A LITERATURE REVIEW
of
THE ECOLOGICAL EFFECTS of HYDRAULIC ESCALATOR DREDGING

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EXECUTIVE SUMMARY

Since its introduction in the early 1950's, the hydraulic escalator dredge has been met with reactions ranging from vociferous opposition to healthy skepticism and cautious acceptance to enthusiastic embrace. As a result, a number of studies on the impact of this device have been conducted over the years in Maryland, where it was invented, as well as other regions. At the request of the Coastal Bays Fishery Advisory Committee, the Maryland Department of Natural Resources (MDNR) Shellfish Program undertook a literature review on the ecological effects of the hydraulic escalator dredge. In order to develop generalizations on the effects of disturbances to the ecosystem that can be applied to the coastal bays, the review was expanded to include not only the hydraulic escalator dredge but also other comparable fishing gear and natural disturbances of similar or larger scale. Because of the sheer volume of material on the subject of ecosystem disturbances, this review is by no means exhaustive. Nonetheless, these papers are a fair representation of this topic and are pertinent and applicable to the Maryland coastal bays.

The hydraulic escalator dredge is used to remove clams from the substrate. As the dredge moves along, hydraulic jets cut into the bottom, leaving behind a trench. The width of the cut generally conforms to the width of the dredge; in Maryland the water manifold across the leading edge of the dredge cannot exceed 36 in. The depth of the track is largely determined by the target species. Since hard clams live close to the surface of the substrate, a coastal bays hydraulic escalator dredge is typically set to cut 2.5 - 4 in. below the bay bottom, leaving behind a trench four to eight inches deep. Prop wash in shallow water can scour out deeper trenches. The tracks have been reported to persist anywhere from a few hours to three years, depending on the erosional characteristics of the site; the majority of the studies found that the tracks disappeared within one to two months. Because of the shallow nature of the Maryland coastal bays, wind events can readily disturb the bottom, resulting in short persistence times for dredge tracks. The primary exception is in vegetation beds, where trenches were noticeable for at least a year due to the energy dampening and sediment stabilizing effects of the seagrasses.

The amount of incidental sedimentation outside of the dredge track depends on the type of substrate being worked as well as currents and depth of cut. The maximum distance of detectable deposits resulting from hydraulic dredging was 75 ft. from independent studies in Maryland and Virginia. Another study in Maryland found negligible sedimentation at 15 ft. from a dredging site.

The silt/clay particles stirred up by the hydraulic dredge remain in suspension the longest, resulting in a turbidity plume. Hence, the total amount of suspended solids in the plume and its duration depends on substrate composition, while the distance and direction the plume travels is a function of water currents. The depth of the cut will also affect sediment loadings. In an extreme case, suspended solids measured at the conveyor belt of a dredge working in a silt/clay mud flat dropped by an order of magnitude within a distance of 200 ft., although a plume was still visible. Values at the dredge were about 30% higher than background silt loadings; at 200 ft. plume concentrations were well below maximum background levels. Other studies have shown that natural environmental factors such as wind and tidal-induced events can produce background particle loadings that equal or exceed levels resulting from dredging.

The winnowing of sediments by the dredge can leave the track with lower silt/clay content, depending on the initial sediment makeup. However, changes in sediment composition in the coastal bays due to clam dredging likely are insignificant compared to natural processes. This system is a high energy, erosion/deposition environment, resulting in the addition of both silt/clays and sand into the bays. Biological processes also play a factor, with previously sandy bottoms in seagrass beds accumulating a surface covering of fine particles and organic detritus. Thus, as seagrasses expand there is a net loss of surficial sand substrate.

The effect of hydraulic dredging on cultch (shell or other hard fragments that provide habitat for epibenthic organisms) depends on the environment and circumstances in which it occurs. A layer of displaced sediment can bury exposed cultch located immediately down current from dredging. Sediment type and currents influence the distance the cultch will be affected. On the other hand, the hydraulic escalator dredge can expose previously buried shell, leaving it accessible to epibenthic organisms.

Toxic contaminants in the sediment such as heavy metals and hydrocarbon compounds, if resuspended, can be concentrated by filter-feeding organisms. One study concluded that in areas of low initial concentrations, contaminant resuspension from hydraulic escalator dredging is not a problem. Aside from the relatively low contaminant levels in the Maryland coastal bays, there are other ameliorating factors concerning this issue. Clam dredging only superficially penetrates the substrate compared to activities such as channel dredging and sand borrows. Contaminant accumulation is unlikely to build up in clamming areas due to naturally occurring surficial sediment disturbances such as storms and bioturbation. In addition, since biological activity is lowest during the winter months when much of the clamming takes place, potential bioaccumulations of contaminants through filtration is minimal.

In contrast to a conventional dredge which forces its way into the bottom, the hydraulic escalator dredge uses jets of water to cut through the substrate, suspending animals and floating them onto the conveyor belt. As a result of this jetting action the majority of the catch is largely undamaged. Mortalities of the fragile softshell clam averaged 5% due to a hydraulic dredge, compared with a 50% mortality associated with hand digging. Juvenile clams were no more prone to incidental damage from the hydraulic dredge than the adults. Hard clams, because of their thick and heavy shell, are even less susceptible to breakage, with about one in 2,000 clams damaged by the hydraulic escalator dredge. One of the rationales for legalizing this gear in the coastal bays was that it would reduce incidental clam mortalities compared with the conventional dredges in use at the time. Both juvenile and adult hard clams have the ability to dig through the thin overburden of sediment cast by the dredge. Hydraulic dredging does not seem to have a negative impact on clam recruitment, but whether settlement and recruitment is enhanced by tilling the substrate with the hydraulic harvester is uncertain.

Predatory species such as crabs and fish may benefit from exposure of prey items by dredging. However, much of the clamming season occurs during the colder months when predators are either inactive or have left the area.

Benthic faunal communities in high disturbance areas such as coastal ecosystems readily recover and persist in the face of environmental perturbations, whether acute or chronic. Recovery of community parameters such as abundance, diversity, structure, and function is usually on the order of months, largely depending on the reproductive cycles of the constituent species. A study evaluating four years of intensive dredging within a confined (1 km^2) area found no effect on the functioning and production of the zoobenthic community, despite a decrease in overall biomass due to the harvesting of two comparatively large, slow growing target species.

The direct impact of dredging on seagrass beds is catastrophic, with plants completely uprooted in the process. Vegetative recolonization can be slow, on the order of two years or more. Repeated dredging within a bed can greatly restrict or completely inhibit recovery. Dredge tracks, which persist for longer periods in rooted vegetation, can be subjected to disturbances that may suppress seed germination, further delaying recovery.

The impact of turbidity plumes on seagrasses is less clear. The possibility of localized effects on the grass beds is reduced by a number of factors. Most of the seagrass beds are located adjacent to sandy areas that produce less of a plume due to fewer silt/clay particles; even plumes in siltier substrate can be expected to be largely dissipated within 100 meters. Wind, the primary agent of water movement in Chincoteague Bay, does not always direct the plumes towards the seagrass beds. In addition, during the course of a season clammers move around to different areas and are not necessarily in close proximity to the seagrass beds. Despite an increase in harvesting activity over the past few years, seagrass acreage in the Maryland coastal bays has more than tripled during this same period.

In summary, the ecological effects of hydraulic escalator dredging may be largely mitigated by the physical dynamics of the coastal bays ecosystem as well as the characteristics of the benthic faunal community that has developed under such conditions. Regulatory restrictions further reduce the impact of this activity through a closed season during the warmer months when biological processes such as feeding, respiration, growth, reproduction, and recruitment are at their peak and by prohibiting harvesting in vulnerable seagrass beds.

INTRODUCTION

Since its introduction in the early 1950's, the hydraulic escalator dredge has been met with reactions ranging from vociferous opposition to healthy skepticism and cautious acceptance to enthusiastic embrace. As a result, a number of studies on the impact of this device have been conducted over the years in Maryland, where it was invented, as well as other regions. The earliest studies investigated its effect on softshell clam and neighboring oyster populations, including physical alterations to the habitat. Later research attempted to take a more comprehensive approach, looking at various ecosystem components such the benthic faunal community and seagrasses.

