high concentration of particles and lack of significant dilution. Because of this, pressure from the head built up by the continuous discharge of high mud concentrations becomes an important factor in the movement of dredged sediments. This force causes the mud to be pushed out away from the dredge and can result in the mud flowing uphill or opposite to current forces. The entire process can be likened to pouring syrup on a platter. Thus, the predominant factors of dredge spoil dispersion in estuaries are those which contribute to or influence the formation and movement of flocculated density layers and mud flows.

Normal wind and tidal forces do not have a great influence on density layers but contribute to the dispersion of very fine collodial-like clays and organic matter which sometimes increase turbidity. Such fine particles contribute very little to silting and do not measurably exceed levels created by normal winds except within a few hundred feet of the discharge. Tidal direction may slightly alter the pattern of mud dispersion and cause density flows to extend further in the direction of the current. Mixing by strong wind tends to keep particles in suspension longer thereby slightly increasing the extent and distance of spoil dispersion. Roiling of the mud flow by the water discharge increases turbidity near the dredge, promotes particle sorting and extends the dispersion of suspended solids. Water movements are not sufficient in Gulf estuaries to allow dilution to be a very important factor around a large dredge. On the other hand, the lack of significant dilution promotes rapid formation of highly concentrated density layers. Higher salinity in the discharge or near the bottom promotes flocculation and more rapid settlement but may increase the alluvial spoil dispersion near bottom beyond the mud flow because it provides more buoyancy for the sediment. Temperature stratification in most Gulf estuaries is slight and would have little buoyancy effect.

Other important factors which determine spoil dispersion are the size and kind of particles being pumped, the concentration and volume of material being discharged and the bottom configuration. High percentages of fine clays and silty clays rapidly form density layers and move away from dredges as density flows. The more of this type material in the discharge the greater is the density pressure, and therefore the distance it travels is greater. Heavier particles are piled directly under the discharge and extensive sediment flows do not occur if the overburden is composed mostly of sand. The shape of the bottom contributes to determining both the direction and distance which the spoil moves since gravity is the primary transporting force. The bulk of shell dredge spoil flows back into the cut from which it was taken and a lesser amount is transported outside of cuts along the paths of least resistance. Masch and Espey (1967) have shown that spoil dispersion could be controlled by the proper use of submerged dikes and trenches which are a normal product of dredging operations.

Saline Wedges

A different type of density layer can also be formed as a result of wedges of water with near oceanic salinity being introduced into estuaries by deep channels or passes being dredged at the mouths of bays and rivers. High salinity intrudes the Mobile River as far as 30 miles upstream from its mouth due to the channel from the Gulf into the river (Robinson, Powell, and Brown, 1956). The open waters of most estuarine bays are stratified by salinity, the degree depending on water depth and the relative amount of mixing of the salt water and fresh water entering the estuary. Salinity density layers which resist mixing can alter sedimentation rates and water quality and affect the distribution of many species of motile and sessile organisms.

Patterns of salinity and water circulation are extremely important parameters in estuarine ecology. Their importance is not just directly to the animals in the water but they determine to a great extent the assimilation capacity of estuaries for natural and man-induced pollutants. It is frequently overlooked that the major economic use of many estuaries and their rivers is as a water supply and cesspools for municipalities and industries. If this use is to continue compatible with other valuable uses, alterations of salinity and circulation patterns by dredging must be carefully considered. Because of such alterations, channel dredging and associated spoil disposal influence the ecology of many estuaries.

Sediment-Water, Chemistry

Estuarine muds are complex in their composition and behavior and the mechanisms which determine the effects of dredging bottom material and discharging it overboard are complicated. The muds are unique assemblages of matter and they contain significant quantities of nutrients and trace elements composed of various inorganic and organic substances from natural and man-made sources. Most of these chemicals in the mud are at levels many times higher than the small quantities found dissolved in water because of the attraction of the negative surface of clay particles for the cations of saltwater. Among these elements and compounds are many which are basic for life and their concentrations regulate the kind and amount of biological processes in water. Natural muds are not known to be toxic to aquatic life whether deposited or suspended, however, some of the materials found in mud may be harmful to aquatic life if their dissolved concentrations in the water are too high.

Components of the mud which are of special importance include hydrogen sulfide, pesticides, metals and phosphorus and nitrogen compounds. Hydrogen sulfide is a toxic gas which results from the reduction of sulfates. It is often associated with sulfate-rich sludges from pulp mills and is commonly found in anaerobic water.

In contrast to most mud components, pesticides are almost exclusively man-made. The extent and importance of pesticide pollution in estuaries are not fully understood (Butler, 1966a, b; Johnson, 1968). Butler (in press) reported that DDT residues in oysters in 15 coastal states, including Alabama, were not observed be of such magnitude to cause damage to mollusks or constitute a human health problem (Butler, 1971). However, residues in oyster tissues were enough to pose a threat to other organisms through recycling and magnification. Butler, Childress and Wilson (1970) felt that suspended DDT in estuarine waters was probably sorbed on silt. They hypothesized that there was a partitioning between DDT levels in the sediment and water which is regulated by the solubility and concentration of DDT in water and that resuspension of sediment by storms may increase the amount of DDT available for biological uptake.

Metals and other trace elements enter the aquatic ecosystem from natural weathering processes of rocks and soils and by anthropogenic pollution on land and into air and water. Little information on metals in estuaries is available and natural levels in most water bodies or their significance are not well known (Jennings, 1972). Some metals may be noxious if dissolved into the water at even their natural levels in some mud. Zinc, a common mud component, is an almost universal constituent of living matter (Rice, 1961) but is highly toxic when dissolved concentrations are too high. Increases in phosphorus and nitrogen compounds and many metals may be harmless, beneficial, or detrimental depending on concentration. Photosynthesis in some estuaries has been shown to be limited by availability of nitrogen and phosphorus but not iron, trace metals, silicate, sulfate or vitamins (Parker, 1962; Thayer and Williams, 1970). Fournier (1966), however, found in the York River, Virginia that all or some of the trace metals are generally limiting to phytoplankton production throughout the year in addition to phosphate and nitrate. Pomeroy et al. (1972) stated phosphorus does not seem to be a limiting nutrient in any except some of the clearest, sediment-free estuaries.

Since materials in mud are exposed to the water during overboard disposal of dredge spoil, the complex physical and chemical interrelationship between mud and water is essentially what determines the degree that dredging affects water quality.

Although bacteria are important in biological exchanges between mud and water (Hayes and Phillips, 1958; Burchard, 1971) it is apparently not of immediate importance to the situation of dredging. Much work remains in determining the chemical mechanisms which regulate the exchange of these components between mud and water and their influence on aquatic biota. Little is known of the physicochemical forms of these elements, their relative stabilities or their rates of interconversion and exchange in water and sediment (Wolfe and Rice, 1972). However, their properties and behavior are adequately known to explain with some degree of certainty the lack of wholesale release into the water during dredging.

Many of the most important reactions between mud and water components are oxidation-reduction (redox) reactions and sorption-desorption ionic processes (Nelson, 1962; Lee, 1970). A typical vertical profile of a shallow estuary shows a column of oxygenated water over a thin zone of oxidized brownish to olive grey sediment and an underlying black or medium grey layer of reduced mud. Many metals having several valence states and phosphorus compounds are more soluble in their reduced form and generally precipitate when oxidized. Because the sediment surface is normally oxidized, it acts as a barrier to the more soluble reduced chemicals in the deeper muds (Windom, 1972). Metals may occur in the mud as metallic sulfides many of which are highly insoluble (Lee, 1970). These mechanisms apply to most metals and other mud components but there are exceptions when some forms of certain metals such as mercury are more soluble in an oxidized state than when reduced (Hem, 1970; Yeaple et al., 1972; D'Itri, 1972). However, dissolved mercury is commonly removed from water through adsorption on suspended organic and inorganic particulate matter which precipitates (Fleischer, 1970; D'Itri, 1972).

When the oxidized surface of the sediment is disturbed by dredging and the reduced muds are resuspended in the water a theoretical possibility exists that large amounts of some of the chemicals in the mud could become dissolved into the water. Several investigators have partially explained why this does not occur. There is a large concentration of reduced iron in the sediments (Windom, 1972). Iron comprises about 5 percent of the sediments in Mobile Bay (unpublished, Gulf South Research Institute) which is similar to other bays (Biggs, 1967). When it is dredged and placed into suspension it is immediately oxidized forming iron hydroxide. The iron hydroxide then has the capability of scavenging other metals out of solution and precipitating them with the iron. In addition, some of the other metals may precipitate as hydroxides (Nilsson, 1971). This process is aided by the organic matter and the high concentration of clays in dredge effluent which are capable of adsorping large amounts of metals (Lee, 1970). In addition, it is possible that the solubility rates of many metallic forms are too slow to allow release under the observed conditions of rapid settlement in dredge effluents.

Sediment acts as an effective buffer on phosphorus and the concentration in water remains fairly constant (Pomeroy, Smith and Grant, 1965). The reversible exchange system involves an ion-exchange process in which clay, iron and other metals are directly involved (Jitts, 1959). In the presence of oxygen, phosphorus in the water may combine with iron to form ferric iron-phosphate or more probably is sorbed on some complex or hydrous oxide of ferric iron (Lee, 1970) which are insoluble and precipitate. The chemical mechanisms of nitrogen exchange are different than phosphorus but are largely dominated by the redox system (Keeney, 1972). Nitrogen release by sediments is favored by oxidizing conditions but the release is slight and is apparently not rapid. Nitrate is different in that it shows essentially no sorption tendencies on clay minerals (Lee, 1970) but clays readily sorb organic nitrogenous compounds (Keeney, 1972).

The extent to which spoil disposal would be expected to alter dissolved concentrations of these materials is largely dependent on how it affects the conditions which regulate these exchange processes. The mechanisms are influenced by pH, the presence or absence of hydrogen sulfide and dissolved oxygen, and the composition and concentration of suspended sediments. Little change in pH and no hydrogen sulfide was detected around dredges during this study. The release of large quantities of reduced sediments into the water by dredges creates a rapid oxygen demand which reduces dissolved oxygen to some degree. However, the solids settle so rapidly that the area of low oxygen is mostly confined to the areas of extremely high suspended solid concentrations in the mud flow. Oxygen levels that may have been low enough to influence the release of chemicals into the water were not found in the water around the dredge discharges studied. Unless the oxygen concentration is very near zero the redox potential remains oxidative and is little affected (Mortimer, 1971; Keeney, 1972). Reducing conditions were not found in the water around dredges operating in Mobile Bay. In oxygenated water, as long as pH and eh (redox potential) are not greatly changed, no large-scale release of nutrients or trace elements would be expected to occur (Mortimer, 1971) especially in the presence of high mud concentrations.

Thus, the lack of total oxygen depletion, rapid settlement of solids and the formation of highly concentrated density layers strongly influence the distribution and fate of the mud components. The high clay concentrations in the discharge and flocculation cause components of the mud to remain associated with the suspended solids and to settle rapidly into the mud flow. They are trapped there because of the large adsorption capacity of the sediments and the oxygenated condition of the overlying water.

It was found in this study that the concentration of most materials in the sediment has little relationship to the effect dredges have on water quality. This has been observed in other areas also (Windom, 1972) and it is apparently valid for undisturbed sediments as well (Lee, 1970). This may not be true where the sediments are very heavily polluted but in a typical estuary no simple relationship has been observed. This is a very important point since it has been assumed by the Environmental Protection Agency that the quality of sediment determines the effects that dredge effluents have on water quality. Further, attempts to regulate dredging activities based on sediment criteria alone would be a mistake. Until all of the many interrelated factors which determine how dredge effluents may or may not affect water quality are better understood, arbitrary standards should not be established. Future research should be directed at a more complete knowledge of sediment-water chemistry and at determining the actual effect on water quality when dredging sediments of various grades.

Turbidity

The most obvious thing a dredge does is muddy the water. There is a lot of concern about turbidity from dredges silting beaches or fishing grounds and reducing the aesthetic quality of water. The Environmental Protection Agency has suggested that dredging operations be regulated by turbidity measurements and states have adopted turbidity criteria in their water quality standards. Reduction in light, essential for photosynthesis, can theoretically decrease primary productivity which is the basis for some professional concern about turbidity produced by dredges. From a lay view, turbidity produced by dredges is the visual evidence upon which much of the opposition toward dredging is based. Dredges often do increase turbidity over large areas so the effect of this aspect deserves to be considered.

Turbidity is a measurement of the amount of light that will pass through a liquid. It describes the degree of opaqueness produced by particulate matter suspended in water. The major components of turbidity in estuaries are silt, clay and organic matter. Turbidity measurement is usually expressed as Jackson Turbidity Units (JTU). These measurements cannot be meaningfully correlated with the amount of suspended matter in the water in a practical sense because of the varying optical properties of turbidity producing substances and dissolved materials (Taras, 1971). Turbidimeters have been shown to be unreliable when analyzing the same sample. Turbidity is a questionable measurement of suspended solids in water even at relatively low concentrations (Duchrow and Everhart, 1971) and at higher concentrations the accuracy of determinations are reported within the nearest 50 to 100 units.

Turbidity produced in the immediate vicinity of an active dredge discharge may exceed the capabilities of this method to measure it accurately. On relatively calm days the visible plume from an active dredge may be detectable from an aircraft for over a mile down current. On windy days the levels are usually lost both visually and quantitatively in background levels beyond a few hundred feet from the dredge. Although ambient surface turbidity levels may be exceeded over a large area of a particular day, natural levels produced by freshets and moderate winds are not exceeded beyond a few hundred feet from the discharge. Light reduction caused by a dredge plume would have the same effect on photosynthesis as materials put in suspension by natural causes but over a smaller area.

The extended turbidity is caused by very fine colloidal-like particles which are maintained in suspension by water currents. These add color to the water but, under most circumstances, the visible plume beyond a few hundred feet from the dredge has little relationship to the distribution of dredged sediments. Turbidity measurements are of little use in evaluating effects of dredging and they should not be used to regulate the practice since increases in turbidity are not quantitative and have no correlation to the transport of dredge effluent.

Total and Volatile Suspended Solids

In contrast to turbidity, determination of suspended solids is a quantitative measure of the actual amount of material in the water. Measurement of the weight of suspended solids is the only means by which the effect of dredging on sedimentation can be meaningfully evaluated. The weight of filtered and dried solids is an expression of the total amount of material in suspension. The weight lost by igniting the dried solids is an expression of the organic matter and other volatile solids. This fraction contributes greatly to the quality of sediment and if the amount is great enough its decay can degrade overlying water. However, in open water dredging, oxidation of organic matter found in typical sediments is too slow and the solids settle too rapidly to be of any consequence compared with the immediate chemical oxygen demand of reduced inorganic chemicals in the sediments. The importance of high concentrations of volatile solids in sediment to be dredged is that they may have already lowered water quality by depleting oxygen and producing hydrogen sulfide. In such cases, removal onto land of sediment high in organic matter such as are commonly found in industrial harbors may improve water quality although the quality of the effluent may be much lower than when dredging in less organic sediment.

It is the quantity of volatile solids that is of importance rather than percent. If percent volatile solids is applied as a quality criterion to dredge effluents, the case exists where the water being pumped lowers the quality of the mud. Suspended solids in Mobile Bay waters averaged 29 percent volatile solids. Samples of clear water from the Gulf of Mexico off the Alabama coast averaged 33 percent. The sediment in the bay ranged from [illegible] to 11 percent and averaged about 7 percent volatile solids. When mud and water are mixed by a hydraulic dredge, the effluents usually have a lower percent volatile solids than the receiving waters. Although the volatile solids content is important in characterizing sediments it does not appear to be a usable criterion for regulating dredging practices in typical situations.

EFFECTS OF DREDGING ON ESTUARIES

It has been observed that the only important direct effect channel and shell dredge effluents have on water quality in open Alabama estuaries is to temporarily increase suspended solids over a relatively small area. Most of the sediment discharged by dredges very quickly settles to the bottom and forms a highly concentrated density flow out to a distance of about 1,600 feet or less. This fluid mud which is partially oxygenated displaces the bottom water and consolidates rapidly without potentially harmful components of the mud becoming dissolved into the interstitial or overlying water. Dissolved oxygen is little affected except in the mud flow near bottom. The mud flow outside of dredge cuts consolidates to form a layer from less than one inch to several inches thick that covers the original bottom and suffocates some benthic organisms such as worms and small mollusks. Most macroscopic organisms in the material actually dredged are buried and killed. However, it has been shown that dredged areas become repopulated in a fairly short time (Harrison, 1967; Virginia Institute of Marine Science, 1967; Flemer et al., 1968; Cronin et al, 1970).

E. E. Jones (unpublished, University of South Alabama) did a limited faunal investigation around the shell drenge during this study period by comparing undredged and dredged bottoms. He concluded that repopulation of a dredged area probably occurs within a two-month period and that physical characteristics of dredged mud reverts to the undredged characteristics in approximately six months. He found that destruction of bottom fauna by dredging is minor and transitory.

John L. Taylor (unpublished) also conducted a restricted benthic survey around the shell dredge in Mobile Bay during the study period by comparing undredged bottoms with various aged dredge cuts and adjacent areas which had been affected by mud flows (Table 12). He reported that all bottom dwelling invertebrates were destroyed in a new dredge cut and that 70 percent or more was destroyed on bottoms receiving spoil in comparison with undredged bottoms. He found repopulation of cuts and spoil areas in Mobile Bay to be reasonably fast. The number of invertebrates present after a 6-month period or perhaps less, were equal to or greater than the number found in some areas of undisturbed bottom. However, the species diversity and abundance among stations in undisturbed areas were higher than the dredged areas in all but one case. He interpreted this to mean that areas of Mobile Bay influenced by dredging do not generally return to what may be considered a normal condition for a period of at least 2 years following dredging.

Limited, nonconclusive data collected during the present study at the stations shown in Figure 2 indicate that dredge cuts become fairly well repopulated after about 2 years but that species composition may not be as diversified (Table 13). None of the benthic studies in Mobile Bay considered seasonal or areal variations in the populations, differences in bottom type or known variations in water quality such as salinity and dissolved oxygen, so they are of limited use. Even so, the data are in general agreement with previous studies in other bays that areas affected by dredging do repopulate with benthic organisms within a fairly short time. Small temporary reductions in benthic organisms restricted to small areas are probably of little consequence to the estuarine ecosystem of Alabama.

Bacteria are an important component of estuarine muds and they are undoubtedly affected by dredging. Their importance as an ecological factor is much more than being a potential health hazard since they play an important role in determining sediment quality and nutrient exchange (Zobell and Feltham, 1942). Bacteria and fungi are thought to be the most important link in the food chain of omnivorous detritus consumers such as penaeid shrimp and many other common estuarine species (Odum, 1971). Increases in productivity which have been reported following dredging (Odum and Wilson, 1962; Odum, 1963; Virginia Institute of Marine Science, 1967) and motile animals congregating around dredges (Ingle, 1952; Viosca, 1958) may in part be due to increased bacterial activity in response to aeration of the sediment and the freshly exposed organic matter rather than a direct nutrient release. Bacteria are known to have an affinity for sediments and particularly organic matter (Volkmann and Oppenheimer, 1962) and bacterial levels have been observed to be higher when sediment is stirred into the water since levels adsorped to sediments are much higher than in overlying waters (Oppenheimer and Jannasch, 1962). Coliform bacteria levels were measured in undredged sediments but not in the water during the present study (Table 3). Since volatile solids in dredge effluents are distributed in association with the inorganic solids, both of which settle quickly, it can be tentatively assumed that bacteria in the mud are redistributed but remain associated with the suspended solids.

The holes that are sometimes left in the botton of Mobile Bay by shell dredges usually fill in to approximately predredging depths within 1 to 12 months (Figure 27). Consequently, any affect they may have is only temporary. There is no appreciable change in the dry weight density of the bottom (Table 3) and the redeposited material should not be more susceptable to resuspension than much of the original bottom. An experienced investigator is required to detect old dredge cuts by probing since water depth and the bottom consistancy is very similar to, or more frequently identical to, surrounding bottoms within a short time after dredging. The bay probably has not been deepened appreciably by removing shell because of the small area affected and the high rate of natural sedimentation. Volumetrically, an average of over 5.4 times more sediment enters Mobile Bay each year than the volume of shell removed.

Oyster reefs, in almost all cases, are raised above the surrounding bottom and would not be greatly susceptible to coverage by dredge effluents if proper precautions are followed. Spoil piles left from previous dredging operations which were less than two feet higher than the bottom had no silt deposition on them even within 100 feet from an active shell dredge. Oysters on the spoil bank of the Mobile Ship Channel were not silted when a shell dredge operated within 700 feet from them, nor was silt deposited on the spoil bank immediately adjacent to a dredge cut. Under controlled operating conditions with knowledge of bottom configuration and continuous sampling of suspended solids, dredging could be done very near producing oyster reefs, shorelines and existing navigation channels without damage. A fixed distance for dredging near such areas would not apply in all cases and is not recommended.

When a shell dredge begins a new cut, the coarser material may form spoil piles several feet above bottom if the dredge is discharging from the stern. This is especially true when dredging in sandy bottoms, but usually not on soft bottoms. After the dredge proceeds forward so that its discharge is over the new cut, all of the coarse material settles into the dredged hole along with most of the finer material. These piles are usually less than 150 feet long and are mostly eroded away within a few months although oysters sometimes become established on them. In fairly shallow water these piles may temporarily interfere with small boat navigation and on some occasions in Mobile Bay they have been removed by the shell dredging company with draglines. Because of their small size and temporary nature they have little effect on water circulation.

Shell dredging, as it is presently practiced, appears to be one of the least harmful methods of recovering and processing a natural mineral resource. It releases no deleterious concentrations of chemicals into the water or atmosphere and produces only minor and transitory physical and biological effects. The entire operation goes on unnoticed by most people and has been conducted for 26 years in Alabama without any discernible harm. Since no significant or lasting environmental damage is apparently done by shell dredging in Alabama, the benefits derived from the practice should be considered by all those concerned. The actual effects of shell dredging and the adverse sentiment against it are far outweighed by the conservation and economic benefits derived from the wise utilization of this resource.

The need for channel dredging is obvious although there are problems associated with it which must be considered. In contrast to shell dredging, all the material disposed of in open water by channel dredges is put on top of the original bottom. This results in islands or large submerged piles being formed which may be several hundred feet wide and extend the entire length of an estuary which greatly restrict boat traffic. These spoil areas have been indiscriminately placed in every major estuary in the United States without regard for changes they would cause in water circulation. There was little concern for what effect salt water introduction by deep channels would have on the ecological balance of estuaries. Many of the effects are insidious and have been poorly documented. Most of them may never be known because so little historical data are available on salinity, water quality and aquatic biology. In most places, the effects are sometimes difficult to separate from natural changes over the long period of time dredging has been done.

Although it may not be possible to determine historical effects of salt water intrusion in most bays, the effects of salinity regimes on aquatic and benthic organisms are well recognized (Gunter, 1961). The relationship of salinity to aquatic fauna deserves to be studied in all estuaries where channel dredging has been done or is anticipated since salinity plays an important role in the ecology of many important organisms. H. A. Swingle and D. G. Bland (unpublished, Alabama Marine Resources Division) found that fishes were less abundant numerically in the Mobile

Ship Channel than in other areas of the bay and that there were about 1/3 more species present in the channel than in adjacent areas. Nelson found that croakers (*Micropogon undulatus*) leave shallow and moderately deep areas in colder months and concentrate in and near the ship channel. Salinity greatly influences the well being of oyster populations since spat set and survival are affected by relatively small salinity gradients (May and Bland, 1970). Major salinity changes, both natural and man made, can influence the survival and distribution of oysters (May, 1971; 1972) and the relationship of such changes to dredged channels should be investigated.

