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WSG 75-2

A REVIEW OF THE HYDRAULIC ESCALATOR SHELLFISH HARVESTER AND ITS KNOWN EFFECTS IN RELATION TO THE SOFT-SHELL CLAM, *MYA ARENARIA*

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FOREWORD

Many tidelands of Puget Sound boast substantial stocks of soft-shell clams--a seafood delicacy which to date has been available mostly on tables of recreational clam diggers because there have been few commercial harvests of this clam in Washington.

The most efficient means of commercially harvesting the soft-shell clam is with a hydraulic escalator shellfish harvester. But local experience with the harvester has been limited and little information has been available about the long-term effects of the harvester on the environment.

Recently, many questions concerning the advisability of mechanical harvesting operations in Washington have been raised by a number of Puget Sound businesses, by concerned citizens, and by state resource management and regulatory agencies.

In response to their questions, the Washington Sea Grant program undertook the survey reported in this publication to find out and make available existing information on the known long-term effects of mechanical harvesting on the environment.

Through the survey and this report, the Sea Grant program is attempting to provide decision makers with available information as a basis for their decisions concerning applications for commercial clam-harvesting permits.

John Dermody
Assistant Director for Operations
Washington Sea Grant Program

ACKNOWLEDGMENTS

The authors consulted several specialists in as many fields as related to mechanical shellfish harvesting. We are indebted to all of those individuals who have communicated with us. Without their cooperation, the report could not have been completed. When the report was in the draft stage, a number of specialists were asked to critically review the manuscript. The comments and suggestions that these reviewers made were very valuable in completing the final manuscript.

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CONTENTS

Soft-shell clams, *Mya arenaria*, have traditionally been harvested on the Eastern Seaboard by professional hand-diggers who use a tined "clam-hoe" and dig in the intertidal zone by hand (Fig. 1). Until the early 1950's New England was the principal supplier of hand-dug soft-shell clams. However, as demands grew and stocks decreased drastically because of heavy fishing pressures (Glud [sic] 1951), the New England states were no longer able to meet increasing demands. At this time Chesapeake Bay was producing only small amounts of clams by hand-digging. Although Chesapeake Bay has large stocks of *M. arenaria*, these are mostly subtidal while those in New England are primarily intertidal (Manning and Dunnington 1956; Hanks 1963).

In 1950-51, Fletcher Hanks of Oxford, Maryland, invented the hydraulic escalator clam harvester, which was put into commercial operation in 1952 (Manning 1957). Through the use of this harvester on subtidal stocks, northern Chesapeake Bay quickly became a major supplier of soft-shell clams. Success of this harvester prompted eastern Canada and the states of Florida, Maine, New York, North Carolina, South Carolina, Virginia, and Washington to investigate its use over the next two decades.

Eastern Canada was the first area after Maryland to use escalator harvesters for experimental fishing (Dickie and MacPhail 1957). After improvements, Hanks harvesters were approved for use on "quahaugs," "bar clams," oysters, and *Mya* and are presently being used commercially on a limited basis (Medcof, personal communication).[1] British Columbia, also tried the harvester but with limited success because of topography and small stocks of soft-shell clams (Quayle and Bourne 1972).

In the United States, Washington was the first state outside the Chesapeake Bay region to use mechanical harvesters. They were first used for harvesting various species of hard-shell clams and oysters as far back as 1958 (McLeod 1958), and commercial use dates back over 10 years (Goodwin 1973). They have also been used since 1969 to harvest soft-shell clams.

A second state of the Chesapeake Bay region, Virginia, has also investigated the use of the Maryland dredge (Haven 1970). Hydraulic harvesters started operating in Virginia after those in Maryland, but have not been really significant because Virginia is close to the southern distributional limit of the soft-shell clam (Haven, personal communication).

However, commercial harvesting of the quahaug or hard-shell clam is taking place in both North Carolina (Street, personal communication) and South Carolina (Burrell and Gracy, personal communication). A New York

[1]Personal communications are listed at end of article in more complete form.

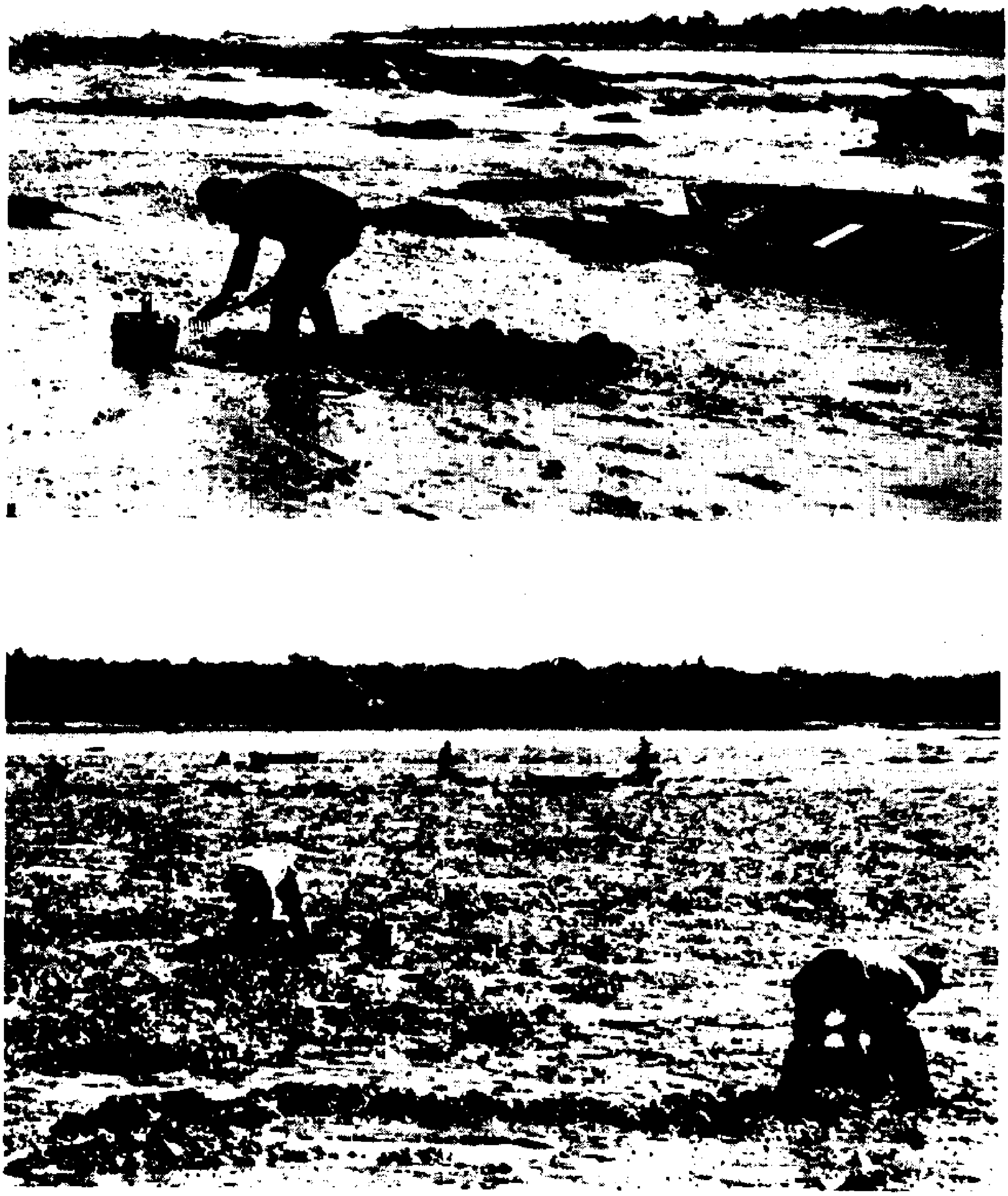

Fig. 1. Methods of digging clams in New England have hardly changed since the commercial fishery began. Upper photo, taken on the Maine coast around 1891, is nearly identical to similar scenes on clam flats today (lower photo). (From Hanks 1963)

commercial bait company has also used harvesters to work quahaug and old oyster beds (Medcof, personal communication), but no published information on this activity is available.