At the request of the Coastal Bays Fishery Advisory Committee, in 2001 MDNR Shellfish Program staff undertook a literature review on the ecological effects of the hydraulic escalator dredge. In order to develop generalizations on the effects of disturbances to the ecosystem that can be applied to the coastal bays, the review was expanded to accommodate a wider range of impacts, including other comparable fishing gear and natural disturbances of similar or larger scale. Because of the sheer volume of material on the subject of ecosystem disturbances, this review is by no means exhaustive. Nonetheless, these papers are a fair representation of this topic and are pertinent and applicable to the Maryland coastal bays.

I. EFFECTS ON SUBSTRATE

Dredge Tracks

As the hydraulic dredge moves along, the hydraulic jets cut into the bottom, leaving behind a trench. The width of the cut generally conforms to the width of the dredge; in Maryland the water manifold across the leading edge of the dredge cannot exceed 36 in. (COMAR 08.02.02.03). The depth of the track is largely determined by the target species. Softshell clams in Chesapeake Bay live deep in the substrate; consequently dredges are set to cut between 18 in. and 24 in. below the surface of the bay floor (Glude, 1954). On the other hand, hardshell clams, with their shorter siphons and heavier shells, live close to the substrate surface. Typically, a coastal bays hydraulic escalator dredge is set to cut 2.5 - 4 in. below the bay bottom.

The trench is partially backfilled by heavier sediment particles coming almost immediately out of suspension as well as clumps of sediment deposited off the end of the escalator belt. The degree of backfilling is determined primarily by sediment characteristics. Fine sediments tend to remain in suspension longer and may be carried away from the track by currents. At the same time, sediments with high clay content tend to stay clumped so that they are redeposited off the belt. Although propeller wash can assist in filling in the trench (Glude, 1954), in very shallow water prop wash can actually scour out the backfill, deepening and widening the track (Manning, 1957; MacPhail, 1961; Godcharles, 1971). This can be remedied by use of a simple prop guard or shield (MacPail, 1961). The drawback is that it reduces boat speed by about 15%.

The length of time required for the dredge tracks to fill in is highly variable, depending on location as well as the original depth of the trench. Factors that affect track persistence include sediment type, depth, wind and tidal currents, vegetation, and whether an area is subtidal or intertidal.

Sandy bottoms appear to recover quickly, often on the order of days. Glude (1954), using the recently developed SCUBA, observed an area of coarse sand in the Miles R. (Maryland) that had been extensively clammed. The bottom appeared fairly uniform with wave produced ripples and an occasional depression 4 - 10 in. deep. Nowhere were deep furrows or holes found. He does not comment on how recently clamming activity had taken place in the area. In Virginia, Haven (1970), using a hard-clam hydraulic dredge on sandy bottom, observed trenches up to 4 - 6 in. deep; these filled in within one to two months. Godcharles (1971) found that sand in high energy areas recovered almost immediately (one day). Other sand trenches lasted one week with no evidence whatsoever after three months; they had firmed up over that period of time. Caddy (1973), citing another study, states that clamming tracks last several days; no details are provided. The track of a hydraulic dredge 4 ft. wide and 9 in. deep through silty sand was difficult to recognize after 24 hours (Meyer et al., 1981). Hall et al. (1990), using a suction dredge on sandy bottom at a depth of 7 m. (23 ft.), saw no evidence of dredging after 40 days, despite the initial presence of holes 3.5 m wide and 0.6 m deep (11.5 ft. by 2 ft.). The intervening period was characterized by stormy conditions that stirred the bottom. Eleftheriou and Robertson (1992), dragging a scallop dredge on sand in depths less than 10 m (33 ft.), observed that although furrows were evident initially (1.2 m/4 ft. wide by 0.04 m/1.5 in. deep), they were eliminated shortly after the four days of experimental dredging had ended. They concluded that track persistence depended on wave action and tidal condition; the experiment site was characterized as a high-energy embayment.

Dredge tracks persist longer in bottoms with lower potential for erosion. These include both fine, consolidated sediments and coarser grained substrates such as gravel, some intertidal flats, established vegetation beds, and probably most importantly, areas with low energy regimes including deeper regions removed from wave action.

Fine, consolidated sediments in low energy systems allow tracks to persist, as in the Lagoon of Venice, where tracks originally 9 ft. wide and 4 in. deep in a silt bottom were still evident two months later[1] (Pranovi & Giovanardi, 1994). The extent of recovery over this period

[1] These may also have been in *Zostera* beds (see paragraph below on vegetation beds).

was not described. In comparison, Manning (1957) found that tracks in a firm, muddy bottom had filled in from an average of 5 in. to an average of 3 in. deep four to six days after dredging. These were obliterated in a relatively short period of time (no specifics provided) but some of the tracks remained soft after four months. The difference is that a strong tidal current (up to 1 kn.) existed at the Manning study site. Tracks through coarse sediments such as gravel (1 cm diameter) can also persist for extended periods, particularly in low current environments, although no time estimate was provided (Caddy 1973).

Dredging in an intertidal setting may increase track persistence. Hydraulic escalator dredge tracks through an intertidal flat of compact mud in Maine were noticeable for up to one and a half years, while cuts in an intertidal silty-sand flat in Washington were observed for up to three years (Kyte & Chew, 1975). Kyte and Chew (1975) speculate that intertidal flats are more compact and stable than comparable subtidal habitats due to draining and drying when the tide is out, resulting in much more persistent cuts. However, they do not comment on the energy regimes of these study sites. In contrast, Beukema (1992) noted that dredge tracks through an intertidal sand flat in Holland comparable to those of a Maryland clam dredge were erased in a matter of days by tidal currents.

Established vegetation beds can stabilize the substrate and dampen the effect of waves and currents, allowing dredge tracks to remain longer. Godcharles (1971) observed evidence of trenching in submerged aquatic vegetation (*Thallassia*) from one to ten months. The most long-lived track he recorded, 11 months, was through a cover of *Caulerpa*[2], a macroalga that establishes persistent, non-transient beds by means of rhizomes that maintained the shape of the trench. This was also in shallow water where the prop wash scoured the bottom, so that some of the trenches were up to 18 in. deep. Although at most of Godcharles' sites the substrate within the trench hardened to pre-dredging consistency inside of a month, some spots in the vegetation beds remained soft for over 500 days.

Sedimentation

Immediately after suspension by the water jets of the dredge, the heaviest material such as pebbles, coarse sand, and shell fragments settle out, followed by progressively smaller particles from medium to fine and very fine sand, and finally the silts and clays. Thus the amount of incidental sedimentation outside of the dredge track depends on the type of substrate being worked as well as currents.

From an experiment in which an escalator dredge worked on a section of muddy creek

[2] *Thallasia* (turtlegrass) is replaced by *Zostera* (eelgrass) in more northern areas, including Maryland. *Caulerpa* or equivalent rhizomatous macroalgae species that establish stable beds are not found in the coastal bays; most of the species there are drift macroalgae or those attaching to structure, particularly seagrasses, and are usually transient.

bottom for nine hours, Manning (1957) estimated that sedimentation was not detectable beyond 75 ft. downstream of the dredged area. All dredging was done on ebb tide with currents approaching 1 kn. The boat ran aground several times, displacing additional sediments by prop wash. Intermediate distances down current of the dredged area had sediment deposits of about 1.2 in. at 25 ft. and 0.6 in. at 50 ft. Haven (1970), testing a hydraulic escalator dredge in Virginia, concurred that deposition of sediments is negligible 75 ft. down current from dredging. In comparison, Drobeck and Johnston (1982), repeating the Manning study but in sandy substrate, found sedimentation greatly reduced. Sediment accumulation was approximately 0.12 in. at 15 ft. down current of the dredging zone. In addition to the difference in substrate type, Manning's Cox Creek site was considerably more narrow and shallow than the later experimental site in the Patuxent River, which had maximum currents of 0.27 kn.

Black and Parry (1999) are in agreement with the above studies. A 10 ft. wide scallop dredge towed at 6 kn. over fine sand and muddy fine sand bottoms deposited 2 mm (0.08 in.) of sediment within a few meters of the dredge; at 20 m (66 ft.) deposition was negligible (0.1 mm/0.004 in.).

Turbidity Plumes

The silt/clay particles stirred up by the hydraulic dredge remain in suspension the longest, resulting in a transient turbidity plume. Thus, the total amount of suspended solids in the plume and its duration depends on substrate composition, while the distance and direction the plume travels is a function of water currents. The depth of the cut, hence the volume of displaced sediments, will also affect the concentration of suspended particles.