Lack of sufficient water circulation in Mobile Bay results in widespread oxygen depletion during the summer. This is caused by salinity stratification in sinks created by shoals in the lower bay and spoil banks from the ship channel (May, in press). During the summer of 1971 dissolved oxygen of 3.0 ppm or less was found in 44 percent of the bottom waters of Mobile and Bon Secour bays. Approximately 56,000 acres were found which had less than 1.0 ppm in the bottom three feet. This is highly unusual since the average depth of Mobile Bay is only 9.7 feet and most shallow bays are well mixed. This condition has existed for over a century and has caused considerable fishery losses and affected the ecology of many species although the total effect is not fully known. Future modifications from channel spoil are expected to worsen this condition and fisheries losses will continue.

The importance of adequate circulation to the assimilation capacity of estuaries must be recognized as being of foremost concern if coastal bays are to continue to serve multiple usage. Spoil placement from channels can no longer be done as in the past without further altering the usefulness and value of many estuaries. This point should be given full attention by the Corps of Engineers and other responsible agencies. Long-term plans for wise spoil disposal must be developed for each coastal area to eliminate some of the present problems and avoid creating other harmful effects.

CONCLUSIONS

On the basis of these findings and other studies, the following conclusions about dredging and open water spoil disposal can be made.

1. The water and sediment in coastal Alabama are similar to many other estuaries and the determinations made in this study should be applicable in other areas since certain basic hydrological concepts control dredge effluent dispersion and subsequent effects on water quality.
2. Almost all dredged material disposed of in open water settles very rapidly and enters dredge cuts or is transported by gravity along the bottom as a flocculated density flow separate from the water column. All other measurable sediment transport does not exceed natural levels caused by normal winds beyond about 1600 feet or less from the discharge. Suspended solids are temporarily increased to high levels over a limited area but this causes little deleterious environmental effect. There is a limited, temporary reduction in macroscopic benthic organisms in areas affected by dredging.
3. The widespread visible turbidity sometimes produced by dredges does not exceed natural levels caused by freshets or normal winds beyond a few hundred feet from the discharge. The visible plume has little relationship to the distribution of dredged sediments and it does not measurably increase silting. Turbidity measurements have no useful application to dredging situations since the actual concern is with the amount of solids suspended in the water.
4. The distance that suspended sediment from dredge effluents in estuarine water will exceed ambient levels or will cover an area of the bottom is dependent upon the kind and amount of material being pumped and the bottom configuration. With this information, the safe distance from channels, shorelines and oyster reefs that dredges can discharge can be determined by

monitoring the existing circumstances. Because of variations in conditions, a fixed distance from such areas is not applicable in all cases.

5. If it is desirable to confine spoil to a more limited area, discharge pipes should be directed upward above water without any modifications except devices or methods to decrease the velocity of the fluid as much as possible to reduce roiling of the density layer. Discharging on the surface reduces the velocity of the effluent on contact with the water surface and promotes more rapid settling and consolidation.

6. The concentration of materials normally found in typical estuarine sediments has little relationship to the effect on water quality except for reduced elements which create an immediate oxygen demand which is mostly limited to the density flow near bottom. Because of rapid settlement, volatile solids are of little importance to dredging situations unless they are high enough to have already degraded water quality.

7. Both organic and inorganic constituents of effluent sediments remain largely adsorbed or insoluble under aerobic dredging conditions in the presence of high clay concentrations and the common ions of brackish water and potentially harmful components of the sediment are not dissolved into the water. Consequently, biological uptake of potentially deleterious components of the mud is not expected.

8. Water quality can be affected indirectly by gross physical modifications as a result of channel dredging and spoil disposal. This should be given close attention in every dredging situation to prevent harmful alterations of water circulation, salinity and obliteration of existing water areas. The effect of existing modifications should be determined and appropriate long term spoil plans should be developed for every estuary.

9. The desirability of establishing limiting criteria on sediments or water to be dredged is questionable and it appears that standards are not necessary to protect water quality in open estuaries. Present Environmental Protection Agency guidelines are inadequate and should be re-evaluated. Future research should be directed at determining the effect of major physical modifications, developing a more complete knowledge of sediment-water chemistry and at determining the actual effect on water quality when dredging sediment of various grades.

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LITERATURE CITED

Bardarik, Daniel G., Jon C. Alden, and Robert L. Shema. (No date). The effects of in-stream sand and gravel dredging on the aquatic life of the upper Allegheny River. Environmental Sciences, Inc. Pittsburgh, Pennsylvania. 108 p.

Bault, Edward I. 1972. Hydrology of Alabama estuarine areas--cooperative Gulf of Mexico estuarine inventory. Alabama Dep. Conserv. Nat. Resour., Dauphin Island, Alabama. Alabama Mar. Resour. Bull. 7: 36 p.

Biggs, Robert B. 1967. The sediments of Chesapeake Bay. p. 239-260. In G. H. Lauff (ed.) Estuaries. Amer. Ass. Advance. Sci.

_______________. 1968. Environmental effects of overboard spoil disposal. J. Sanitary Eng. Div. 94(SA3): 477-487.

Briggs, Philip T., and Joel S. O'Connor. 1971. Comparison of shore-zone fishes over naturally vegetated and sand-filled bottoms in Great South Bay. New York Fish Game J. 18 (1): 15-41.

Breuer, Joseph P. 1962. An ecological survey of the lower Laguna Madre of Texas, 1953-1959. Univ. Texas, Pub. Inst. Mar. Sci. 8: 153-183.

Brown, Charles L., and Robert Clark. 1968. Observations on dredging and dissolved oxygen in a tidal waterway. Water Resour. Res. 4 (6): 1381-1384.

Burchard, Robert P. 1971. Chesapeake Bay bacteria able to cycle carbon, nitrogen, sulfur and phosphorus. Chesapeake Sci. 12 (3): 179-180.

Butler, Philip A. 1966a. The problem of pesticides in estuaries. p. 110-115. In A symposium on estuarine fisheries. Amer. Fish. Soc. Spec. Pub. 3.

_______________. 1966b. Fixation of DDT in estuaries. Trans. 21 N. Amer. Wildl. Natur. Resour. Conf. 184-189.

_______________. 1971. Influence of pesticides on marine ecosystems. Proc. Roy. Soc. London B. 177: 321-329.

_______________. In press. Organochlorine residues in estuarine molluscs, 1965-1972. A report of one segment of the national pesticide monitoring program. Pesticide Monitoring J.

Butler, Philip A., Ray Childress, and Alfred J. Wilson, Jr. 1970. The association of DDT residues with losses in marine productivity. Food Agr. Organ. United Nations, Rome, Italy. FIR: MP/70/E-76. 13 p.

Casper, V. L., R. J. Hammerstrom, E. A. Robertson, Jr., J. C. Bugg, Jr., and J. L. Gaines. 1969. Study of chlorinated pesticides in oysters and estuarine environment of the Mobile Bay area. U. S. Dep. Health, Educ. and Welfare, Public Health Serv., Dauphin Island, Alabama. 47 p.

Carlston, Charles W. 1950. Pleistocene history of coastal Alabama. Bull. Geol. Soc. Amer. 61 (10): 1119-1130.

Copeland, Charles W. 1968. Geology of the Alabama coastal plain--a guidebook. Geol. Surv. Alabama. Circ. 47: 97 p.

Corliss, Jane, and Lee Trent. 1971. Comparison of phytoplankton production between natural and altered areas in West Bay, Texas. U. S. Nat. Mar. Fish. Serv. Fish. Bull. 69 (4): 829-832.

Cronin, L. Eugene, Robert B. Biggs, David A. Flemer, Hayes T. Pfitzenmeyer, Frank Goodwin, Jr., William L. Dovel, and Douglas E. Ritchie, Jr. 1970. Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Nat. Resour. Inst., Univ. Maryland. Contrib. 397, Spec. Rep. 3. 66 p.

D'Itri, Frank M. 1972. Mercury in the aquatic ecosystem. Michigan State Univ. Inst. Water Res. Tech. Rep. 23. 101 p.

Duchrow, Richard M., and W. Harry Everhart. 1971. Turbidity measurement. Trans. Amer. Fish. Soc. 100 (4): 682-690.

Engle, James B. 1962. Dredging for buried shell in the coastal waters of North Carolina. U. S. Dep. Interior Bur. Com. Fish. Biol. Lab. Oxford, Maryland. Mimeo 11 p.

Environmental Protection Agency. 1971. Methods for chemical analysis of water and wastes. Water Quality Office, Analytical Quality Control Lab., Cincinnati, Ohio. 312 p.

Feick, G., R. A. Horne, and D. Yeaple. 1972. Release of mercury from contaminated freshwater sediments by the runoff of road deicing salt. Science. 175 (4026): 1142-1143.

Fitzgerald, George P. 1970. Aerobic lake muds for the removal of phosphorus from lake waters. Limnol. Oceanogr. 15(4): 550-555.

Fleischer, Michael. 1970. Summary of the literature on the inorganic geochemistry of mercury. p. 6-13. In Mercury in the environment. Geol. Surv. Prof. Paper 713.

Fournier, Robert O. 1966. Some implications of nutrient enrichment on different temporal stages of a phytoplankton community. Chesapeake Sci. 7 (1): 11-19.

Flemer, David A., William L. Dovel, Hayes T. Pfitzenmeyer, and Douglas E. Ritchie, Jr. 1968. Biological effects of spoil disposal in Chesapeake Bay. J. Sanitary Eng. Div. 94 (SA4): 683-706.

Godcharles, Mark F. 1971. A study of the effects of a commercial hydraulic clam dredge on benthic communities in estuarine areas. Florida Dep. Natur. Resour. Div. Mar. Resour. Tech. Ser. 64. 51 p.

Gunter, Gordon. 1938. A new oyster clutch for the Texas coast. Proc. Texas Acad. Sci. 21: 14.

————. 1961. Some relations of estuarine organisms to salinity. Limnol. Oceanogr. 6 (2): 182-190.

————. 1969. Reef shell or mudshell dredging in coastal bays and its effect upon the environment. Trans. 34 N. Amer. Wildl. Natur. Resour. Conf. p. 51-74.

————. In press. Use of dead reef shell and its relation to estuarine conservation. Trans. 37 N. Amer. Wildl. Natur. Resour. Conf.

Gustafson, J. F. 1972. Beneficial effects of dredging turbidity. World Dredging Mar. Construction 8 (13): 44, 45, 47, 48, 50-52, 72.

Harrison, W. 1967. Environmental effects of dredging and spoil deposition. First World Dredging Conf. New York. 535-559.

Hayes, F. R., and J. E. Phillips. 1958. Lake water and sediment IV. Radiophosphorus equilibrium with mud, plants, and bacteria under oxidized and reduced conditions. Limnol. Oceanogr. 3 (4): 459-475.

Hellier, Thomas R., Jr., and Louis S. Kornicker. 1962. Sedimentation from a hydraulic dredge in a bay. Univ. Texas, Pub. Inst. Mar. Sci. 8: 212-215.

Hem, John D. 1970. Chemical behavior of mercury in aqueous media. p. 19-24. In Mercury in the environment. Geol Surv. Prof. Paper 713.

Hill, Floyd R., and Frank D. Masch. 1969. General considerations prerequisite to further Galveston Bay shell removal. Center for Res. in Water Resour. Univ. Texas, Austin, Texas. Tech. Rep HYD 15-6901; CRWR 48. 50 p.

Huggett, Robert J., Michael E. Bender, and Harold D. Slone. 1971. Mercury in sediments from three Virginia estuaries. Chesapeake Sci. 12 (4): 280-282.

Hutton, Robert F., Bonnie Eldred, Kenneth O. Woodburn, and Robert M. Ingle. 1956. The ecology of Boca Ciega Bay with special reference to dredging and filling operations. Florida State Bd. Conserv. Tech. Ser. 17 (1): 1-86.

Ingle, Robert M. 1952. Studies on the effect of dredging operations upon fish and shellfish. Florida State Bd. Conserv. Tech. Ser. 5: 26 p.

Ingle, Robert M., A. Russell Ceurvels, and Richard Leinecker. 1955. Chemical and biological studies of the muds of Mobile Bay. Rep. to Div. Seafoods, Alabama Dep. Conserv. Univ. Miami Contribut. 139: 14 p.

Jennings, Feenan D. 1972. Baseline studies of pollutants in the marine environment and research recommendations. Int. Decade Ocean Exploration Baseline Conf. May 24-26, 1972, New York. 54 p.

Jitts, H. R. 1959. The adsorption of phosphate by estuarine bottom deposits. Australian J. Mar. Freshwater Res. 10 (1): 7-21.

Johnson, Donald W. 1968. Pesticides and fishes--a review of selected literature. Trans. Amer. Fish. Soc. 97 (4): 398-424.

Keeney, Dennis R. 1972. The fate of nitrogen in aquatic ecosystems. Univ. Wisconsin Water Resour. Center, Lit. Rev. 3: 59 p.

Kerr, Alex. 1967. The Texas reef shell industry. Bur. Business Res., Univ. Texas. Texas Industry Series 11: 80 p.

Lee, G. Fred. 1970. Factors affecting the transfer of materials between water and sediments. Eutrophication Info. Prog. Water Resour. Center, Univ. Wisconsin. Lit. Rev. 1: 35 p.

Louisiana Wild Life and Fisheries Commission. 1968. The history and regulation of the shell dredging industry in Louisiana. Rep. to the Governor of La. submitted by Leslie L. Glasgow. 32 p.

Lunz, G. Robert, Jr. 1938. Oyster culture with reference to dredging operations in South Carolina. Rep. to U. S. Engineers Office, Charleston, South Carolina. 1-135.

________________. 1942. Investigation of the effects of dredging on oyster leases in Duval County, Florida. In Handbook of Oyster Survey, Intracoastal Waterway, Cumberland Sound to St. Johns River. Spec. Rep., U. S. Army Corps of Engineers, Jacksonville, Florida.

Mackin, John G. 1962. Canal dredging and silting in Louisiana bays. Univ. Texas, Pub. Inst. Mar. Sci. 7: 262-314.

Masch, Frank D., and William H. Espey, Jr. 1967. Shell dredging a factor in sedimentation in Galveston Bay. Center for Res. in Water Resour. Univ. Texas, Austin, Texas. Tech. Rep. HYD 06-6702; CRWR-7. 168 p.

May, Edwin B. 1971. A survey of the oyster and oyster shell resources of Alabama. Alabama Dep. Conserv., Dauphin Island, Alabama. Alabama Mar. Resour. Bull. 4: 53 p.

____________. 1972. The effect of floodwater on oysters in Mobile Bay. Proc. Nat. Shellfisheries Ass. 62: 67-71.

____________. In press. Extensive oxygen depletion in Mobile Bay, Alabama. Limnol. Oceanogr.

May, Edwin B., and Donald G. Bland. 1970. Survival of young oysters in areas of different salinity in Mobile Bay. Proc. SE Ass. Game Fish Comm. 23: 519-521.

May, Edwin B., and Kenneth R. McLain. 1970. Advantages of electronic positioning and profiling in surveying buried oyster shell deposits. Proc. Nat. Shellfisheries Ass. 60: 72-74.

McCoy, Edward G., and Kenneth H. Johnston. (No date). The effects of wind and salinity upon the sedimentation rates of soils from dredging in Albemarle Sound, North Carolina. Div. Inland Fish. North Carolina Wildl. Resour. Comm. Mimeo. 9 p.

Mortimer, C. H. 1971. Chemical exchanges between sediments and water in the Great Lakes--speculations on probable regulatory mechanisms. Limnol. Oceanogr. 16 (2): 387-404.

Murawski, Walter S. 1969. A study of submerged dredge holes in New Jersey estuaries with respect to their fitness as finfish habitat. New Jersey Dep. Conserv. Econ. Development, Misc. Rep. No. 2M: 32 p.

Nelson, Bruce W. 1962. Important aspects of estuarine sediment chemistry for benthic ecology. p. 27-41. <u>In</u> Nelson Marshall (ed.) The environmental chemistry of marine sediments. Univ. Rhode Island. Occasional Pub. 1.

Nelson, Walter R. 1969. Studies on the croaker, <u>Micropogon undulatus</u> Linnaeus, and the spot, <u>Leiostomus xanthurus</u> Lacepede, in Mobile Bay, Alabama. Univ. Alabama, J. Mar. Sci. 1 (1): 4-92.

Nilsson, Rolf. 1971. Removal of metals by chemical treatment of municipal waste water. Water Res. 5: 51-60.

Odum, Howard T. 1963. Productivity measurements in Texas turtle grass and the effects of dredging an intracoastal channel. Univ. Texas, Pub. Inst. Mar. Sci. 9: 48-58.

Odum, Howard T., and Ronald F. Wilson. 1962. Further studies on reaeration and metabolism of Texas bays, 1958-1960. Univ. Texas, Pub. Inst. Mar. Sci. 8: 23-55.

Odum, William E. 1971. Pathways of energy flow in a south Florida estuary. Univ. Miami, Sea Grant Tech. Bull. 7: 162 p.

Oleszkiewicz, Jan H., and Peter A. Krenkel. 1972. Effects of sand and gravel dredging operations on water quality in the Ohio River. Vanderbilt Univ. Environ. Water Resour. Eng. Tech. Rep. 29: 154 p.

O'Neal, Gary, and Jack Sceva. 1971. The effects of dredging on water quality in the Northwest. Environmental Protection Agency, Region 10, Seattle, Washington. 158 p.

Oppenheimer, C. H., and Holger W. Jannasch. 1962. Some bacterial populations in turbid and clear sea water near Port Aransas, Texas. Univ. Texas, Pub. Inst. Mar. Sci. 8: 56-60.

Pomeroy, Lawrence R., L. R. Shenton, [illegible] and Robert [illegible]. Nutrient flux in estuaries. Amer. Soc. Limnol. Oceanogr. Spec. Symp. Michigan St. Univ. 1: 274-293.

Parker, Patrick L. 1962. Zinc in a Texas bay. Univ. Texas, Pub. Inst. Mar. Sci. 8: 75-79.

Pomeroy, Lawrence R., E. E. Smith, and Carol M. Grant. 1965. The exchange of phosphate between estuarine water and sediments. Limnol. Oceanogr. 10 (2): 167-172.

Rice, T. R. 1961. Review of zinc in ecology. Proc. First Nat. Symp. Radioecology, 1961. 619-631.

Robinson, W. H., W. P. Powell, and Eugene Brown. 1956. Water resources of the Mobile area, Alabama. U. S. Geol. Surv. Spec. Rep. 373. 45 p.

Rochford, D. J. 1951. Studies in Australian estuarine hydrology. I. Introductory and comparative features. Australian J. Mar. Freshwater Res. 2: 1-116.

Ryan, John J. 1969. A sedimentologic study of Mobile Bay, Alabama. The Sedimentological Res. Lab., Dep. Geol., Florida State Univ., Tallahassee, Florida. Contribut. 30: 109 p.

Servizi, J. A., R. W. Gordon, and D. W. Martens. 1969. Marine disposal of sediments from Bellingham Harbor as related to sockeye and pink salmon fisheries. Intern. Pacific Salmon Fish. Comm. New Westminister, B. C., Canada, Progress Rep. 23. 38 p.

Sherk, J. Albert, Jr., and L. Eugene Cronin. 1970. The effects of suspended and deposited sediments on estuarine organisms, an annotated bibliography of selected references. Univ. Maryland Nat. Resour. Inst. Reference No. 70-19: 61 p.

Swingle, H. S. 1964. Methods of analysis for waters, organic matter and pond bottom soils used in fisheries research. Auburn Univ. Dep. Fisheries and Allied Aquacultures, Auburn, Alabama. Mimeo. 107 p.

Stickney, Robert R. 1972. Effects of intracoastal waterway dredging on ichthyofauna and benthic macroinvertebrates. Skidaway Inst. Oceanogr., Savannah, Georgia. 27 p.

Sykes, James E., and John R. Hall. 1970. Comparative distribution of mollusks in dredged and undredged portions of an estuary, with a systematic list of species. U. S. Fish Wildl. Serv. Fish. Bull. 68 (2): 299-306.

Taras, Michael J. (Chairman). 1971. Standard methods for the examination of water and wastewater. Amer. Public Health Ass., Washington, D. C. 874 p.

Taylor, John L., and Carl H. Saloman. 1968. Some effects of hydraulic dredging and coastal development in Boca Ciega Bay, Florida. U. S. Fish Wildl. Serv. Fish. Bull. 67 (2): 213-241.

Taylor, John L., John R. Hall, and Carl H. Saloman. 1970. Mollusks and benthic environments in Hillsborough Bay, Florida. U. S. Fish Wildl. Serv. Fish. Bull. 68 (2): 191-202.

Thayer, Gordon W., and Richard B. Williams. 1970. Identity and regulation of nutrients limiting photosynthesis in an estuarine system. Bull. Ecol. Soc. Amer. 51 (2): 32.

U. S. Army Corps of Engineers. 1967. Report of water quality investigation Chickasaw Creek dredging project--1967. Mobile District, Mobile, Alabama. 31 p.

__________________________. 1968. Surveillance program of sedimentation effects of dredging Gulf Intracoastal Waterway Bon Secour Bay Section July-December 1967. Mobile District, Mobile, Alabama. 19 p.

__________________________. 1971. Dredge disposal study for San Francisco Bay and estuary. San Francisco District, San Francisco, California. 38 p.

Viosca, Percy. 1958. Effect of dredging operations. Louisiana Wild Life and Fish. Comm. Biennial Rep. 1956-1957. p. 96, 106.

Virginia Institute of Marine Science. 1967. A study of the effects of dredging and dredge spoil disposal on the marine environment. Final Rep. to U. S. Army Corps of Engineers Spec. Rep. in Applied Mar. Sci. and Ocean Eng., Gloucester Point, Virginia.

Volkmann, Carol M., and Carl H. Oppenheimer. 1962. The microbial decomposition of organic carbon in surface sediments of marine bays of the central Texas Gulf Coast. Univ. Texas, Pub. Inst. Mar. Sci. 8: 80-96.

White, William Allen. 1966. Controlled investigation of the movement of dredge sediments as a density current. M. S. Thesis, Univ. Texas, Austin, Texas. 57 p.

Wilson, William B. 1950. The effects of sedimentation due to dredging operations on oysters in Copano Bay, Texas. M. S. Thesis, Texas A & M Coll., College Station, Texas. 128 p.

Windom, Herbert L. 1972. Environmental response of salt marshes to deposition of dredged materials. Preprint In 1972 Amer. Soc. Civil Eng. Nat. Water Resour. Eng. Conf. 1612: 1-26.

Wolfe, D. A., and T. R. Rice. 1972. Cycling of elements in estuaries. U. S. Nat. Mar. Fish. Serv. Fish. Bull. 70 (3): 959-972.