In Maine, one of the chief New England suppliers of hand-dug clams, the hydraulic escalator harvester is limited to the subtidal zone and is legal in only two restricted areas of the coast. Despite this and the fact that the populations of *M. arenaria* are mostly intertidal (Hanks 1963; Kyte et al. 1975), one commercial harvester is licensed on the central Maine coast. However, no appreciable amounts are being produced by this harvester (Maine Department of Marine Resources, Wallace, personal communication 1975). Florida is the only other state that has investigated the Hanks dredge. Large stocks of hard-shell species are available in this area for harvesting by mechanical means (Godcharles 1971), but no escalator harvesters are presently operating in Florida (Joyce and Costello, personal communication).

In addition to harvesting marketable species and sizes of clams, the escalator clam harvester has actually been used or suggested for use in surveys, scientific investigations, and aquaculture. Because populations of harvestable *M. arenaria* in Chesapeake Bay are not evenly distributed, the Maryland dredge has been extensively used to locate and survey areas that might contain harvestable beds of clams (Manning and Pfitzenmeyer 1958*a*; Pfitzenmeyer 1961, 1963). Recently, the harvester has also been used in that area to estimate hard-shell clam abundance (Loesch and Haven 1973).

It has also been suggested that the harvester be employed to collect juvenile seed clams for use in the aquaculture of *M. arenaria*. A similar use would be to till the sediment of clam beds to increase production and survival of settling larvae (Dana Wallace, personal communication; Pfitzenmeyer 1972). Drills, starfish, and other predators would be brought to the surface and culled. Also the tilling would remove large concentrations of old shell. This shell, in the form of compacted beds, prevents juvenile clams from burrowing and probably lowers their survival rate (personal observation in Maine and Wallace, personal communication).

In Canada, harvesters have been used not only for harvesting marketable oysters, but also to clean old oyster beds. And finally, because the harvester does collect a majority of the sedentary benthic macrofauna in its path, it has been used for quantitative investigations of the benthos (Manning 1959; Pfitzenmeyer 1961; Godcharles and Jaap 1973).

PRINCIPLES OF THE HYDRAULIC ESCALATOR SHELLFISH HARVESTER

The engineering details of the Maryland dredge are given by Manning (1957), Dickie and MacPhail (1957), Manning and McIntosh (1960), MacPhail (1961), and Mathieson and DeRocher (1974). Figure 2 illustrates the harvester as it is generally rigged; although some fishermen use a catamaran arrangement (*see* Godcharles 1971; Mathieson and DeRocher 1974). In general, the hydraulic shellfish harvester consists of a bank of water jets in front of a conveyor belt. Sediment containing clams is eroded by the jets, and bivalves are washed onto the upward-moving belt and brought to the surface, where a crew culls desired items. Unretrieved material remains on the belt and is returned to the water. The forward speed of the harvester and the amount of area that can be harvested in a given time, as well as the depth and permanency of the resulting trench, greatly depend on sediment type. Sands permit rapid rates of harvesting, and the trenches left are shallow. Clay-silt muds require slower speeds and the resulting scars are deeper. More details on the effects of harvesting are given below. Various fishermen and researchers have modified the basic Hanks' design to gain more efficiency and to harvest epifaunal species such as oysters and mussels. Some of these modifications and other specifications are described by the above authors.

The Maryland dredge can cover 10 to 60 times more ground in a given time than can a hand-digger (Manning 1959; MacPhail 1961). Also it is much more efficient in terms of catch, and usually involves less breakage (Manning 1959; Medcof 1958, 1961). Details of this efficiency and its effect on resource stocks will be discussed later.

Yet in considering this efficiency, one must consider the economic factors involved. The capital and operating expenses of a single unit are considerable, especially in contrast to those of a New England hand-digger, which are negligible. However, a hand-digger would have had to work in a population density of over 400 bushels per acre to make as much profit in 1959 as a mechanical harvester working in a density of 50 bushels per acre (Manning 1959). In 1959-1960, a minimum clam density of 50-55 bushels per acre was necessary for the average harvester to make a "reasonable living" (Manning 1957, 1959; Pfitzenmeyer 1960). With rising fuel, equipment, and living costs, this minimum was up to 250 bushels per acre in 1974 (John Harris, New England Fish Co., personal communication). Densities required for a commercial hand-digger in Maine to make a living at 1974 prices were approximately 75-100 bushels per acre (Wallace, personal communication).

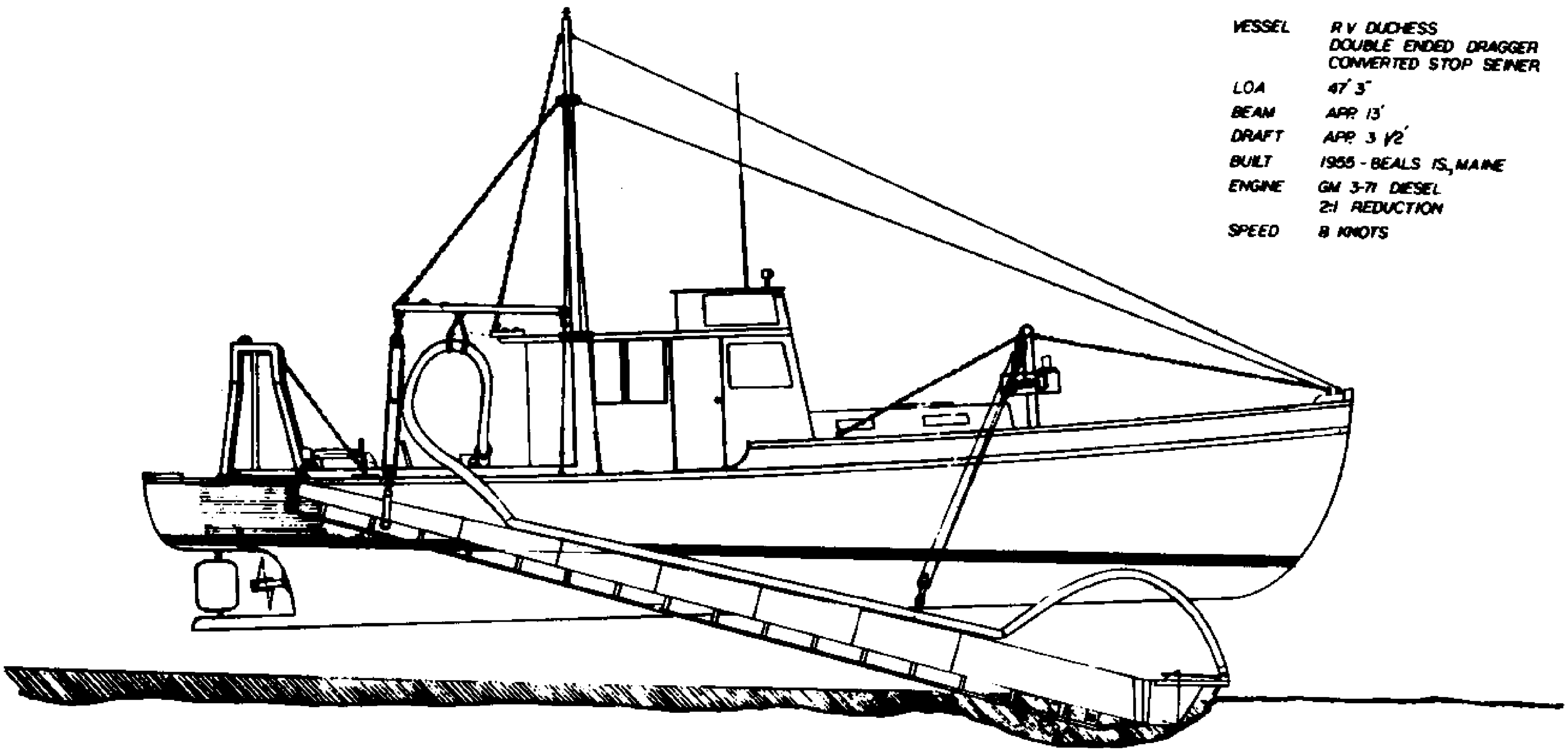

Fig. 2. A hydraulic escalator shellfish harvester (from Mathieson and DeRocher, 1974).

