St. Mary's River Oyster Reef Restoration: Construction and Monitoring

Final Report

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Executive Summary

Chesapeake Bay oyster reefs were massive shelves or mound-like structures that extended from the shoreline into deep water, and these structures supported a living skin or living veneer of eastern oysters (*Crassotrea virginica*) on their surfaces. Centuries of exploitation by Native Americans and early colonists did little to disrupt the ecological integrity of these reefs, but human demand and the collapse of oyster fisheries elsewhere resulted in mounting harvest pressure in the Chesapeake at the time of the Civil War. By the 1890's massive harvests began to reduce the seemingly inexhaustible supply of oysters. After 1900 shell mining further reduced standing stocks and oyster harvests began to plummet. Then in the 1950's introduced oyster disease and poor water quality took further tolls, with the ultimate consequence that oyster harvests today are less than 1% of those in the 1890's. Furthermore, reef structure has been destroyed and continued dredge harvesting has flattened reefs making them more susceptible to sedimentation, poor water quality, and disease.

Wide spread concern for the decline of Chesapeake Bay oysters has prompted many groups to actively engage in oyster restoration efforts. Over the past 30 years these initiates have grown substantially and much has been learned about how oyster recovery can be facilitated, what materials work best, and what criteria should be used to assess success or failure. Despite these gains and insights, the effectiveness of recent oyster restoration methods and 3-dimensional reefs in particular still remains very much a question. The purpose of our study was to analyze the scientific oyster restoration literature in order to propose a methodology for the St. Mary's River, Maryland, and to estimate the costs for restoring a 5 acre site adjacent to St. Mary's College of Maryland.

Because few studies have compared the effectiveness of elevated, 3-dimensional reef structures to simply placing oyster shell on the bottom, we advocate that the proposed restoration be experimental. Our analysis of the literature suggests to us that 3-dimensional structure may be a preferred method of restoration compared to simply placing oyster shell on the bottom, but this needs to be tested experimentally. The raised structure may reduce sedimentation and improve oyster survivorship by providing good water circulation through the reef structure and by moving the living oyster veneer off the bottom where low oxygen and disease susceptibility limit reproduction and growth. Our literature review also showed that oyster shell is clearly the best substrate for enhancing oyster reproduction and spat set compared to clam shell, concrete, various types of mineral rock, and porcelain. But oyster and clam shell supplies are limited making concrete a viable, economically attractive alternative for reef cores. Reef Balls™ have also been used successfully nationwide and in Maryland to build 3-dimensional reef structure. While the initial cost of Reef Ball™ molds is substantial, production of the concrete reef balls is labor intensive but inexpensive. Therefore, we propose building reef cores from recycled, crushed concrete and from aggregations of Reef Balls™. Although oyster shell is considered to

be the best material for spat set, concrete also has the potential to attract and hold spat. Thus we propose several surface treatments that include not covering the core material, covering the core material with a 0.2 m oyster shell veneer, and covering the core material with a 0.2 m oyster shell veneer with a top layer of spat on shell.

The proposed project would have two phases, an initial pilot study phase and a full build out phase that would expand on the pilot study. We suggest that the pilot study consist of six different mound reefs, each 6 m in diameter and 1.5 m high. These would be placed in the 2.8 acre north area of the study site with their surfaces within 0.3 m of mean low water. Two of the reefs would simply consist of either crushed concrete or reef balls. Two reefs would have these core materials but would be covered with a 0.2 m oyster shell veneer treatment. Finally, the last two reefs would have the two different cores, oyster shell veneers, and then shell that has been seeded with spat. We estimate the cost of the construction of the reefs in the pilot project to be $18,682. The second phase of the project would add 18 additional reefs to the 2.8 acre northern portion of the study site, so there would be a total of 24 reefs in that location. The 18 second phase reefs would provide 3 replicates of the pilot project treatments. In the second phase of the project, the bottom of 2.2 acre south area would be covered with a 0.2 m layer of oyster shell to mimic current reefs in the St. Mary's River. We estimate that the cost for building the reefs for the second phase will be $178,802.

Critical to the goals of this project is monitoring to determine 1) the restoration success of the reefs and 2) whether the reefs provide ecological services such as improve water quality by removing suspended sediments, phytoplankton and nutrients and providing habitat for estuarine animals such as fishes and crustaceans. To assess whether restoration success, monitoring should continue for at least three years from the initial construction of the phase one reefs. Longer term monitoring is preferable (up to five years); however, we have estimated costs for only three years. The estimated monitoring costs are $13,452 for year 1 and $10,252 for year 2 and 3 for a total of $33,956.

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Project Background

In 2009 the Maryland Oyster Advisory Commission recommended the creation of large-scale sanctuaries to 1) conserve oyster brood stock, 2) conserve remnant viable reefs and 3) promote development of disease resistance (MOAC 2009). The Commission also recommended the re-establishment of three dimensional reef structures (MOAC 2009). In the fall of 2010 the Upper St. Mary's River Oyster Sanctuary was created (MD DNR, 2010; Fig. 1). This sanctuary, encompassing 1,289 acres, begins from a line across the river at Church Point and extends up-river to the extent of tidal waters. While the harvest of wild oysters is prohibited in sanctuaries, they were opened to aquaculture leases in 2011 (House Bill 208; see http://mlis.state.md.us/2011rs/bills/hb/hb0208t.pdf). These "aquaculture enterprise" leases can take no more than 10% of a sanctuary and must be compatible with restoration.

In the fall of 2010 representatives from the Rotary Club, St. Mary's River Watershed Association (SMRWA) and St. Mary's College of Maryland (SMCM) began meeting to discuss the construction of oyster reefs in the St. Mary's River Oyster Sanctuary and developed a project proposal in the spring of 2011. This was followed by the signing of a MOU between the Leonardtown Rotary Club, SMCM and SMRWA to develop a framework of cooperation around an oyster restoration project adjacent to the College. Over the next year an area was selected and an application to perform oyster reef restoration was submitted. In April of 2012 the permits for the oyster restoration received final approval.

The project encompasses the restoration of 5.0 acres of oyster reef habitat along the shore in front of St. Mary's College of Maryland (Fig. 2), 95% of which is currently unproductive bottom. Two types of oyster reef restoration are included in the permit. At the northern end (2.8 acres) a 3-dimensional reef will be constructed, whereas in the southern end (2.2 acres) a 2-dimensional shell pile oyster bar will be constructed (Figs. 3-5). The 3-dimensional reef must be at least one foot below mean low water and will be constructed of approximately 2,500 cu. yards (1,911 m^3) of alternate materials such as stone, concrete rubble, concrete oyster balls, gabion rock, clam shell, and oyster shell. The permit states that both areas will be planted with the native oyster, *Crassostrea virginica*, at a density of four million spat per acre. The goals of the project include providing ecological services such as increasing the area of active oyster bottom, providing habitat for a variety of estuarine species and improving water quality. The project will provide educational opportunities for community members and college students. Finally, the project offers the opportunity for research on the use of alternate materials for reef building and a side by side comparison of 3-dimensional reefs and a shell pile oyster bar. The project may also be coupled with the restoration of submerged aquatic vegetation (SAV) and/or living shoreline projects.

The purpose of this report is to evaluate the design, recommend construction materials, and develop an implementation plan with cost estimates for the construction of the three-dimensional oyster reefs. In addition we recommend methods for both oyster and water quality monitoring. Some of the questions addressed in this report include:

1) What are the advantages of 3-dimensional oyster reefs relative to 2-dimensional shell pile oyster bars?
2) What is the best reef morphology for the restoration site?
3) What are the materials available to construct 3-dimensional oyster reefs, what are the cost differences, and how do they differ in oyster recruitment/mortality and ecological services?
4) What is the best way to set oyster spat on the 3-dimensional reef structure?
5) How should restoration success be evaluated?
6) What are some educational and research opportunities associated with the oyster reef restoration project?

Introduction

The eastern oyster, *Crassostrea virginica*, has been an important component of the Chesapeake Bay estuarine ecosystem. Oysters act as biological filters by removing phytoplankton and particulate matter from the water, and as a consequence reduce nutrient concentrations and bottom hypoxia (Dame et al., 1984; Dame, 1996; Nelson et al., 2003; Newell et al., 2007; Grizzle et al., 2008). Newell (1988) estimated that at pre-1870 population levels oysters could filter the entire Chesapeake Bay's water volume in just 3 to 6 days during the summer. The filtration capacity of Bay oysters declined in the 20th century with the estimated number of days to filter the Bay rising to 325 days in 1988 (Newell, 1988). However, the importance of biofiltration of the Chesapeake Bay by oysters and the role it plays in reducing bottom hypoxia is a topic of ongoing debate (Pomeroy et al., 2006; Newell et al., 2007; Pomeroy et al., 2007). Other ecosystem services that oyster reefs provide include providing habitat for benthic animals, facilitating fisheries, stabilizing benthic and intertidal communities and providing shoreline protection (Coen et al., 2007; Scyphers et al., 2011).

Reduction in this keystone species' once prolific populations in the Chesapeake can be attributed to various factors that seem to have compounded over time. Historically, the oyster populations in the Chesapeake Bay were subject to overharvesting as early as the late 19th century (Kirby and Miller, 2005), and with the invention of destructive mechanical harvesting tools such as dredges and patent tongs the damage to the fishery escalated (Rothschild et al., 1994; Jackson et al., 2001). Not only were the oysters overharvested, but the oyster reefs themselves destroyed (Hargis and Haven, 1995, 1999; Paynter, 1996). Hydraulic-powered patent tongs introduced around 1950 were most destructive to the oyster bar's substrate, flattening the reefs, and making them more prone to the effects of sedimentation (Rothschild et al., 1994). Additionally, waterfront construction and dredging beginning in the early 20th century displaced sediment that settled and suffocated oyster beds. Eutrophication began to cause hypoxic and anoxic conditions throughout the Chesapeake, creating massive oxygen-depleted dead zones where oyster reefs cannot survive. Furthermore, diseases caused by parasitic protozoans decimated large numbers of oysters as early as 1949 (Kirby and Miller, 2004). These combined factors have reduced oyster populations in the Chesapeake Bay to less than 1% of their historic highs (Greenhawk et al., 2007; Wilberg et al., 2011; National Marine Fisheries Service, 2012). Beck et al. (2011) estimated that more than 85% of the world's oyster reefs are gone.

With the decline of the oyster's biofiltration capacity and an increase in nutrient pollution and sediment run-off, phytoplankton densities and suspended sediments have increased, blocking light that would otherwise penetrate deeper into the water column and support submerged aquatic vegetation (SAV) communities (Kemp et al., 2004, 2005). The decline of SAV has further degraded the Chesapeake Bay ecosystem as SAV communities provide numerous ecological services (Orth et al., 2006).