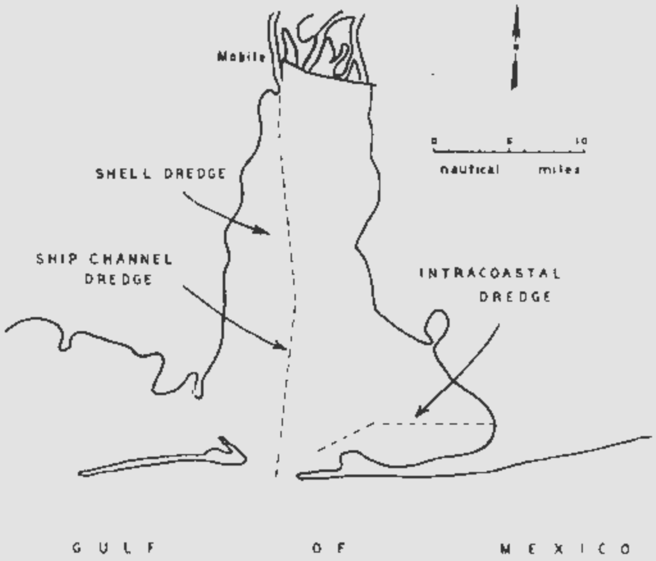
Yeaple, Donald S., George Feick, and Ralph A. Horne. 1972. Dredging of mercury-contaminated sediments. Preprint In Fourth Ann. Offshore Technol. Conf. 1 (1584): 695-702.

Zobell, Claude E., and Catharine B. Feltham. 1942. The bacterial flora of a marine mud flat as an ecological factor. Ecology 23 (1): 69-78.

Figure 1. Locations of sediment cores and water samples for background physical and chemical analyses taken in October 1971 from Mobile Bay.

Figure 2. Station locations of surface mud samples and bottom cores for biological, physical and chemical analyses collected in May 1972.

Figure 3. Locations of three hydraulic dredges studied in Mobile Bay and Bon Secour Bay.



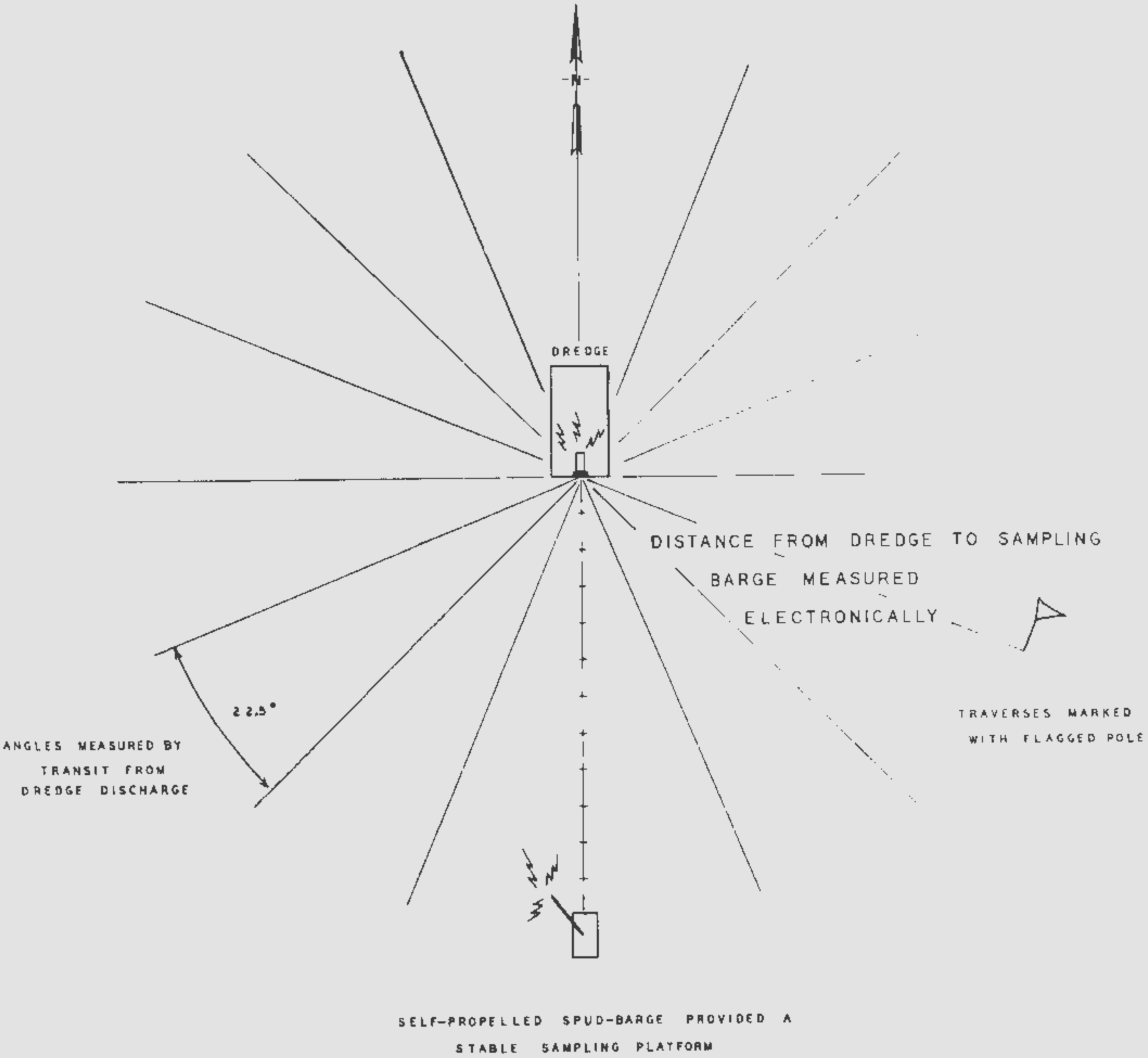


Figure 4. Radial grid pattern used to sample dredge effluent. Samples were taken along each traverse at points located by electronic positioning.

Figure 5. Heavy metals (mg/l) in sediments from major estuaries along the Gulf of Mexico.

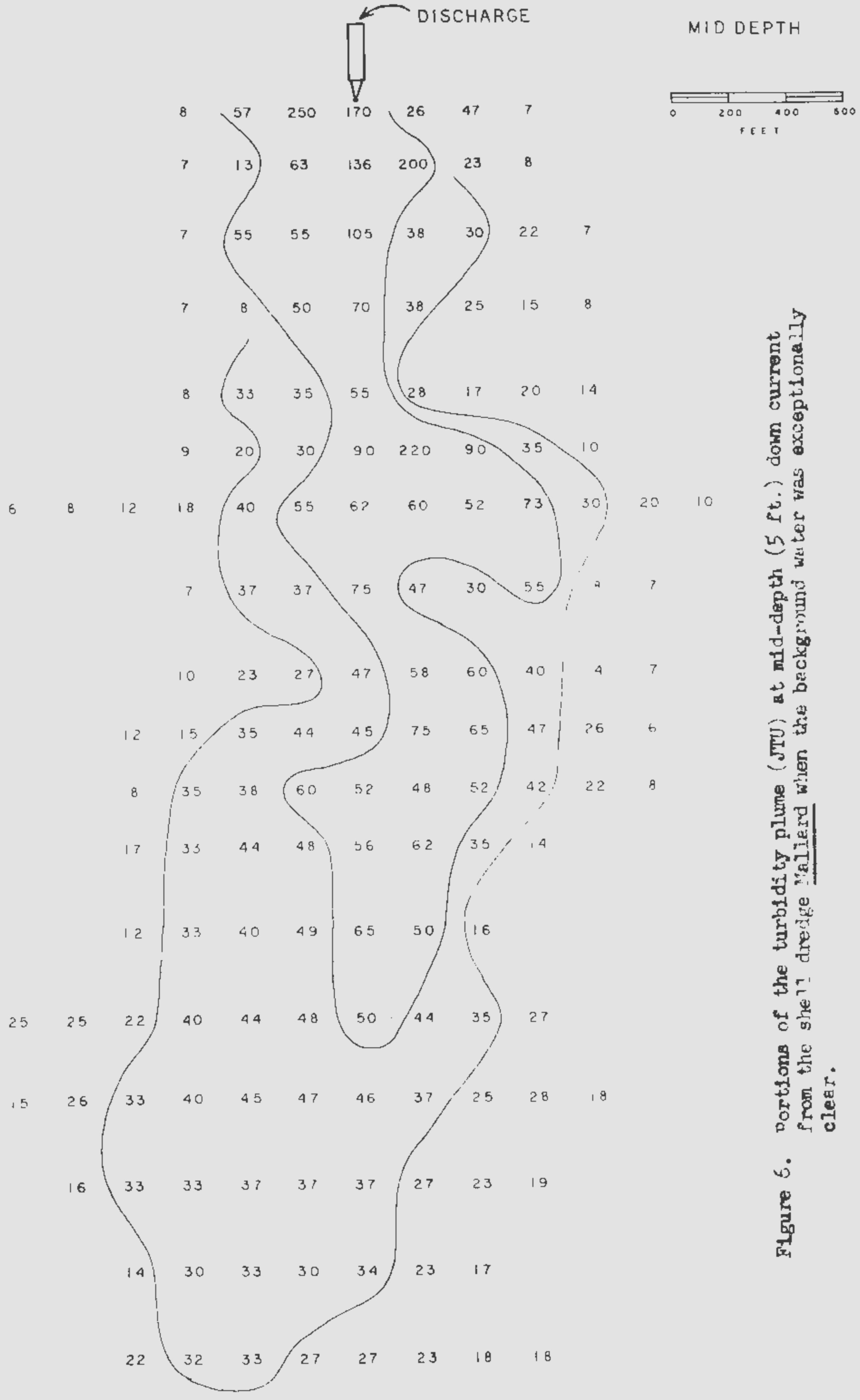
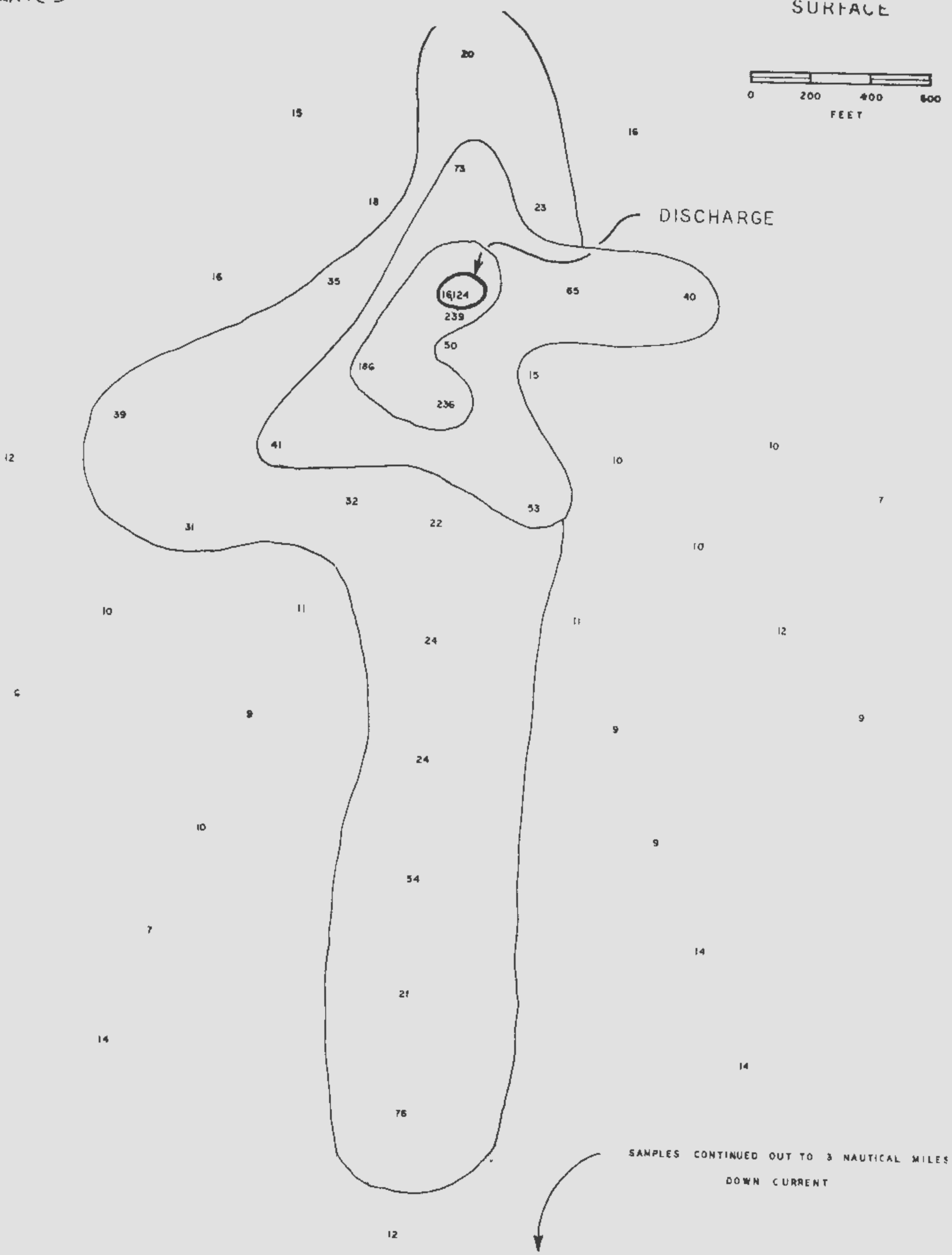
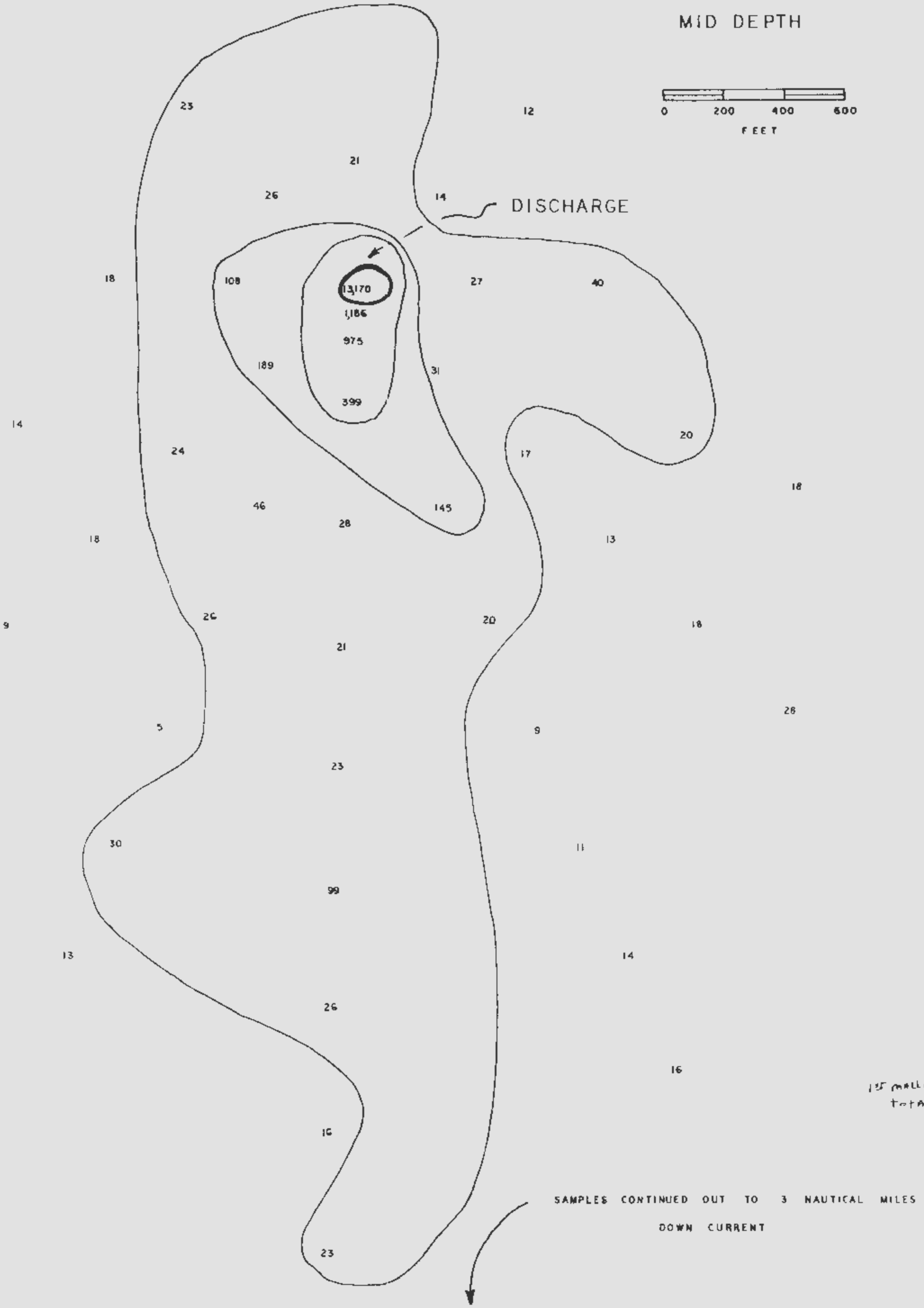


Figure 6. Portions of the turbidity plume (JTU) at mid-depth (5 ft.) down current from the shell dredge *Mallard* when the background water was exceptionally clear.

Figure 7. Horizontal distribution at three depths of total suspended solids in mg/l around the shell dredge Mallard during a 1 to 8 knot NE-E wind on 30 September 1971.