SOFT-SHELL CLAM FISHERIES OF NEW ENGLAND, CHESAPEAKE BAY, AND WASHINGTON

The appearance of the Hanks clam harvester had a significant effect on the soft-shell clam fishery of Chesapeake Bay. Before 1951 no landings of *M. arenaria* were reported for that area by the Bureau of Commercial Fisheries, now the National Marine Fisheries Service (NMFS 1951-1974). Beginning in 1951 a dramatic increase began in both number of dredges and in amount and worth of soft-shell clam landings (Fig. 3). In 1970 Maine and Maryland were nearly equal in soft-shell clam production with approximately $2.5 million of landings (Fig. 3). However, since 1972, production in the Chesapeake Bay fishery has declined drastically because of the effects of Hurricane Agnes (Shaw and Hamons 1974) and increasing mortalities due to a fungus-type disease (Haven and Pfitzenmeyer, personal communication).

The Hanks dredge also had a definite effect in Washington. Table 1 illustrates the growth and extent of the Washington soft-shell clam fishery since 1969, when the first landings were reported (Dale Ward, Department of Fisheries, Statistics, personal communication). Before 1969, the escalator dredge was occupied solely in the oyster and hard-shell clam industries. Starting in 1969, harvesting of *M. arenaria* beds located in Port Susan and Skagit Bay began, but soft-shell clam landings are not yet a significant part of the Washington shellfish industry. Escalator harvesters are regulated in Washington by the state (Westley and Goodwin, personal communication), which has developed stringent regulations. These regulations are administered both by the permit system of the Department of Fisheries and by individual counties as specified by the Shoreline Management Act. Operators are restricted to clam ground owned privately or leased from the state.

Table 1. Washington State shoft-shell clam industry from 1969-1973[1]

Year	Number of harvesters licensed	Landings (lb)	Value of landings (dollars)
1969	1	6,998	1,749.50
1970	1	44,826	11,631.00
1971	1	1,020	255.00
1972	1	37,425	9,356.00
1973	2	103,944	10,752.00
1974	1	36,832[1]	9,208.00[2]

[1]Statistics from Dale Ward and Lynn Goodwin, Washington State Department of Fisheries.
[2]Values for September and November 1974 alone.

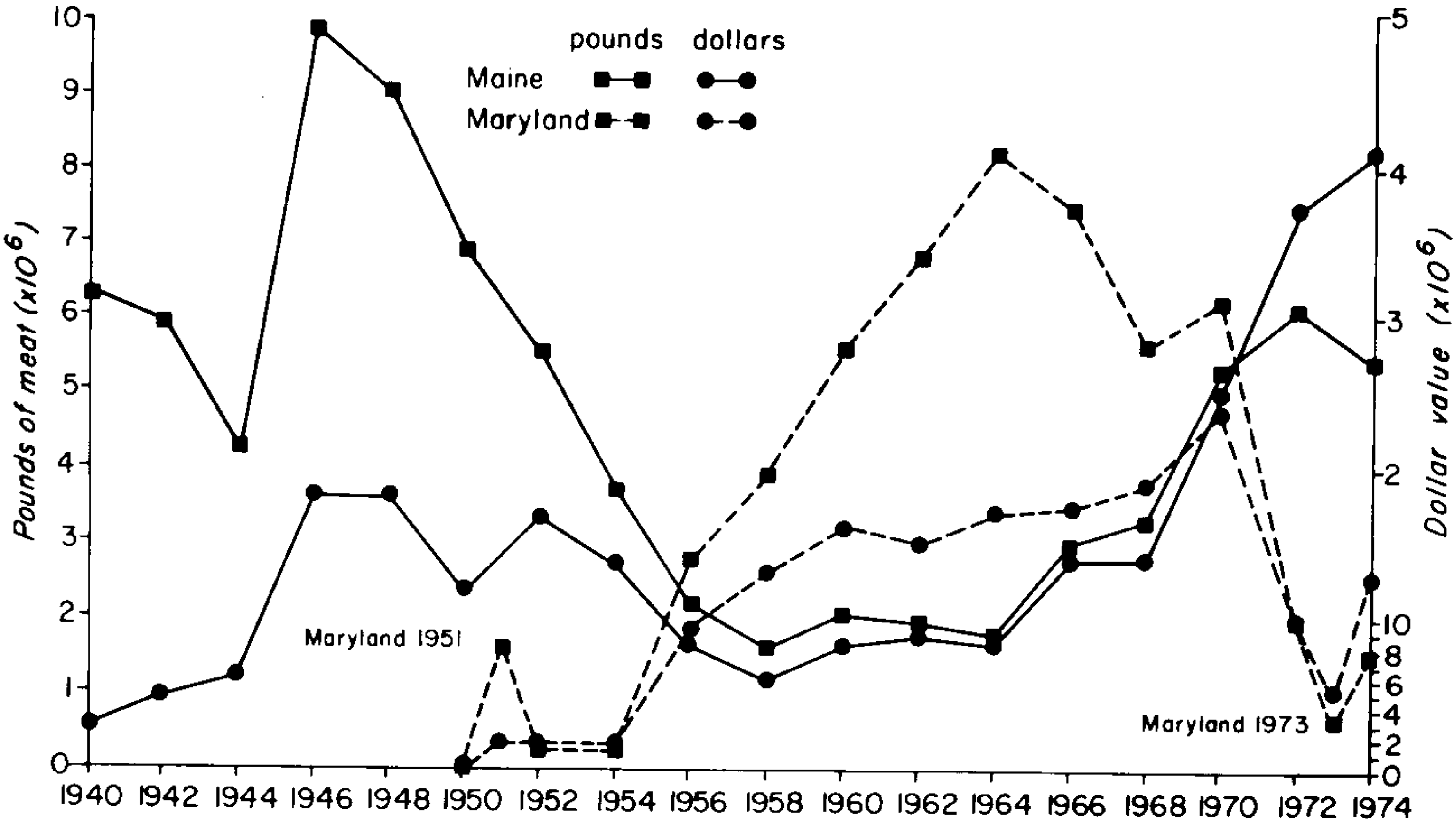

Fig. 3. Growth and status of the soft-shell clam industry in Maryland and Maine (1940-1974) (from NMFS 1951-1974; Shaw and Hamons 1974; and Shaw, personal communication).

A potential for a soft-shell clam fishery in Washington apparently does exist (John Harris and William Meagher, personal communication). This potential is due not only to possible extensive stocks of *M. arenaria* (Smith and Herrmann 1972; Herrmann 1969, 1974) but also to the fact that stocks on the East Coast have declined because of increasing pollution (Dow and Wallace 1961; Hanks 1963), environmental disasters (e.g., Hurricane Agnes), and increasing disease mortalities (Haven and Pfitzenmeyer, personal communication). With the eastern suppliers not being able to meet national demands, the stocks in clean, unpolluted areas such as Washington and Alaska (Feder and Paul 1974) become increasingly valuable.

BIOLOGY OF *MYA ARENARIA*

Before discussing results of the various studies mentioned above, it is necessary to define the nature of *M. arenaria* and the environment in which it is found and harvested. Particulars of the biology and physiology of this clam are described in detail in various publications; Pfitzenmeyer and Schuster (1960) give a partial bibliography.

Mya arenaria has wide geographic distribution, which indicates that it is tolerant of a variety of environmental conditions (Hanks 1963; Porter 1974). Soft-shell clams are euryhaline and can survive and adapt to salinities as low as 4-5^{o}/oo (Green 1968). This tolerance allows the clam to inhabit estuaries and other inshore areas that are subject to periodic salinity depressions. Also, soft-shell clams are tolerant of wide fluctuations in other water quality parameters, such as temperature, pH, and hydrogen sulphide and dissolved oxygen levels. It is known that *M. arenaria* can survive several days of essentially anaerobic conditions (Ricketts, Calvin, and Hedgpeth 1968). Turbidity in the form of suspended solids is another environmental factor to which *M. arenaria* is subject, but no definitive studies have been completed at this time on effects of turbidity on its biology. However, the soft-shell clam is probably tolerant of high concentrations of suspended solids (Newell 1970) because the lower salinity areas of estuaries where *M. arenaria* normally are found are also the areas with the highest turbidities (Cronin and Mansueti 1971).