Despite all the difficulties facing reestablishment of the once prolific oyster fishery, many recent efforts have been aimed at restoring oyster reefs (e.g. Luckenback et al., 2005; Schulte et al., 2009a, 2009b; Burke, 2010). In the past, oyster reef restoration projects generally involved dumping small piles of oyster shells in designated areas. However, these efforts to restore reefs often failed from the onset due to mortality, poor recruitment, disease, stress and predation (Lenihan, 1999; Mann and Powell, 2007). Yet, over the past decade there has been a dramatic resurgence of successful oyster restoration projects that have the potential to restore lost ecological services (Luckenback et al., 2005). Although Mann and Powell (2007) concluded that efforts to restored oyster populations in the Chesapeake have failed, Powers et al. (2009) found that oyster reef restoration in no-harvest sanctuaries was largely successful.

Project Goals

Having clear goals is essential for evaluating the success of restoration projects (Allen et al., 2011). Coen et al. (2007) identified six major goals for oyster restoration projects. These are: habitat creation, shoreline stabilization, water quality improvement, harvesting enrichment, broodstock enhancement, and educational outreach.

The permit application for the St. Mary's oyster reef restoration project states that it is for ecological and educational purposes. Purposes and goals are further described in the Rotary International District 7620 grant application for the project. The application identifies the following "elements" to be addressed:

- providing optimal conditions for oyster growth by constructing 3-demensional reefs;
- reducing turbidity and nutrient loads around the project site to extend the optimal conditions to greater depths; and
- protecting and promoting oyster reproduction and other marine biodiversity at the project site.

"Objectives" are also defined in the permit application that include:

- significantly increasing the number of oysters within the St. Mary's River Oyster Sanctuary;
- engaging an estimated 5,000 people in the program to enable hands-on experience and education;
- measuring the productivity in the new reef by size and in-stream spat production; and
- measuring the improvement in water quality.

The project also includes opportunities for research and providing useful information for future oyster restoration projects. These include:

- conducting research on the ecological benefits of 3-demensional oyster reefs as compared to a shell pile oyster bar; and
- comparing a variety of artificial substrates used in oyster reef restoration.

All of the above can be combined into a few clear goals:

1) Construct artificial oyster reefs in the St. Mary's River Oyster Sanctuary that sustainably restore native oyster habitat and ecosystem services. The reefs should support the growth and recruitment of oysters and other species associated with oyster reefs and should provide other services that include improving water clarity and oxygen levels.
2) Conduct monitoring and scientific research on this project to demonstrate the benefits and sustainability of 3-dimensional reefs as a restoration technique that can be potentially replicated elsewhere in the Chesapeake Bay and the world. Communicate the results of the research to stake holders, managers and the scientific community through publications and/ or presentations.
3) Provide educational outreach opportunities by involving students. rotarians and members of the local community in the construction and monitoring of the reefs.

These goals have guided our review of the literature and our recommendations for the construction of the reefs and the monitoring of restoration success.

Reef Design

Morphology

Oyster reef structure, long since eradicated on the east coast, was a huge pile of shell extending from deep water to the surface, and these reefs were exposed at low tide (Fig. 6). Known as "rocks" because of their exposure, they were so extensive that they were hazards to navigation (Wharton, 1957). Native Americans and European colonists harvested of oysters, but their impact was relatively slight because of low human population density (Miller, 1986). All this changed with human population increases and refinement of harvesting technology (Kirby and Miller, 2005). The tremendous Chesapeake Bay oyster harvests began during the Civil War and peaked in the 1880's when 20 million bushels were taken in Maryland alone. Most scientists agree that the declines in oyster harvests between 1880 and 1905 were due to over-fishing and the wanton destruction of the reefs themselves (Rothschild et al., 1994; Jackson et al., 2001). Oystermen contend that oyster beds need to be continuously "scraped" with dredges to remain free of sediment that suffocates and kills oysters, but to our knowledge this has never been substantiated. The susceptibility of flattened reefs to sedimentation may be a consequence, in part, to their loss of three-dimensional structure (Rothschild et al., 1994). It is likely that mounds of dead shell underlying a veneer of living shell promotes water circulation and improves the ecological filtering capacity of oysters.

Vertical relief in oyster reefs decreases sedimentation on the reef, reduces hypoxia, increases flow rates and increases oyster survival (Hargis and Haven, 1999; Lenihan, 1999; Coen et al., 2007). Oyster reef structure plays a key role in marine ecosystems by altering hydrodynamic conditions (Nelson et al., 2003). For example vertical reefs also allow for infectious materials to be carried away from the reefs due to the higher flow rates (Hargis and Haven, 1999; Lenihan, 1999). Overall, oyster reefs with greater relief and more interstitial space tend to have greater success and survival of oysters. Schulte et al. (2009a) found that high relief reefs in the Great Wicomico River, Virginia, had 4 times as many oysters than low relief reefs and that recruitment was greater and more consistent on the high relief reefs. According to Lenihan (1999) taller reefs generally perform better in all conditions, regardless of water depth. Higher reefs afford for greater water flow, which reduces sedimentation and prevents hypoxia. He found that water flow speed was significantly greater over artificially constructed "tall" reefs of 1-2 meters in height in 3-6 meters water depth, as compared to water flow speeds at similar depths lacking reef structures (Fig. 7). Oysters in these tall artificial reefs experienced significantly greater growth rates when compared to oysters on short (0.1-0.6 meter) reefs, likely due to enhanced feeding rate and efficiency from faster flowing water. Mortality was also significantly reduced in taller reefs because sedimentation, burial, and parasitism were inhibited by increased flow speed. Moroney and Walker (1999) also compared oyster growth and survival at different heights and found an overall significantly higher oyster survival and growth rates higher on the reef compared to those near the bottom. Therefore, instituting height and width requirements for oyster reef construction based on water depth seems wise and would likely reduce mortality and vastly improve reef sustainability.

Vertical relief also enhances the habitat for other species, including many fish species (Coen et al., 2007). Natural oyster reefs are loose open structures. Habitat complexity created by crevices and interstitial spaces allows for higher survival rates by creating refugia from predators and reducing physical stress (Bartol et al., 1999). A more complex reef will have greater community diversity because it provides an abundance of shelter and nesting sites (Coen et al., 2007). Hence, a constructed reef using artificial materials should also have crevices and substrate complexity to provide similar ecosystem services to that of a natural reef.

Current velocities affect the survival and growth of oysters (Lenihan et al., 1996), and vertical relief increases the velocity of flow over a reef (Fig. 7; Lenihan, 1999). Tidal currents at the project site are oscillatory, flowing parallel to the shore at velocities generally less than 0.1 ft/sec (3 cm/sec) (USACE, 2006). The shoreline in front of the College has historically eroded at a rate of around one foot (0.3 m) per year. Most of the energy for the movement of sediments comes from wave action, not tidal currents, with the largest waves approaching the site from the northwest (USACE, 2006). The construction of 3-demensional reefs at the project site should increase the current velocity with distance from the bottom, reducing sedimentation and increasing oyster survival and growth (Lenihan, 1999; Coen et al. 2007). In addition the reefs should protect the shoreline by providing natural breakwaters, reducing erosion rates (Coen et al., 2007; Scyphers et at., 2011). Protected areas behind vertical reefs may be more suitable for restoration of submerged and emergent vegetation.

Another important characteristic is reef arrangement. Natural reefs are often irregular in shape and can be oriented parallel or perpendicular to the contours of the bottom and prevailing bottom currents (Hargis and Haven, 1999; Allen et al., 2011). The location of cultch (substrate for oysters to set on) and currents will affect the shapes and arrangements of reefs. Restored reefs may be single large mounds or fragmented into a cluster of smaller reefs. Fragmenting the reef increases the surface area and edge (Coen et al. 2007). The USACE Native Oyster Restoration Master Plan (USACE, 2012) recommends that reef fragmentation be part of the oyster reef design. Hargis and Haven (1999) suggest that an ideal arrangement is to have a large brood stock preservation and spawning reef in the center surrounded by numerous small satellite production reefs (Fig. 8). However, not much is known about how habitat fragmentation affects the dynamics of reef systems (Coen et al., 2007).

Reef Materials

Because of the scarcity of oyster shell, a variety of alternative materials have been used for constructing oyster reefs (Schulte et al., 2009b). While these alternative materials have generally been used alone (Burke, 2007; Schulte et al., 2009b), they can be used in combination with an overlying 10 to 20 cm thick veneer of oyster shell (Schulte et al., 2009b; USACE, 2012) as has been proposed for this project (Fig. 4). We provide here an evaluation of oyster reef restoration materials for the construction of 3-dimensional reefs.

Oyster Shell

Oyster bars or oyster reefs are made of live oysters, dead oyster shells, and shell fragments. The core of the reef is made of dead shells and shell fragments, silt, sand and detritus, and the veneer of the reef has the living oysters and shells of recently dead oysters (Hargis and Haven, 1999). Several studies have found that oyster shell is overwhelmingly the best substrate for oyster reef reconstruction because oysters are the natural material of the reefs and oyster spat preferentially settle on shells as opposed to other alternative substrates like concrete (Eastern Oyster Biological Review Team, 2007; Brumbaugh and Coen, 2009; Powers et al., 2009). However, oyster shell has very limited availability and is a quickly declining resource. According to Campbell (2008) at the Maryland Department of Natural Resources (DNR), oyster shell was dredged from upper bay in the past and planted in other, restoration areas of the Chesapeake Bay. Therefore, few shell deposits remain as much of the shell has been harvested (Seliger and Boggs, 1988). Maryland DNR would also use fresh shell from the oyster industry in Maryland to plant on the bottom of the Bay, however with the oyster industry’s decline, there is still not enough oyster shell for everyone who wants it. There is a very well run program that has been recycling oyster shell in South Carolina since 2001, and this South Carolina Oyster Restoration and Enhancement (SCORE) program is supported by the South Carolina Department of Natural Resources (2012). Recycling programs also exist in North Carolina, and there are start up programs in Alabama, Georgia, Louisiana, New Hampshire, and Virginia (Brumbaugh and Coen, 2009). Oyster shell must weather and dry for at least 6 months to make sure no infections are introduced into the water, but otherwise recycled shell is a great substrate (South Carolina Department of Natural Resources, 2012). Oyster restoration projects around the Chesapeake Bay are seeking alternative substrates with which to build reefs instead of natural oyster shell. Another possibility is building a reef core with an alternative substrate and covering it with a thin veneer of oyster shell.