Values as high as 584 mg/l of suspended solids were recorded at the conveyor belt of a dredge working in a silt/clay mud flat (Kyte & Chew, 1975). This value rapidly dropped to 89 mg/l at a distance of 61 m (200 ft.) from the dredge, although a plume was still visible. Background silt loadings at the site varied from 4 to 441 mg/l.

Using a 10 ft. wide scallop dredge, Black and Parry (1999) conducted a detailed analysis of plume dynamics. They found particle concentrations in a sediment plume to be 2-3 orders of magnitude higher (2000 - 5000 mg/l) than background levels in the first 20 sec. after dredging. This quickly dropped so that after 9 min. suspended sediment concentrations were equivalent to values during a large storm, and after 30 min. sediment loadings had dropped 98%, bringing them back to natural background levels. After one hour particle concentrations were extremely low (10 mg/l or 0.2% of initial values); by this time the plume had moved 350 m. Plume sediments beyond 50 m of the dredge were entirely silts and clays. These values were for a muddy sand (30% mud) bottom; plumes in sandier areas dropped out more rapidly. The authors concluded that low concentrations of suspended fine grain particles (silt and clay) might be present for several hours but that suspended sediment concentrations more than 100 m (328 ft) from a dredge are insignificant and would not induce far-field effects.

Ruffin (1995) studied the effects of softshell clam dredging on turbidity in the Chester River, Maryland. Although there are key differences between this system and the coastal bays in geomorphology, hydrodynamics, energy input, substrate composition, and clamming methodology (e.g. dredging depth), this is the only study to have looked at the plumes resulting from this activity in terms of light attenuation and persistence. The greatest increase in turbidity was found in shallow water with fine-grained sediments. The plumes dissipated rapidly at first as the larger particles settled out. Estimates of time to return to background levels were much higher than those of Black and Parry (1999), averaging 2.9 hours for turbidity and 4.8 hours for light attenuation; generally, their values approached background levels much sooner than these averages (i.e. plume dissipation was exponential rather than linear, except in the shallowest areas). Eulerian (fixed location) time-series in shallow water were even longer, taking up to 22 hours for the light attenuation coefficient to return to background levels. Plumes in shallows persisted longer than in deeper areas. Based on aerial photos, the plume area was extremely variable among boats and river systems, averaging 8 ha/boat in the Chester River and 4.5 ha/boat in the Wye River.

Natural environmental factors can produce background particle loadings that equal or exceed levels resulting from dredging. A study in Washington found values of 32 to 54 mg/l in the vicinity of a hydraulic escalator dredge, while a nearby river mouth produced levels of 39 to 63 mg/l (Kyte & Chew, 1975). Light transmission varied from 4 to 80 percent at the dredge and 2 to 65 percent at the river mouth. The investigators concluded that the effects of the clam harvester on water quality were minor compared to the river. Drobeck and Johnston (1982) arrived at a similar conclusion, stating that wind and tidal-induced events may have a more profound effect on the total suspended sediment load at their experiment site in the Patuxent River than does dredging. Control values ranged from 51 to 101 mg/l in the three days before the dredging experiment; average levels for these control days were 89.7 mg/l, 81.0 mg/l, and 68.15 mg/l. The mid-impact zone immediately prior to dredging had levels between 37 and 75 mg/l, averaging 55.2 mg/l, while during dredging these ranged between 37.5 and 112 mg/l with an average of 64.4 mg/l. Bioturbation, the reworking of sediment by benthic fauna, can also elevate turbidity, with values as high as 35 mg/l within 3 m of the bottom reported by Rhoads (1973).

Bottom Composition

The winnowing of sediments by the dredge can leave the track with a lower silt/clay content, depending on the initial sediment makeup. In relatively homogenous, muddy sediments there was no detectable difference in sediment composition after dredging (Kyte & Chew, 1975). Sandier areas showed varying degrees of change and recovery, depending on the heterogeneity of the substrate and the energy regime of the area. Immediately after dredging, Haven (1970) reported a decline of fines in a predominantly sand bottom; no change in bottom composition was detected beyond 75 ft. Recovery time was not investigated. Godcharles (1971) found that two of six stations showed measurable losses of silt/clay particles after dredging. One station recovered to pre-dredging proportions but the changes persisted at the second station over a one-year monitoring period. Pfitzenmeyer (1972) did not observe a loss of fines from a low silt/clay content bottom in Chesapeake Bay. Also, organic carbon content was not significantly different after dredging. Working in a high-energy area with a predominantly sand bottom, Eleftheriou and Robertson (1992) found no change in sediment grades or organic carbon content after a scallop dredge had been dragged through the same track up to 25 times. In Washington, reduced levels of silt/clay particles and organic carbon persisted for several months (Kyte & Chew 1975). Details such as degree of change and length of time were not provided.

In certain situations, long-term intensive harvesting may result in a shift in bottom composition. In the Lagoon of Venice, a "moderate/low energy" ecosystem in Italy, clamming is concentrated in a relatively confined portion of the lagoon (~18 km^2 /7 mi^2) using large (9 ft. wide) hydraulic dredges (Pranovi & Giovanardi, 1994). Despite the fact that law prohibited it, this activity had markedly increased in the five to ten years prior to this study. Experimental dredging did not significantly affect particle size immediately before and after the treatment, both in clamming areas and non-clamming areas. However, the results of a sediment study conducted in the clamming areas a few years before clamming intensified showed a significant shift to sandier substrate over the intervening period. No such change had occurred in the non-clamming area.

Rice et al. (1989), found a slight but statistically higher amounts of very fine sand, silt, and clay in non-clamming areas when compared to clamming areas in Rhode Island, but there was no difference in the total organic carbon between the two sites. The non-clamming areas had been closed since the 1930's. The authors noted that clamming activity, using tongs and bullrakes, stirs up the sediments.

Changes in sediment composition in the coastal bays due to clam dredging likely are insignificant compared to natural processes. This system is a high energy, erosion/deposition environment, resulting in the addition of both silt/clays and sand into the bays (Bartburger & Biggs, 1970; Boynton & Nagy, 1993). Biological processes also play a factor, with previously sandy bottoms in seagrass beds accumulating a surface covering of fine particles and detritus sometimes ankle deep (pers. observ.). Thus, as seagrasses expand there is a net loss of sandy surficial substrate.

Cultch

The effect of hydraulic dredging on cultch (shell or other hard fragments that provide habitat for epibenthic organisms) depends on the environment and circumstances in which it occurs. Exposed cultch located immediately down current from dredging can be buried by a layer of displaced sediment (Manning, 1957; Drobeck & Johnston, 1982). Sediment type and currents influence the distance the cultch will be affected.

On the other hand, the hydraulic escalator dredge can retrieve previously buried shell, leaving it accessible to organisms. The Canadian Department of Fisheries demonstrated the dredge's ability to clean oyster bars (MacPhail, 1961). As a result of escalator dredging, Haven (1970) reported surface shell covering 20% of what had been bare sand bottom. Godcharles (1971) noted that buried shell had been dredged up and redeposited in and alongside the dredge track, leaving it exposed on the bottom. Athough Drobeck and Johnston (1982) observed oyster shell on the escalator belt, there was no evidence of this shell at the substrate surface; only softshell clam shells were seen. Presumably the heavier oyster shell had been reburied in the deeper track of the softshell clam dredge. Apparently, cultch skimmed with a shallow dredge setting from a thick shell base would be less likely to get reburied because there is no sediment involved save what had been on the shells. A hydraulic escalator dredge recently was used to clean relict oyster bars in the seaside bays of Virginia (J. Wesson, VMRC, pers. com.).

Chincoteague Bay has relatively little in the way of exposed cultch. Most of the old oyster bars have long been buried to varying degrees through natural sedimentation (Sieling, 1960; Tarnowski, 1997). A study was conducted to retrieve this buried shell on three former oyster bars with different substrate characteristics using a hydraulic escalator dredge (Tarnowski & Homer, 2003). Buried shell was recovered to varying degrees depending on bottom type, the amount of buried shell accessible to the dredge, and the intensity of the effort. Dredging on the sandy and solid shell substrate sites increased the amount of surface shell by 700%, while the muddy substrate site had a 32% increase in surface shell.

Substrate Contaminants

Toxic contaminants in the sediment such as heavy metals and hydrocarbon compounds, if resuspended, can be concentrated by filter-feeding organisms. After conducting an elemental analysis of the silt/clay fraction at their experiment site, Drobeck and Johnston (1982) concluded that in areas of low initial concentrations contaminant resupension is not a problem as the fine particles are diluted in distribution.