The reproductive biology and growth rates of *Mya* have been well studied because of the commercial value of the clam. In Washington, as in Maine, soft-shell clams spawn from May to September with one peak in June to July (Porter 1974; Dow and Wallace 1957). In contrast, Chesapeake Bay *Mya* have two yearly spawning periods (Pfitzenmeyer 1962). Survival of larvae and settled spat is limited by intensive predation (Dow and Wallace 1957; Hanks 1963) and larval sensitivity to environmental conditions. Ayers (1956) studied population dynamics of *M. arenaria* in Massachusetts and arrived at a minimum number of 40 spat per pair of adult clams per year that have to survive to maintain the population. This minimum, along with mortality and flushing rates within an estuary, can be used to determine the stability of a *M. arenaria* population and the amount of fishing it can sustain (Ayers 1956).

After clam larvae have metamorphosed and settled out of the plankton, their growth rate varies with the region. In Washington it is approximately 60 mm in three years (Porter, personal communication). In Maine, the growth varies with substrate and the clams take an average of five years to attain about 51 mm (Wallace, personal communication). This length is legal size in most areas. *Mya* in Chesapeake Bay region usually reach market size in less than two years (Hanks 1963).

Within the food-web relationships of *M. arenaria*, the predators are well cataloged, but the feeding habits of the predators are less well known. Dow and Wallace (1957), Hanks (1963), and Haven (1970) list several species that prey on both young and adults, including crabs, prosobranch snails, shore birds, and fish. On the other hand, it is known that *M. arenaria* is a suspension feeder consuming phytoplankton and detritus (Green 1968).

Hanks harvesters are used commercially to collect soft-shell clams only in estuary environments. Estuaries in recent years have received much attention (Green 1968; Cronin and Mansueti 1971) because of their importance in the life cycles of many species of commercial and sport wildlife and the possible deleterious effects on these species and their estuarine habitat by human activities. Certain details of estuarine biology need to be discussed here as background before the implications of escalator dredging can be understood.

An estuary typical of those in which *M. arenaria* is found in Maine, Maryland, and Washington is dominated by an inflow of freshwater from a river of some size. The river inflow not only affects salinity of the estuary, but also brings in sediment that affects turbidity and subsequently suspension feeders among the fauna and the photosynthetic rates of the flora. Sediment is also deposited in the form of banks and flats. This influence of freshwater is moderated by the tidal flow of sea water in the estuary. The extent of mixing and the relative concentrations of sea water and river water play a large role in determining distribution and abundance of estuarine flora and fauna.

Within this system *M. arenaria* can be found in a variety of vertical locations and types of sediments. In Maine, for instance, this bivalve is found from the lowest intertidal zone to just below the high tide mark (Dow and Wallace 1957). Washington soft-shell clams are distributed in the intertidal zone in Puget Sound, Grays Harbor, and Willapa Bay (Smith and Herrmann 1972; Herrmann 1969, 1974). It is not known positively what determines in any given area where the bivalve will be found, but temperature and sediment regimes are thought to be major factors. *Mya* may be found in upper parts of an estuary partly because of the presence of flagellates rather than diatoms (Green 1968).

The sediment type from which the clams are harvested is important in considering the impact of escalator harvesting on the estuarine environment as an ecosystem and on the population of *M. arenaria*. The soft-shell clam can be found in nearly all types of sediment firm enough to support it. New England soft-shell clams are found in a variety of substrates including gravel-sand deposits in rock crevices, firm muddy sands, and soft clay mud. However, *M. arenaria* most commonly occurs in stable sands or firm muds. Sand and mud sediments present very different faunal environments and do not react the same to hydraulic harvesting. Estuarine stable sands (median grain size about 1.0 mm) have a higher species diversity (MacArthur 1965; Sanders 1968) and different species inhabiting them than mud (median grain size around 0.02 mm).

Because of the extent and nature of biological and geological interactions, an intertidal sand flat may be more easily disturbed ecologically than a mud or rock region. Sandy clam flats usually contain a small but important percentage of silt and clay particles that bind and stabilize the larger sand grains (Horn, personal communication). During harvesting it has been shown that the fine sediment fractions are suspended, and varying portions of these are removed at least temporarily from the harvesting track (*see* next section). The possible changes due to fine sediment removal are not well documented. Observations in Maine have shown that dredging in mud also disturbs the flat, but a significant alteration of the environment does not occur as the fine sediments compose nearly the total substrate and a small loss probably does not seriously change the composition of the substrate. This situation will be elucidated below by results of actual studies.

EFFECTS OF THE HYDRAULIC ESCALATOR HARVESTER

Areas in Which Effects Have Been Investigated

The hydraulic escalator shellfish harvester not only removes quantities of organisms but also leaves noticeable trenches. Extended operation will suspend visible quantities of sediment for various lengths of time. These effects have caused much concern about the environmental impact of harvesters since their introduction into the shellfish industry. As a result a number of studies have been conducted in regions that have either an active or potential Hanks dredge shellfish industry.

Maryland, where the harvester originated, was the first to conduct impact studies. Glude (1954*a*), Manning and Dunnington (1956), Manning (1957, 1959), Manning and Pfitzenmeyer (1958*b*), Pfitzenmeyer and Drobeck (1967), and Pfitzenmeyer (1972) have all been concerned with the effects of the harvester on stocks of *M. arenaria* and the associated environment. In Virginia, another state in the Chesapeake region, Haven (1970) has conducted studies of the environmental effects of the dredge.

Washington is the only region on the North American Pacific Coast where escalator harvesters are being used commercially. Long-term studies on the hydraulic escalator hard-shell clam fishery are being conducted by the Washington State Department of Fisheries. Only limited information is presently available on the soft-shell fishery and environment, but the Washington State Department of Fisheries and the Washington State Department of Game are planning such studies and have already gathered preliminary data (Westley, Goodwin, Brewer, personal communication).

Elsewhere in the United States, Florida, Maine, North Carolina, and South Carolina have conducted research on use of the harvester. Godcharles (1971) assessed the impact of a Maryland dredge working on populations of hard-shell clams in marine grass beds in Florida. In Maine, Kyte et al. (1975) and Smeltzer (1974) have examined the feasibility and effects of harvesters working on a compact mud soft-shell clam flat. In North Carolina a preliminary environmental impact analysis for the escalator harvester working with hard-shell clams was prepared (Anon. 1973). Also, South Carolina (Burrell and Gracy, personal communication) has reviewed the effects of harvesting on subtidal hard-shell clam beds.

The use of the harvester has also been investigated in British Columbia, which has stocks of *M. arenaria*, but no impact studies have been done. Eastern Canada is the only other known region to have investigated the harvester. Dickie and MacPhail (1957), Medcof (1958, 1961), and MacPhail (1961) studied effects of the harvester on beds of *M. arenaria*.

Effects on Soft-shell Clam Stocks

The first concern when a hydraulic escalator harvester is used in a soft-shell clam bed is the effect of harvesting on clam stocks. Fishing efficiency; mortalities resulting from breakage, burial, or exposure; effects on juvenile clams; and effects on future sets are all parameters of concern.

When the impact of harvesters on *M. arenaria* is considered, it is usually compared to the impact of commercial hand-digging (Fig. 1) in New England and Canadian Maritime Fisheries. It has long been known in these areas that hand-digging is detrimental to clam stocks. Dow et al. (1954) give a breakage range of 3 to 45 percent and a mean breakage of 19.6 percent on the Maine coast. More compact sediments and higher population densities result in higher breakage rates. Burial by overturning of the sediments, with resulting failure of the fisherman to harvest all the clams in a given area, is equal in importance to breakage. Mortalities of 45-71 percent (Glude 1954*b*) occur among those clams left buried in a Maine hand-digger's path. Fishing catch efficiency in Maine is 84 percent (Dow et al. 1954; Dow and Wallace 1961), resulting in numbers of clams left in the hand-digger's path either buried or exposed on the surface.

In Canada, Needler and Ingalls (1944), Dickie and MacPhail (1957), and Medcof and MacPhail (1967) also found that high mortalities resulted from breakage or burial by Maritime professional clam diggers. In these studies mortality averaged 48 percent and ranged from 60 percent in compact clays to 37 percent in loose sandy soil. Fourteen percent of the clams that diggers left exposed had lethal shell damage. Bivalves that are buried in the digging spoils probably have a lower breakage. However, smothering by deep burial was the main source, as in Maine, of mortalities incidental to hand harvesting (Medcof, personal communication). Medcof and MacPhail (1967) report digging efficiencies ranging from 25 to 89 percent with an average of 60 percent. These are somewhat lower than those in Maine.