Clam Shell

One of the most widely used of the substrate alternatives to oyster shell is clam shell. Clam shell is one of the most natural materials used for restoration, so no special permits other than those required for using oyster shell are required (Nestlerode et al., 2007; National Oceanic and Atmospheric Administration, 2012). According to Mann and Powell’s (2007) assessment of oyster restoration goals in the Chesapeake, shell generated by the offshore surf clam and ocean quahog fisheries have the greatest potential for reef creation in the Chesapeake Bay. They suggest better management of this resource for usage in an environmentally constructive manner. In a review by Coen and Grizzle (2007) for the Atlantic States Marine Fisheries Commission, they note that New Jersey artificial reef sites constructed from 20-25% surf clam and 75-80% ocean quahog shell had equal spat set compared to reefs entirely constructed of oyster shell. However, spat settlement on ocean quahog was significantly lower than on oyster shell. Despite this difference, they deemed the clam shell mixture a successful alternative to oyster shell. Soniat et al. (1991) report greater settlement of oysters on clam shell when compared to concrete and gravel. Additionally, they found that settlement on clam shell was equivalent to settlement on limestone. Nestlerode et al. (2007) compared oyster settlement and survival on artificial intertidal reefs constructed with oyster and surf clam (*Spisula solidissima*) shell. There was no difference in recruitment between the two substrates, but higher post-settlement mortality was observed on the clam shell reef. Furthermore, they constructed a clam shell reef at a subtidal location. Shell morphology and substrate quality varied depending on the location on the reef mound. Settled oysters were largest and more numerous at the base of the reef where the clam shell fragments were larger, which afforded greater interstitial space. The shell was highly fragmented and compacted at the crest of the reef, so the oyster communities were much less vigorous at this elevation. The lack of interstitial space makes young more vulnerable to predation, and provides little refuge for other members of the benthic community (O'Beirn et al., 2000). However, clam shell has other advantages in that it is one of the lightest cultch materials per unit surface area, and it becomes less imbedded in the substrate when compared to limestone, gravel, and concrete (Soniat et al., 1991). The substrate of our proposed site has a high percentage of sand, so sinking of reef materials should not be an issue. In an oyster restoration report by the United States Army Corp of Engineers (USACE, 2012) surf clam shells were found to be fragile and break more easily than hard clam shells, providing very little interstitial space. However, hard clam shells which would produce larger interstitial space are in short supply.

Concrete

The Louisiana Department of Wildlife and Fisheries (LWFW, 2004) compared survival of young oysters and oyster size when grown on crushed limestone, crushed concrete, and crushed oyster shell. Surprisingly, they found much higher survival on the limestone and concrete. However, oyster size was significantly larger on both the concrete and oyster shell when compared to the limestone. They also discuss costs of the three materials. As of 2003 in Louisiana, crushed oyster shell (\$35.71/yard^3) was actually the cheapest, followed by crushed concrete (\$38.71/yard^3) and finally crushed limestone (\$39.71/yard^3). However, after the experiment, it was calculated that crushed oyster shell actually produced the least mean number of seed oysters/dollar (73.09), followed by crushed limestone (237.79) and finally crushed concrete (337.18). They concluded that considering all costs and success rates, crushed concrete was the most suitable cultch material. Because all these materials were crushed and because the goal was having individual oysters as an end product, reef building did not seem like an objective in the LDWF experiments. They did mention that the reduction of material volume may have played a role in spat set and add that alterations of mass, density, and shell structure may also account for the lower number of oysters on shell. Field experiments by Soniat et al. (1991) demonstrated that oyster settlement on concrete is significantly greater than settlement on gravel. However, settlement on concrete was not significantly different from either limestone or clam shell. Additionally, fouling appeared to be greater on concrete and limestone when compared to gravel. According to the

USACE (2012), reefs constructed with artificial materials such as concrete are less likely to be poached. Additionally, artificial materials are structurally persistent in the environment, which is another attractive feature.

Limestone and Sandstone

Another commonly considered alternative to oyster shell are natural stone materials such as limestone and sandstone. Soniat and Burton (2005) mention an older study by Chatry et al. (1986) where about twice as much spat set was observed on limestone when compared to clamshell. Considering this, Soniat and Burton (2005) tested to see if quartzite sandstone was a suitable alternative to siliceous limestone. However, they found an overwhelmingly higher settlement on limestone when compared to sandstone. They concluded that sandstone is not an economically feasible alternative substrate considering the low spat yield. Soniat et al. (1991) report a greater oyster settlement on limestone when compared to clam shell and gravel in a field experiment. In a laboratory setting, spat set was greater on limestone when compared to concrete and gravel, but not clam shell. The LDFW (2004) report discussed earlier reported that crushed limestone was more suitable for the production of seed oysters when compared to crushed oyster shell, but that limestone was not as suitable as crushed concrete. While limestone has attracted a large number of spat in a number of studies, it may also be one of the most expensive alternative materials. According to LDWF crushed limestone was more expensive to obtain than either crushed concrete or crushed oyster shell in 2003.

Reef Balls

Reef Balls™ have been found to be a good form of alternative substrate for restoration of many different kinds of reefs. Reef Balls™ are used for and have had success in coral and oyster reef restoration and have been used as mangrove pots to enhance fishing/diving and reduce erosion (Reef Balls Foundation, 2011). They are hollow concrete mounds with large holes in them, and depending on the depth of the water, need to be anchored to the substrate. They can be made in a variety of sizes and styles, and can even have different coverings such as oyster shell fragments. They are built of marine friendly concrete, which has a lower pH than normal concrete. They range in size from very large structures to the “oyster” style which is quite small (1.5 ft. tall) and designed for use in large numbers to build reefs. They cost $40 apiece plus shipping, or the mold can be purchased and the balls constructed on site. According to the NOAA Chesapeake Bay Office (2012), all alternative substrates must be analyzed to make sure they do not contain toxic materials, which could leach into the water harming the ecosystem. Many tests must also be done to see if the substrate will succeed as an oyster reef, and the reef should be monitored after construction and deployment. In Maryland special permits are required to place anything other than oyster and clamshell on the bottom. Reef Balls™ had been used in the Chesapeake Bay with limited success, so the Chesapeake Bay Foundation tried an experiment in which some of the Reef Balls™ were placed in tanks with larvae so spat would set on the balls before they were placed in the Bay (Blankenship, 2006). After one year, the Reef Balls™ were completely covered by oysters and unrecognizable, however the Reef Balls™ that had not been pre-set with spat had nothing on them. They also attempted a project where they mixed oyster shell fragments in with the concrete and the oysters set much better on them. Overall, Reef Balls™ have great potential for oyster reef substrate in Chesapeake Bay and St. Mary's River restoration projects.

Porcelain

Recycled porcelain (such as toilets and sinks) has been studied as an alternative substrate for oyster reefs, but few reports document the success of porcelain as an acceptable substrate. Porcelain is mentioned in reports by the Eastern Oyster Biological Review Team (2007), Mann and Powell (2007), Brumbaugh and Coen (2009), Burke (2010), as well as on NOAA's Chesapeake Bay Office website. The Bay Journal carried two articles (2001, 2004) covering a project in the Back River near Langley Air Force Base and the Lafayette River in Norfolk where an oyster reef was constructed of crushed porcelain fixtures. After two years they found that this was a suitable substrate for oysters. However, moving and preparing the porcelain was actually more expensive than using natural oyster shell.This is still a fairly new option for a reef substrate, so more research is necessary before Porcelain could be considered for use in the St. Mary's River.

Recommended Reef Design

Oyster reef restoration and the research on materials used in restoration efforts is still in its infancy. Luckenback et al. (2005) state that there are few analyses of oyster reef restoration outcomes and that few study results have been published in the primary scientific literature. They also note that many state and federal agencies as well as local groups are now engaged in oyster restoration projects, but that metrics for the evaluation of ecological restoration goals are just now emerging.

Because the science is new and there has not been sufficient time to empirically conclude that one material out performs others, our evaluation of the literature has not found a fool-proof protocol for the St. Mary's River oyster reef project. In addition, the cost and availability of materials is quite variable and has influenced our final recommendations. Clearly, oyster shell is the best material for building reefs, but its availability is quite limited and as a consequence relatively expensive ($2.50-$5.00/bushel). This has driven those involved in restoration work to seek alternative materials. It seems that clam shell is the next best material, but again clam shell is becoming scarce and is not as durable as other materials. Consequently, researchers have turned to concrete rubble and structures made from poured concrete, and given concrete's availability, it is probably our best option. Porcelain is not a likely candidate for the St. Mary's River in our estimation because of availability, cost, and an unproven track record.

The building of 3-dimensional reefs with alternative materials in an area where the harvest of oysters is prohibited presents a rare opportunity for research on reef design and the use of alternative materials. Furthermore, we are exploring opportunities to collaborate with MD DNR on this research. Considering these research opportunities and our evaluation of construction materials, we are recommending using concrete rubble and poured concrete structures (Reef Balls™) for the substructure of the St. Mary's reef. The purpose of the substructure will be to build elevation into the reef core, enhancing water circulation over and through the structure. We also advocate that some concrete rubble and Reef Balls™ be covered with a veneer of loose clean oyster shell, 10 to 20 cm deep (Hargis and Haven, 1999; Luchenbach et al., 2005). Some of these treatments should be seeded with spat on shell while others should not be seeded, thus providing a controlled experiment to assess natural spat set on both the substructure of the reef itself and the substructure with an oyster shell veneer. The construction of multiple small reefs with different combinations of core materials and top treatment will inform the later construction of large-scale reefs in the St. Mary's River. The fragmented reef design proposed here resembles the arrangement shown by Hargis and Haven (1999; Fig. 8) and has the advantage of increasing surface area and rugosity, features that should enhance oyster settlement and growth.

We propose two phases to reef construction at the St. Mary's River/St. Mary's College site. The first phase will be a small-scale pilot project that should be started in the summer-fall of 2012 with construction being finished in the winter of 2013. Six mound reefs, approximately 6 m in diameter and 1.5 m tall (Table 1), will be constructed close to the shore within the restoration area (Fig. 9). Three of these reefs will have concrete rubble at their core and three will have Reef Ball™ cores (Fig. 10). One concrete-core and one of the Reef Ball™-core reefs will receive a veneer of 20 cm of oyster shell and then seeded with spat-on-shell, two reefs will receive only veneer, and two reefs will have neither the veneer of shell nor the spat treatments. The purpose of these three treatment types is to assess the core material's ability to attach and hold spat. Our goals for the pilot project are to assess the difficulty of reef construction, to preliminarily evaluate the success of the reef designs, and to compare the treatments for their ability to enhance oyster reproduction.

Table 1. Proposed reef structures to be constructed in the St. River oyster restoration area.