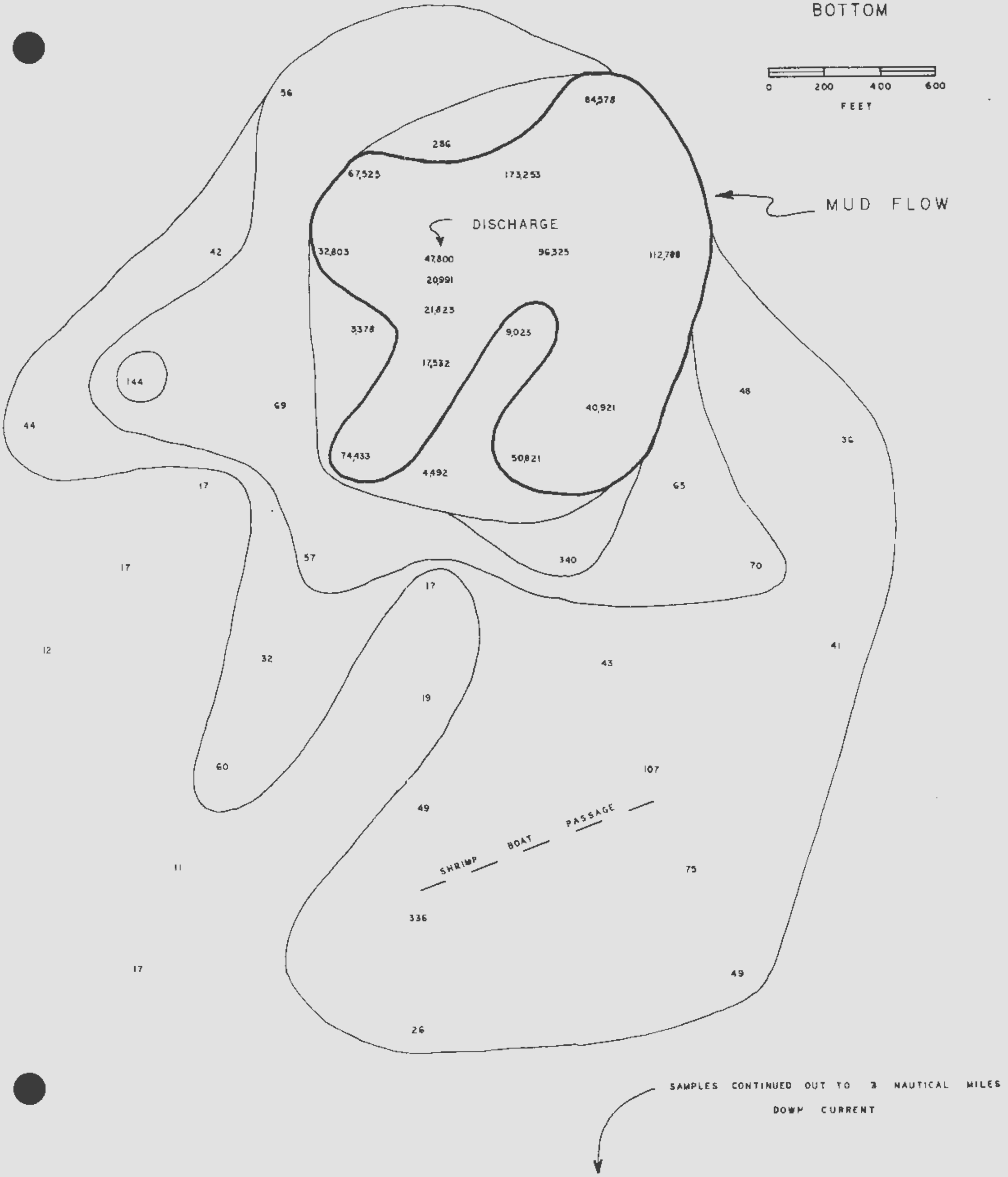
3 PLATES





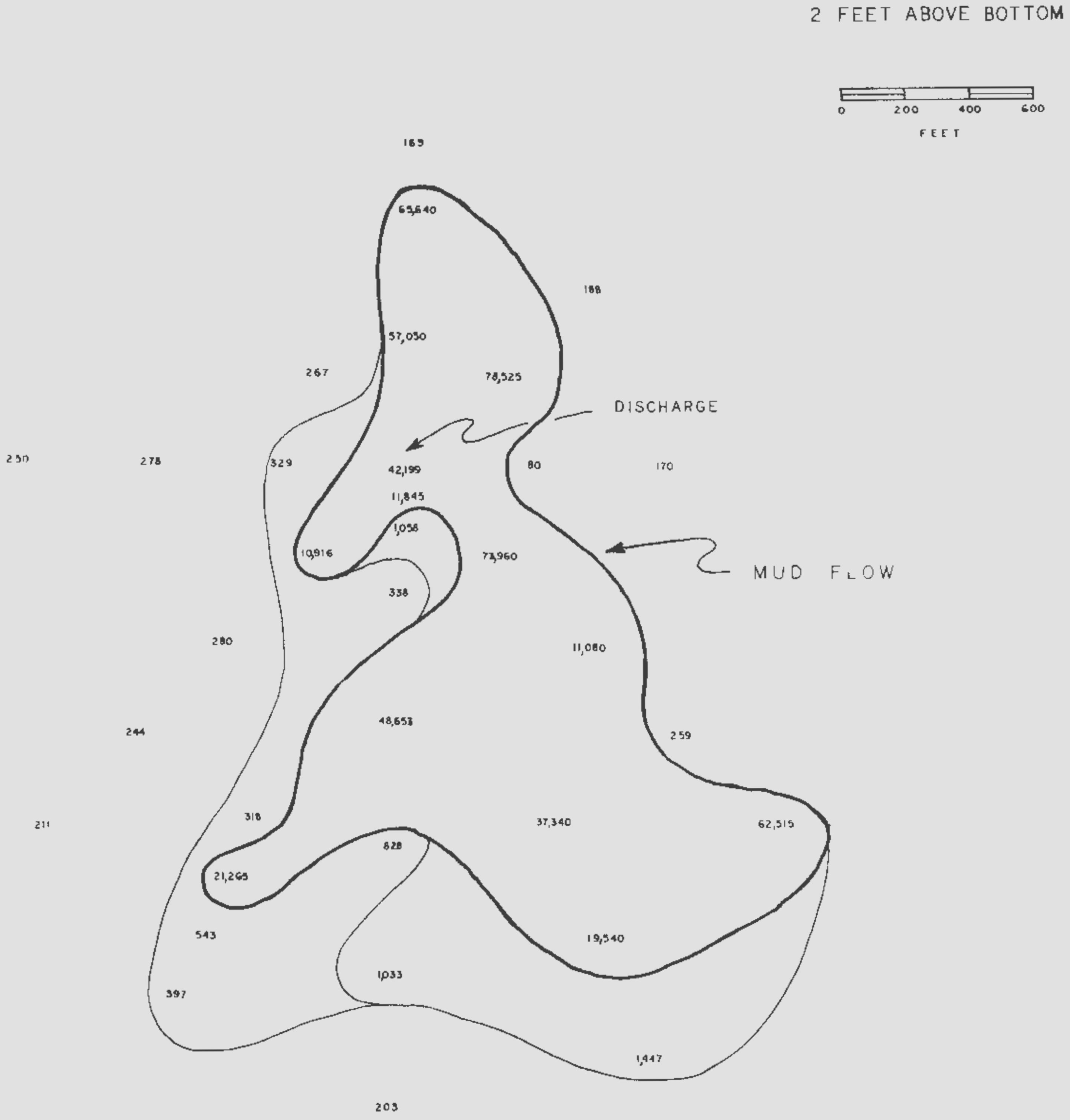
1-5 mallard middle
total 5

BOTTOM

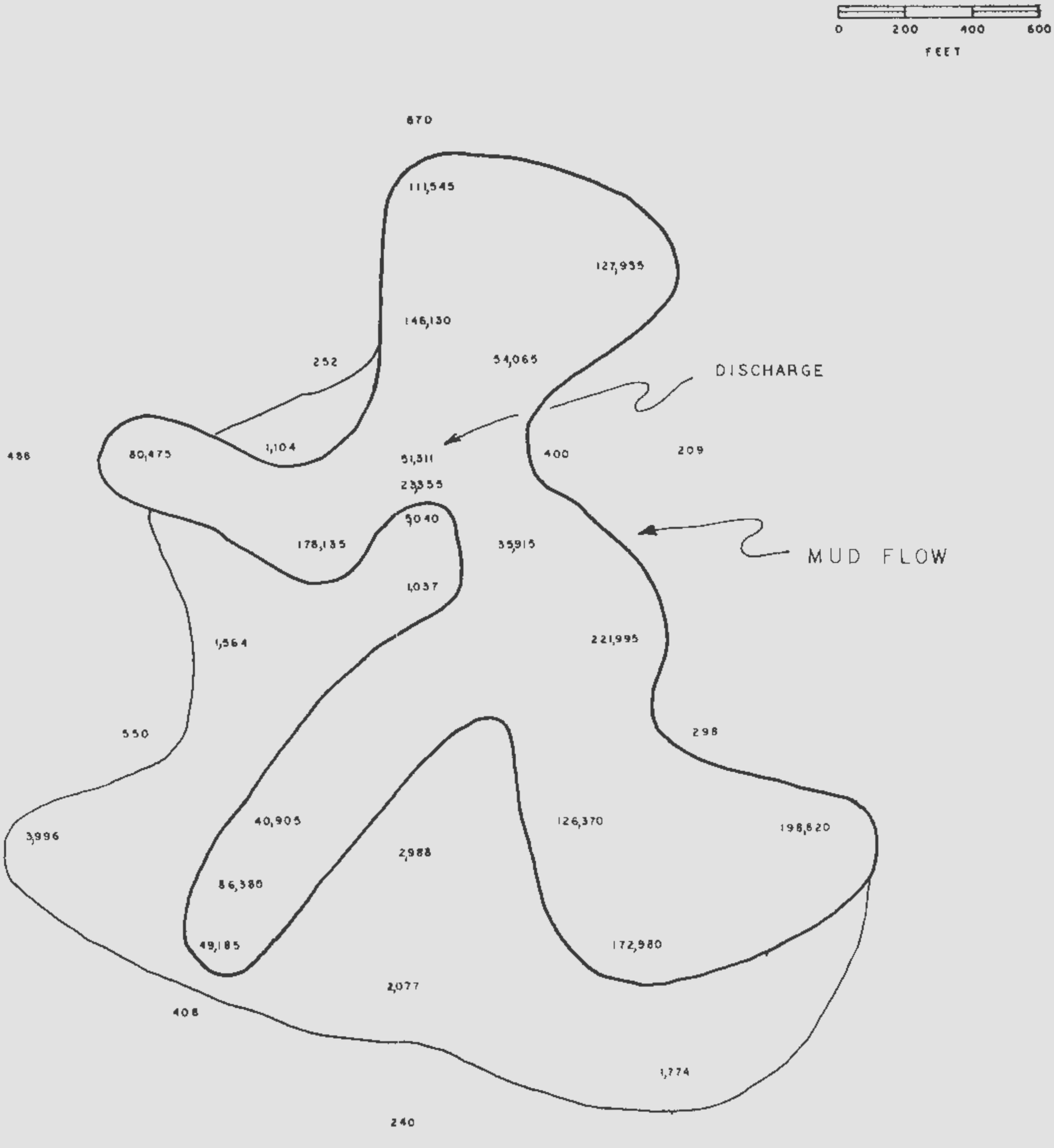


SAMPLES CONTINUED OUT TO 3 NAUTICAL MILES DOWN CURRENT

Figure 8. Horizontal distribution of total suspended solids in mg/l around the shell dredge Mallard during a 20 to 25 knot wind on 3 November 1971.



0.5 FEET ABOVE BOTTOM



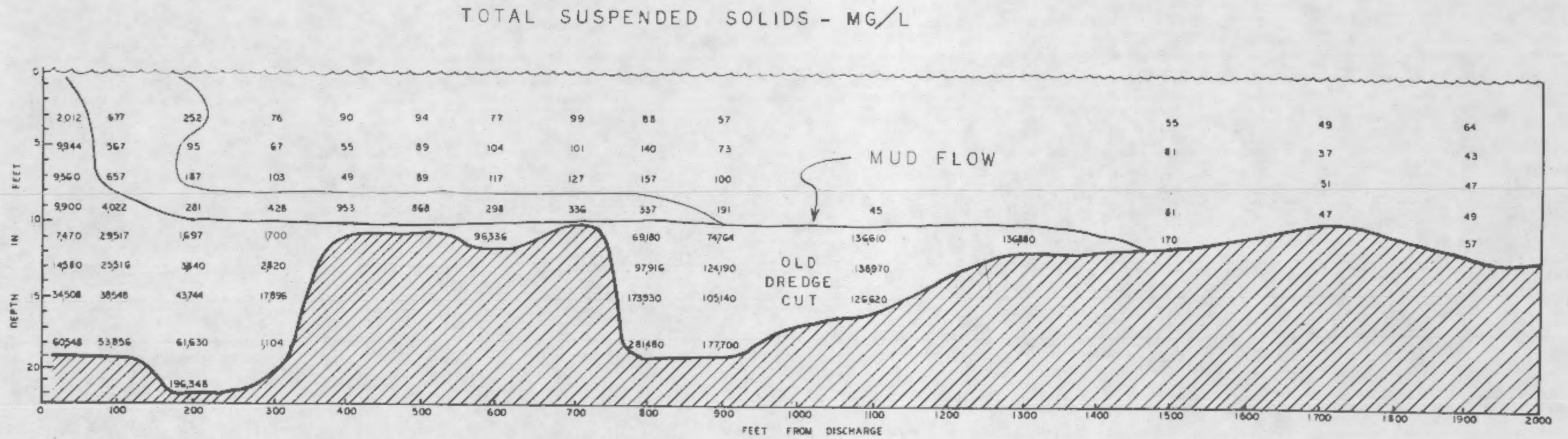


Figure 9. Vertical distribution of total suspended solids down current from the shell dredge Mallard on 21 January 1972.

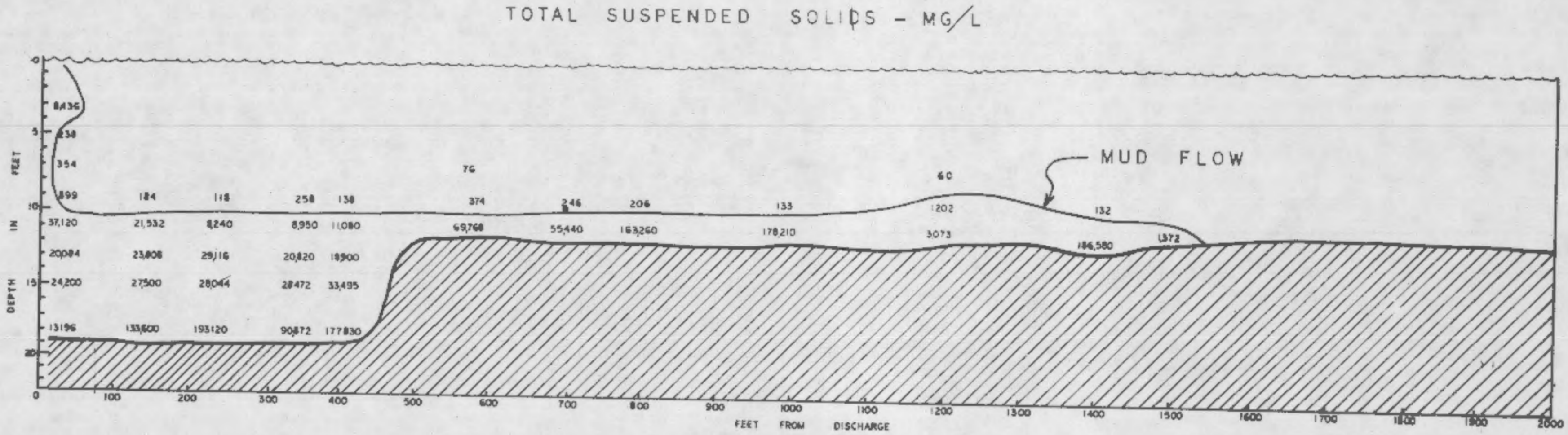


Figure 10. Vertical distribution of total suspended solids at a right angle to the current direction around the shell dredge Mallard on 21 January 1972.

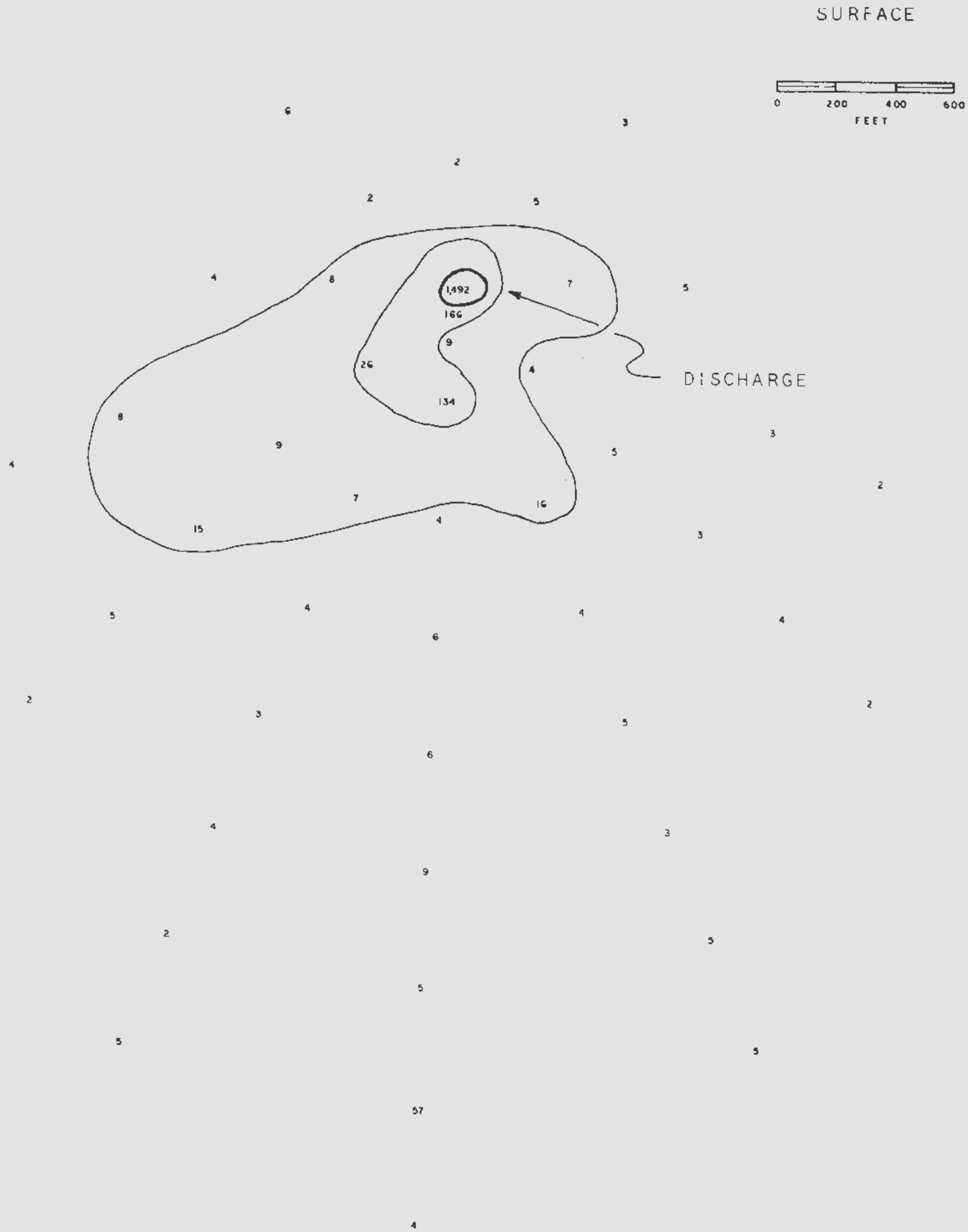
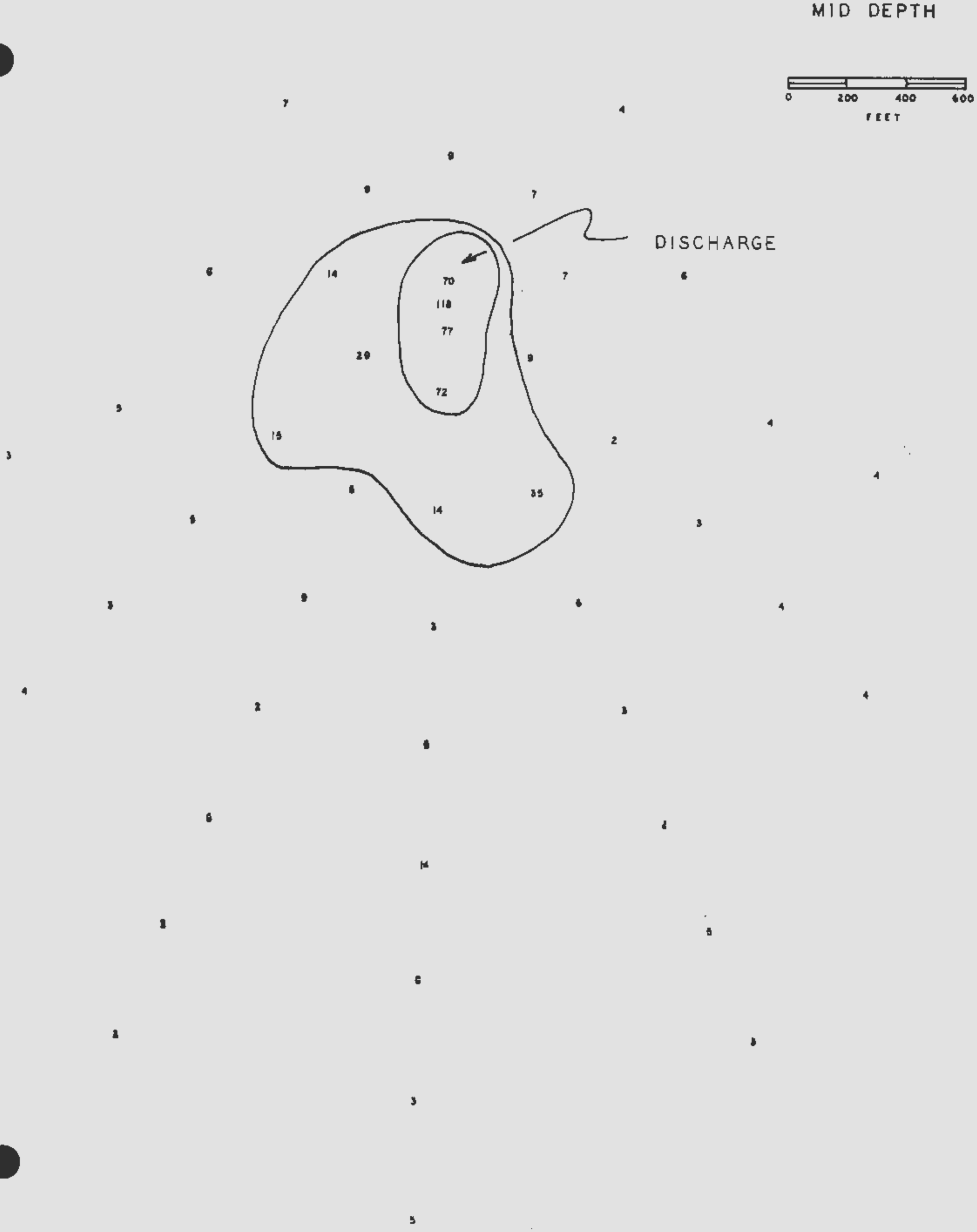
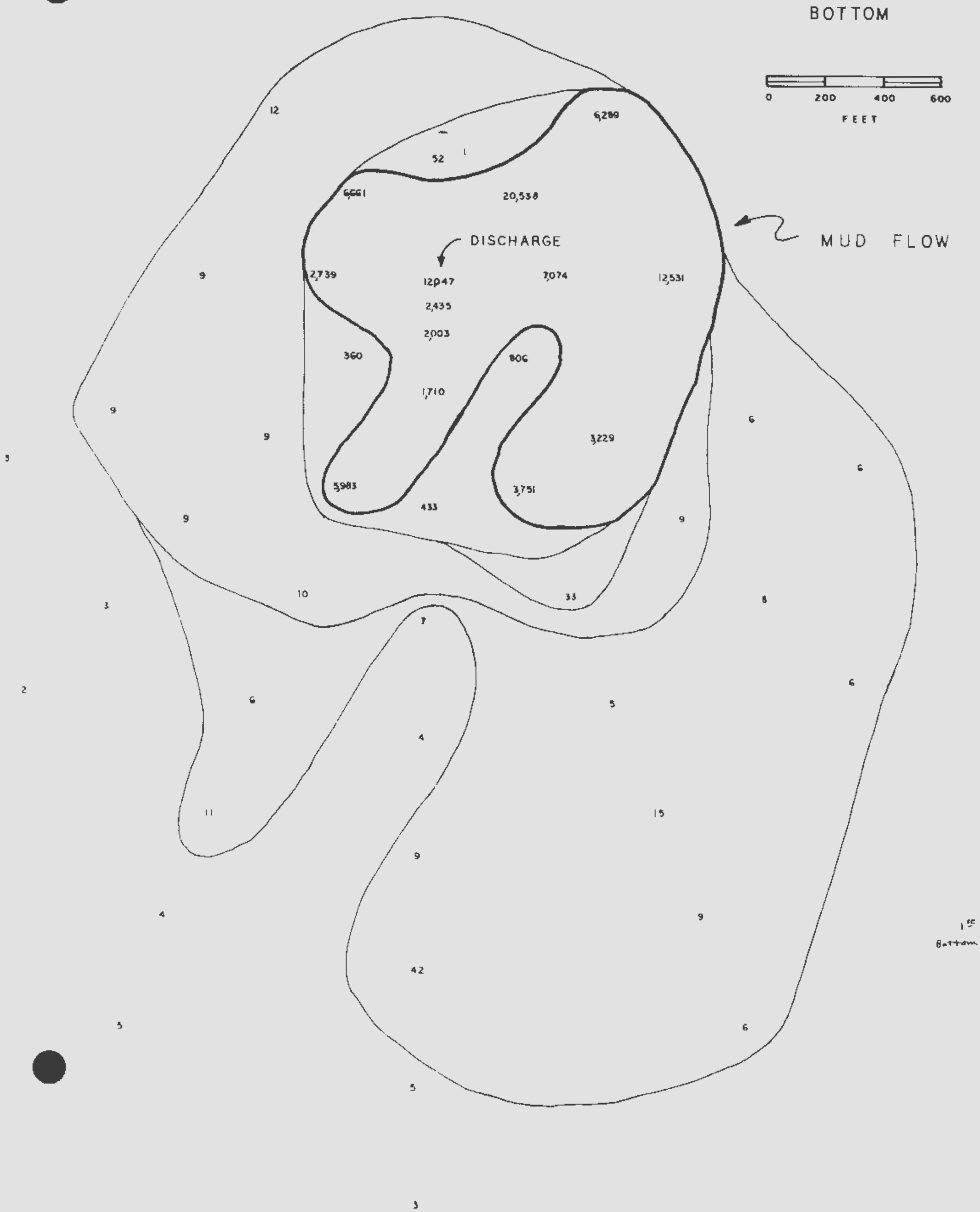


Figure 11. Horizontal distribution at three depths of volatile suspended solids in mg/1 around the shell dredge Mallard during a 1 to 8 knot N-E wind.