In general, it can be seen that for every 100 adult clams dug in an area, a hand-digger removes only 60 to 84. Among those left in the track, including juveniles, 70 percent will die from breakage, from exposure, or from smothering caused by burial (Hanks 1963). This digging mortality, coupled with increasing pollution, has been a major factor in causing the decline of clam production in New England and eastern Canada (Glud [sic] 1951; Dickie and MacPhail, 1957; Medcof 1958; Medcof and MacPhail 1967).

In contrast to hand-digging, the escalator harvester is surprisingly gentle with soft-shell clams. Systematic studies of breakage by the harvester have been done in Canada and Maine. Medcof (1961) found that at worst the harvester caused a 10-percent breakage, and normally it was 5 percent or less. Also, while large numbers of juvenile clams are *killed* by hand-digging through burial Medcof (1961) found in Nova Scotia that the harvester returned approximately 90 percent of the small clams in its path to the surface of the track where they rapidly reburrow. Haven (1970) and Pfitzenmeyer (1972) also found that dredging had little effect on the population of juvenile *M. arenaria* in Chesapeake Bay. In fact, Pfitzenmeyer states "The smaller the clams, the greater their ability to overcome disturbance created by dredging activity." When juveniles are returned to the track, they can easily reburrow because of the comparative softness and looseness of the track (Baptist 1955; Medcof 1961; Pfitzenmeyer and Drobeck 1967). It is known also that small juvenile *M. arenaria* move horizontally (O. R. Smith 1955) and so can move into or out of a dredging scar.

Kyte et al. (1975) also found that the harvester has a much lower breakage rate than a hand-digger. Despite operator inexperience, the experimental nature of the dredge machinery, and the extremely compact nature of the flat, an average breakage of only 9.6 percent was found. Higher amounts of 13 percent to 14 percent occurred at the beginning of the experiment when operators and machinery were not functioning at their maximum efficiency. Also, it was found in Maine that very little decrease in numbers of juvenile *M. arenaria* occurred after dredging. In fact, 10 months after dredging the population of juvenile clams in the harvest scars was several times greater than before dredging (Kyte et al. 1975; Smeltzer 1974). On the other hand, total mortalities in the Maine study were probably much higher than indicated by breakage. Because of very compact clay mud in Maine, a large number of clams were deposited with the spoils by being cast aside by the harvester. On the next low tide, these exposed clams that were unable to reburrow because of the hardness of the spoils were heavily preyed on by herring gulls (Kyte et al. 1975).

In addition to probable high adult mortalities the fishing efficiency of the Maryland harvester in the very compact mud of this Maine study was very low. On the basis of the total estimated number of *M. arenaria* available for harvest in the experimental area before dredging and the total number caught, the efficiency was about 11 percent. This low number was probably due to the unusual exceedingly compact nature of the sediment and the high number of clams tossed aside onto the spoils by the lateral movements of the harvester and other unknown factors (Mathieson and DeRocher 1974). In contrast, fishing efficiencies found by Medcof (1958, 1961) with the harvester working in firm sands were nearly 95 to 100 percent. Also, Medcof did not observe the loss of clams that Kyte et al. (1975) experienced.

The overall, long-term effect on standing stocks and on maintenance of sustained yields has been well demonstrated in one situation by the catch statistics from Chesapeake Bay (Fig. 3). When the mechanical harvester was first becoming established, it was feared that the industry was going to be a "mining industry" with stocks very quickly becoming depleted (Anon. 1955; Manning 1957). However, the stocks of *M. arenaria* in Chesapeake Bay have been shown to be a renewable resource because of rapid growth rates (18 to 22 months to reach market size); large parent stocks that cannot be harvested; and the low mortality of juveniles subjected to harvesting (Manning 1957, 1959, 1966).

The belief that mechanical harvesting benefits future sets of larval *M. arenaria* has been expressed. The tilling or turning over of the sediment was thought to enhance the environment and provide a higher survival of settling larvae. Because of the obvious benefits of such a result from escalator harvesting, this aspect was closely examined by Haven (1970) and Pfitzenmeyer (1972) in Chesapeake Bay. Both found that clam sets following dredging were about the same. Pfitzenmeyer, while finding no increase in the clam set, did find increased survival-recruitment rates of juveniles where adult populations were reduced. Haven's study did not show this result. In Maine, Kyte et al. (1975) found significant increases in spat and juveniles in the dredged tracks the following season after harvesting. It must be noted that the Chesapeake Bay studies were on uniform medium and fine subtidal sands, whereas the results in Maine were from an intertidal silt-clay mud flat.

The documented results of the Chesapeake Bay hydraulic escalator harvester fishery cannot be applied without qualifying research to other regions with fishable stocks of *M. arenaria*. Growth rates of the soft-shell clam vary widely, and differing sediment situations can have marked effects on harvesting efficiencies and impact, as has been seen already.

Effects on Water Column

Turbidity and chemical changes in the water column have been examined in a few short-term studies in an attempt to determine their effects on clam stocks. No evidence is available on the positive or negative effects of increased turbidity, pH changes, or temporarily lowered levels of dissolved oxygen or elevated levels of dissolved hydrogen sulphide. As has been discussed above, *M. arenaria* is probably tolerant of fluctuations of a temporary nature such as those that could be created in the vicinity of a working harvester. The reactions of many associated plants and animals could be different from those of the ubiquitous and hardy soft-shell clam. Before dealing with the potential impact of harvesting on the associated flora and fauna of a clam flat, the known effects of escalator dredging on the geology and hydrography of the flat should be summarized.

When an escalator harvester works across a clam flat, the ground in the path of the harvester is disturbed and visible trenches are created (Manning 1957; Kyte et al. 1975). No matter what kind of sediment is dominant, the trenches for some time differ in several characteristics from the virgin flat. The source of this disturbance is, of course, the erosion and suspension of the sediment by the hydraulic jets. As a harvester progresses, the jets suspend all matter with the exception of large logs and boulders, within the potential trench (Fig. 4). This suspended material is sieved through the conveyer belt, and objects larger than the mesh of the belt are brought to the surface. Those materials in temporary suspension that pass through the belt or those that are rejected by the fishermen (shell, rocks, clay chunks, etc.) and fall off the end of the conveyor may be deposited back into the trench or drop outside of it. Their particular fate depends on several factors including jet water pressure, currents, and lateral movements of the harvester vessel.

The action of the harvester on the sediments is a winnowing process like that used to separate grain from chaff (Fig. 4). The heavier sand particles, "grain," settle faster than the lighter silt and clay sizes, "chaff," which often form a visible sediment plume extending away from the actual dredging site (Manning 1957; Kyte et al. 1975). Because of this winnowing process, the sediment composition and structures within the trenches can differ from those of the untouched flat. The degree of possible difference depends on many factors, the most critical of these