Substructure	Covering	Seeding	Notes
Concrete rubble	None	No	Control
Concrete rubble	Oyster shell veneer	No	
Concrete rubble	Oyster shell veneer	Yes	
Reef Balls™	None	No	Control
Reef Balls™	Oyster shell veneer	No	
Reef Balls™	Oyster shell veneer	Yes	

The second phase will be the construction of 18 experimental mound reefs at different depths, but each mound reef will be approximately 6 m in diameter and will vary in height up to 2-2.5 m (Table 2). The pilot project may shed some light on the design of second phase reef cores, but we anticipate using the same 6 treatments with 3 replicates of each as used in the pilot project phase (Table 1, Fig. 9). A minimum of three randomly assigned replicate reefs for each treatment is required for statistical analyses and for the evaluation of restoration success. The reefs will be arranged in two rows along the outer edge of the restoration area with the rows being about 5 m apart to minimize differences in depth. The reefs in the two rows will also be staggered so they have similar exposure to waves coming from the northwest (Fig. 9). Coupled with this, 3 areas in the shell bar area (approximately 6 m in diameter) will be covered with oyster shell that has not been seeded. These areas, which will have no vertical structure, will allow for comparison of the natural set on the 2-dimensional shell oyster to the 3-dimensional reefs in the northern part of the study site. Timing of the second phase will depend on the availability of funds, but we recommend that construction of reefs begin in the spring of 2013 and completed by mid-summer of that year.

Table 2. Characteristics of proposed 3-dimensional reefs. The Phase II reefs in row 1 are the furthest from shore. Volumes for reefs are calculated for oblate domes. See Fig. 9 for position of reefs in the restoration area.

Reef Row	Number of Reefs	Depth Range Below MLLW (m)	Average Reef Height (m)	Reef Diameter at Base (m)	Reef Area on Bottom per Reef (m^2)	Reef Volume per Reef (m^3)
Phase I Reefs	6	1.8	1.5	5 to 6	16	24
Phase II Row 1	9	2.4 to 2.7	2.3	6	28	43
Phase II Row 2	9	2.1 to 2.3	1.9	6	28	36
				Total for All Reefs	**605**	**856**

An area inshore from 3-dimensional reef reefs will remain available for construction of additional reefs if funding becomes available. This area could be used to test the use of other reef construction materials such as clam shell and/or rock.

Evaluation of Restoration Success

Kennedy et al. (2011) found that of over a thousand oyster projects in Maryland and Virginia between 1990 and 2007, less than half included both restoration and monitoring. They and others (Coen and Luckenbach, 2000; Allen et al., 2011) have called for future oyster restoration projects to have goals linked to clearly articulated success criteria and evaluation methodology that includes replication, quantitative sampling and monitoring prior to and after the restoration activities. The communication of restoration and evaluation results to a larger audience is just as important as articulating goals. Of the three goals identified for this project, two are related directly to function of the restored oyster reef. The first goal is to restore native oyster habitat and ecosystem services. The second goal is to conduct scientific research specifically focusing on comparing the ecological function of 3-dimensional reefs to a shell oyster bar and for different alternative substrates. Methods to evaluate restoration success linked to these goals are described in the following sections. Although oyster reefs have multiple impacts on the surrounding environmental conditions, reef health and success is best measured through monitoring of oyster densities and growth rates, spat settlement and survival patterns, and sampling of the reef community. The reef's impact on local water quality can be monitored through measuring several key water quality indicators which, when collected over a series of years, can be used to examine both short and long term impacts of the oyster reef on water quality.

Oyster Monitoring

Live oyster density, biomass and spat settlement have all been used to assess the health of oyster reefs and the suitability of an area to support an oyster reef (Luchenbach et al., 2005; Powers et al., 2009, Allen et al., 2011; USACE, 2012). As the St. Mary's oyster reef project will begin with new substrate with and without artificially set spat, spat density will be used to assess restoration success in the first year. Survival and growth rates of spat set in the first year and along with biomass will be measured in the second and third year. Long term targets are a mean density of 50 oysters per m^2 and 50 grams dry weight of oyster biomass per m^2 and at least two year classes. These are targets recommended by Allen et al. (2011). However, USACE (2012) suggest that the biomass target of 50 grams dry weight per m^2 will take 6 years to achieve and will require densities of 159 oysters per m^2 and greater to reach the biomass target. Monitoring methods are described below.

For 3-dimensional experimental reefs with a shell veneer we will use methods modified from Luchenbach et al. (2005), Nestlerode et al. (2007) and Powers et al. (2009). Shell will be collected from reefs to a depth of 10 cm within quadrats that are 0.25 m x 0.25 m (0.0625 m^2). Three quadrat samples will be collected from each reef, one from the top of the reef, one from the flank of the reef (0.8 m above the seabed) and one from the base of the reef (0.2 m above the seabed). Position of each quadrate on the reef will be recorded so that the same location will not be sampled more than once. Shell within each quadrate will be collected by SCUBA, placed in mesh bags and transported back to the lab where they will be held in flowing St. Mary's River water until processed. In the first year, live spat will be counted and measured (from the hinge to the ventral shell margin). In addition, "gapers" (dead oysters that have gaping shells and meat inside) and "boxes" (dead oysters with gaping shells but no meat) will be counted. Reefs will be sampled twice in the first year. In the second and third years, live oysters will be counted and placed into three size classes, $\leq$ 25mm (spat), > 25 to less than 75 mm, and oysters $\geq$ 75 mm (market oysters). Harding et al. (2008) and Mann et al. (2009) found that it took between 2 and 3 years for oysters to reach 75 mm. Gapers, boxes and "scars" (marks left from recently detached oysters) will also be counted. Oysters greater than 25 mm will be measured, and the flesh will be harvested, dried and weighed.

The methods described above will also be used to monitor oysters in the 2-dimensional shell oyster bar (3 quadrat samples from areas set with spat and 3 samples from areas with shell that were not set).

For experimental reefs without veneers, oysters will be counted and measured within 0.0625 m^2 quadrats in situ by SCUBA divers. If the concrete rubble is composed of small pieces (15 cm or smaller), then samples may be collected and transported to the lab as described for reefs covered with oyster shell veneers. Oyster biomass will not be measured for these reefs.

Oyster Disease

One of the factors causing the decline of oyster populations in the Chesapeake Bay is diseases (Andrews, 1979). Two protozoan oyster diseases, MSX, caused by *Minchinia nelson*, and Dermo, caused by *Perkinsus marinus*, have caused large-scale mortalities of oysters in the Chesapeake Bay. However, MSX is usually inhibited at salinities found in the St. Mary's River Santuary ($\leq$ 15 ppt; Ford, 1985) and is generally not prevalent in the river (Tarnowski, 2010). Dermo is less affected by salinity and has been prevalent at Pagan Point in the St. Mary's River (Tarnowski, 2011). Since 1990 MSX has been found in 3 annual oyster disease surveys at Pagan Point, whereas Dermo has been found every year and often in prevalence greater than 90% (Fig. 11; Tarnowski, 2011).

As Dermo is prevalent on the Pagan Point reef, a reef near the St. Mary's oyster restoration site (Fig. 2), and vertical relief increases the velocity of flow over a reef, potentially carrying potentially carrying infectious materials away from the reef (Hargis and Haven, 1999; Lenihan, 1999), we recommend the monitoring of the prevalence of infected oysters on the experimental reefs and adjacent sampling sites on the shell bar reef. Dermo usually sporulate annually in May-June, so it is best to monitor the oysters for the diseases from August to October (Andrews, 1979). Two methods that are used to identify the disease are the thioglycolate assay and a PCR-based assay (Robledo et al., 1998; Villalba et al., 2004). Dermo prevalence will be determined with the Ray's fluid thioglycollate medium (RFTM) assay (Burreson, 2009; Paynter et al., 2010) for this project as this assay is used for the Maryland fall oyster surveys (Tarnowski, 2011) and will allow for comparison to the reference reef at Pagan Point. As disease prevalence increases with age (Paynter et al., 2010) and does not normally appear until the oysters are 2 years and older, disease monitoring will begin two years after construction of the reefs. Analyses will either be conducted at St. Mary's College or by staff of the Oyster Disease Research Project at the Cooperative Oxford Laboratory. We have been touch with the staff of this lab, and they are willing to train SMCM faculty members in the methods for detecting oyster diseases.

Ecosystem Services

Restoring ecosystem services provided by oyster reefs is the overarching goal for this and most other oyster restoration projects (Coen and Luckenbach, 2000; Luchenbach et al., 2005; Allen et al., 2011). Ecosystem services performed by oysters and oyster reefs include providing habitat for a diverse faunal community, biofiltration of phytoplankton and suspended solids and related nutrient removal, improved water clarity and stabilization of the bottom and shoreline (Nelson, et al., 2004; Walters and Coen, 2006).

Oyster Reef Community

In addition to providing a habitat for oyster settlement and growth, oyster reefs play an important role in the development of diverse biotic communities. Three-dimensional oyster reefs in particular provide an area for refuge, nesting and foraging for many species, and, thus, the success of an oyster reef should not be solely based on the abundance of harvestable-sized adult oysters (Luckenback et al. 2005). One way to understand and document the health of a habitat is through measurement of the biodiversity of the organisms residing in the area. Studies have documented that a higher amount of biodiversity is found on an oyster reef than on an adjacent oyster-barren, sedimentary habitat (Coen and Luckenback, 2000).

We recommend methods described in Luckenback et al. (2005) and Coen et al. (2007) for quantifying reef-associated fauna. To sample small animals (fishes and crustaceans) resident within the reef, 30 cm diameter baskets will be filled with oyster shells or concrete rubble (for reefs constructed from concrete rubble without veneers) and will be embedded into the surface of the reefs. For reefs constructed of Reef Balls™ without veneers, the baskets will be filled with oyster shell. The baskets will be constructed of 30 cm diameter PVC pipe, cut into 15 cm lengths. The bottom end and three 15 cm oval shaped holes on the side will be covered with 1 mm mesh to allow for exchange of water with the surrounding reef. The baskets will be periodically retrieved and transported to the lab for processing. Animals will be removed from the baskets, preserved and later identified and enumerated. Transient species will be estimated using minnow traps placed on the top of 3-dimensional reefs and on the shell bar area. Other methods such as seines, trawls and/or gill nets may also be used to sample transient species (see http://www.oyster-restoration.org/metrics/metricspdfs/AssocFauna01.pdf for a list of methods for monitoring fauna associated with oyster reefs).

Water Quality

Oysters may improve water quality by filtering suspended solids and algae from the water column (Nelson et al., 2004), with reductions in chlorophyll a concentrations (an indicator of phytoplankton densities) as high as 75% (Dame et al., 1984). The filtered solids and phytoplankton, and their associated nutrients, are then extruded from the oyster in the form of feces and pseudofeces (Kennedy, et al., 1996). Lower suspended solids and phytoplankton densities can reduce the severity of hypoxia in deep water (Newell, 1988), and improved water clarity from oyster biofiltration may facilitate the restoration of submerged aquatic vegetation (Newell and Koch, 2004).