The Maryland coastal bays have generally low levels of substrate contaminants (EPA 1996). Of the 45 compounds and elements tested, none exceeded effects-range medium (ER-M) values in the bays proper, using the stringent Long and Morgan thresholds[3]. It should be noted

[3]The U.S. EPA (1996) used these particular thresholds because values were available for most of the contaminants tested. According to their report, this method is more conservative than other means of determining contaminant thresholds, such as the EPA Sediment Quality Criteria. When applied to this study, the standard EPA criteria and other alternative approaches reduced the apparent number and geographic extent of exceedences.

that only one sample each was taken in Assawoman and Sinepuxent Bays (exclusive of the dead-end canals), while four samples were obtained from Chincoteague Bay. Effects-range low (ER-L) values were barely exceeded for at most three contaminants at these sites. These were nickel, arsenic, and DDT as shown in Table 1a for the "remaining Maryland" sites (specific sites were not characterized in the report; values were lumped into either artificial lagoons, St. Martin River or remaining Maryland). Three other compounds listed by the MCBP (1997) report as potential problems in the combined Delaware-Maryland coastal bays system were below thresholds in the Maryland bays proper (Table 1b), as were the remaining contaminants tested for by the EPA (1996). In contrast, more contaminants were found with higher concentrations in the dead-end canals due to their poor flushing characteristics and proximity to sources.

Aside from the relatively low contaminant levels in the Maryland coastal bays, there are other amelioratory factors concerning this issue. Contaminant accumulation is unlikely to build up in clamming areas due to naturally occurring surficial sediment disturbances such as storms and bioturbation (Rhoads, 1973; Kraeuter & Fegley, 1994). Furthermore, clam dredging only superficially penetrates the substrate compared to activities such as channel dredging and sand borrows. In addition, since biological activity is lowest during the winter months when much of the clamming takes place, potential bioaccumulations of contaminants through filtration is minimal.

II. BIOLOGICAL EFFECTS

Clams

Market Clams

A towed, non-hydraulic dredge captures the targeted species by mechanically forcing its way through the bottom; towed Shinnecock or bull rakes function in a similar fashion. In comparison, the hydraulic dredge use jets of water to cut through the substrate; the leading edge or knife of the dredge collects the objects suspended by the jets but generally is not forced through the bottom. Also, the conveyor system helps reduce incidental damage. A non-conveyor dredge, as it begins to fill, drops in efficiency so that animals are cast aside rather than gathered into the dredge (Meyer et al. 1981). Those animals are often left damaged or exposed to predators. In addition, more fragile species can be crushed as the dredge travels along the bottom accumulating its catch; some dredges can collect hundreds or even thousands of pounds of shellfish. The conveyor belt of the hydraulic escalator dredge prevents the catch from accumulating by continuously moving animals and debris away from the head of the dredge, keeping them spread out and reducing the possibility of them being damaged.

The hydraulic escalator dredge was developed in Maryland originally to harvest subtidal populations of softshell clams (*Mya arenaria*), which as the common name implies have thin, fragile shells. As a result, most of the early research concerning impacts from this device focused on softshell clams as well as neighboring oyster bars.

In New England and eastern Canada, digging softshell clams manually results in non-catch mortalities of about 50%, contributing to the decline of the populations in these areas during the 1950's (MacPhail, 1961; Kyte & Chew, 1975). In contrast, softshell clam mortalities due to the hydraulic escalator dredge averaged about 5% with 10% as an extreme (Medcof 1961). Kyte and Chew (1975) offer a slightly higher average of 9.6%, which they attributed to operator inexperience and the extremely compact nature of the substrate. Incidental mortalities of clams left in the bottom were almost non-existent since the harvester is over 95% efficient (MacPhail 1961).

Hard clams, because of their thick and heavy shell, are even less prone to breakage. In Virginia, Austin and Haven (1981) found about one in 2,000 clams were damaged by the hydraulic escalator dredge. One of the rationales for legalizing this gear in the coastal bays was that it would reduce incidental mortalities compared with the conventional dredges in use at the time (Md. Bd. Nat. Res., 1967).

Juvenile Clams

The effect of the hydraulic escalator dredge on juvenile softshell clams has been systematically studied (Medcof, 1961; Haven, 1970; Pfitzenmeyer, 1972; Kyte & Chew, 1975). As with adults, mortalities attributable to this gear are slight. Small clams either slip through the belt or are carried off the end of it; most of the clams are redeposited back in the track or immediately adjacent to it (Medcof, 1961). The juveniles can readily reburrow because of the softened sediment in the track (Medcof, 1961; Pfitzenmeyer & Drobeck, 1967). However, redigging times are variable and in the interim the small clams are vulnerable to predation. Kyte and Chew (1975) suggest that mortalities of softshell clams in Maine were probably higher than the breakage rate due to the inability of the clams to reburrow into the hard, compact sediments of an intertidal flat, leaving them as prey to gulls. Highly motile predators such as crabs and fish have been observed moving into dredge tracks within an hour of dredging (Caddy, 1973). Hard clam juveniles, possessing stout shells that they can close tightly, are less vulnerable than softshell clams of comparable size, which have thin shells that gape. Nevertheless, predation of redeposited hard clam juveniles can possibly be a problem during the warmer months. As temperatures cool predation drops off; predators are either inactive or leave the area during the colder months when most clamming takes place. Blue crabs, one of the most important predators of hard clams, stop feeding when water temperatures drop below 10☜C (Van Heukelem, 1991). In Maryland, Drobeck and Johnston (1982) did not consider predation to be a serious factor by mid-October. Haven (1970) states that predators become active around the beginning of May in Virginia.

Hard clams, both juveniles and adults, have the ability to dig through the thin overburden of sediment cast by the dredge, since they can escape burial in 10 - 85 cm of native sediment (Kranz, 1974; Maurer et al., 1980). Young clams can dig out of sediment depths at least five times their shell height (approximately seven times their length) (Stanley & DeWitt, 1983). Burrowing takes place even at winter temperatures and burial survival is enhanced during this period (Maurer et al. 1980).

Suspended sediments can reduce filtration and growth in hard clams (Roegner & Mann, 1992). Sediment plumes from dredging are ephemeral, however, quickly subsiding after operations cease for the day (Black & Parry 1999), particularly in the sandy substrate where clams are more abundant and where harvesters would more likely be working (Wells, 1957; Drobeck et al., 1970). The eggs and larvae of hard clams are sensitive to high levels of suspended sediments, but these stages occur when the clamming season is closed (Stanley & DeWitt, 1982; Roegner & Mann, 1992).

Settlement and Recruitment

Hydraulic dredging does not seem to have a negative impact on clam recruitment. In Maryland, softshell clam harvest areas consistently produced clams on annual to triennial cycles (Manning, 1957; MacPhail, 1961). Despite being confined to a relatively small area, the Venetian Lagoon clamming fishery continued and expanded in intensity over a period of years (Pranovi & Giovanardi, 1994), suggesting continued recruitment in this region.

Whether settlement and recruitment is enhanced by tilling the substrate with the hydraulic harvester is unclear. Beginning in the early 1900's, bottom cultivation was carried on in Massachusetts to enhance bivalve settlement (Rice et al. 1989). Neither Haven (1970) in Virginia nor Pfitzenmeyer (1972) in Maryland found increased settlement of softshell clams as a result of hydraulic dredging. Pfitzenmeyer did find enhanced survival and recruitment of juveniles in dredged areas, but Haven found no differences between worked and unworked areas. Ten months after dredging in a Maine intertidal flat, softshell clam populations within the dredge tracks had increased several-fold over pre-dredging levels (Kyte & Chew, 1975). In a study of Rhode Island hard clam populations, settlement and recruitment in a clamming area occurred at a significantly higher rate than in areas closed to clamming (Rice et al. 1989). The investigators suggest that the higher clam densities in the closed areas (190 clams/m^2) may have inhibited settlement; alternatively, the reduction of the silt/clay fraction in the sediment due to clamming activity may enhance setting rates, since hard clams prefer sandier substrates. On the other hand, low and irregular settlement is characteristics of hard clam populations in Georgia regardless if the area is harvested or not (Walker, 1987).