3 PLATES


MID DEPTH
0
200
400
600
FEET
DISCHARGE
70
118
77
72
29
14
15
35
14
9
2



1st Mallard
Bottom ORGANIC SS

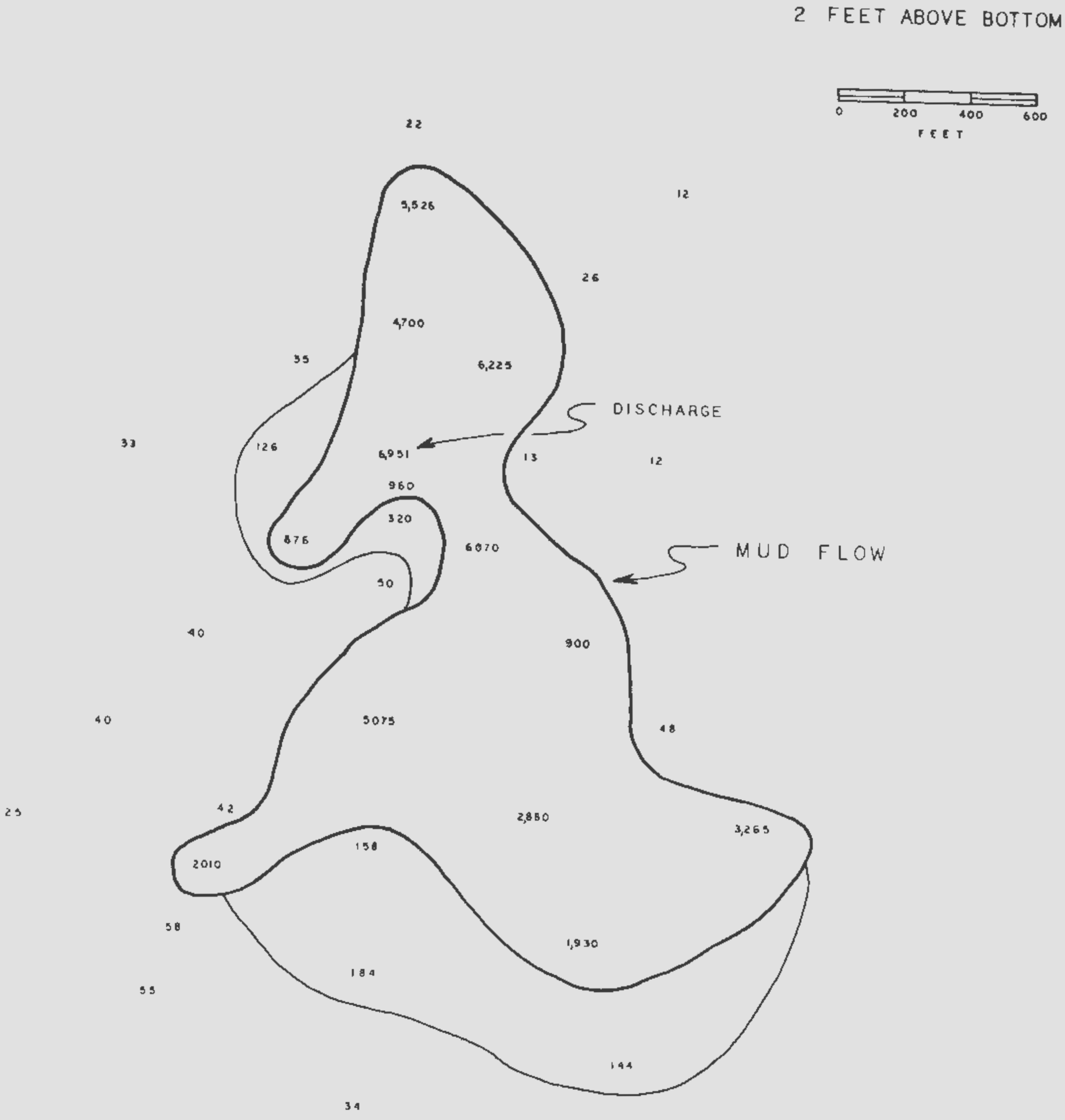


Figure 12. Horizontal distribution of volatile suspended solids in mg/l around the shell dredge Mallard during a 20 to 25 knot N wind.

2PLATES

0.5 FEET ABOVE BOTTOM

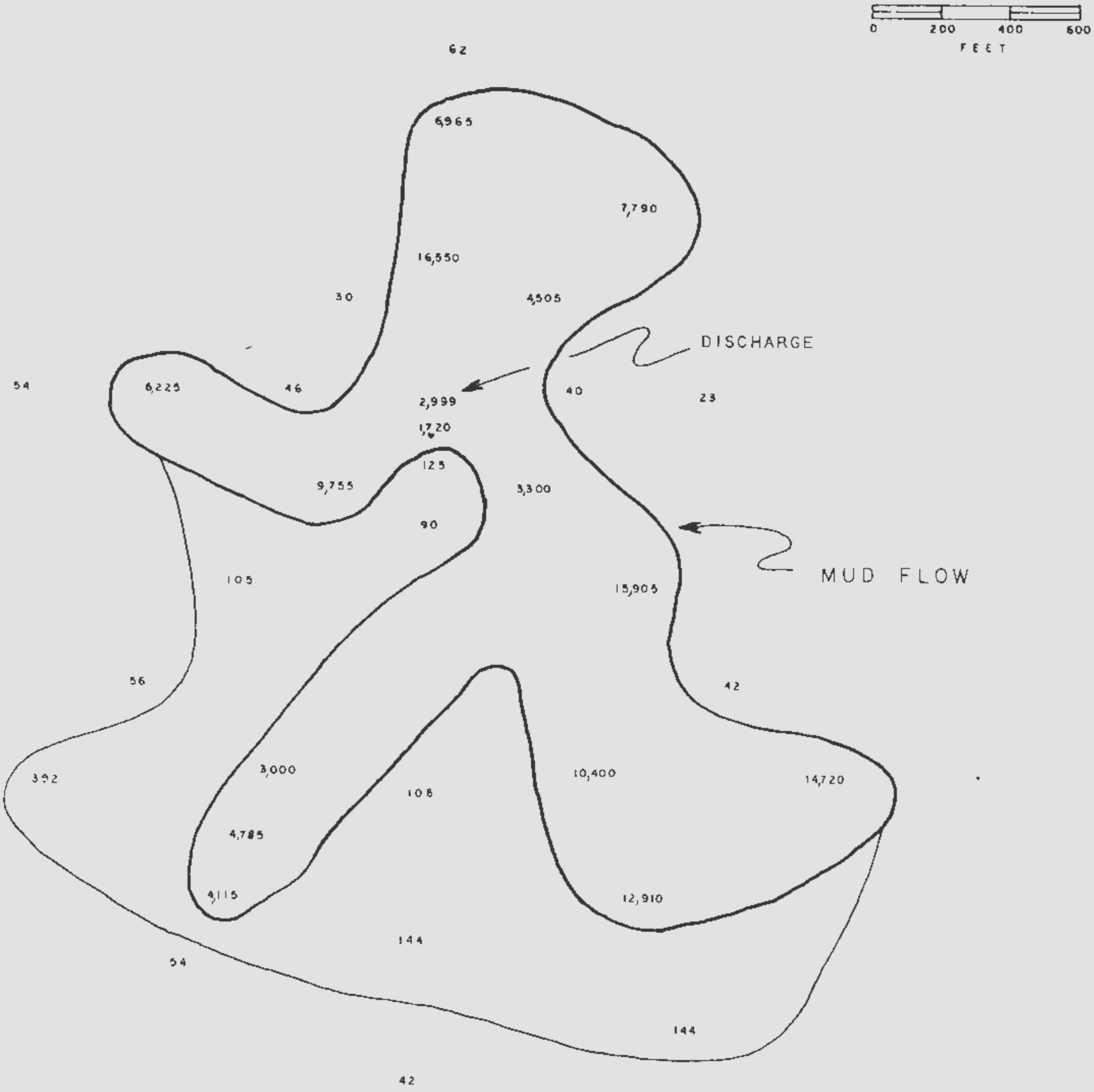


Figure 13. Dissolved oxygen in ppm around the shell dredge Mallard during a 1 to 8 knot NE-E wind. Bottom D. O. within 500 feet is in the highly concentrated mud flow.

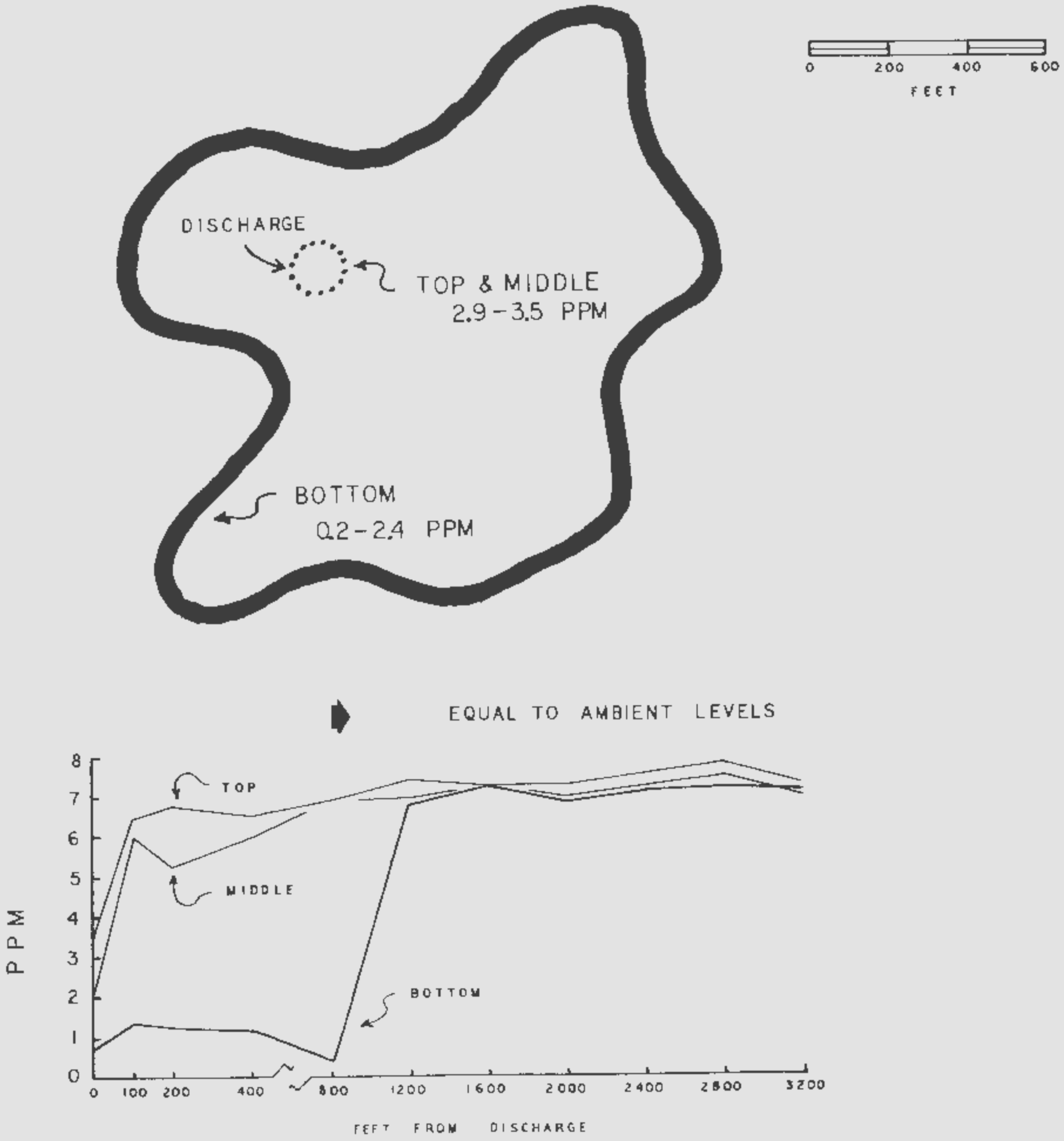
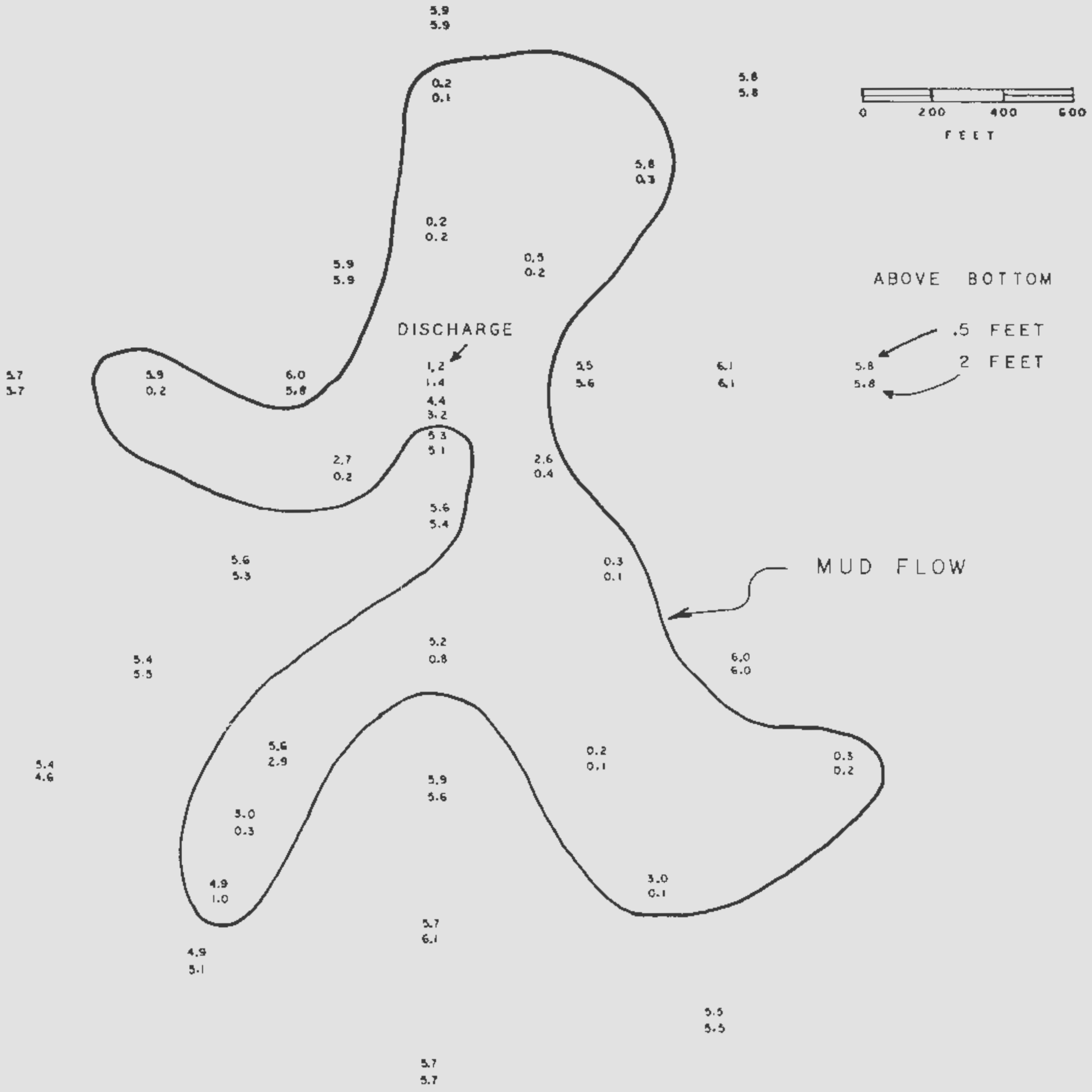


Figure 14. Dissolved oxygen in ppm in the mud flow around the shell dredge *Mallard* during a 20 to 25 knot N wind.



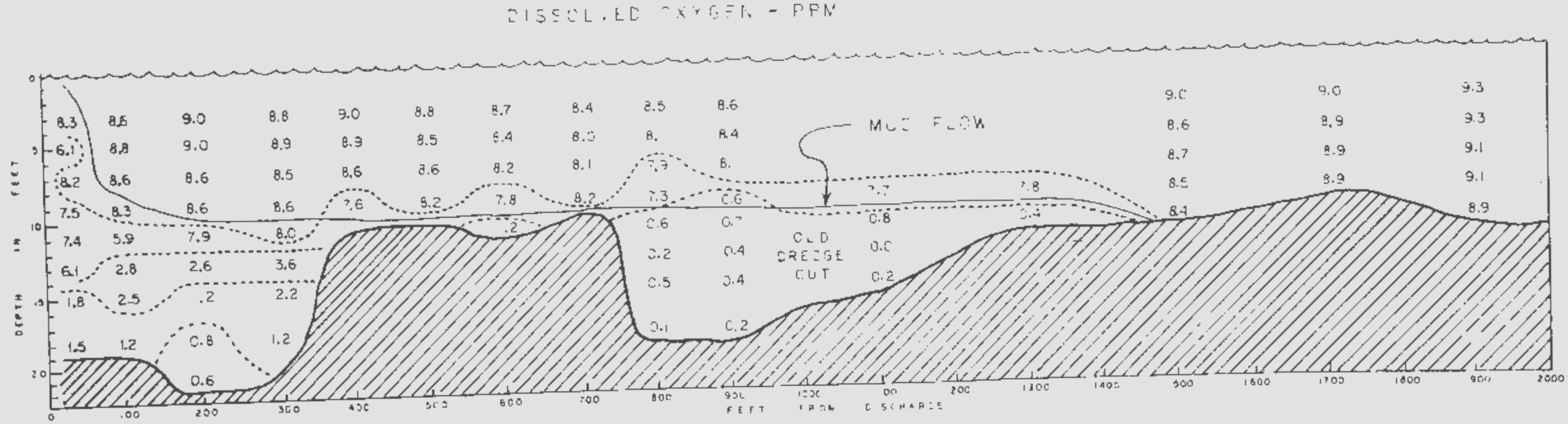


Figure 15. Vertical distribution of dissolved oxygen down current from the shell dredge *Mallard* on 21 January 1972.

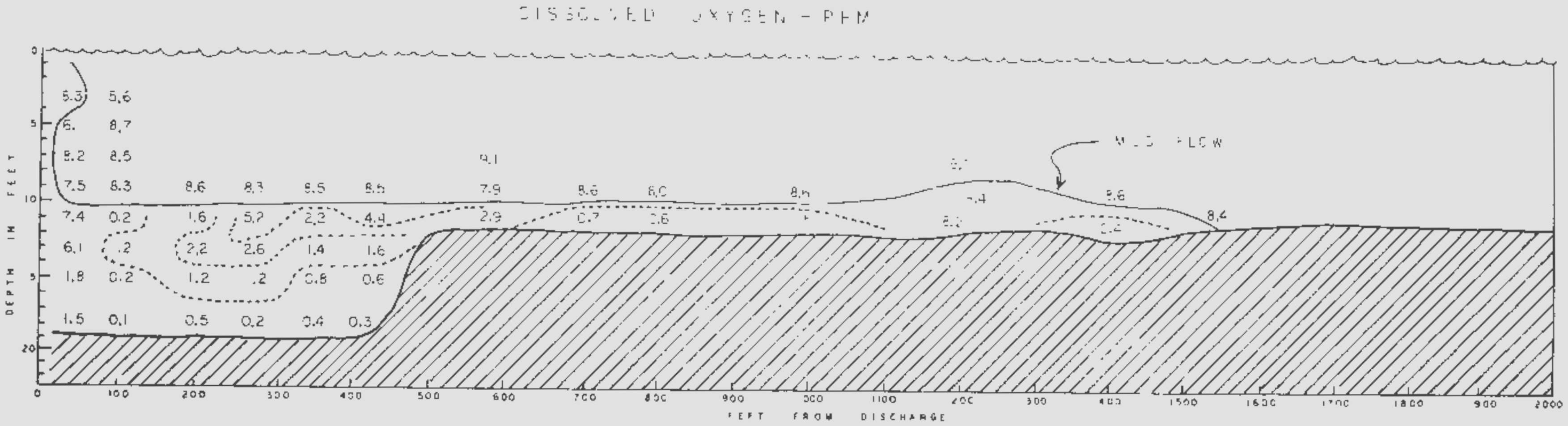


Figure 16. Vertical distribution of dissolved oxygen at a right angle to the current direction around the shell dredge *Mallard* on 21 January 1972.

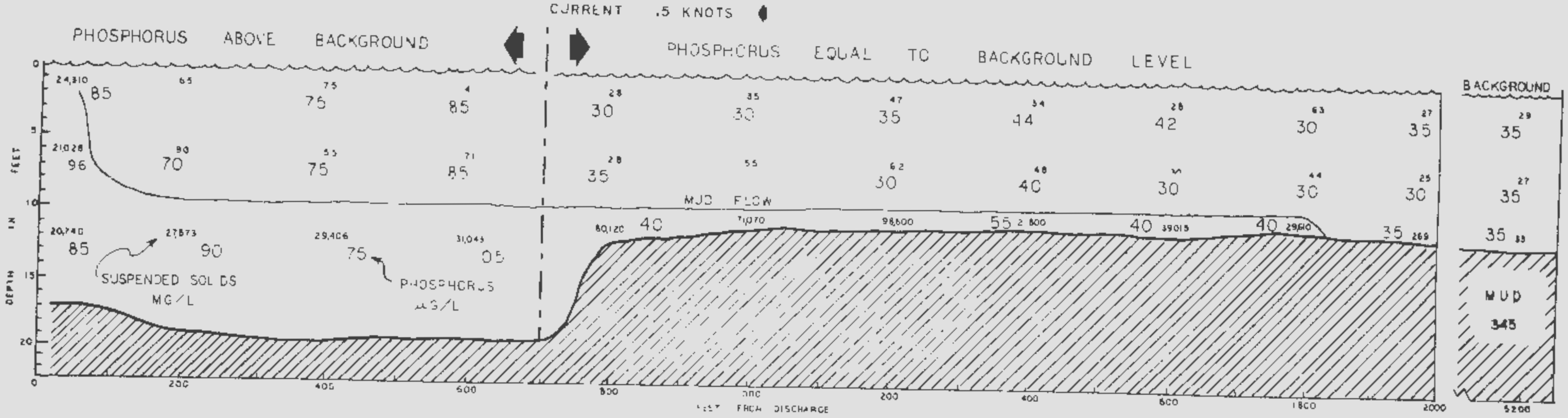


Figure 17. Total phosphorus from settled samples up current from the shell dredge *Mallard* on a calm day on 29 March 1972.

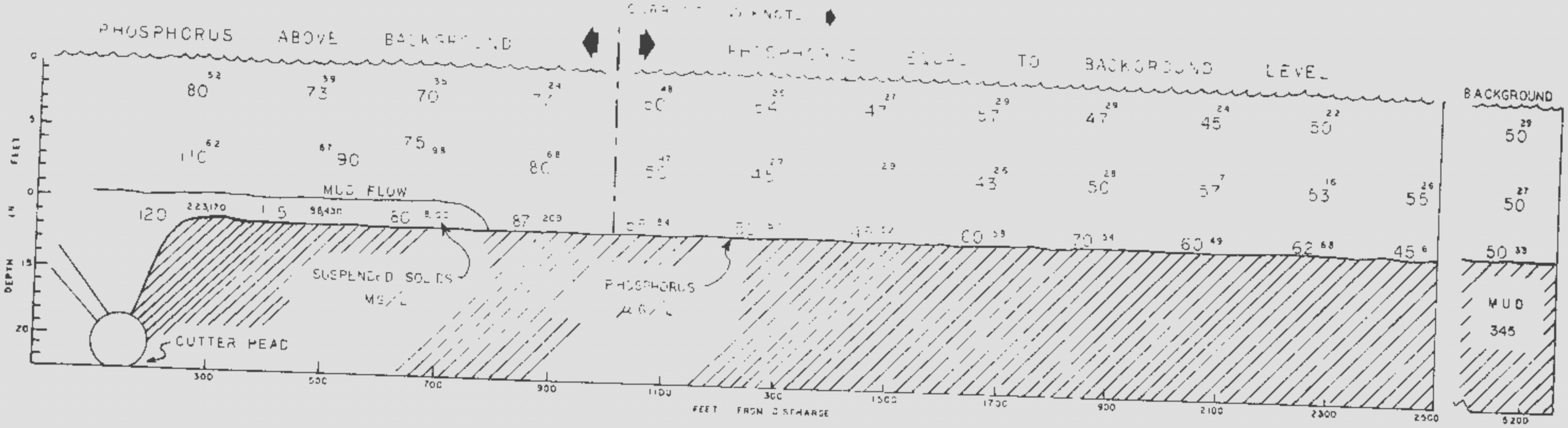


Figure 18. Total phosphorus from settled samples and concentration of total suspended solids down current from the shell dredge Mallard on a calm day on 29 March 1972.