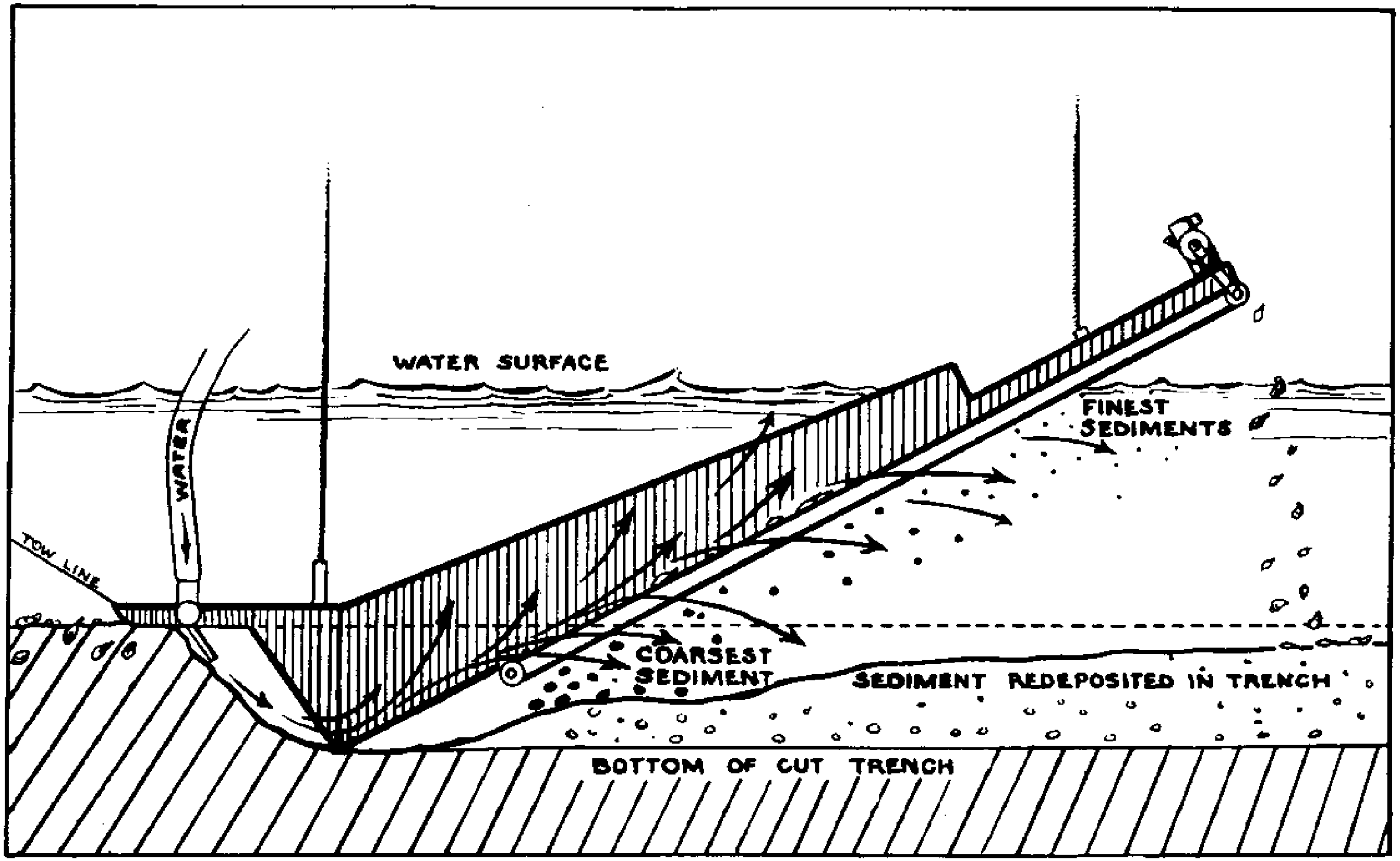

Fig. 4. Disposition of hydraulic escalator dredged material (from Manning, 1957).

being the original sediment composition. Kyte et al. (1975) found that on a mud flat in Maine composed of 90 percent or more of silt and clay particles, the grain-size distribution in the trenches did not differ significantly from that of the virgin flat. In this case the material transported away during the actual harvesting did not differ in composition from that redeposited in the trenches and the only loss was in quantity of sediment, not in quality. The harvester tracks in Maine were found to be softer, to contain more water, and to be lower than the surrounding flat. These conditions persisted at least one and a half years after the actual harvesting.

The harvester has potentially a much different effect on a flat that is predominantly sand than on a silt-clay mud flat. Soft-shell clams are presently harvested commercially from sand flats in two different situations: in Chesapeake Bay the commercial sand flats are entirely subtidal, while in Washington they are intertidal. This difference is important in relation to the impact of a harvester. An intertidal flat is subject to periodic draining and drying and hence is more compact and stable than comparable subtidal sediments which contain more water within the soil (Horn, personal communication).

The suspension and sediment transport associated with escalator harvesting on a sand flat result in not only a quantitative loss from the trenches but also a qualitative one. The finer sediments are removed and other changes also occur as a direct result of the natural sorting process caused by the forceful suspension of the sediments (Manning 1957; Haven 1970; Pfitzenmeyer, personal communication; Kyte et al. 1975). Figure 4 illustrates this suspension, sorting, and transport.

Loss of finer size sediments from sandy harvester tracks and other changes have been documented both in subtidal areas of Chesapeake Bay and Florida and in intertidal areas of Washington. No systematic studies on changes in the sediment due to escalator harvesting are available from British Columbia or Eastern Canada. Pfitzenmeyer (1972) in Maryland found that because of the very low silt-clay content and uniform nature of the sediments, no observable loss of fines due to harvesting occurred. The organic carbon content of the sediment was redistributed but not markedly changed after dredging. However, sediment in the dredge scars was noticeably less firm or compact for at least one year after harvesting.

In contrast to Pfitzenmeyer's grain-size results, Haven (1970) and Godcharles (1971) found that a harvester did remove a significant percentage of the silt-clay sediment fraction. Prior to harvesting, a test area in Virginia contained an average of 2.4 percent silt-clay and after dredging the percentage was reduced to an average of 0.6 percent. Similar results were obtained in Florida by Godcharles. Haven also found that the effects in the form of sediment transport and redeposition of the harvester extended up to 23 m from the harvesting site, but no effects could be observed beyond this limit. Neither Haven nor Godcharles performed compactness or organic carbon analyses. Godcharles in Florida did observe that some of the scars continued to be "soft" from several days to nearly two years after dredging. None of the three authors was able to do long-term studies on test plots.

No systematic study like that of Haven (1970), of Pfitzenmeyer (1972), or of Kyte et al. (1975) has been completed or published in Washington. The Washington State Department of Fisheries in the course of regulation of the activities of escalator harvesters and the Washington State Department of Game in their estuarine marsh studies have taken a number of sediment samples both in and out of harvester tracks. Results from samples taken immediately and a few months after harvesting show a definite reduction in both fines, less than 63 μ, sediments, and volatile solids, which are a measure of the organic content (Westley, Goodwin, and Jeffrey, personal communication). The available samples indicate that differences persist at least for several months. No information relative to soft-shell clam harvesting is available on the compactness and water content of harvesting scars or on possible redeposition of sediments outside.

In general then, knowledge about the effects of a clam harvester on the sediments of an intertidal clam flat is incomplete and more studies are needed. It is known from Washington and from one study in Chesapeake Bay that a harvester can cause the loss of a portion, sometimes major, of the finer sediments from the harvester's track. This, in turn, usually lowers the level and has been seen to reduce the firmness of the track. In addition, the erosional characteristics of the area may be changed. This was seen by Kyte et al (1975) in Maine. It is also indicated that there may be a loss or redistribution of organic matter from these sediments.

It is not known how long harvesting scars can persist. Studies in Florida and Maine have shown tracks to be noticeable up to one and one-half years after harvesting (Godcharles 1971; Kyte et al. 1975). Tracks have been observed for up to three years in Skagit Bay and Port Susan, Washington (Brewer and Jeffrey, personal communication). Horn (personal communication) feels that the scars will remain for a period of time dependent on the dynamics of the estuary and its sedimentary environment. It is not known what effect biological reworking and deposition may have on these tracks. A number of other parameters describing sediment chemistry and structure may be important but have not been investigated in relation to the Hanks harvester.

Another aspect of the sediment disturbance problem is the effect of the sediment suspension on the water column. One obvious result of escalator harvesting is the creation of a turbidity plume composed of sediment suspended by the hydraulic jets. As the heavier and larger particles settle out, the plume extending away from the site of actual harvesting is composed primarily of silt and clay particles. These settle out at rates determined by hydrographic conditions and the physical properties of the particles themselves.

Theoretical settling rates are available in geological oceanography literature (Sverdrup, Johnson, and Fleming 1942). However, these rates are modified by conditions of turbulence caused by waves, currents, and particle characteristics. Clay particles, for example, aggregate and carry ionic charges that affect their action in suspension (Horn and Hendershott, personal communication). Much information relevant to this problem exists in the literature on effects of harbor and channel dredging. One study by Westley et al. (1973) has recently been carried out in southern Puget Sound on channel dredging with a large 24-inch pipeline dredge. Westley et al. (1973) state that no significant changes other than a minor decrease in oxygen and a minor increase in biochemical oxygen demand (BOD) were associated with this dredging.