Other Benthic Fauna

Potential Impacts

The potential effects of the hydraulic harvesters on the benthic fauna are essentially the same as for clams. No systematic studies have been found that evaluate the direct mechanical effect of this type of dredge on incidental species. Anecdotally, because of the way it works the hydraulic escalator dredge would appear to do little damage to the bycatch, including such soft bodied animals as polychaetes and nemertean worms (Manning, 1959; Godcharles, 1970), although some percentage of the smaller, more delicate forms may get caught in the machinery (pers. observ.). Drobeck and Johnston (1982) surmised that the majority of the small animals washed through the dredge unharmed. It has even been suggested using this gear as a collection device for benthic fauna, providing the receptacle for the animals contained water to cushion the fall off the end of the belt (Manning, 1959; Godcharles, 1970). In contrast, gears that are forced into the bottom, such as scallop dredges, can kill or damage epifaunal and large infaunal organisms, sometimes in large numbers (Caddy, 1973; Eleftheriou & Robertson, 1992).

This is not to say that benthic populations are unaffected within and immediately adjacent to the dredge tracks, but to what degree is uncertain. An experiment in Maine found temporary declines in the infauna that quickly recovered, although no details were provided (Kyte & Chew, 1975). Animals can be displaced from the trench by the hydraulic jets or removed and redeposited outside of it by the conveyor. Some of these are probably lost to predation or damaged by the dredge. The relative importance of each possible fate is undetermined, although predation declines during the colder months (see above). No lasting effects of hydraulic escalator dredging on the benthic community have been observed (see *Response to Disturbance* section).

Regarding sedimentation, presumably most of the infaunal species can dig their way out of the light sediment covering (McCauley et al. 1977; Maurer et al., 1980; Beukema, 1995). However, filtering may be temporarily disrupted. Godcharles (1971) found no evidence of mass mortalities due to sedimentation from dredging. Motile epifauna should not be affected by sedimentation, but non-motile species could be buried. Dredging-related oyster mortalities due to smothering were 100% at a distance of up to 25 ft. for adults and 75 ft. for spat (Manning, 1957; Drobeck & Johnston, 1982)[4]. Sponges are one of the most conspicuous sessile epifaunal forms in Chincoteague Bay that could be impacted by sedimentation; however, these generally occur in the seagrass meadows. Much of other sessile epifauna are associated with hard substrate which would not be affected by clamming (e.g. riprap, pilings, etc.), except perhaps on some of the remnant oyster shell bars.

Predators such as crabs and fish are undoubtedly sources of mortality to animals returned

[4] No subtidal oyster populations currently exist in the coastal bays (Tarnowski, 1997).

to the bottom. Manning (1957) reported crabs and several fish species attracted to areas of active dredging, but specifics were not given. Caddy (1973) directly observed predators, especially winter flounder but also sculpin and rock crabs, attracted to scallop dredge tracks within one hour of dredging at densities up to 30 times those outside the tracks. Similarly, Eleftheriou and Robertson (1992) noted congregations of fish (primarily pleuronectids, gadoids, and gobies) feeding in scallop dredge tracks, as well as seastars and a large variety of crustaceans. Meyer et al. (1981) categorized two types of predators of surf clams exposed by a hydraulic dredge: scavengers such as lady crabs, rock crabs, and spot feeding on damaged clams and those that preyed on undamaged clams, including seastars, horseshoe crabs, and moon snails. Caddy (1973) estimated that the large-scale scallop fishery on Georges Bank could have substantially benefited bottom foraging fish populations.

Concern has been expressed about the possible impact of hydraulic escalator dredging on overwintering blue crab populations in the coastal bays. It is generally believed that crabs remain buried and inactive during the winter, which might leave them vulnerable to smothering from dredging. The literature reviews on blue crabs make no mention of this issue, probably because adult crabs in the Chesapeake Bay overwinter in waters deeper than the operating limit of hydraulic escalator dredges. One study found that locomotor activity in juvenile blue crabs ceased when water temperatures dropped to 5.5°C (Van Heukelem, 1991). However, another study has shown that at low temperatures crabs are still capable of some activity and mentioned that Truitt found overwintering females moving about in schools in the lower Chesapeake (Van Heukelem, 1991).

Response to Disturbance

The primary question concerning the benthic community is how it responds to disturbance. Few studies have been directed toward evaluating the effect of the Maryland hydraulic escalator dredge on the benthic faunal community. In Florida, Godcharles (1971) discovered no lasting impacts on the benthic populations. Using three gear types (benthic corer, trynet trawl, hydraulic escalator dredge) to sample both infauna and epifauna from 5,200 ft.^{2} plots, all but one vegetation station (from benthic core samples) showed little difference between control and experimental dredging sites. Based on the benthic core data, it appeared that recovery was slowest in some of the vegetated areas, which were completely stripped of plants by the dredge. No faunal differences between control and experimental plots, including the vegetated stations, were evident at any time in the trynet samples, which captured mostly the larger epibenthic species. Because stations had varying intervals between the experimental dredging and the final evaluation sampling with the benthic corer, the time course of infaunal recovery is unclear, with a maximum of thirteen months possible. The only definitive estimate was given as within eight months at one station. Similar results were observed in South Carolina, although no details were provided (Kyte & Chew, 1975). A study in Maine found temporary declines initially but full recovery within ten months (Kyte & Chew, 1975). Closer to the coastal bays, a study in the Patuxent River, Maryland reported rapid reestablishment of the benthic infauna, with no significant differences between the dredged and impact zones and the control area within five months of experimental dredging (Drobeck & Johnston, 1982). The general conclusion of these studies was that the benthic infaunal community was capable of recovery in a relatively short period of time.

Because of the limited number of studies involving the hydraulic escalator dredge, the present review was expanded to include the impacts of comparable gears, as well as larger scale natural and anthropogenic disturbances (Tables 2, 3). A variety of coastal habitats from around the world were included. Surrogates were sought which produce similar or greater disruptions to the benthos, including larger hydraulic (non-escalator) dredges, suction dredges, clam "kicking", scallop dredges, oyster shell dredges, channel dredging, dredge spoil dumping, pollution, and natural perturbations. The scale of the impacts ranged from experimental plots to a square mile dredge spoil site to entire estuaries (Table 2). The common thread of these studies is that they attempted to measure the response of the benthic faunal community to disturbance.

With few exceptions recovery was rapid, in most cases on the order of months (Table 3). This resiliency of the benthos is characteristic of shallow-water coastal and estuarine systems, which are subjected to continual disturbances (Turner et al., 1995). Studies with multiple locations showed that recovery times could vary due to differences in habitat (Godcharles, 1971; Kyte & Chew 1975; Pranovi and Giovanardi,1994; Thrush et al. 1995), community (Kyte & Chew 1975; Beukema, 1995; Thrush et al. 1995), and time of year (Hall & Harding, 1997).

Recovery time was largely tied to the reproductive cycle of the constituent species. Disturbances that disrupt this cycle (elimination of spawners and/or offspring, inhibition of gametogenesis, interference with settlement, etc.) can delay re-establishment until the next spawning period. One community took 11-13 months to recover from a red tide outbreak occurring during the height of the reproductive season (Simon & Dauer, 1977). In temperate climates, the majority of the species reproduce during the warmer months. These usually have planktonic larvae that can travel some distance to recolonize areas. Some repopulation also takes place through active migration and passive transport of post-metamorphosed juveniles and adults from outside the disturbed area, as well as through the re-establishment of animals originally displaced within the affected zone.

In Chincoteague Bay, a study to recover buried shell with a hydraulic escalator dredge found that the habitat provided by the excavated shell was rapidly colonized by epibenthic fauna (Tarnowski & Homer, 2003). Between June and September (the interval between sampling dates), at least ten types of attached organisms, primarily tube-building serpulid worms, as well as numerous motile individuals such as amphipods, became established on the reclaimed shell.

During the recovery process, a successional pattern has been observed (Thistle, 1981). Community parameters, including total numbers of individuals and species, rebound quickest, often exceeding levels in comparable control locations. These species may be characterized as "opportunistic" species that are adapted to rapidly exploiting disturbed habitat. During the course of succession, the opportunists are then replaced by more established species of the community, leading to the re-establishment of species structure and hierarchy. Biomass is the parameter slowest to recover, since it is dependent on the growth rates of newly settled individuals or the immigration of adults into the disturbed zone. Small-scale (subsystem) disturbances create a spatial and temporal mosaic of successional states, allowing certain species to persist in a community where they were competitively inferior (McCall, 1977; Thistle, 1981). This results in an increase in diversity within the community.