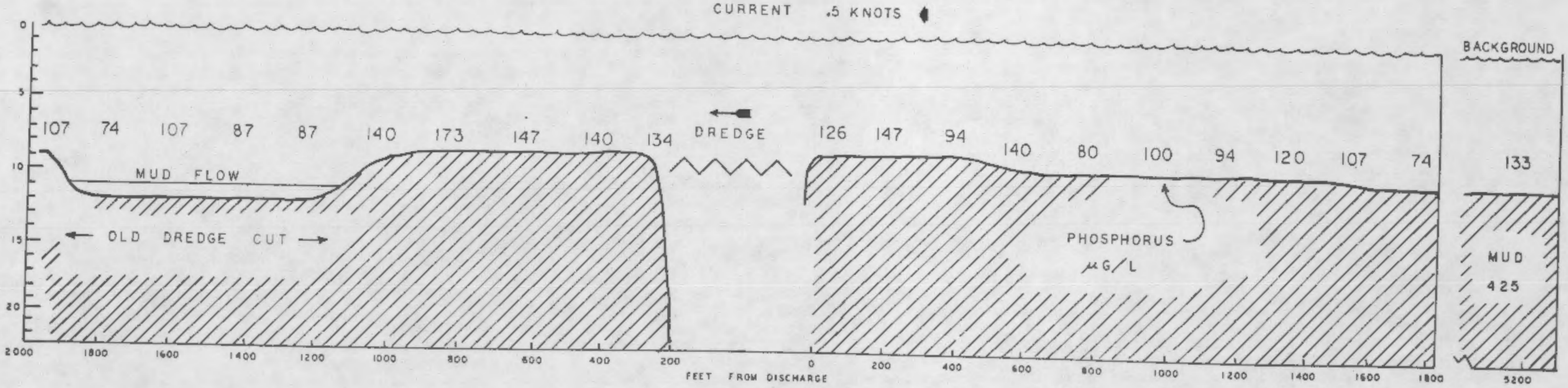
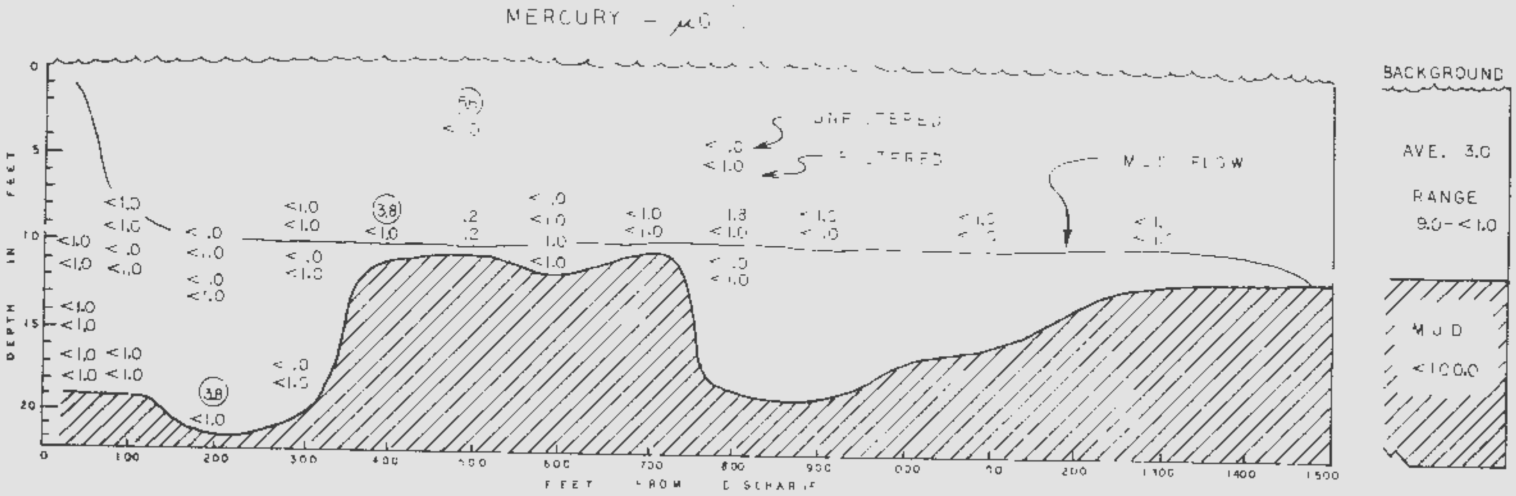


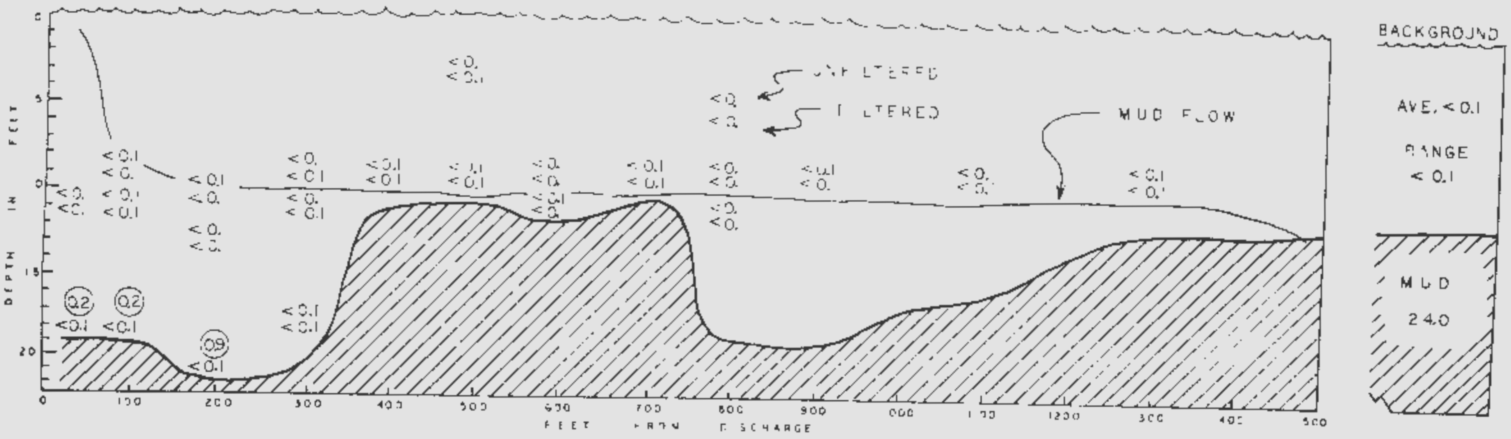
Figure 19. Total phosphorus from partially settled samples down current and up current from the shell dredge Mallard during a 5 knot S wind on 20 April 1972.

Figure 20. Distribution of selected metals in unfiltered and filtered samples down current from the shell dredge Mallard on 21 January 1972.

5 PLATES

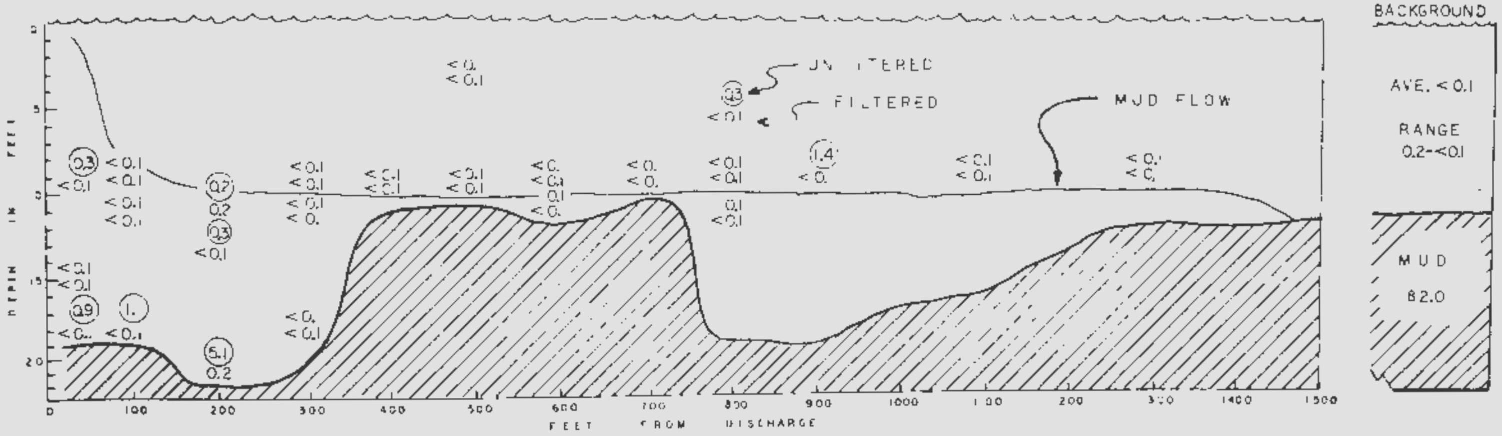


LEAD — MG/L

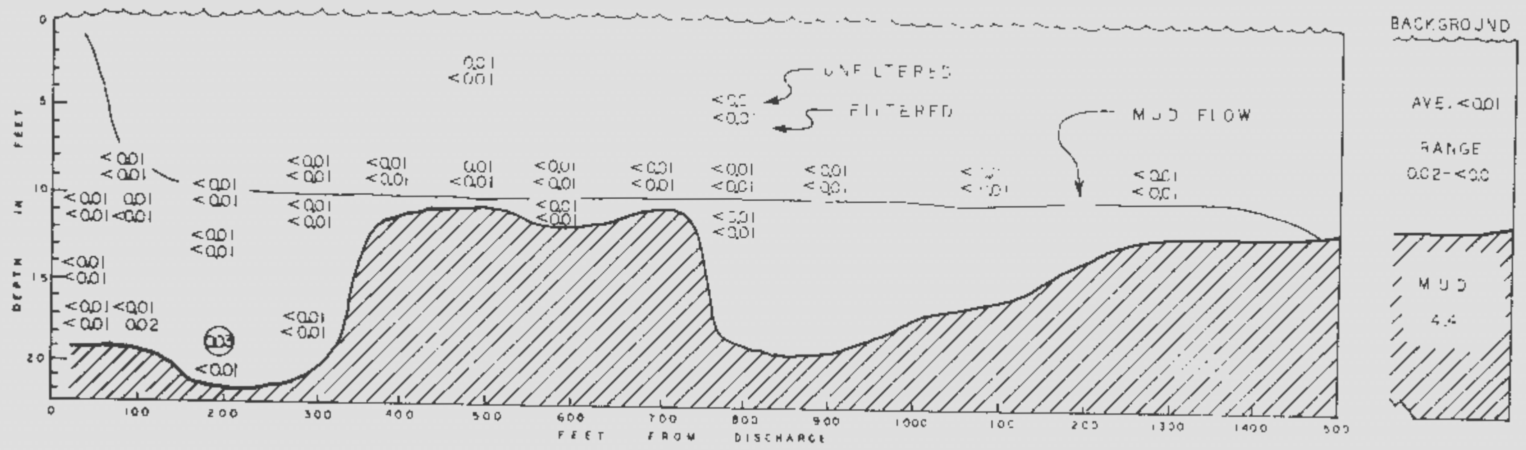


DEPTH IN FEET
0
5
10
15
20
FEET FROM DISCHARGE
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
UNFILTERED
FILTERED
MUD FLOW
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
0.2
<0.1
0.2
<0.1
<0.1
<0.1
<0.1
<0.1
0.9
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
<0.1
BACKGROUND
AVE. <0.1
RANGE
<0.1
MUD
24.0

ZINC - MG/L


DEPTH IN FEET
0
5
10
15
20
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
FEET FROM DISCHARGE
UNFILTERED
FILTERED
MUD FLOW
0.3
< 0.1
< 0.1
< 0.1
0.9
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
1.
< 0.1
0.7
0.2
0.3
< 0.1
5.1
0.2
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
0.1
< 0.1
< 0.1
< 0.1
0.3
< 0.1
< 0.1
< 0.1
0.1
< 0.1
1.4
< 0.1
< 0.1
< 0.1
< 0.1
< 0.1
BACKGROUND
AVE. < 0.1
RANGE
0.2-<0.1
MUD
82.0

CADMIUM – MG/L



DEPTH IN FEET
0
5
10
15
20
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
FEET FROM DISCHARGE
UNFILTERED
FILTERED
MUD FLOW
<0.01
<0.01
0.01
<0.01
<0.01
<0.01
<0.01
<0.01
0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
0.02
<0.01
<0.01
<0.01
<0.01
0.03
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
<0.01
BACKGROUND
AVE. <0.01
RANGE
0.02–<0.0
MUD
4.4

CHROMIUM — MG/L

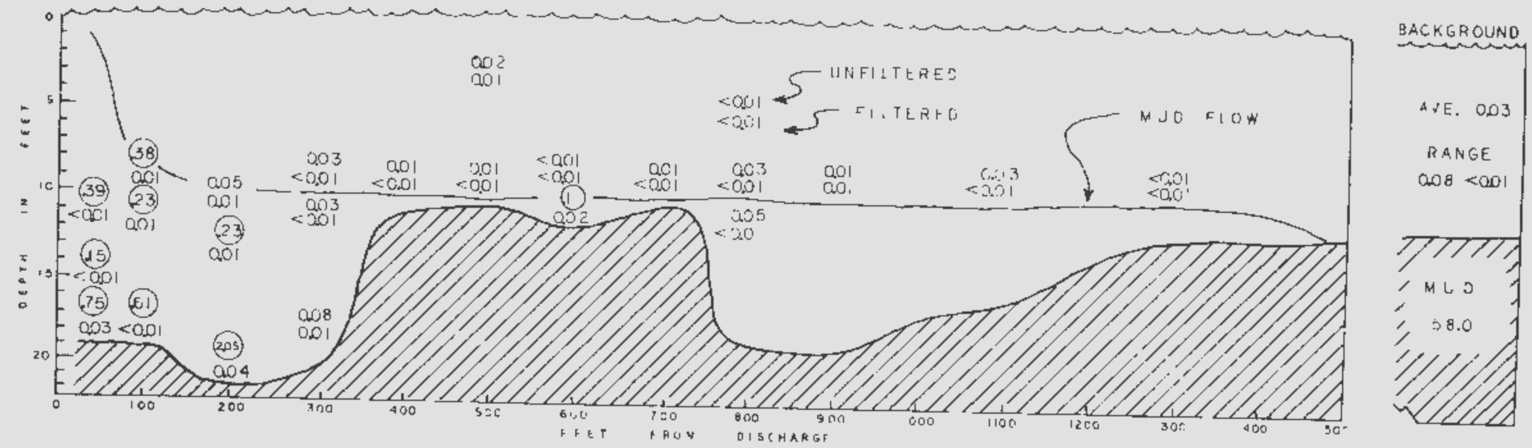
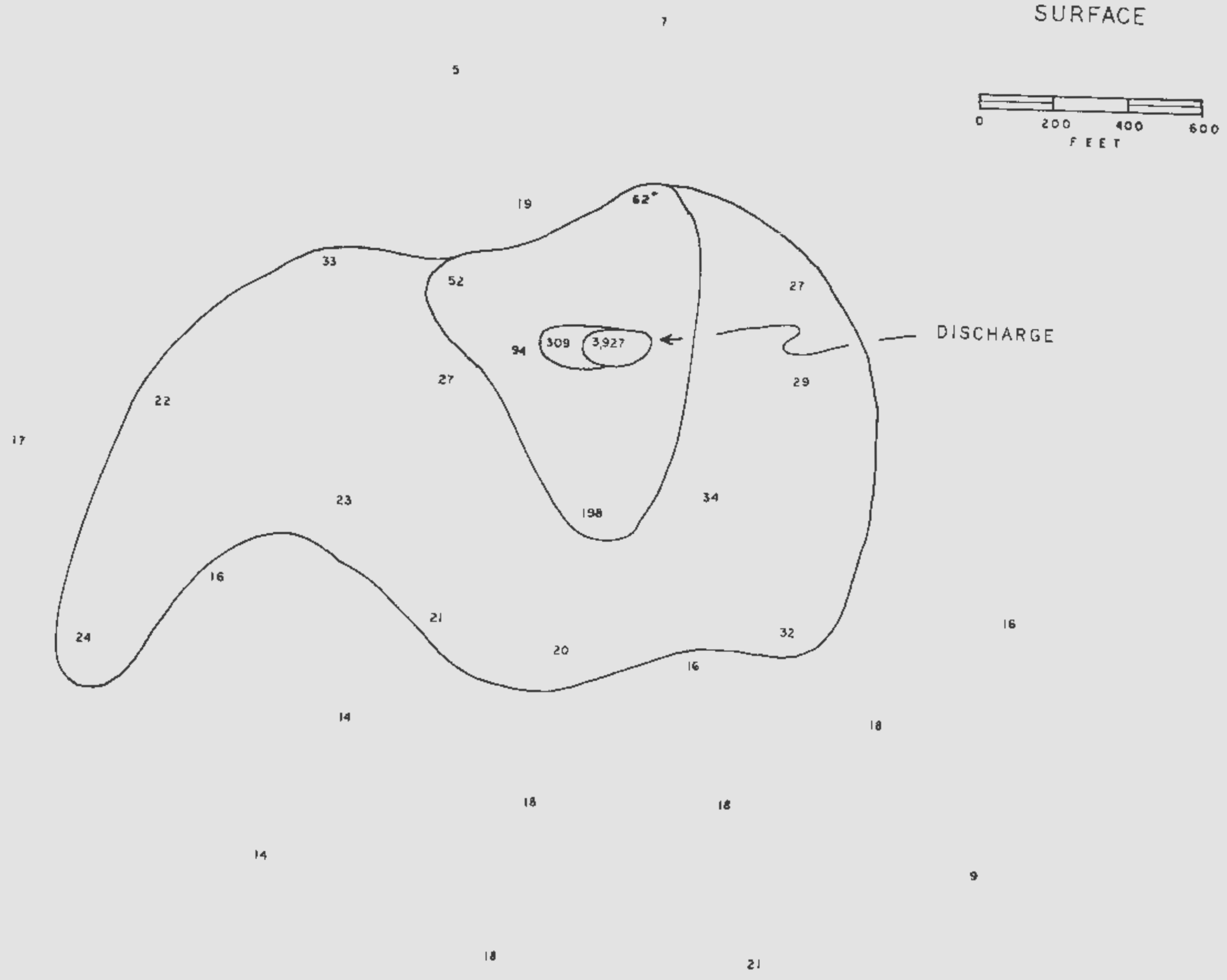


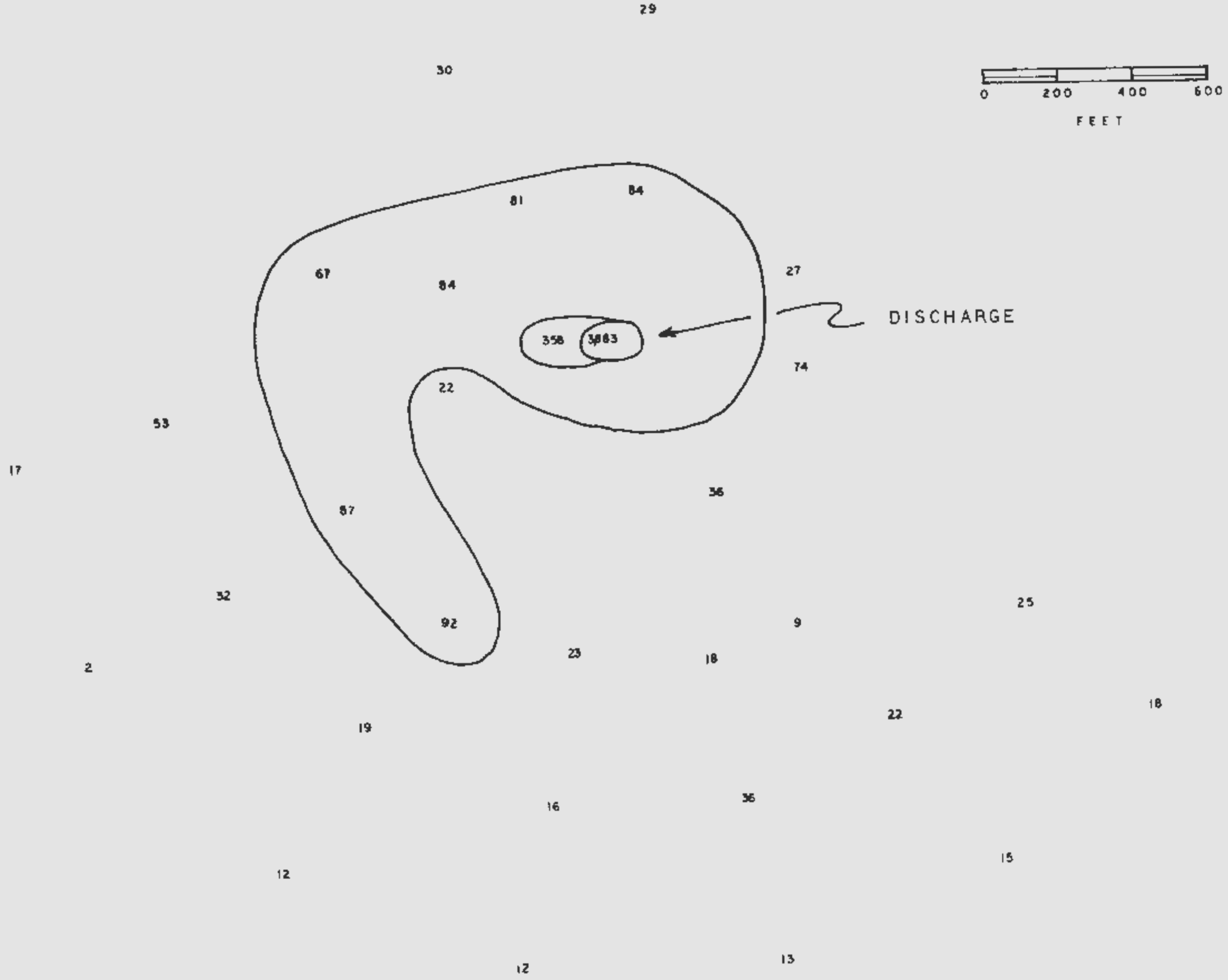
Figure 21. Horizontal distribution of total suspended solids in mg/l at three depths around the discharge of the channel dredge *Orleans*.