However, the degree to which oysters can control phytoplankton blooms and reduce hypoxia in the Chesapeake Bay has been debated (Pomeroy et al., 2006; Newell et al., 2007; Pomeroy et al., 2007). On a smaller scale, Nelson et al. (2003) examined the effectiveness of small (2 x 3 m) transplanted oyster reefs in improving water quality in tidal creeks in Virginia. They found that average concentration of suspended solids both upstream and downstream of the oyster reef were lower most of the year; however, the oyster reefs did not have a significant impact on chlorophyll a concentrations until they were enlarged to 3 x 4 m. Plutchak et al. (2010) found no impact of restored oyster reefs on suspended solids and phytoplankton in tidal creeks along the Gulf of Mexico. In their study the reefs made up 10% of the area of the tidal creeks with target densities of 150 adult oysters per m^2. They concluded that it is difficult to measure the effects of oyster biofiltration on water quality because they are localized and short-lived.

The St. Mary's River oyster reef restoration project will create 3-dimensional reefs that represent around 0.01% of the area of the St. Mary's River Oyster Sanctuary (0.2% if the adjacent oyster shell bar is included), so the effects of the reefs on the overall water quality of the upper river will not be measurable. However, we predict that there will be localized improvements to water quality between and shoreward of the reefs. Although there are many varied indicators of water quality, the ones most directly impacted by oyster filtration are total suspended solids (TSS), the phytoplankton pigments chlorophyll a and phaeophytin, oxygen content, nitrogen concentrations and water clarity. Other parameters that affect oyster survival, growth and disease prevalence include sedimentation, temperature and salinity.

To determine the effects of the reefs on water quality we recommend that three stations be monitored along a transect as shown in Fig. 9. One station will be seaward of the restoration area, a second will be between the rows of the experimental reefs and a third will be shoreward of the reefs. A fourth station will be in the center of the south restoration area over the shell bar. A fifth station will be located to the north of the restoration site at approximately the same distance from shore as experimental reefs (Fig. 9). A sixth reference station will be located over the natural oyster reef at Pagan Point (Fig. 2). The following parameters should be monitored at these stations every two weeks from early March until the end of October after the reefs are established.

- Temperature, salinity, oxygen, pH and chlorophyll a using a YSI 6600 Sonde (an electronic water quality monitoring device). Measurements will be taken at 0.5 m interval from the surface to the bottom.
- Water clarity using either a Secchi disk or Licor submarine irradiance sensors.
- Total suspended solids. Water samples will be collected at a depth of 0.5 m and filtered through pre-weighed GF (glass fiber) filters. The filters will be frozen until they can be processed at the Nutrient Analytical Services Laboratory (NASL; http://nasl.cbl.umces.edu/) at the Chesapeake Biological Laboratory (CBL).
- Chlorophyll a and phaeophytin concentrations. A more accurate method than using the YSI Sonde to measure chlorophyll a is to filter water samples on GF filters, have the samples extracted and the extract analyzed with a fluorometer or spectrophotometer. The filters will be frozen until they can be analyzed by the NASL at the CBL.
- Nitrogen concentrations as an indicator of the effects of the reef on nutrients. Water will be filtered through GF filters to remove TSS and phytoplankton, placed in vials and frozen until they can be analyzed for ammonia, nitrite and nitrate by the NASL at the CBL.

In addition to monitoring periodically at these stations, we recommend that temperature and salinity be monitored continuously by placing a HOBO Conductivity Data Logger underwater on one of the pilings or buoys that mark the periphery of the restoration area. Alternatively, the continuous monitoring station on the St. Mary's College pier can be upgraded and maintained. This station, which is not currently functional, uses YSI Sondes that record the parameters listed in the first bullet above. Relative current flow rates at the top, flank and base of the 3-dimensional reefs can be measured using plaster blocks that dissolve at rates relative to the flow of water around them (Coen et al., 2007). Finally, sedimentation rates can be measured at the top, flank and base of 3-dimensional reefs using sediment traps as described in Lenihan and Peterson (1998).

Cost Estimates

Reef Construction

We estimate the cost of the first phase (pilot project) to be $18,682 (Table 3). These funds would be used to construct the six mound reefs discussed in the Recommended Reef Design section. Approximately 165 tons of crushed concrete would be used for the 3 reefs with concrete cores while 75 Reef Balls™ would be used to make up the cores of these three reefs. The cost of 3 concrete core reefs is $5,709, and the price of three reef ball core reefs is $4,711., and this price includes $3,646 for two Reef Ball™ molds (Bay Ball model). A 20 cm oyster veneer for four of the six reefs will cost approximately $2,362, while marking of the site with buoys will require $1,900. We estimate that the placement of materials on the study site will require a heavy industrial barge with front end loader to pick up and deposit both concrete rubble and Reef Balls™ at specific locations and depths. We estimate that this will cost approximately $4,000.

Table 3. Pilot project cost estimates.

Reef type	Concrete core	Reef ball core	Totals
(Prices per reef)			
Crushed concrete	$903		
Transportation	$1,000		
Readimix concrete and additives		$355	
	$1,903	$355	$2,258
Total for 6 reef cores			$6,774
Bay Ball molds			$3,646
Oyster shell veneer (two reefs)	$1,181	$1,181	$2,362
Barge and materials deployment			$4,000
Study site marking buoys			$1,900
Total pilot project cost			**$18,682**

This cost estimate assumes that Rotary will want to take the opportunity to have Rotarians and other citizen volunteers involved in the building of the reefs and Reef Balls™ as an investment in the project's success. Therefore, we have not included any labor costs apart from barge personnel for the placement of materials. The cost of this material placement is only an estimate and the price quite fluid. We expect that pricing will be based on bids received from marine construction contractors at the time the reefs are built. The seeding of the reefs with spat on shell also has not been included in the cost estimate as we presumed that this seeding material would be provided by the St. Mary's River Watershed Association. We also should note that our estimates are based on the purchase of all materials. Considerable (up to approximately $10,000) cost savings might be achieved if recycled concrete could be obtained from some local demolition project or if an oyster shell donor could be located. Consequently, the cost of the pilot project should be viewed as a rough estimate rather than an empirical value.

In estimating the cost of the second phase of the project we assumed that the total reef build out would include 18 mound reefs with the three different treatments used in the pilot study. Each of the reefs in phase two is larger and has greater core volumes than the pilot study reefs. This is because phase two reefs are located further from the shore compared to the pilot study reefs (Fig. 9). In addition, the reef ball reefs have a slightly different configuration in phase two of the project compared to the pilot study. In the pilot study we will make special provisions for stacking layers of Reef Balls™. However, this will not be possible when the reef ball core will be 2.0 and 2.5 m high. Because it is inadvisable to stack Reef Balls™, we propose that the same size balls and the same configuration from the pilot study, but that the Reef Balls™ rest on either a 0.5 or 1.0 m crushed concrete base, to build these reefs to a height of 2.0 and 2.5 m, respectively. The estimated budget for phase two adjusts for these changes in water depth at the study site.

Therefore, we based the cost of the second phase (Table 4) on the construction of 18 mound reefs and placement of shell on the 2.2 acre southern portion of the study area (identified as the shell bar area in the permit application). The base price for the cores and veneers of all 18 reefs is $48,630, and we estimate that $12,000 will be required for the placement of materials from a barge with front-end loader. A large part of phase two expense is shell for the south part of the study area. To place 0.2 m of shell on the entire 7,808 square meter (2.2 acre) shell bar would require 1,562 cubic meters of shell at $118,172. Obviously, this cost could be halved by using a 0.1 m thickness or by reducing the area by half. Therefore, we estimate that the total cost of the second phase would be $178,802. We are making the same project budget assumptions for the second phase of the project as we did for the pilot project.

Table 4. Cost estimates for second phase and build out of 2.8 acre 3-dimensional reef (north) area and 2-dimensional bar (south) area. Heights of reefs (h) are variable because of water depth.

Reef type	Concrete core 2.5 m h	Concrete core 2.0 m h	Reef ball core 2.5 m h	Reef ball core 2.0 m h	Totals
(Prices per reef)					
Crushed concrete (tons)	94.4	75.4	37.7	18.8	
Crushed concrete (cost)	$3,602	$2,782	$1,996	$1,175	
Transportation	$2,000	$1,500	$1,000	$500	
Readimix concrete and additives			$355	$355	
Oyster shell veneer	$762	$673	$762	$673	
Number of reefs	4	5	4	5	
Total for reef cores	$15,933	$16,608	$7,519	$8,570	$48,630
Barge and materials deployment					$12,000
Oyster shell for 2-dimensional reef (south part of study site)					$118,172
Total phase two project cost					**$178,802**

Monitoring

We recommend three years of monitoring beginning after the complete of the construction of the reefs. Water quality monitoring will take place twice a month from early March through October. We recommend 6 monitoring stations, so this is a total 96 samples for each parameter per year

(16 sampling periods x 6 stations). Oyster monitoring, reef community characteristics and oyster disease can be monitored less frequently (twice a year is adequate). While the monitoring will be planned and supervised by SMCM faculty, much of the actual monitoring will be done by SMCM students and community volunteers trained by SMCM faculty members. Estimated costs are described in Table 5.

Table 5. Monitoring costs over a three year period.

Monitoring Type		Year 1	Year 2	Year 3
Oyster Monitoring				
	SCUBA rentals & air	$500	$500	$500
	Miscellaneous supplies	$100	$100	$100
Oyster Disease				
	Stains & reagents	$100	$100	$100
Water Quality Monitoring				
	Service to YSI 6600 Sonde	$2,000		
	Onset HOBO Salinity/Temperature Logger (underwater)	$1,200		
	TSS Samples ($4.25 per sample x 96 samples)	$408	$408	$408
	Chlorophyll a ($6.75 per sample x 96 samples)	$648	$648	$648
	Phaeophytin ($1.50 per sample x 96 samples)	$144	$144	$144
	Nitrogen (NH3, NO2, NO3) ($12.00 per sample x 96 samples)	$1,152	$1,152	$1,152
	Miscellaneous supplies for current flow rate and sedimentation	$200	$200	$200
Boat Use				
	Gas and maintenance	$1,000	$1,000	$1,000
Planning and Supervision by SMCM Faculty		$2,000	$2,000	$2,000
Student Intern (Summer)		$4,000	$4,000	$4,000
TOTAL		**$13,452**	**$10,252**	**$10,252**
TOTAL FOR ALL 3 YEARS				**$33,956**

Literature Cited

Allen, S., A.C. Carpenter, M. Luckenbach, K. Paynter, A. Sowers, E. Weissberger, J. Wesson, and S. Westby. 2011. Restoration Goals, Quantitative Metrics and Assessment Protocols for Evaluating Success on Restored Oyster Reef Sanctuaries. *Report of the Oyster Metrics Workgroup, Submitted to the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program.*, Annapolis, MD, USA.