The few studies where recovery was incomplete can be divided into two classes. The first of these includes those where studies were conducted for a relatively short time period. Pranovi and Giovanardi (1994) looked at the impact of hydraulic dredging in commercial clamming and non-clamming areas of the Venice Lagoon in Italy over a two month period. By the end of this interval, the benthic community in the clamming area had essentially recovered save for biomass[5], which is consistent with the successional process given the brief time period that had elapsed. Within the non-clamming area, no statistical differences were detected immediately after dredging. However, after two months several community parameters (number of individuals, number of species, biomass) within the experimental plot had fallen significantly below levels in the control plot, although diversity indices were similar. The authors partly attributed these results to macroalgae (*Ulva*) accumulation in some segments of the dredge track of the non-clamming station. This station was within a seagrass bed, a habitat where tracks persist longer and macroalgae tends to accumulate, which could explain why the clamming station was not similarly affected. The actual interval for recovery at the non-clamming station is unknown since the study ended after two months.

Thrush et al. (1995), using a scallop dredge, also found differences in recovery between two sites, with neither location fully restored after three months (the length of the study). These were believed to be related to differences in initial community composition and environmental characteristics. Hall and Harding (1997), investigating the effects of two types of suction dredges, considered recovery essentially complete after 56 days despite some small but statistically significant differences. Also, recovery processes varied between the two gears, which they felt was probably due to the different times of year the experiments were conducted

[5] Biomass was measured as wet weight, including shells.

(the location was the same). They concluded that recovery was rapid and the overall effect on the infaunal community was low.

The second class of impact studies involved large-scale, tributary/ecosystem-wide disruptions where recovery was incomplete after two years. Dean and Haskin (1964) followed the recovery of an entire estuary from decades of pollution after a massive abatement project was completed. This study extended from the mouth of the Raritan River to its freshwater reaches, a distance of 20 km. The abatement resulted in rapid recolonization within six months. After 2.5 years the distribution of species number and abundance from freshwater through brackish to estuarine conditions returned to a classic V-curve, suggesting re-establishment of the benthic community in terms of these parameters. However, interannual variations in species composition and structure might have been an indication that the community had not yet stabilized, although this could be the result of natural variability in these populations. The extent of the impact precluded establishing proper reference stations for comparison. Boesch et al. (1976) studied the effects of Tropical Storm Agnes on the benthos of several Virginia estuaries. At a 10 m deep mud site in the lower York River, salinity stratification due to the storm resulted in intermittent hypoxic conditions for over a month, devastating the benthic community. The community had not returned to pre-Agnes conditions after two years, although this may have also been affected by unusual environmental conditions during this period. In contrast, a nearby 3 m deep station was impacted for a much shorter time period by fresh water (but not hypoxia) and was largely recovered after five months.

Although most of the studies concluded that the disturbances caused no long-term effects on the benthic faunal community, two papers expressed reservations. Both were concerned with the effects of chronic fishing disturbance on benthic habitat. Pranovi and Giovanardi (1994) showed a significant change of bottom composition in areas of the Venetian Lagoon that had been intensively dredged for a number of years. They felt that the shift to sandier substrate would modify the community to the detriment of species associated with finer particles, which is generally found in the remainder of the lagoon. Unfortunately, although control sites existed for both fished and unfished areas, the respective community structures were not statistically compared. The potential impact of dredging on seagrass colonization in the dredging areas was also discussed, as seagrasses were common around the clamming grounds (for further discussion on seagrass impacts see *Submerged Aquatic Vegetation* section below). The authors’ objection to dredging essentially was that dredging might result in a habitat distinctly different from its surrounding environment. In contrast, Thrush et al. (1995) were concerned about the homogenization of bottom characteristics due to long-term, large-scale scallop dredging. They argued that habitat heterogeneity is important to the diversity, stability, and functioning of ecosystems. The authors also commented on the possible impact to community structure by removing larger, longer-lived sedentary species. Their conclusions were more cautionary than dire, suggesting ways to better predict potential large-scale impacts.

Most of the studies in Table 2 looked at the effects of one time, acute perturbations. Beukema (1995) had an opportunity to investigate a chronic, intensive disturbance over an extended time period when a lugworm (*Arenicola marina*) dredge began harvesting at one of his long-term benthic monitoring sites in the Dutch Wadden Sea. This activity continued for four years within a 1 km^2 sandy intertidal area. The dredge created tracks similar to a Maryland hydraulic escalator dredge, and in fact softshell clams (*Mya arenaria*) were a secondary target species for harvest. At the end of the four-year dredging period total biomass had declined. This was to be expected since the two target species accounted for almost 80% of the biomass. In addition to removal through harvesting, many of the non-harvested softshell clams were subjected predation and breakage by the dredge. Because *Arenicola* and *Mya* are slower growing, long-lived species, biomass recovery took about five years. With one exception, the remaining non-target species showed no negative effects from dredging. One polychaete worm species was adversely impacted but rapidly recovered after dredging ceased. On the other hand, the population of a small clam species, *Macoma balthica*, an important constituent of the biomass, was enhanced during the dredging period. The author concluded that even though the benthic community biomass structure took an extended period to recover, “the functioning of the community appeared to be hardly affected”. This is because the biomass decline was primarily confined to the removal of a relatively low number of larger animals with low production:biomass ratios, whereas the remaining species were responsible for the bulk of benthic faunal production.

Submerged Aquatic Vegetation

One of the primary concerns regarding the hydraulic escalator dredge is its impact on seagrass beds. Maryland law currently prohibits this gear in designated submerged aquatic vegetation areas (§4-1006.1).

Direct Impacts

The direct impact of dredging in seagrasses is catastrophic. Dredging uproots plants, leaving behind trenches that may persist for lengthy periods of time (Godcharles, 1971; Peterson et al., 1987). Recovery by vegetative propagation is slow, on the order of two years or more (Godcharles, 1971; Peterson et al., 1987). Restoration is facilitated by natural reseeding, but may be limited by disturbances within the track. The cuts may trap drift macroalgae (Pranovi & Giovanardi, 1994) that commonly accumulate in seagrass beds, possibly suppressing seed germination. Also, stingrays utilize the open spaces through the seagrass beds created by the dredge and can be very disruptive to the bottom by digging pits (J. Orth, VIMS, pers. com.). Repeated harvesting within a vegetation bed can greatly restrict or completely inhibit recovery

(Manning, 1957).

Burial also adversely affects seagrasses, suppressing the ability of the leaves to function and diminishing the plant's activities. The shoots and leaves of some SAV species can become buried by just a few centimeters of sediment (Stephan et al. 2000). In sand substrates, measurable quantities of displaced sediment can be expected at least within 15 ft. of the dredge[6] (Drobeck & Johnston, 1982). The seagrass area closure largely mitigates this concern, except perhaps for plants within the sedimentation zone if boats are working along the closure boundary.

Indirect Impacts

The indirect effects of hydraulic escalator dredging, specifically turbidity plumes, on seagrasses are less clear. Ruffin (1995) states that light attenuation was great enough to potentially inhibit the growth of redhead grass (based on inference rather than direct observation) in the shallower portions of the Chester River where the proportion silts and clays was higher, depending on how often the plants were shaded. Shading was a function of winds, tide, bottom type, and the location of the clam boats, all of which were variable. Since this study was essentially a "snap-shot" on a daily time frame, the author suggested that long-term research on this issue was needed. In contrast, Black & Parry (1999) concluded that for sand substrates, suspended particles drop out over relatively short distances, with far-field effects on seagrasses unlikely beyond 100 m of the dredge.

The possibility of localized plume effects on the Maryland coastal seagrass beds is reduced by a number of factors. Since most of the seagrass meadows in the coastal bays are located adjacent to sandy areas (Bartberger & Biggs, 1970; Orth et al., 1993) that produce less of a plume due to fewer silt/clay particles, the effect of plumes would be expected to be less in the coastal bays than in the muddier tributaries of the Chesapeake. Also, the hard clam dredge displaces about one-fourth of the sediment than the deeper cutting softshell clam dredge. Wind, the primary agent of water movement in Chincoteague Bay, may not always direct the plumes towards the seagrass beds. Seasonal wind patterns tend to blow from the cooler ocean to the warmer land during the spring and summer, keeping the plumes away from the majority of the beds, which are located along Assateague Island[7]. In addition, during the course of a season clamming activities shift around to different areas and are not necessarily in close proximity to the seagrass beds.

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[6] Drobeck and Johnston (1982) measured displaced sediment accumulations of 0.3 cm at 15 ft.