3PLATES



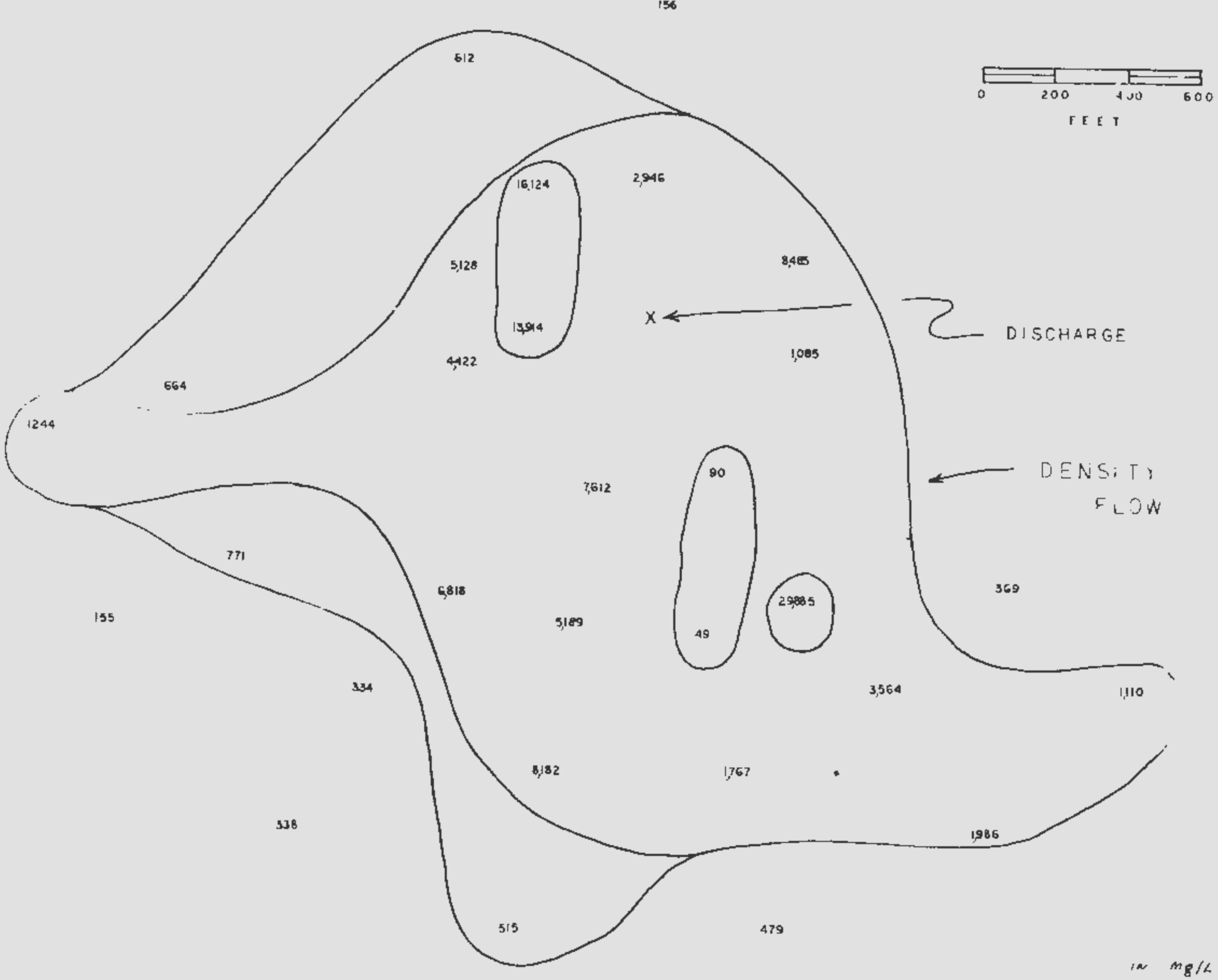
ORLEANS top TOTAL SS

MID DEPTH



0 200 400 600
FEET
DISCHARGE
29
30
81
84
67
84
27
358
3083
74
22
53
17
36
87
32
25
9
92
23
18
2
22
18
19
16
36
15
12
13
12

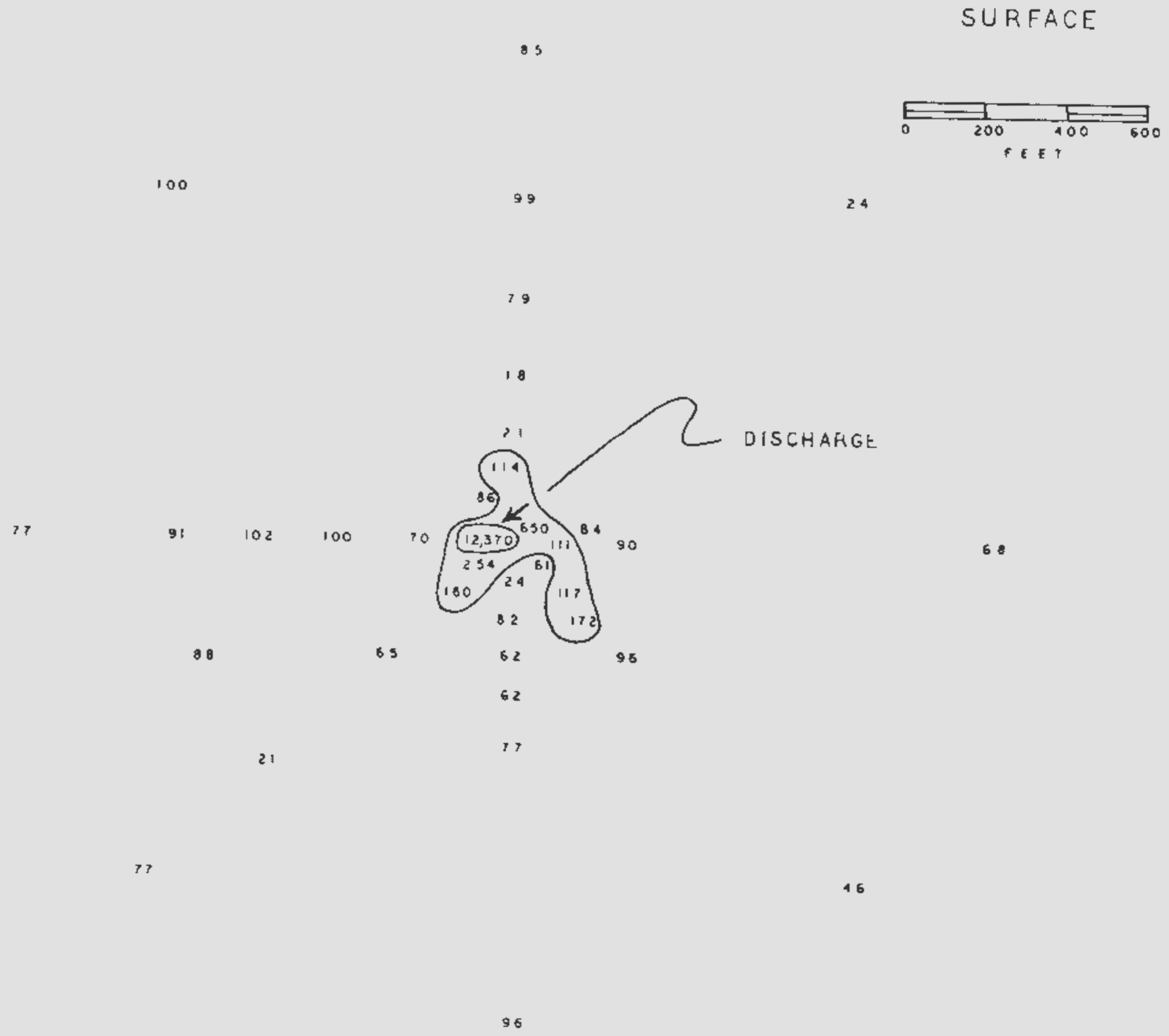
BOTTOM



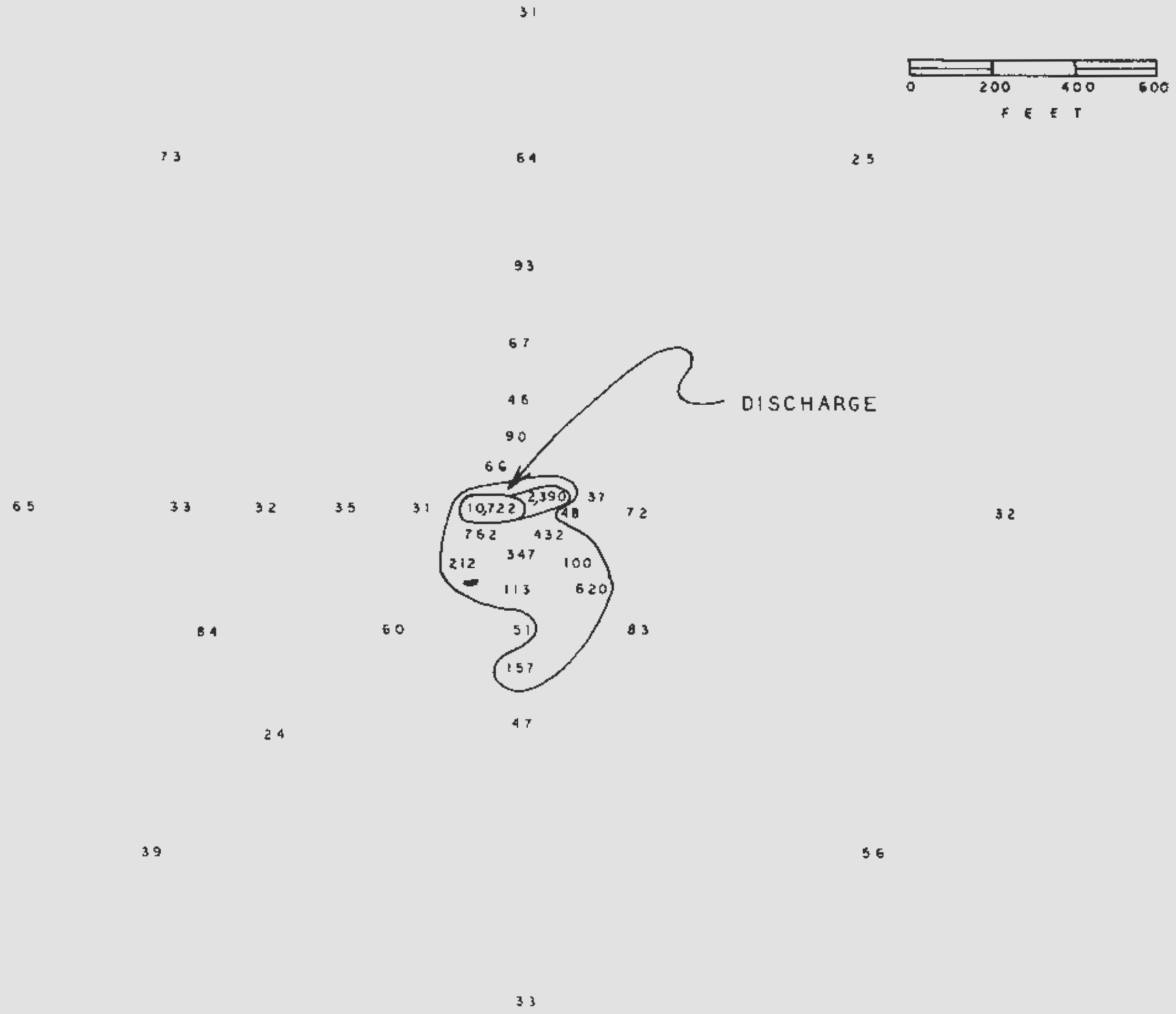
in mg/L
Total SS. Orleans
Bottom

gure 22. Horizontal distribution of total suspended solids in mg/l at three depths around the discharge of the intracoastal waterway dredge *Arkansas*.

3 PLATES



MID DEPTH


0
200
400
600
FEET
31
73
64
25
93
67
46
DISCHARGE
90
66
2,390
37
65
33
32
35
31
10,722
48
72
32
762
432
212
347
100
113
620
84
60
51
83
157
24
47
39
56
33

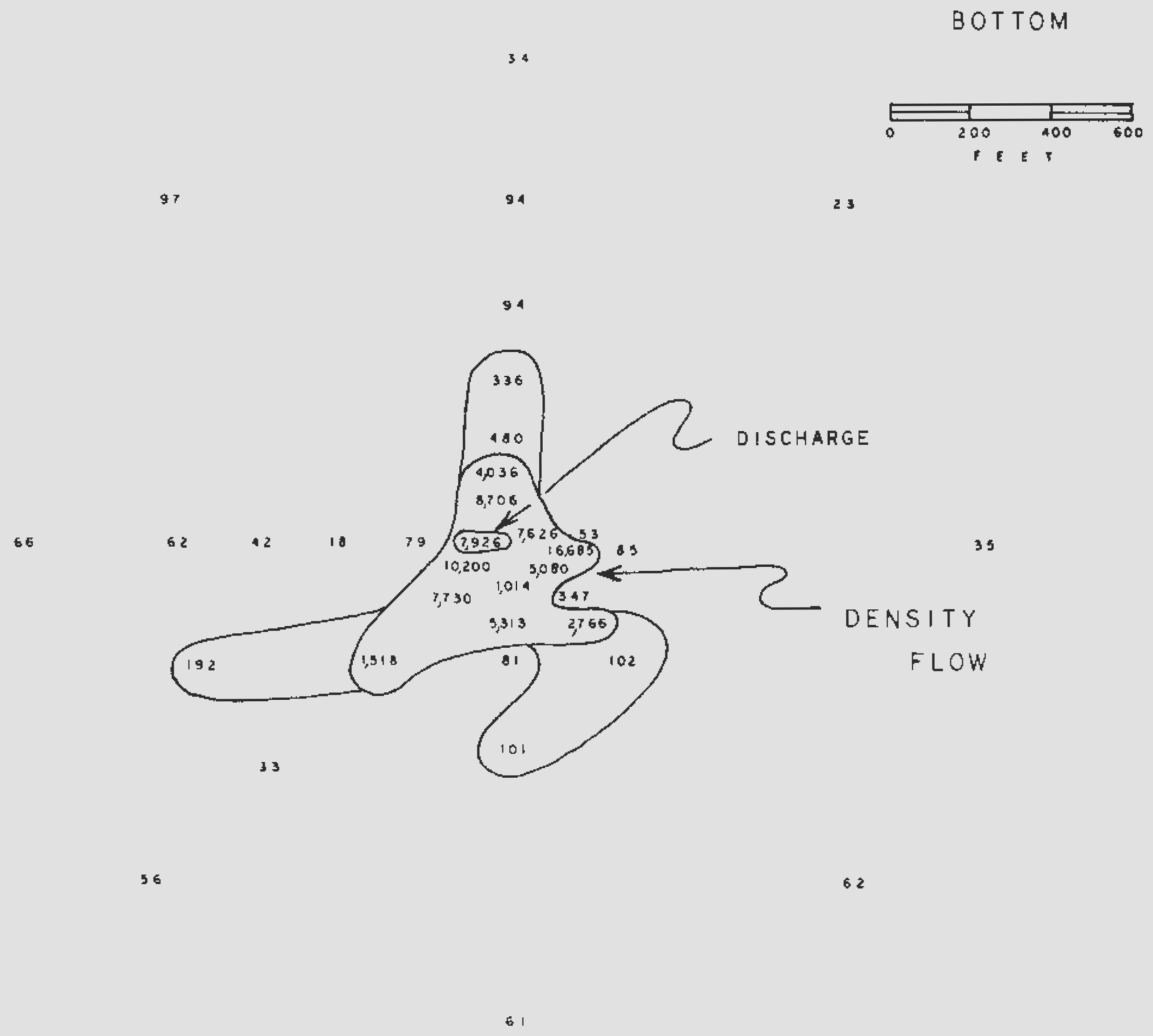
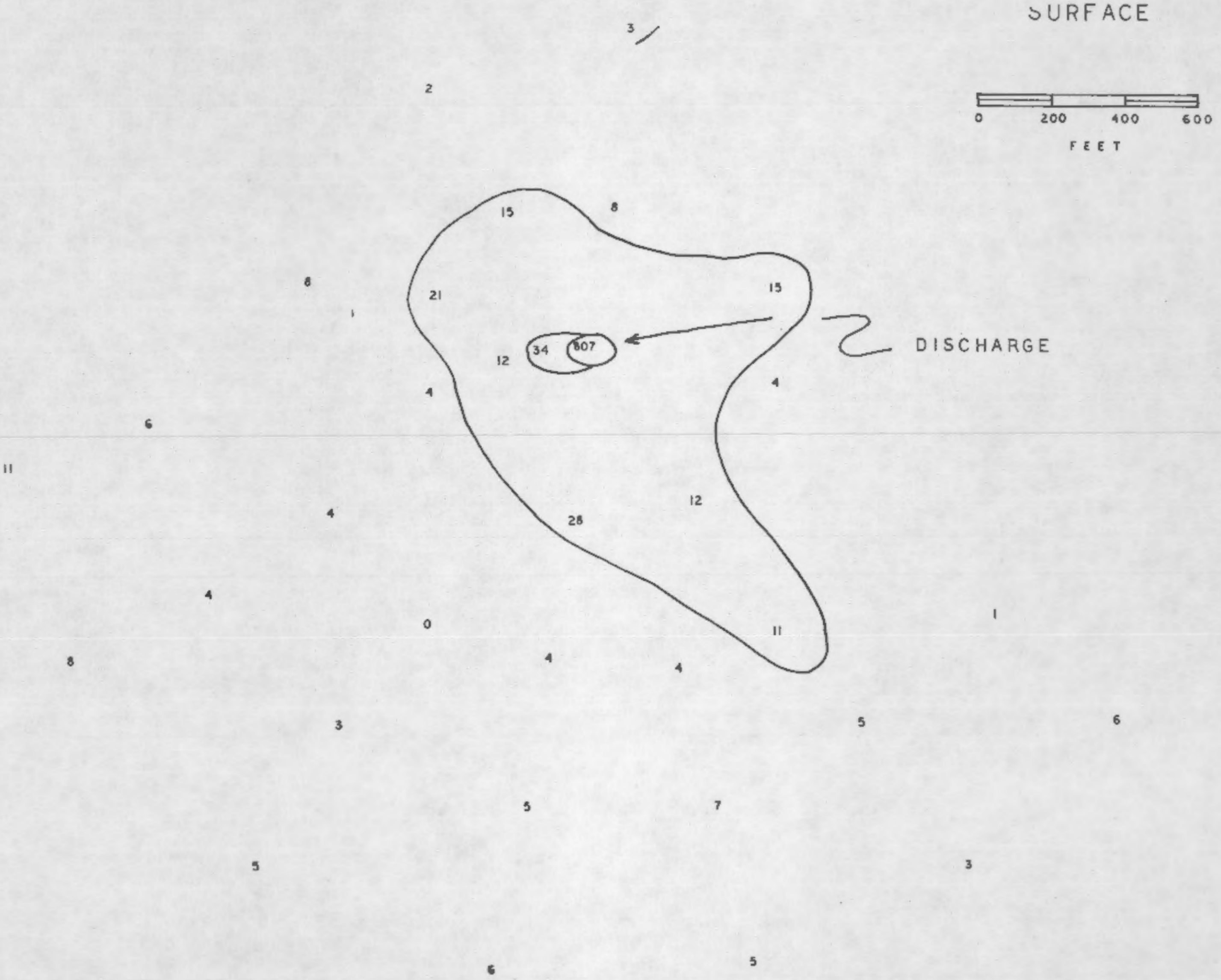
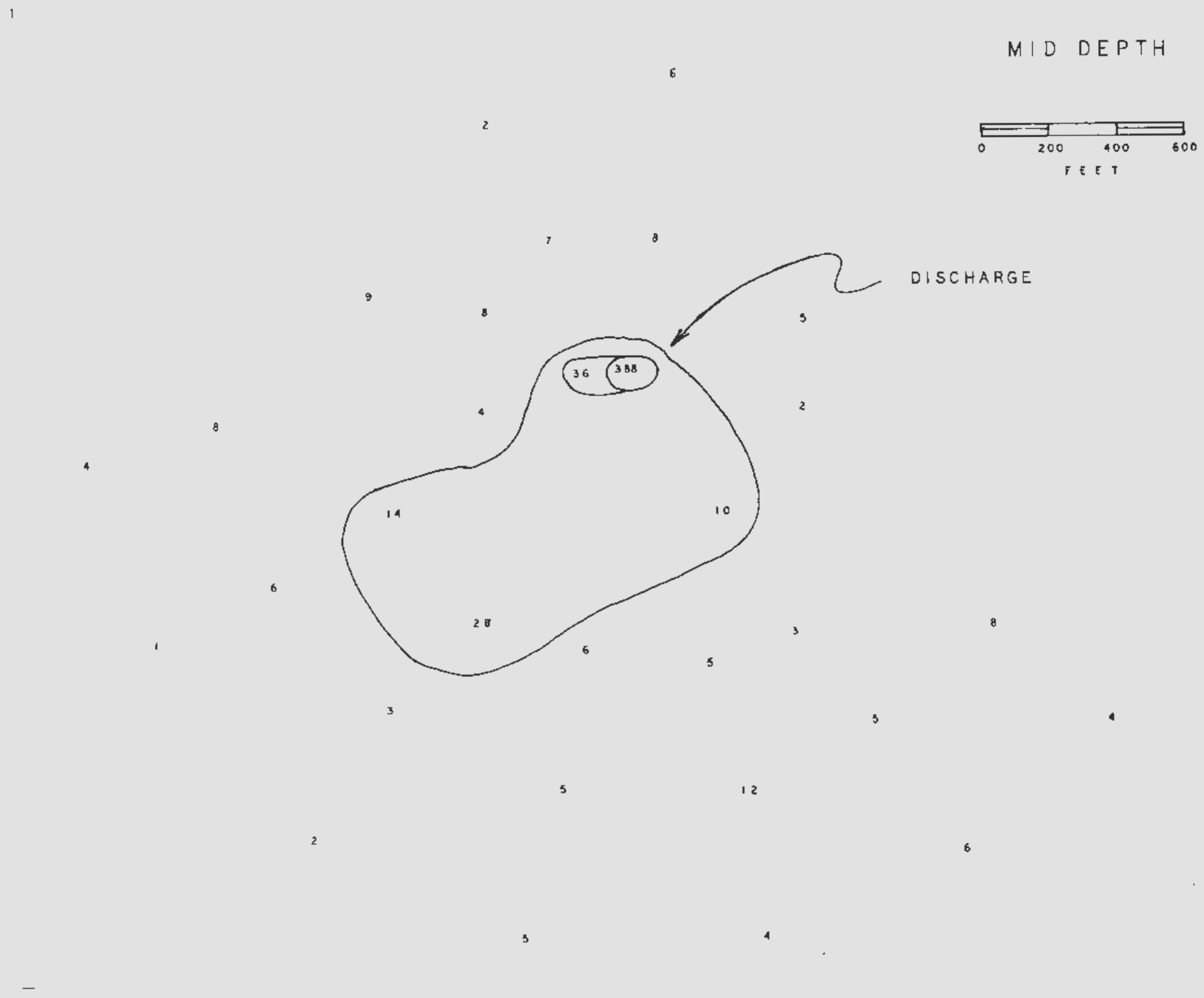
BOTTOM
0 200 400 600
FEET
34
97
94
23
94
336
DISCHARGE
480
4,036
8,706
66
62
42
18
79
7,926
7,626
53
16,685
85
35
10,200
5,080
1,014
DENSITY FLOW
7,730
347
5,313
2,766
192
1,518
81
102
101
33
56
62
61

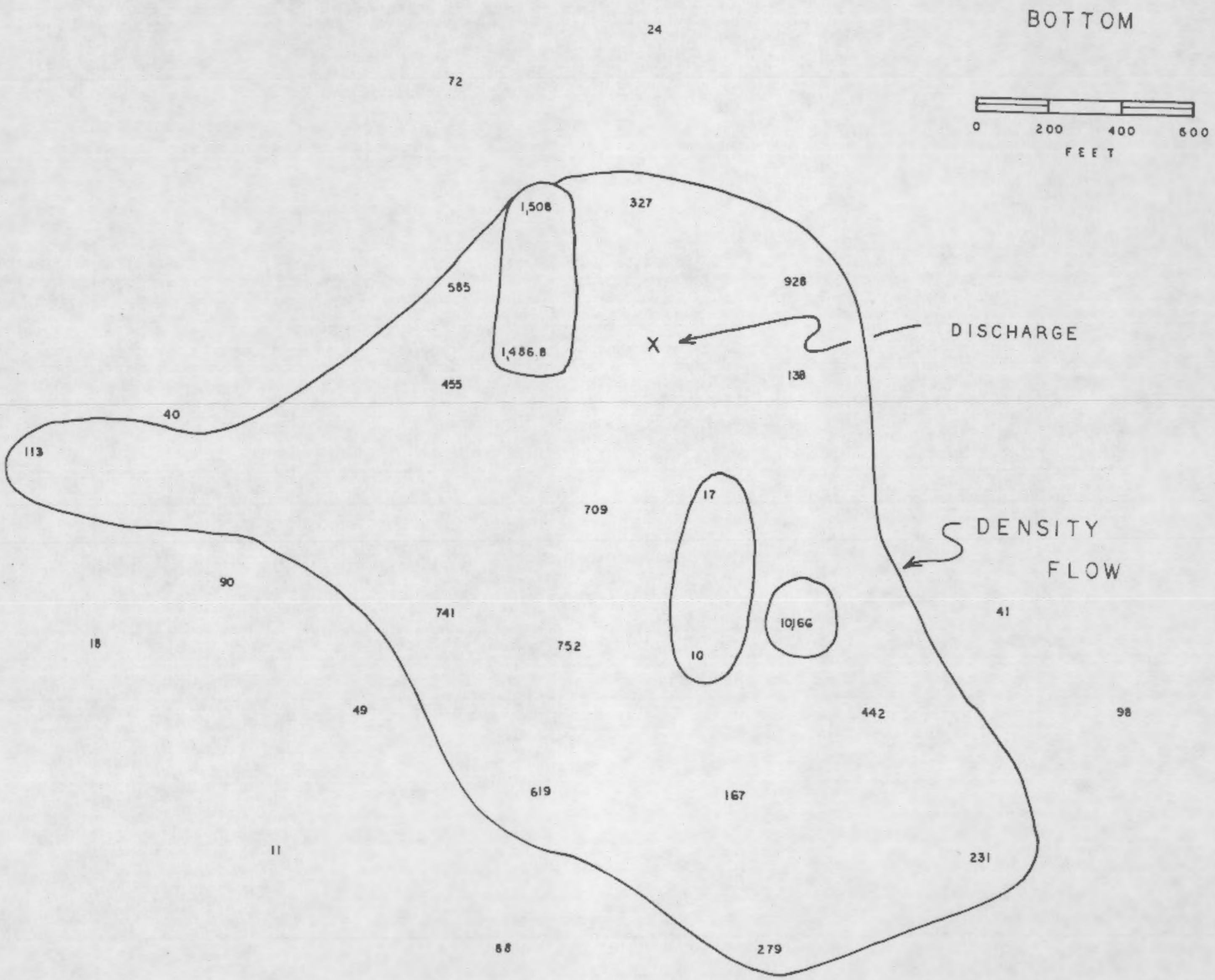
Figure 23. Horizontal distribution of volatile suspended solids in mg/l at three depths around the discharge of the ship channel dredge Orleans.