Andrews J.D. 1979. Oyster diseases in the Chesapeake Bay. *Marine Fisheries Review* 41: 45-53.

Bartol, I. K., R. Mann, and M. Luckenbach. 1999. Growth and mortality of oysters (*Crassostrea virginica*) on constructed intertidal reefs: Effects of tidal height and substrate level. *Journal of Experimental Marine Biology and Ecology* 237: 157-184.

Beck, M.W., R.D. Brumbaugh, L. Airoldi, A. Carranza, L.D. Coen, C. Crawford, O. Defeo, G.J. Edgar, B. Hancock, M.C. Kay, H.S. Lenihan, M.W. Luckenbach, C.L. Toropova, G. Zhang & X. Guo. 2011. Oyster reefs at risk and recommendations for conservation, restoration, and management. *BioScience* 61, 107–116.

Blankenship, K. 2006. Scientist's hope to get Bay's oyster restoration rolling with reef balls. Website http://www.bayjournal.com/article.cfm?article=2951 [Accessed 3 April 2012].

Brumbaugh, R. D. and L. D. Coen. 2009. Contemporary approaches for small-scale oyster reef restoration to address substrate versus recruitment limitation: A review and comments relevant for the Olympia oyster, *Ostrea lurida* carpenter 1864. *Journal of Shellfish Research* 28: 147-161.

Burke, R. P. 2010. Alternative substrates as a native oyster (*Crassostrea virginica*) reef restoration strategy in the Chesapeake Bay. PhD dissertation, Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, Virginia, USA.

Burreson, E. M. 2009. Infection with *Perkinsus marinus*. pp. 342–353 In: Manual of diagnostic tests for aquatic animals, 6th edition. Office International des Epizooties, Paris, France.

Campbell, E. 2008. Oyster restoration in Maryland. Website http://www.dnr.state.md.us/fisheries/recreational/articles/oysterrestoration.html [Accessed 2 April 2012].

Chatry, M.C., Dugas and G. Laiche. 1986. Comparison of oyster setting rates on clamshell and crushed limestone. *Louisiana Wildlife and Fisheries Commercial Technical Bulletin* 40:54-60.

Coen, L.D., R.D. Brumbaugh, D. Bushek, R. Grizzle, M.W. Luckenbach, M.H. Posey, S.P. Powers and S.G. Tolley. 2007. Ecosystem services related to oyster restoration. *Marine Ecology Progress Series* 341: 303–307.

Coen, L. D. and R. E. Grizzle. 2007. The importance of habitat created by molluscan shellfish to managed species along the Atlantic coast of the United States. ASMFC Habitat Management Series #8, Atlantic States Marine Fisheries Commission, Washington, D.C., USA.

Coen, L.D. and M.W. Luckenbach. 2000. Developing success criteria and goals for evaluating oyster reef restoration: Ecological function or resource exploitation? *Ecological Engineering* 15: 323-343.

Coen, L., K. Walters, D. Wilber, and N. Hadley. 2007. A South Carolina Sea Grant report of a 2004 workshop to examine and evaluate oyster restoration metrics to assess ecological function, sustainability, and success: Results and Related Information. South Carolina Sea Grant, Charleston, SC, USA.

Dame, R. F. 1996. Ecology of Marine Bivalves. CRC Press, Boca Raton, FL, USA.

Dame, R. F., R. G. Zingmark, and E. Haskin. 1984. Oyster reefs as processors of estuarine materials. *Journal of Experimental Marine Biology and Ecology* 83:239-247.

Eastern Oyster Biological Review Team. 2007. Status review of the eastern oyster (*Crassostrea virginica*). Report to the National Marine Fisheries Service, Northeast Regional Office, Gloucester, MA, USA.

Ford, S. E. 1985. Effects of salinity on survival of the MSX parasite *Haplosporidium nelsoni*. (Haskin, Stauber and Mackin) in oysters. *Journal of Shellfish Research* 5: 85-90.

Greenhawk, K., T. O’Connell, and L. Barker. 2007. Oyster population estimates for the Maryland portion of the Chesapeake Bay 1994-2006. Maryland Department of Natural Resources, Fisheries Service, Annapolis, MD, USA.

Grizzle, R.E., J.K. Greene, and L.D. Coen, 2008. Seston removal by natural and constructed intertidal eastern oyster (*Crassostrea virginica*) reefs: a comparison with previous laboratory studies, and the value of *in situ* methods. *Estuaries and Coasts* 31:1208-1220.

Harding, J. M., R. Mann, and M. Southworth. 2008. Shell length at-age relationships in James River, Virginia oysters (*Crassostrea virginica*) collected four centuries apart. *Journal of Shellfish Research* 27: 1109–1115.

Hargis, W. J., and D. S. Haven. 1995. The precarious state of the Chesapeake public oyster resource. pp. 559-584. *In* P. Hill and S. Nelson (eds.) Proceedings of the 1994

Chesapeake Research Conference, Towards a Sustainable Coastal Watershed: The Chesapeake Experiment. Chesapeake Research Consortium No. 149, Chesapeake Research Consortium, Edgewater, MD, USA.

Hargis, W. J., and D. S. Haven. 1999. Chesapeake oyster reefs, their importance, destruction, and guidelines for restoring them. pp. 329-358. *In* M. W. Luckenbach, R. Mann, and J. A. Wesson (eds) Oyster Reef Habitat Restoration: A synopsis and synthesis of approaches. Virginia Institute of Marine Science, Gloucester Point, VA, USA.

Jackson J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J.Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S.Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J.Tegner, and R.R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629-637.

Kemp, W.M., P. Bergstrom, E. Koch, L. Murray, J.C. Stevenson, R. Bartleson, et al. 2004. Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: water quality, light regime, and physical chemical factors. *Estuaries* 27:363–377.

Kemp, W. M., W. R. Boynton, J. E. Adolf, D. F. Boesch, W. C. Boicourt, G. Brush, J. C. Cornwell, T. R. Fisher, P. M. Gilbert, j. D. Hagy, L. W. Harding, E. D. Houde, D. G. Kimmel, W. D. Miller, R. I. E. Newell, M. R. Roman, E. M. Smith, J. C. Stevenson. 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. *Marine Ecology Progress Series*: 303: 1-29.

Kennedy, V.S., R.I.E. Newell, and A.F. Eble. 1996. The Eastern Oyster. Maryland Sea Grant College, University of Maryland System, College Park, Maryland, U.S.A.

Kennedy, V.S., D.L. Breitburg, M.C. Christman, M.W. Luckenbach, K. Paynter, J. Kramer, K.G. Sellner, J. Dew-Baxter, C. Keller and R. Mann. 2011. Lessons learned from efforts to restore oyster populations in Maryland and Virginia, 1990-2007. *Journal of Shellfish Research* 30: 719–731

Kirby, M.X. and H.M. Miller. 2005. Response of a benthic suspension feeder (*Crassostrea virginica* Gmelin) to three centuries of anthropogenic eutrophication in Chesapeake Bay. *Estuarine, Coastal and Shelf Science* 62: 679-689.

Lenihan, H. S. 1999. Physical-biological coupling on oyster reefs: How habitat structure influences individual performance. *Ecological Monographs* 69: 251-275.

Lenihan, H. S. and C.H. Peterson. 1998. How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs. *Ecological Applications* 8: 128-140.

Lenihan, H.S., C.H. Peterson, and J.M. Allen. 1996. Does flow speed also have a direct effect on growth of active suspension feeders: an experimental test on oysters *Crassostrea virginica* (Gmelin). *Limnology and Oceanography* 41: 1359-1366.

Luckenbach, M.W., L.D. Coen, P. G. Ross, Jr., and J.A. Stephen, 2005. Oyster reef habitat restoration: relationships between oyster abundance and community development based on two studies in Virginia and South Carolina. *Journal of Coastal Research (Special Issue)* 40:64-78.

LWFW (Louisiana Department of Wildlife and Fisheries). 2004. Final report for Louisiana's oyster shell recovery pilot project. Baton Rouge, LA, USA.

Mann, R. and E. N. Powell. 2007. Why oyster restoration goals in the Chesapeake Bay are not and probably cannot be achieved. *Journal of Shellfish Research* 26: 905-917.

Mann, R., M. Southworth, J. M. Harding, and J. Wesson. 2009. Population studies of the native oyster, *Crassostrea virginica* (Gmelin), in the James River, Virginia, USA. *Journal of Shellfish Research* 28:193–220.

MD DNR. 2010. Oyster Sanctuaries of the Chesapeake Bay and Its Tidal Tributaries. Maryland Department of Natural Resources (September 2010).

Miller, H. M. 1986. Transforming a "splendid and delightsome land": Colonists and ecological change in the Chesapeake 1607-1820. Journal of the Washington Academy of Sciences 76:173-187.

MOAC (Maryland Oyster Advisory Commisssion). 2009. Implementation of House Bill 133 Natural Resources – Chesapeake Bay – Oyster Restoration. Maryland Oyster Advisory Commission's 2008 Report Implementation of House Bill 133 Concerning Maryland's Chesapeake Bay Oyster Management Program. Submitted to the Governor and General Assembly (January 2009).

Moroney, D. A. and R. L. Walker. 1999. The effects of tidal and bottom placement on the growth, survival and fouling of the eastern oyster *Crassostrea virginica. Journal of the World Aquaculture Society* 30: 433-442

National Marine Fisheries Service. 2012. Annual commercial landing statistics. Website:http://www.st.nmfs.noaa.gov/pls/webpls/mf_annual landings.results [Accessed 17 May 2012].

National Oceanic and Atmospheric Administration (NOAA). 2012. Chesapeake Bay Program, Oyster restoration. Website: http://chesapeakebay.noaa.gov/oysters/oyster-restoration [Accessed 2 April 2012].

Nelson, K.A., L.A. Leonard, T.D. Posey, A. Mallin, and M.A.Mallin. 2004. Using transplanted oyster (*Crassostrea virginica*) beds to improve water quality in small tidal creeks: a pilot study. *Journal of Experimental Marine Biology and Ecology* 298: 347-368.

Nestlerode, J. A., M.W. Luckenbach, and F.X. O'Beirn. 2007. Settlement and survival of the oyster *Crassostrea virginica* on created oyster reef habitats in the Chesapeake Bay. *Restoration Ecology* 15: 273-283.

Newell, R. I. E. 1988. Ecological changes in the Chesapeake Bay: Are they the result of overharvesting the American oyster (*Crassostrea virginica*)? pp. 536-546. *In* Understanding the estuary: Advances in Chesapeake Bay research, Chesapeake Research Consortium Publication 129, Chesapeake Research Consortium, Edgewater, Maryland, USA.

Newell, R.I.E. and E.W. Koch. 2004. Modeling seagrass density and distribution in response to changes in turbidity stemming from bivalve filtration and seagrass sediment stabilization. *Estuaries* 27: 793-806.