[7] For the year 2000, daily average wind directions at the Assateague I. weather station (National Park Service, unpub. data) were calculated for 12 hr. periods corresponding with clamming activity. The longitudinal axis of Chincoteague Bay was taken to run 34☜/214☜T. Winds blowing from east of or along this line (from 34☜ up to 214☜T) were assumed to be keeping turbidity plumes away from the major seagrass beds. During March-May and September (2nd half) winds blew from east of this axis 68% of the days, shifting to 48% in October and 27% in November.

III. THE COASTAL BAYS ECOSYSTEM

Although all of the aforementioned studies were conducted outside of the Maryland coastal bays, they or at least portions of them are pertinent and applicable to the situation in this region. Three factors are of importance in assessing the potential impact of the hydraulic escalator dredge on the coastal bays ecosystem: the physical environment, the characteristics of the benthic faunal community that has developed in this environment, and the nature of the fishery.

Physical Environment

The coastal bays ecosystem is a physically dynamic environment (Truitt, 1968; Bartberger & Biggs, 1970). Although tidal currents can be strong in the vicinity of the inlets, wind is the main agent of disturbance in this system. Sustained winds of 20 mph or greater were recorded on 33 days during the year 2000 at the Assateague Island weather station; gusts of 20 mph or greater occurred on 236 days (NPS, unpub. data). McCall (1977) found that a 25 kn. wind in Long Island Sound was capable of disturbing the sea floor as deep as 66 ft. Depths in the coastal bays average 4 ft. and seldom exceed 8 ft. Winds capable of disturbing the bottom vary in intensity and duration from summer afternoon on-shore breezes and squalls to three days of hard westerlies and winter nor'easters up to the occasional hurricane (Truitt, 1968). Waves pound along the western shore, eroding away the banks, while storm overwashes and Aeolian transport deposit fine sand from Assateague Island into the bays. The net result is a very active system geologically speaking, so much so that the bays and their barrier islands are actually migrating westward (Bartberger & Biggs, 1970). From this perspective the effect on the physical environment of hydraulic escalator dredging at its current scale is negligible and in most cases is probably erased in relatively short order. The primary exception is in seagrass beds, where the energy dampening effect of the plants and sediment stabilization by the root/rhizome system allow physical disturbances to persist for longer periods.

Two other parameters of the physical environment need to be considered, not because they directly interact with clam dredging but for their role in defining the benthic and pelagic communities. On an annual basis water temperatures can vary from -2°C (28°F) to as high as 35°C (95°F). Owing to the shallowness of the bays, water temperatures are heavily influenced by air temperatures and can fluctuate sharply over a short period of time. The waters of Chincoteague Bay can approach hypersaline (higher than seawater) conditions during very dry summers[8]. These extremes in temperature and salinity create a harsh environment, restricting organisms to those that can tolerate or are adapted to changing conditions.

[8] Low salinity has not been much of an factor as it is in riverine estuaries since the stabilization of the Ocean City inlet, but prior to 1933 it was probably the major influence in species distribution in the coastal bays (Grave, 1912).

Benthic Faunal Community

The Maryland coastal bays belong to a highly changeable system, with extremes in conditions including both regular, seasonal fluctuations and unpredictable, sometimes catastrophic disruptions. Historically, as inlets were created by storms and filled in again, salinity regimes in the bays rose and fell. It is within this set of conditions that the benthic faunal community has developed over the past seven decades. The environment of the upper bays was very different prior to the stabilization of the Ocean City inlet in 1933[9]. These were so brackish that oysters occasionally suffered mortality from freshets as far south as the upper portion of Chincoteague Bay and oysters did not inhabit the bays above South Point (Grave, 1912).

Natural physical disturbance is recognized as a structuring force in many communities (Thistle, 1981). Since communities can become established in dynamic, naturally disturbed environments such as the Maryland coastal lagoons, they are necessarily adapted to accommodate disruption. Adaptation to disturbance allows a particular suite of organisms to form a community within the boundaries of their habitat requirements while excluding other, less tolerant species. Barring some fundamental, long-term change that deleteriously alters the environment of the constituent species (e.g. salinity regime, disease, etc.), these communities are characterized by their resilience and persistence in the face of disturbance (Turner et al., 1995).

Many of the species that presently inhabit the coastal bays can rapidly exploit new habitats resulting from disruptions. In one documented example, hard clams, which require higher salinities, were not found in the brackish water bays above Chincoteague Bay during the early twentieth century. Then, a winter storm in 1920 created an inlet below Ocean City, elevating the salinity and allowing hard clams to quickly recolonize Sinepuxent Bay. Within five years this population had flourished to the extent that harvesters could make a decent living ($35/day), with hundreds of thousands to nearly two million clams harvested annually (Md. Conserv. Dept., 1929; 1931). This inlet subsequently closed up during the late 1920's and the hard clam population disappeared as the salinity once again declined.

Submerged Aquatic Vegetation

Seagrass acreages in the coastal bays climbed throughout the 1990's and reached a historic peak in 2001 (MDNR website), despite a substantial increase in harvesting activity

[9] Except for the 1920's, which was a period of higher salinities (see below).

during this period (MDNR, unpub. data). In Chincoteague Bay alone, seagrass acreage increased 5-fold between 1952 and 2003, mostly within the past 20 years (C. Wazniak, MDNR, pers. com.). Acreages have not increased since then, while clamming has steeply declined; the number of boats working has dropped from about 26 in 2001 to about six in 2004. The Atlantic States Marine Fisheries Commission defines impacts of “significant concern” as those “that result in loss of SAV-habitat”, which is considered to be meadows or patches of SAV but not individual plants (Stephan et al., 2000). The record high levels of seagrass acreage in the coastal bays do not meet this definition of an impacted habitat.

Hard Clam Populations

Historically, population densities in the coastal bays have been low relative to other areas in the U.S. Prior to the opening of the Ocean City Inlet in 1933, hard clams could not live north of lower Chincoteague Bay because the salinity was inadequate for their survival. Since then, surveys conducted in 1952/53 and 1969 found average hard clam densities of about 1/m^2 in Chincoteague Bay (Wells, 1957; Drobeck et al., 1970). In more recent times this average has dropped to about 0.25 clams/m^2. In contrast, the mean densities from over 30 studies in a number of other regions were generally between 4 and 8 clams/m^2 (Fegley, 2001). For example, several surveys in Great South Bay, another coastal lagoon on the south shore of Long Island, averaged between 5 and 24 clams/m^2. Recent surveys in the Virginia portion of Chincoteague Bay, where hydraulic escalator dredging is not permitted, found statistically comparable densities of hard clams as in adjacent areas of Maryland. In 1996 there were 0.42 clams/m^2 in the southeast Maryland quad (0.33 clams/m^2 for both southern quads) vs. 0.41 clams/m^2 in Virginia (Homer, 1997), while in 2005 adjacent areas in Virginia and the southwest Maryland quad both had 0.20 clams/m^2 (VMRC/MDNR, unpub. data). The low clam densities in Chincoteague Bay, coupled with the high incidence of broken, unmarketable clams from traditional gear types, led to the adoption of the more efficient hydraulic escalator dredge in the late 1960’s.

One important function of filter-feeding bivalves in the ecosystem is the removal of phytoplankton and particulate matter from the water column, improving water clarity and transferring nutrients such as nitrogen and phosphorus to the benthos where they can be transformed or sequestered (Newell, 2004). However, clearance rates vary widely among species. Hard clams have low clearance rates - an order of magnitude below oysters (Newell & Koch, 2004). In mesocosm experiments using a mix of juvenile and adult clams, densities of 16 clams/m^2 failed to reduce phytoplankton biomass (Doering et al., 1986). In a modeling exercise examining the effect of hard clams on water clarity, none of the clam densities, including the highest (100 g dry wt/m^2, or about 50 clams/m^2 of 62 – 75 mm shell height) filtered sufficient water to appreciably improve water clarity (Newell & Koch, 2004). Another mesocosm study found that high densities of clams (28 and 56 clams/m^2) prevented outbreaks of brown tide blooms, although the clams had no impact on brown tide once the bloom had become established (Cerrato et al., 2004). Hard clam densities similar to those in an aquaculture setting (500 – 1500 clams/m^2) are probably sufficient to obtain measurable localized improvements in water clarity. Further nitrogen and phosphorus removal from the ecosystem can be effected though harvesting the clams (Newell, 2004).