With hydraulic clam harvesting, a cloud may persist long enough to transport and redeposit some amount of sediment to areas removed from the harvesting tracks. This transport has not been completely described, although some data are available on the concentration of suspended solids in plumes from escalator harvesters. Kyte et al. (1975) in Maine recorded a high value of 584 mg/liter at the conveyor belt of a harvester working on a silt-clay mud flat. This high value rapidly diminished to 89 mg/liter 61 m away from the harvester. At this point a plume was still readily visible. The observations are not comparable to Haven's (1970) because of differing sediment and oceanographic conditions. The background silt load at the site of dredging was found to range from 4.0 to 441.0 mg/liter depending on tide, recent precipitation, and weather conditions.

The only other measurements of turbidity resulting from a harvester are the results of one field investigation conducted by the Washington State Department of Fisheries. These data were gathered during a period of high natural turbidity and the harvesting plume was nearly indistinguishable from the plume resulting from the nearby rivers. Values of 32 to 54 mg/liter were obtained near bottom in the vicinity of the harvester and values of 39 to 63 mg/liter from the nearby river mouth (Tarr 1975). Washington State Department of Fisheries also determined percent of light transmission of the water in this area at the time of sampling. These values ranged from 4 to 80 percent in the vicinity of the harvester and from 2 to 65 percent in the nearby river plume. According to Tarr (1975), "No effect could be detected at the surface. When the effects of the river and harvester on water quality are compared, those of the harvester are minor and will quickly disappear after daily operation ceases, but the major effects of the river will persist as long as high river flow continues." No transmission values are available from the study done in Maine.

Besides simple suspension of sediment, the harvester's plume can be described by a number of other parameters in the water column. These include the dissolved oxygen content, BOD, concentrations of inorganic and organic substances, and phytoplankton production. Little information is available on these aspects of the harvester's plume. Studies in Maine show slight and transient reductions in the dissolved oxygen content and slight indications of temporary higher hydrogen sulphide concentrations in the water immediately adjacent to a harvester (Kyte et al. 1975).

In the single investigation performed during the high runoff period in Port Susan (Tarr 1975), the Washington State Department of Fisheries reported a possible effect of a harvester on one water quality parameter--the inorganic phosphate concentration. Elevated levels were found near the bottom in the vicinity of the harvester. A few samples were as much as 40 percent greater than those elsewhere (Tarr 1975). One station adjacent to the harvester also showed a higher value of organic phosphate. Parameters that showed no effects or only slight ones were chlorophyll *a*, dissolved oxygen, biochemical oxygen demand, and salinity. Chlorophyll *a*, an indicator of phytoplankton standing stock, was probably at a natural seasonally low level.

The region directly above the conveyor and jets and also the area where rejected material falls back into the water showed the greatest disturbance, as indicated by Kyte et al. (1975) in Maine. Measurements from here are important for determining possible extremes to which environment can be exposed and for determining *in situ* settling and dissipation rates of disturbed sediment.

Aside from these two studies in Maine and Washington, no other chemical data relative to this type of harvester exist. More detailed samplings are needed.

Effects on Associated Biota

As an escalator harvester suspends and sieves the sediments in its path, the organisms living in and on this ground are also suspended and filtered through the conveyor. If an organism is large enough, it will be brought to the surface and either collected or rejected and allowed to drop back with the other rejected debris. Also, the disturbance of the water column and potential redeposition of suspended sediments in the vicinity of the clam dredging may affect organisms some distance from the actual harvesting track. In addition, after the clam dredge has left an area, the trenches with their now different sediment composition remain for varying periods of time, as discussed above. Because these trenches are different in some way from the original flat, the organisms that are placed back into them by the dredge or move into them during their normal activities must cope with this different environment in some way.

The best documented effects are those on rooted aquatic vegetation. Interactions between *Zostera* spp., other genera of marine grass, and the escalator dredge have been studied in Florida (Godcharles 1971), Maryland (Manning 1957), Virginia (Haven, personal communication), and Maine (Kyte et al. 1975). In all of these areas, it was found that the vegetation was removed completely by the escalator clam harvester and full recovery to previous levels always took a year or more. Manning (1957) in Maryland observed only a sparse revegetation after one year and Godcharles (1971) did not have any colonization for at least three months and in some cases for nearly two years. Apparently, the colonization of particular marine bottoms by grasses including terrigenous species depends at least partly on the sediment composition (Green 1968; Washington State Department of Game, unpublished data).

Effects of hydraulic escalator harvesters on associated biota other than commercial species and plants are less clear. Only three regions have made an effort to elucidate this problem. Furthermore, results from these studies are not directly applicable to other areas because of differing species and faunal environments. Godcharles (1971) found in Florida that hydraulic dredging for hard-shell species had no discernible effect on animals occurring in the same areas. This conclusion is in part supported by similar findings in South Carolina (Burrell and Gracy, personal communication). The Florida study was conducted in a sandy, subtropical area populated with dense stands of several species of marine grass. Subtropical and tropical estuaries usually have higher species diversities than more temperate and boreal estuaries (Sanders 1968). On the opposite end of the range, the study of Kyte et al. (1975) in Maine dealt with a low diversity but stable mud environment. This experiment had a small number of species to deal with and found that recovery from clam dredging occurred rapidly in all cases. Temporary declines in population levels were seen but within 10 months levels were back to or above predredging values. No definite long-lasting effects on the infauna were seen. In this study, as discussed above, no qualitative change occurred in the faunal environment because of the predominance of one type of sediment, mud. No other Hanks harvester studies on the Atlantic coast have examined the reactions of the clam bed biota to escalator harvesting.

Port Susan and Skagit Bay, Washington, contain a relatively high species number and an abundance of organisms for a temperate region estuary (J. Smith, personal communication). Large numbers of epibenthic and pelagic fish and invertebrates with large numbers of birds are found on estuarine intertidal sand flats. The areas in which *M. arenaria* occur with the highest numbers of invertebrates (J. Smith, personal communication), fish, plant, and bird species (Washington State Department of Game, personal communication) are characterized by a heterogeneous mixture of medium and fine sands stabilized by silt and clay fractions (Horn, personal communication). These flats differ ecologically from the situation reported by Godcharles (1971) and by Kyte et al. (1975). Because of the importance of environmental stability to the maintenance of species diversity and community structure (Sanders 1968; Bella et al. 1972), the relatively small percentage of stabilizing finer sediments may be an ecologically critical limiting resource. Unfortunately, no systematic studies on community structures and population levels have been completed at this time in the areas where commercial quantities of *M. arenaria* occur. Some sampling has been done in connection with the regulation of the hydraulic escalator harvester but only of the infauna larger than a 6-mm mesh. Also, James Smith (personal communication) has done preliminary sampling in preparation for a more extensive study in this area now underway . It is known that to assess benthic infaunal populations and community structures completely, sampling should be done with fine sieves 0.5 mm and smaller (Sanders 1960; Buchanan et al. 1974). Systematic sampling programs necessary to elucidate the relationships between the benthic fauna, estuarine marsh dynamics, sediment structure, and clam harvesting are being planned at this time by Washington State Department of Fisheries and Washington State Department of Game. A study of the community ecology of the estuarine intertidal flats is being conducted by a College of Fisheries graduate student (James Smith).

Two facets of the possible biological interaction common to all areas in which a harvester may operate are the effects of turbidity on the flora and fauna of the area and the reaction of larval forms to the changed nature of the substrate in the trenches. The only documented effects of turbidity besides those on phytoplankton are those on oysters and a few species of hard-shell clams. Although specific data are not presented here, the effects of various concentrations of suspended solids on oyster and bivalve larvae survival and adult feeding rates have been studied (Davis and Hidu 1969; Loosanoff 1962; Loosanoff and Tommers 1948; Loosanoff and Davis 1963; Schink et al. 1974). No studies on reactions to turbidity by *M. arenaria* are available.

No data are available on the effects of changes in sediment on soft-shell clam larval settling and survival other than Pfitzenmeyer's (1972) observations discussed above for Maryland. Thorson (1966) indicated that pelagic larva of some benthic species can postpone metamorphosis in an attempt to select the type of substrate they will settle on, and that the optimum is the type in which the parent population is dominant. Wieser (1959) also revealed that in Puget Sound the distribution of intertidal fauna on beaches is controlled in part by the grain-size distributions of those beaches. Also, Boaden (1962) demonstrated experimentally that the composition and abundance of sand interstitial fauna are dependent on grain size. The changes in the nature of the trenches resulting from escalator harvesting on silty sands may be sufficient to affect the recolonization and subsequent biogenetic healing action in the harvesting scars.