Newell, R.I.E., W.M. Kemp, J.D. Hagy III, C.A. Cerco, J.M. Testa, and W.R. Boynton. 2007. Top-down control of phytoplankton by oysters in Chesapeake Bay, USA: Comment on Pomeroy et al. (2006). *Marine Ecology Progress Series* 341:293–298.

O'Beirn, F.X., M.W. Luckenbach, J.A. Nestlerode, and G.M. Coates. 2000. Toward design criteria in constructed oyster reefs: Oyster recruitment as a function of substrate type and tidal height. *Journal of Shellfish Research* 19(1):387-395.

Orth, R. J., T.J.B. Carruthers, W.C. Dennison, C.M. Duarte, J.W. Fourqurean, K.L. Heck Jr, A.R. Hughes, G.A. Kendrick, W.J. Kenworthy, S. Olyarnik, F.T. Short, M Waycott, and S.L. Williams. 2006. A global crisis for seagrass ecosystems. *BioScience* 56:987–996.

Paynter, K. T., Jr. 1996. Introduction to the 1996 edition, pp. ix-xxxi. *In* W. K. Brooks. The Oyster. The Johns Hopkins University Press, Baltimore, Maryland, USA.

Paynter, K. P., V. Politano, H. A. Lane, S. M. Allen, and D.Meritt. 2010. Growth rates and *Perkinsus marinus* prevalence in restored oyster populations in Maryland. *Journal of Shellfish Research* 29:309–317.

Plutchak, R. R., K. Major, J. Cebrian, C. D Foster, M. E. Miller, A. Anton, K. L. Sheehan, K. L. Heck and S. P. Powers. 2010. Impacts of oyster reef restoration on primary productivity and nutrient dynamics in tidal creeks of the North Central Gulf of Mexico. *Estuaries and Coasts* 33: 1355-1364.

Pomeroy, L.R., C.F. D'Elia, L.C. Schaffner. 2006. Limits to top-down control of phytoplankton by oysters in Chesapeake Bay. *Marine Ecology Progress Series* 325:301–309.

Pomeroy, L.R., C.F. D'Elia, L.C. Schaffner. 2007. Top-down control of phytoplankton by oysters in Chesapeake Bay, USA: Reply to Newell et al (2007). *Marine Ecology Progress Series* 341: 299–301.

Powers, S.P., C.H. Peterson, J.H. Grabowski, and H.S. Lenihan. 2009. Success of constructed oyster reefs in no-harvest sanctuaries: Implications for restoration. *Marine Ecology Progress Series* 389: 159-170.

Robledo J. A. F., J. D. Gauthier, C. A. Coss, A. C. Wright., and G. R. Vasta. 1998. Species-specificity and sensitivity of a PCR- based assay for *Perkinsus marinus* in the eastern oyster, *Crassostrea virginica*: a comparison with the fluid thioglycollate assay. *Journal of Parasitology*. 84: 1237-1244.

Reef Ball Foundation. 2011. The reef-ball foundation-designed artificial reefs. Website http://www.reefball.org/ [Accessed 3 April 2012].

Rothschild, B. J., J. S. Ault, P. Goulleetuer, and M. Heral. 1994. Decline of the Chesapeake Bay oyster population: A century of habitat destruction and overfishing. *Marine Ecological Progress Series* 111:29-39.

Schulte, D.M., R.P. Burke, and R.N. Lipcius. 2009a. Unprecedented restoration of a native oyster metapopulation. *Science* 325: 1124-1128.

Schulte, D., G. Ray, and D. Shafer. 2009b. Use of alternative materials for oyster reef construction. EMRRP Technical Notes Collection (ERDC TN-EMRRP-ER-12). U.S. Army Engineer Research and Development Center, Vicksburg, MS, USA.

Scyphers, S.B., S.P. Powers, K.L. Heck Jr, and D. Byron. 2011. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS ONE* 6(8): e22396.

Seliger, H. H. and J. A. Boggs. 1988. Evidence for loss of habitat for oysters in tributaries of the Chesapeake Bay. pp. 111-127. *In* Understanding the estuary: Advances in Chesapeake Bay Research. U.S. EPA CBPITRS 24/88. CRC Publication 129. Chesapeake Bay Research, Solomons, MD, USA.

Soniat, T.M., R.C. Broadhurst III, and E.L. Haywood III. 1991. Alternatives to clamshell as cultch for oysters, and the use of gypsum for the production of cultchless oysters. *Journal of Shellfish Research* 10: 405-410.

Soniat, T.M. and G.M. Burton. 2005. A comparison of the effectiveness of sandstone and limestone as cultch for oysters, *Crassostrea virginica. Journal of Shellfish Research* 24: 483-485.

South Carolina Department of Natural Resources. 2012. Oyster recycling and restoration program. Website http://saltwaterfishing.sc.gov/oyster.html [Accessed 2 April 2012].

Tarnowski, M. 2011. Maryland Oyster Population 2010 Fall Survey. Maryland Department of Natural Resources. Mitchell Tarnowski, Editor. Shellfish Program and Cooperative Oxford Laboratory, MDNR Publ. No. 17-7302008-328 (August 2010).

The Bay Journal. 2001. VA officials predict oyster reef will be 'flush' with success. http://www.bayjournal.com/article/va_officials_predict_oyster_reef_will_be_flush_with_success [Accessed 17 May 2012].

The Bay Journal. 2004. Cast-off toilets flush with oysters after two years. Website http://www.bayjournal.com/article.cfm?article=2415 [Accessed 5 April 2012].

USACE. 2006. St. Mary's River, St. Mary's College, St. Mary's County, Maryland Section 103 Small Beach Erosion Control Project. U.S. Army Corps of Engineers Baltimore Baltimore District, Baltimore, MD, USA.

USACE. 2012. Chesapeake Bay oyster recovery: Native oyster restoration master plan. Maryland and Virginia, U.S. Army Corps of Engineers Baltimore and Norfolk Districts.

Villalba, A., K. S. Reece, M. C. Ordás, S. M. Casas, and A. Figueras. 2004. *Perkinsosis* in molluscs: a review. *Aquatic Living Resources*. 17, 411-432.

Walters, K., and L.D. Coen, 2006. A comparison of statistical approaches to analyzing community convergence between natural and constructed oyster reefs. *Journal of Experimental Marine Biology and Ecology* 330:81-95.

Wilberg, M.J., M.D. Livings, J.S. Barkman, B.T. Morris, and J.M. Robinson. 2011. Overfishing, disease, habitat loss, and potential extirpation of oysters in upper Chesapeake Bay. *Marine Ecology Progress Series* 436, 131-144.

Wharton, J. 1957. The bounty of the Chesapeake: fishing in Colonial Virginia. Jamestown 350th Anniversary Historical Booklet No. 13, Virginia 350th Anniversary Celebration Corporation, Williamsburg, Virginia, USA.

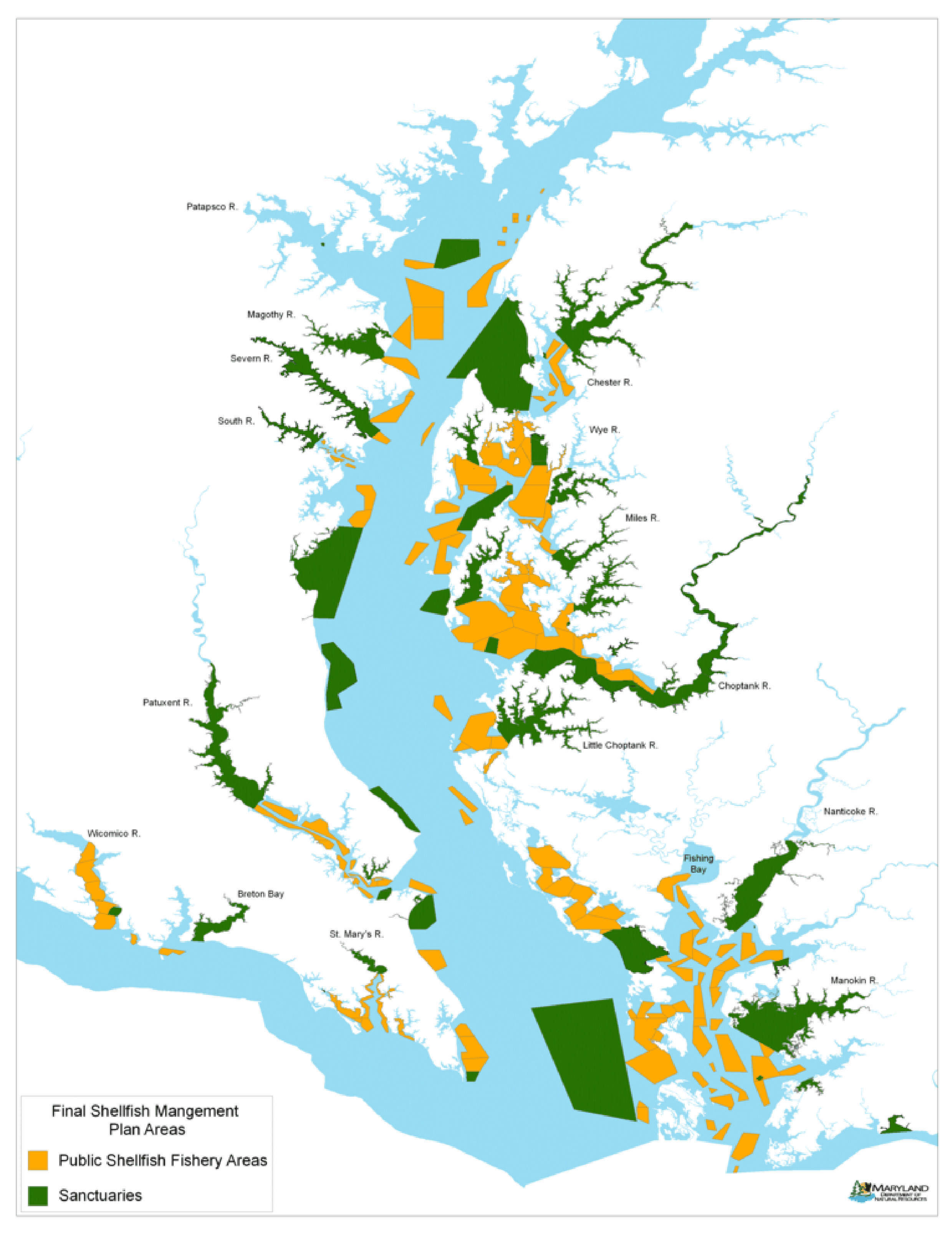
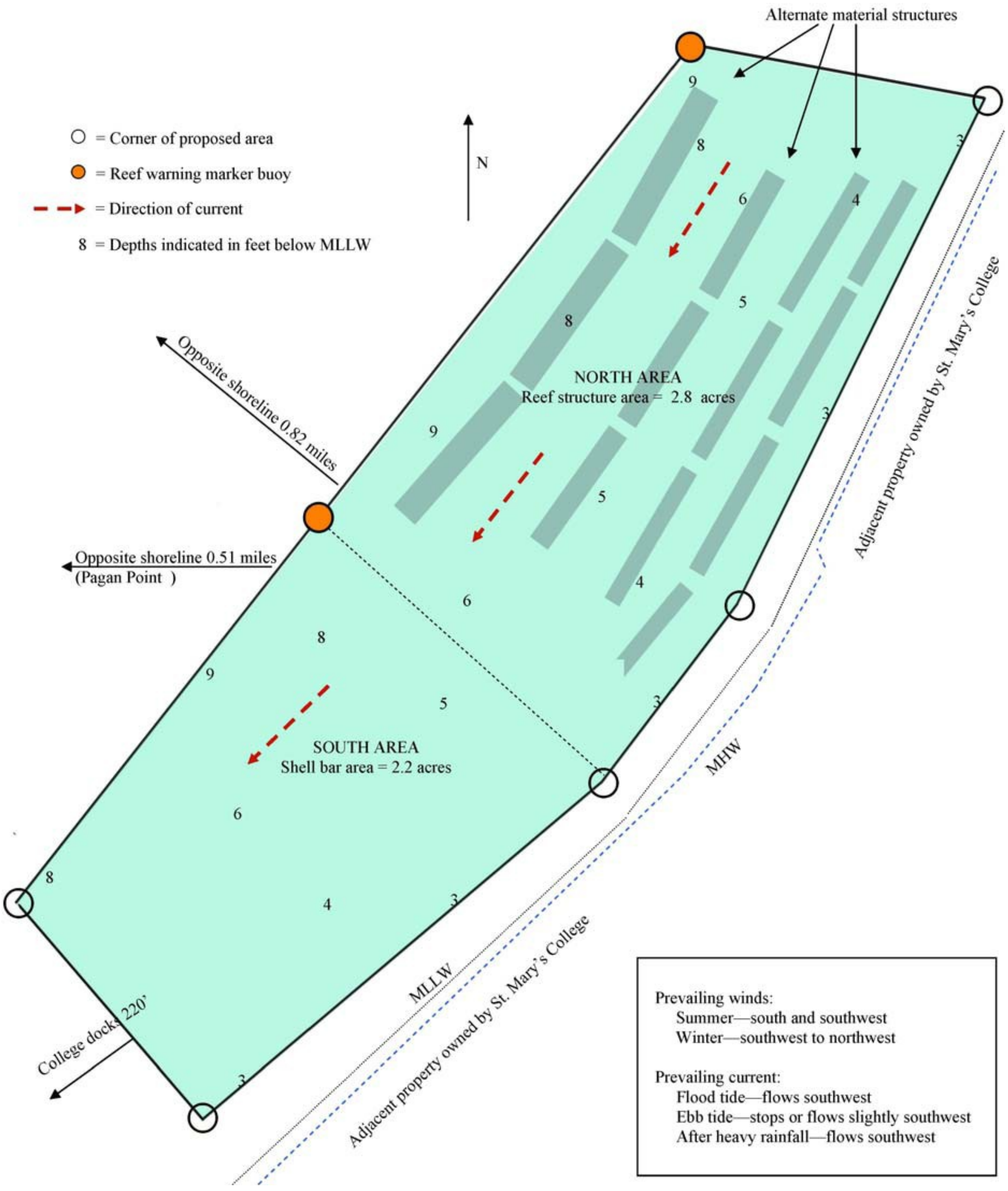