3 PLATES



ORLEANS TOP ORGANIC SS

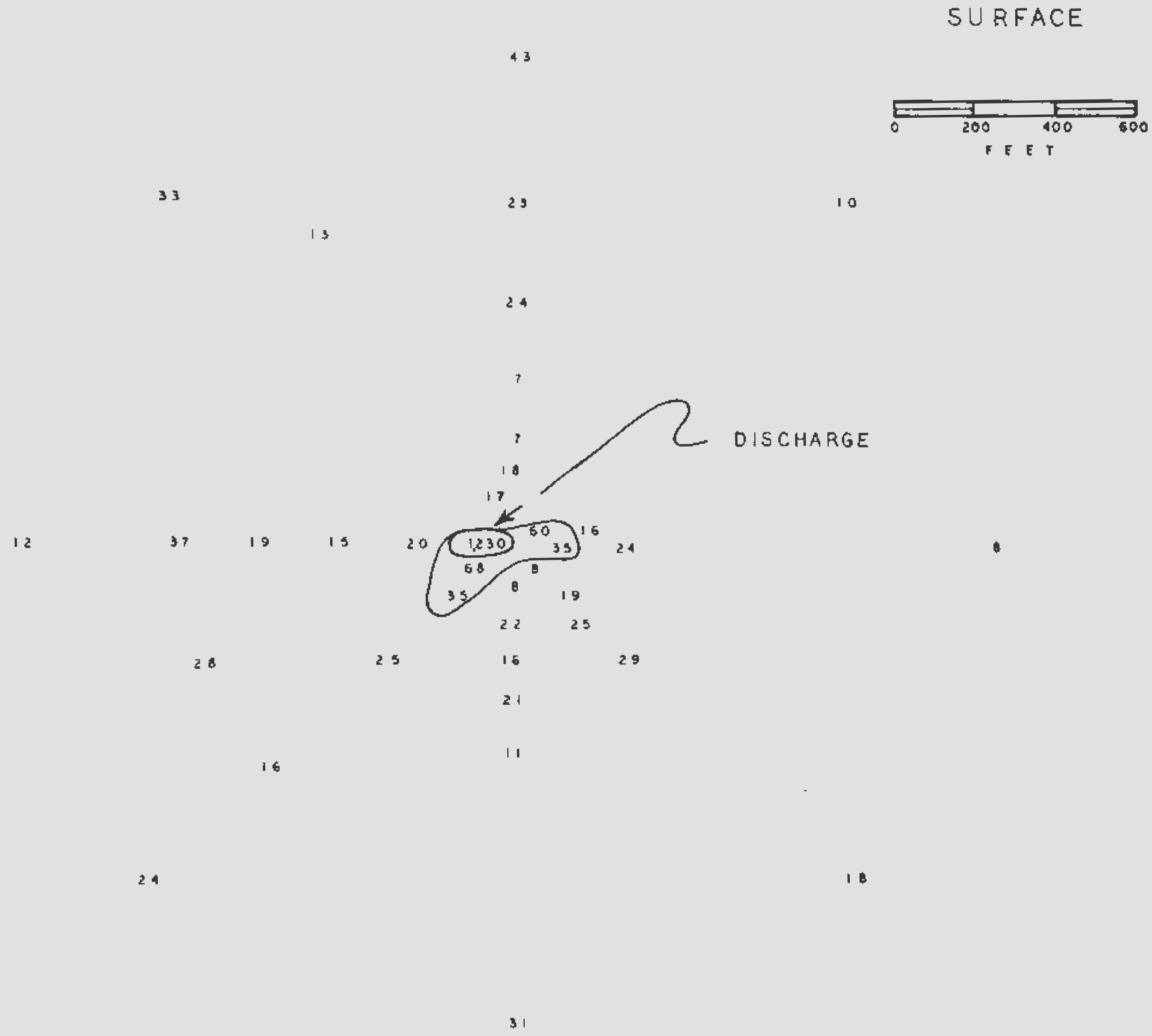

MID DEPTH
0
200
400
600
FEET
DISCHARGE
388
36
10
14
28
1
6
2
7
8
9
8
4
8
4
6
1
3
2
5
5
2
6
5
3
8
5
12
5
4
6
5
4

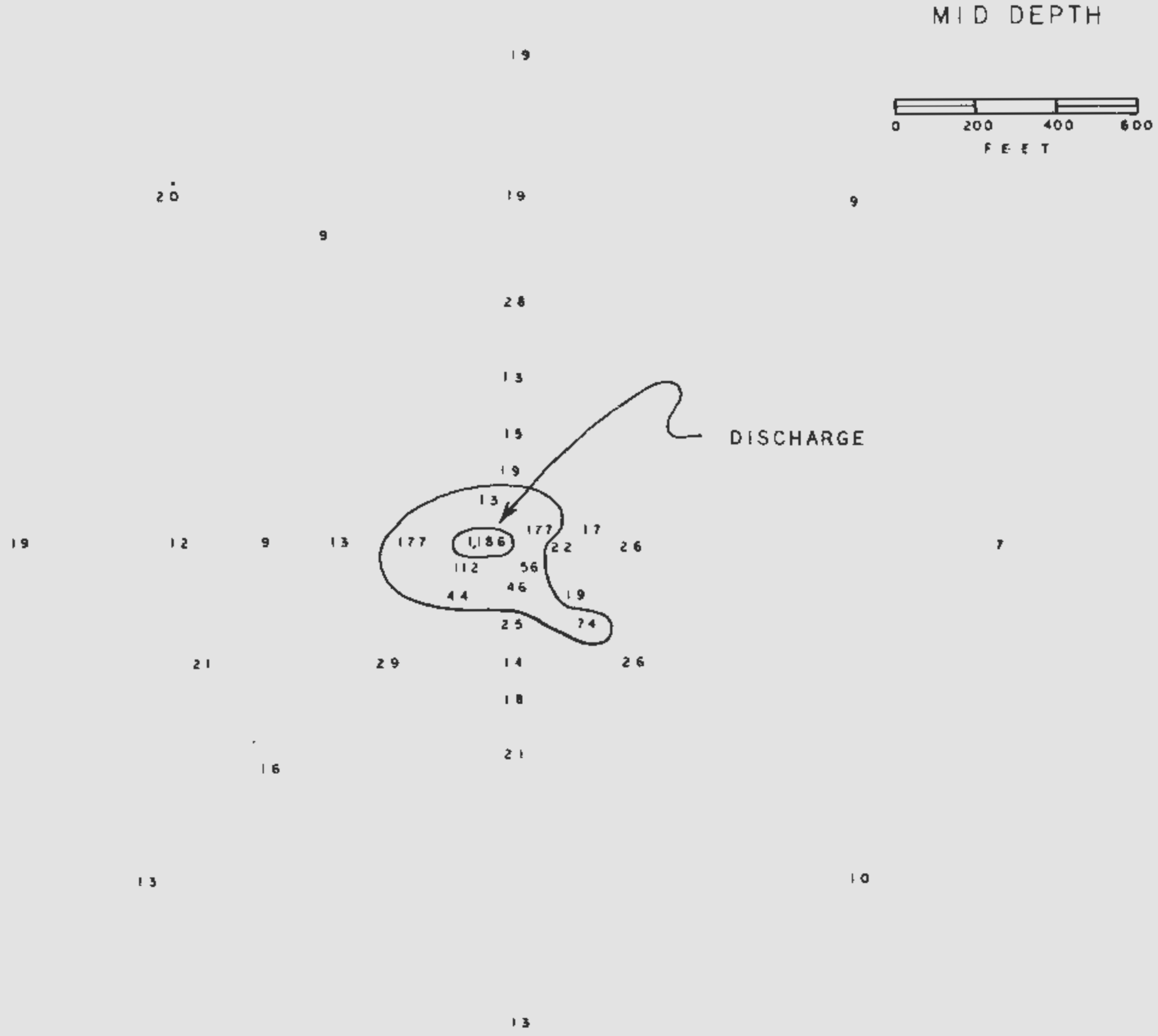


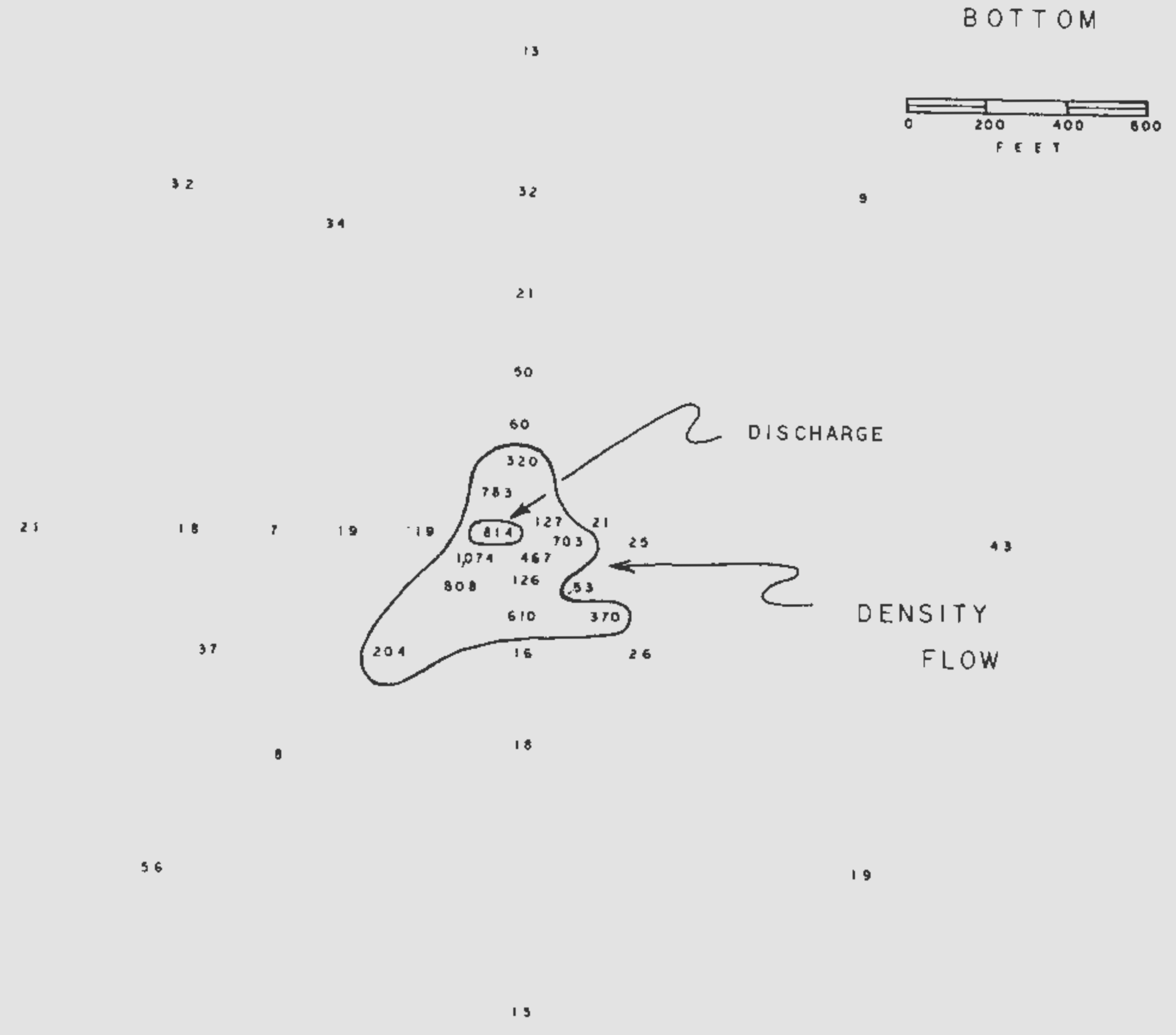
ORLEANS Bottom ORGANIC SS

3 PLATES

Figure 24. Horizontal distribution of volatile suspended solids in mg/l at three depths around the discharge of the intracoastal waterway dredge *Arkansas*.




MID DEPTH
0
200
400
600
FEET
DISCHARGE
19
20
19
9
9
28
13
15
19
13
177
17
19
12
9
13
177
1,186
22
26
7
112
56
46
44
19
25
74
21
29
14
26
18
16
21
13
10
13


BOTTOM
0
200
400
600
FEET
13
32
32
34
9
21
50
60
DISCHARGE
320
783
814
127
21
703
25
21
18
7
19
19
1,074
467
43
808
126
53
DENSITY
FLOW
610
370
37
204
16
26
18
8
56
19
15

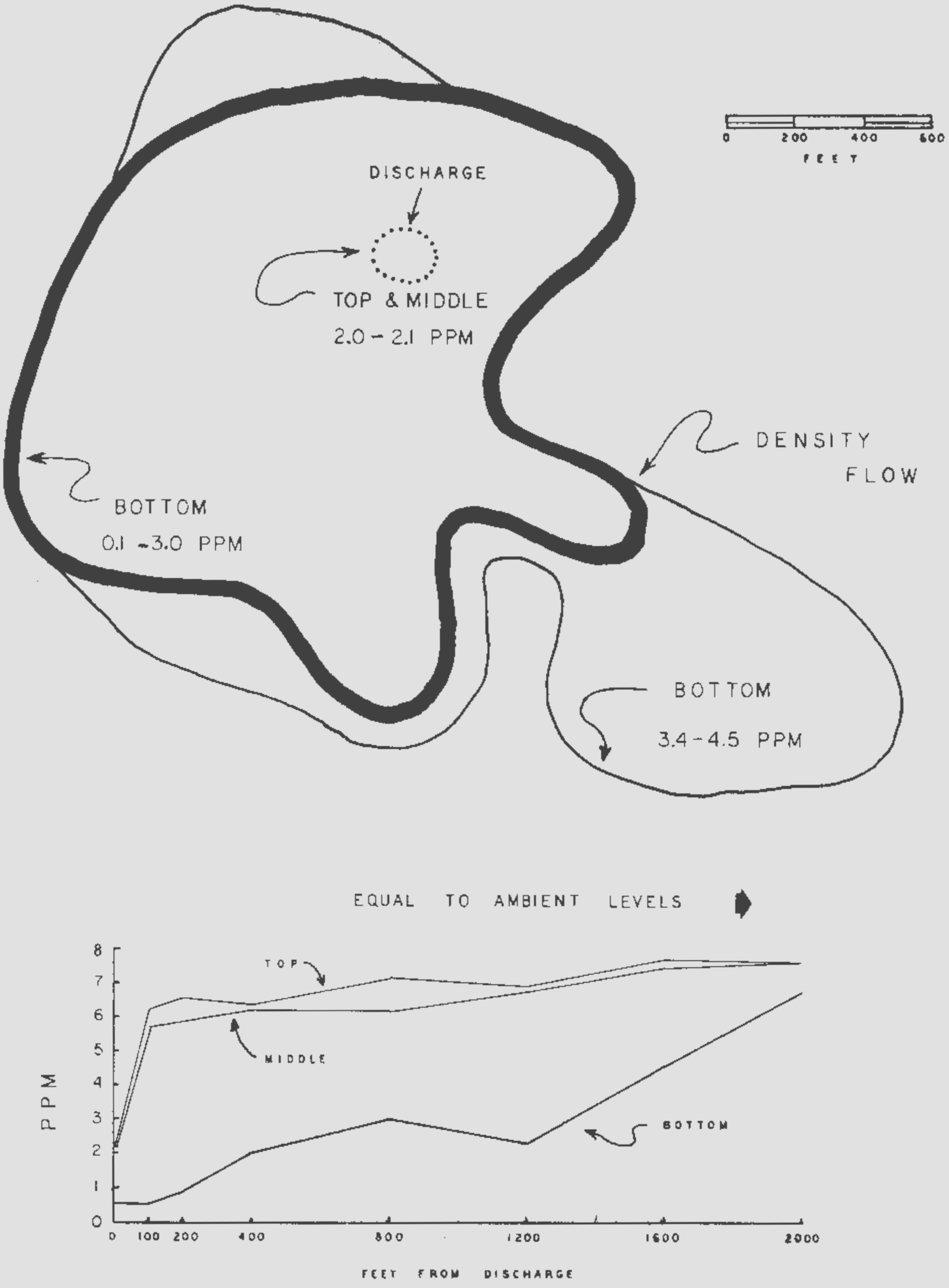


Figure 25. Dissolved oxygen in ppm around the discharge of the ship channel dredge *Orleans* during a 10 knot E-SE wind. Bottom D. O. is in the density flow.

Figure 26. Dissolved oxygen in ppm around the discharge of the intracoastal waterway dredge *Arkansas* during zero to 5 knot W wind. Bottom D. O. is in the density flow.

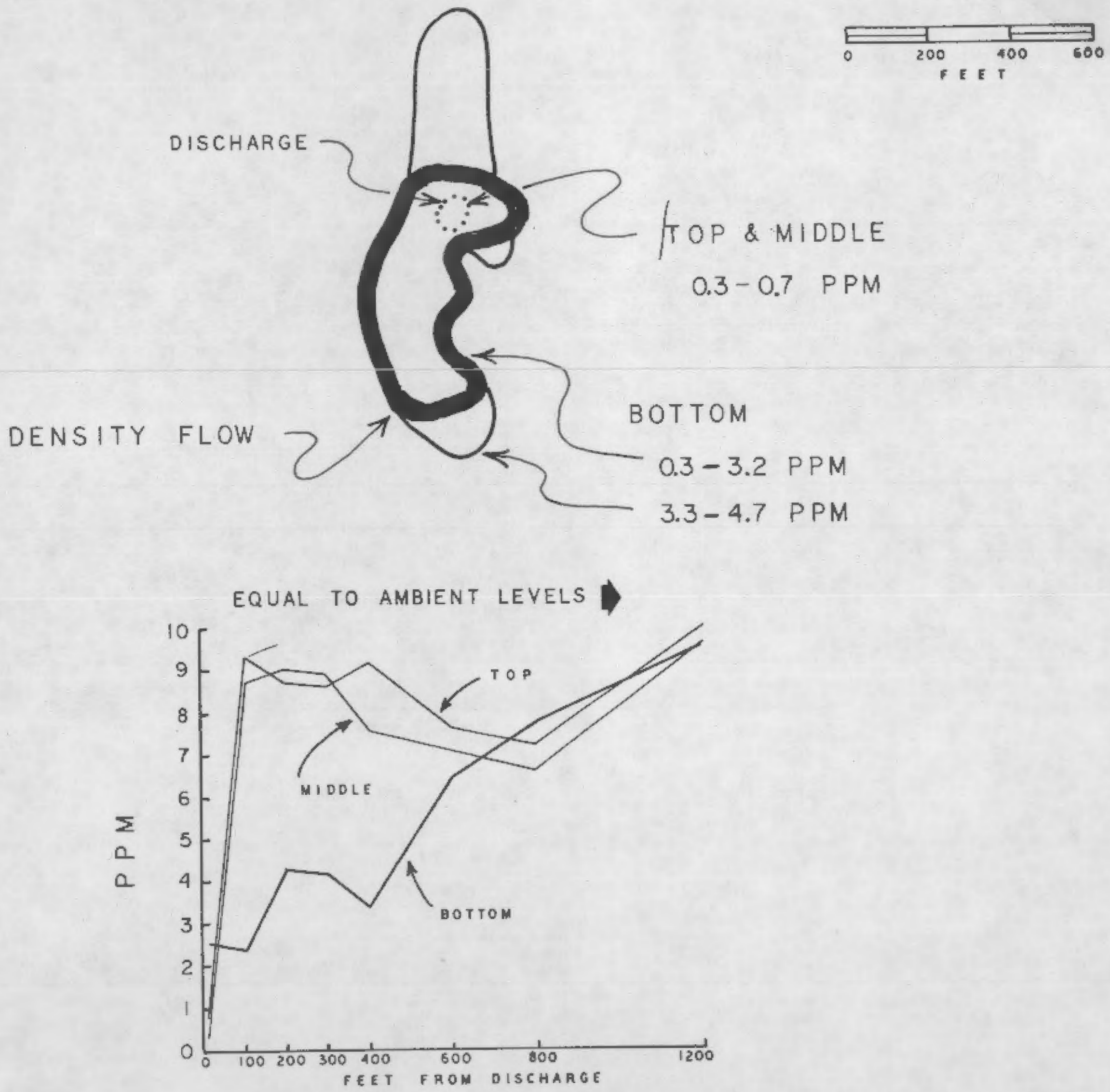


Figure 27. Physical and electronic profiles of three randomly selected shell dredge cuts in Mobile Bay which were 1, 6 and 12 months old showing bottom conditions before and after dredging.