Limitations on the Fishery

Time Restrictions

Regulatory restrictions may mitigate possible negative impacts. The most important of these is the seasonal restriction. The prohibition on hydraulic escalator dredging for hard clams from June through the first half of September is during the period of peak biological activity, including feeding, respiration, and reproduction, and when the most vulnerable stages in the life cycles of many species occur. Predators are most active and abundant during this time. It should be noted that some of these biological processes are ongoing during the season (e.g. eelgrass has its highest growth rates in the spring and fall), but decline with lower water temperatures while others may cease altogether (e.g. larvae production). Also, during the season clamming activity is limited by time of day restrictions, Sunday closures, and daily catch limits. Non-regulatory factors such as bad weather, mechanical failure, market prices, and catch per unit effort also reduce fishing effort.

Area Restrictions

The most significant legislative action in recent years to govern the hard clam fishery is the closing of the seagrass beds to hydraulic escalator dredging. To protect the seagrass beds and its associated faunal community, dredging is restricted from approximately 25% of the coastal bays (about 33% in Chincoteague and Sinepuxent Bays). This has also created a *de facto* hard clam broodstock sanctuary that may ultimately benefit the fishery. Other restricted areas include shoreline buffers, pollution closures in the St. Martin River and smaller areas, and a handful of leased grounds. In addition, factors including weather and clam densities can compel boats to work different areas, so that effort does not remain concentrated in one location for an extended period of time.

CONCLUSIONS

With the closure of seagrass beds to dredging, three basic biological issues regarding the hydraulic escalator dredge remain: 1) the impact of transient turbidity plumes on seagrass populations, 2) the effect of dredging on benthic populations and communities and 3) concern about overwintering blue crabs. Little or no information exists about the crabs that overwinter in the coastal bays, including overwintering areas, the size of this population, the contribution and significance of these crabs to the overall coastal bays population, and the actual impact of hydraulic escalator dredging on overwintering crabs, so that no conclusions can be made regarding this issue. As for seagrasses, the physical attributes (seasonal wind patterns, current regimes, sediment composition) of the coastal bays and the nature of clamming operations reduce the individual probabilities of plume impacts. Lastly, a review of the literature indicates that, in most instances, impacts on the benthic fauna are local and relatively short term. However, although an attempt was made to look at a variety of disturbances, locations, habitats, and scales, the fact remains that none of the studies were conducted in the Maryland coastal bays. Thus, conclusions can be drawn only through the extrapolation of findings from other areas.

Based on these studies, it would appear that the ecological effects of hydraulic escalator dredging is largely mitigated by the physical dynamics of the coastal bays ecosystem as well as the characteristics of the benthic faunal community that has developed under such conditions. Regulatory restrictions further reduce the impact of this activity by prohibiting harvesting in vulnerable seagrass beds and through a closed season during the warmer months when biological processes such as feeding, respiration, growth, reproduction, and recruitment are at their peak.

TABLES

Table 1a. Substrate contaminant levels exceeding Long and Morgan effects-range low thresholds in the mainstem coastal bays of Maryland (EPA, 1996).

Contaminant	**Highest Level**	**Median Level**	**ER-L**	**ER-M**
Nickel	24.1 ppm	17.4 ppm	20.9 ppm	51.6 ppm
Arsenic	12.1 ppm	8.4 ppm	8.2 ppm	70.0 ppm
DDT	2.06 ppb	1.08 ppb	1.58 ppb	46.1 ppb

Table 1b. Substrate contaminant levels below Long and Morgan effects-range low thresholds in the Maryland mainstem coastal bays, but which exceeded these thresholds in other areas of Maryland and Delaware (EPA, 1996) and were of concern in the MCBP (1997) report. The remaining 39 analyzed contaminants of the EPA study were also below ER- L levels in the Maryland mainstem coastal bays.

Contaminant	**Highest Level**	**Median Level**	**ER-L**
Dieldrin	0 ppb	0 ppb	0.02 ppb
Chlordane	0.49 ppb	0 ppb	0.5 ppb
Benzo(a)anthracene	14.2 ppb	0 ppb	261 ppb

Table 2. Extent and duration of natural and anthropogenic disturbances reviewed for this report. Not all of the studies mentioned in the text are included (see Table 3).

Impact	Study	Impact Size	Duration/Coverage
Hydraulic Escalator Dredge	Godcharles 1971	484 m^2/sta. x 6 sta.	4@100%;40%;50%
Hydraulic Escalator Dredge	Drobeck & Johnston 1982	11,250 ft^2	4.5 hrs.
Hydraulic Suction Dredge	Hall et al. 1990	5,000 m^2/sta. x 5 sta.	5 hrs./sta.
Hydraulic Suction Dredge	Hall & Harding 1997	7,850 m^2/plot x 10 plots	20 min./plot
Tractor Dredge	Hall & Harding 1997	225/900/2025 m^2/plot x 8	100 %
Mechanical Dredge	Beukema 1995	1 km^2	4 yrs.
Hydraulic Dredge	Pranovi & Giovanardi 1994	1 track x 2 sta.	?
Prop Wash Kicking	Peterson et al. 1990	1,225 m^2/sta. x 6 sta.	39-230 min./sta.
Scallop Dredge	Thrush et al. 1995	700 m^2/sta. x 2 sta.	?
Oyster Shell Dredge	Connor & Simon 1979	2,500 m^2; 30,000 m^2	4 hrs.; 10 days
Dredge Spoil	Haskin et al. 1978	1 mi^2	2 mos.
Channel Dredging/Spoil Dump	McCauley et al. 1977	8,000 yd^3 x 2 areas	?
Red Tide	Simon & Dauer 1977	300,000 m^2	1-2 mos.?
Winds	Turner et al. 1995	9,000 m^2/sta. x 6 sta.	69 d/yr (winds >33 kn)
Pollution	Dean & Haskin 1964	~20 km^2 (Raritan estuary)	Decades
Hypoxia (TS Agnes)	Boesch et al. 1976	~65 km^2 (Lower York R.)	~6 wks

Table 3. Recovery times of coastal and estuarine benthic fauna to disturbance.
R=recovered; I=incomplete; R/I=mixed results from different sites; nd = not determined by end of study period.

Impact	Study	Study Area	Study Length	Time to Equilib.	# Indiv.	Species Number	Species Makeup	Biomass	Comm. Struct.
HED	Godcharles 1971	Fla.	500 d	<8 mo	R	R	R		
HED	Kyte & Chew 1975	Me.		<10 mo	R	R	R		
HED	Drobeck & Johns. 1982	Md.	11 mo	<5 mo	R	R	R		R
HSD	Hall et al. 1990	Scot.	40 d	<40 d	R	R	R		R
HS/TracD	Hall & Harding 1997	Scot.	56 d	56 d	R/I	R/I	R		
MD	Beukema 1995	Neth.	13 yr	<6 mo	R	R	R	I	I
HD	MacKenzie 1982	N.J.	6 mo	0-6 mo	R	R	R		
HD	Pranovi & Giov. 1994	Ita.	2 mo	nd	R/I	R	R/I	I	
Kicking	Peterson et al. 1990	N.C.	1 yr	<6 mo	R	R	R		
ScDr	Thrush et al. 1995	N.Z.	3 mo	nd	R/I	I			I
OyShDr	Connor & Simon 1979	Fla.	12 mo	6-12 mo	R	R	R	R	R
Dr Spoil	Haskin et al. 1978	N.J.	16 mo	3 mo	R	R	R		
ChannelDr	McCauley et al.1977	Ore.	56 d	28 d	R	R	R		
Dr Spoil	“ ” “ ” “	“	56 d	14 d	R	R	R		
Red Tide	Simon & Dauer 1977	Fla.	2 yr	11 mo	R	R	R/I		R/I
Storms	McCall 1977	Conn.	13/3 mo	3 mo	R	R	R		R
Winds	Turner et al. 1995	N.Z.	5.5 yr	NA	R	R	R		R
Pollution	Dean & Haskin 1964	N.J.	3 yr	nd	R	R	I		I
Hypoxia	Boesch et al. 1976	Vir.	2 yr	nd	R	R	I		I
Exp.Tray	Lu & Wu 2000	HongKong	15 mo	12 mo	R	R	R		R

HED=hydraulic escalator dredge; HSD=hydraulic suction dredge; TracD=tractor dredge; MD=mechanical dredge; HD=hydraulic dredge; Kicking=prop washing; ScDr=scallop dredge; OyShDr=oyster shell dredging

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