HYDRAULIC CLAM RAKE

An escalator harvester requires a major investment and commitment on the part of the fisherman (Manning 1957). Also, to meet operational costs and to make a profit a harvester must either work in areas where soft-shell clams are very abundant or must cover large amounts of bottom, or both. This may be difficult to accomplish because of natural high variability in population densities. In addition to fiscal considerations, an escalator harvester is in principle a dredge and could alter the area in which it is operated, either by improving or degrading its character as a benthic habitat.

It was felt appropriate to look at alternate methods of obtaining the soft-shell clam. Only one method will be seriously discussed. Others may be worth looking at, but details on these are not available at this time. One alternative, commercial hand-digging (Fig. 1), can be dismissed quickly so far as Washington is concerned. It is still favored in certain climates such as in New England, but as shown above hand-digging is wasteful of clam stocks and possibly detrimental to the flat environment if carried to a commercial extent.

Hydraulic clam rakes originally developed on the Eastern Seaboard (Glude et al. 1952; MacPhail and Medcof 1962; Medcof and MacPhail 1964) may be practical alternatives to escalator dredging. A self-propelled version of the hand-operated MacPhail rake was developed recently in British Columbia and modified for large sandy clam flats by Smith and LeBlanc (1974) (Fig. 5). This hydraulic digger was shown to be efficient and relatively easy to use on dry, intertidal sand flats similar to those found in Port Susan and Skagit Bay in Washington. Also, the unit cost is considerably less than that of a Hanks harvester. Efficiency was found by Smith and LeBlanc (1974) to be around 95 percent, with less than 3 percent breakage. Mortalities of undersize clams left by the digger were less than 5 percent. Rate of travel of the harvester varied from 1.5 to 6 m per minute depending on sediment compactness. Efficiency was inversely proportional to speed.

These diggers and modifications of them are presently in commercial use in British Columbia with good results (D. W. Smith, personal communication) and are being considered for use in Maine (Wallace, personal communication).

A hydraulic rake operates on a different principle from the escalator harvester. The rake's jets are vertical and create a heavy, *in situ*, water sediment suspension in which the clams float to the surface (Medcof and MacPhail 1964). The rake seems to displace less sand and the plume, in shallow water, is usually less spectacular than that of a Maryland dredge (Medcof, personal communication). A rake is used at low tide on

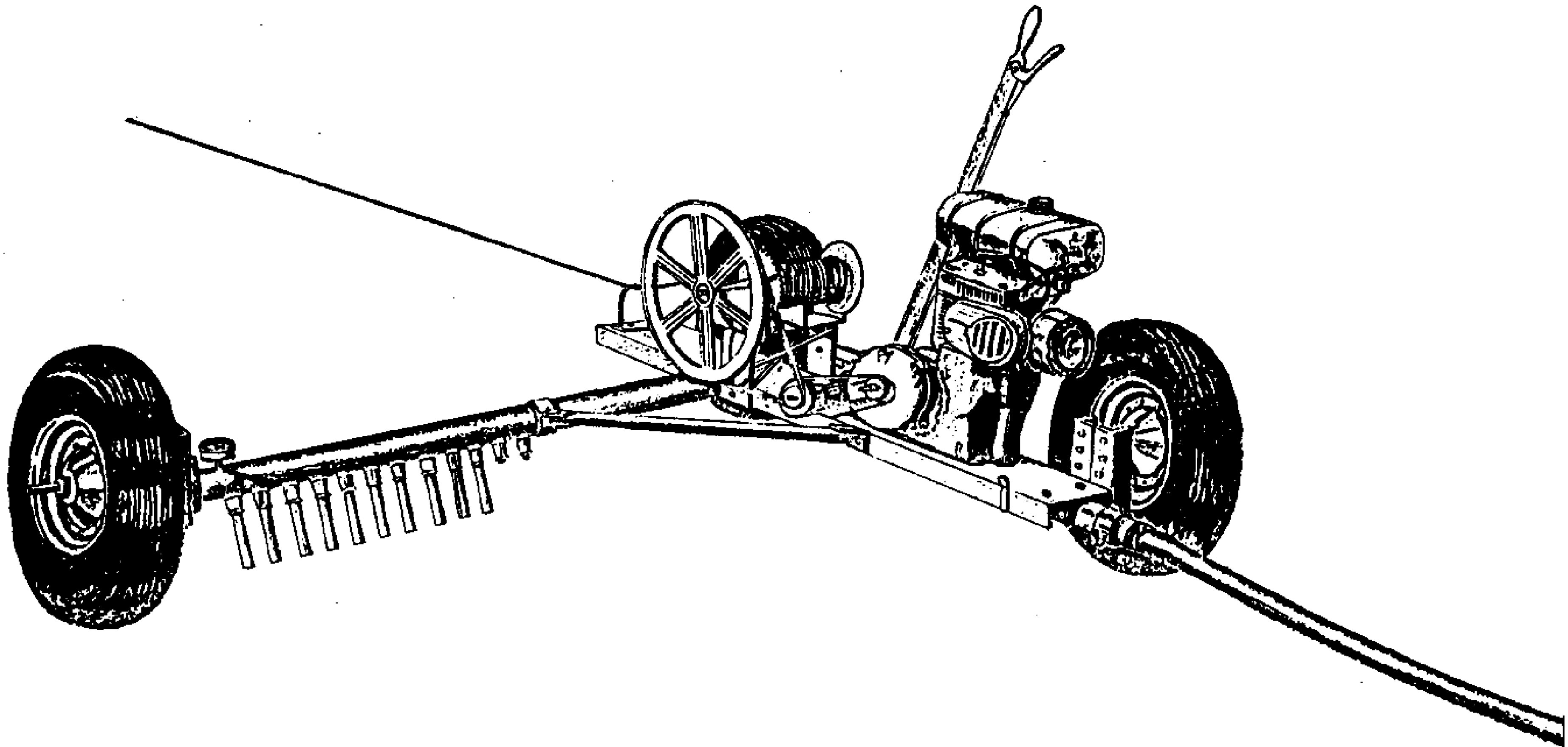

Fig. 5. Hydraulic clam digger for operation on dry, sandy intertidal clam flats (modified from Smith and LeBlanc, 1974).

intertidal beaches on shallow submerged beds and does not require a large vessel.

No studies have been done on the impact of the digger on the clam flat environment, however. A photograph published by Bourne (1967) indicates that a rake leaves a shallower and less disturbed trench than the escalator harvester. Also, it uses only 1.8 to 2.1 kg/m^2 (25 to 30 $lb/inch^2$) of water pressure or less, while a Hanks dredge uses 3.5 kg/m^2 or more. For these reasons it may be found to disturb the estuarine ecosystem significantly less than a Maryland dredge.

SUMMARY

The soft-shell clam, *Mya arenaria*, has a wide geographic distribution, indicating that it is tolerant of a variety of environmental conditions. Reproductive patterns and biology of this species of clam have been studied in Washington, Maine, and Chesapeake Bay. Information from several studies of the harvester on soft-shell clam stocks, associated biota, water column, and clam flat geology has been summarized and is discussed in this report.

Since the invention of the hydraulic escalator shellfish harvester and its commercial operation in Maryland in 1952, many areas of the United States and Canada have used this device for harvesting shellfish. Other than being used to survey and harvest clams, the harvester has been used also to collect quantitative information on sedentary benthic macrofauna. In these studies, it has been shown that the hydraulic escalator shellfish harvester can harvest clams more efficiently and with less breakage than a professional hand-digger. However, an escalator harvester requires a major capital investment. To meet operating costs and to make a profit, a harvester would need to either work in areas where shoft-shell clams are very abundant or else cover a large amount of the bottom, or both. This may be difficult to accomplish because of the natural high variability in population densities.

Since the harvester is, in principle, a dredge, it can alter the area in which it is operated--in some cases improving and in some cases degrading its character as a benthic habitat. The need for continuing studies to determine effects of the harvester is emphasized in this report.

Because of the significant cost and possible impact of the hydraulic escalator harvester, an alternative for harvesting bivalves is suggested and discussed. This alternative, a hydraulic clam rake designed to be operated by one person at low tide on an intertidal clam is described.

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