Figure 1. Oyster sanctuaries and public shellfish fishery areas in the Chesapeake Bay (http://www.dnr.state.md.us/fisheries/oysters/eco_resto/sanctuaries.asp).

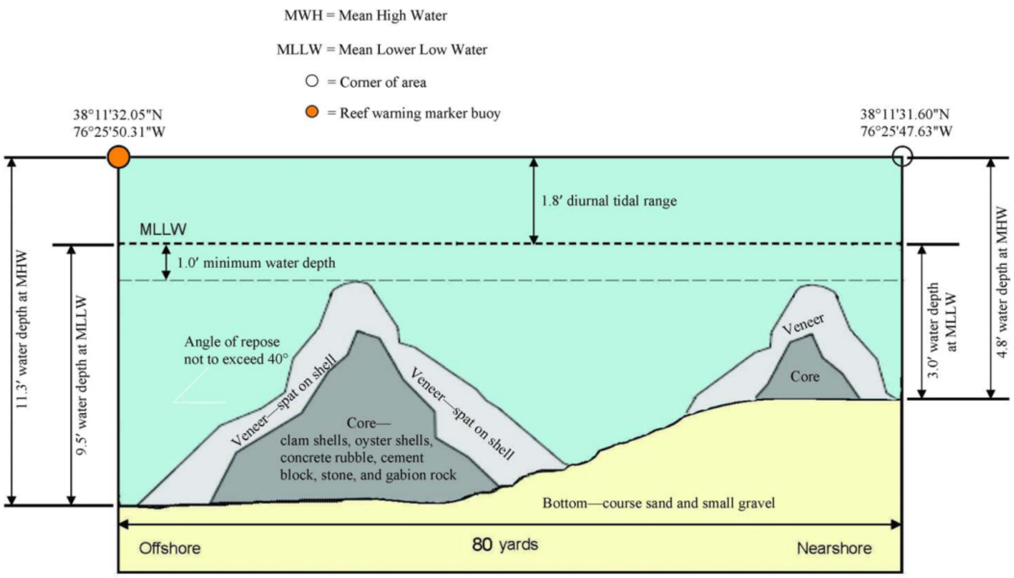
Figure 2. Location of oyster restoration area adjacent to St. Mary's College of Maryland and the natural reference reef at Pagan Point.



Prevailing winds:
Summer—south and southwest
Winter—southwest to northwest

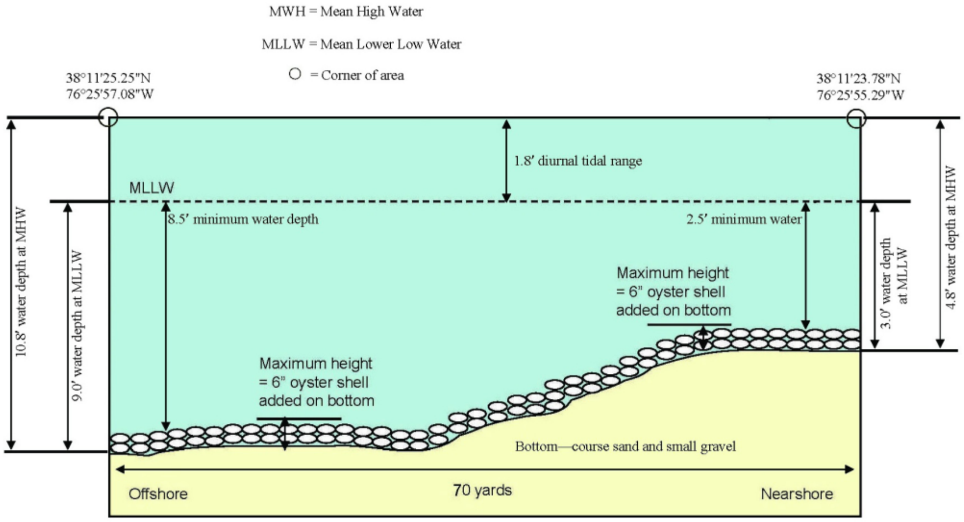
Prevailing current:
Flood tide—flows southwest
Ebb tide—stops or flows slightly southwest
After heavy rainfall—flows southwest

Figure 3. Layout of reef restoration area (from SMRWA permit application).



Linear reef structures:
- vary in height from 2.0′ to 8.5′
- never exceed a height of 1.0′ below MLLW
- vary in length from 15.0′ to 175.0′
- vary in width dependent on height—approx. 2-1 ratio (width -height)
- angle of repose from 25 to 40 degrees

Figure 4. Cross-sectional view of the 3-deminsional oyster reef (from SMRWA permit application).



Target depth of shell added to bottom is 3 inches. Maximum depth of shell added to bottom is 6 inches in any one location.

Shell type will be either oyster or clam, or a combination of both. Permits for importation are required.

Figure 5. Cross-sectional view of the shell pile oyster reef (from SMRWA permit application).

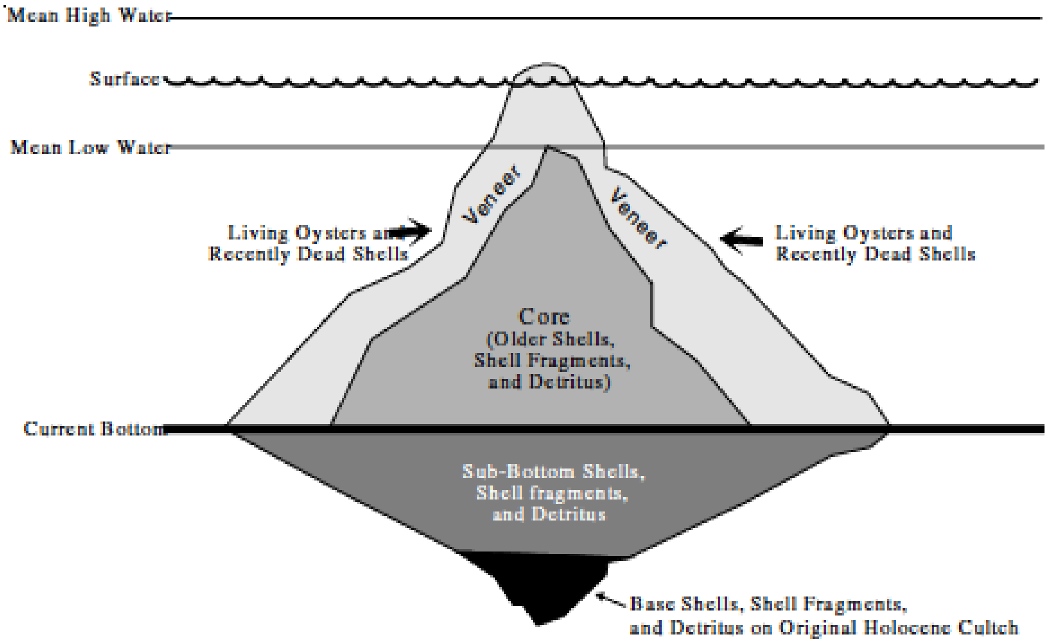


Figure 6. Historic oyster reef structure (Hargis and Haven, 1999).

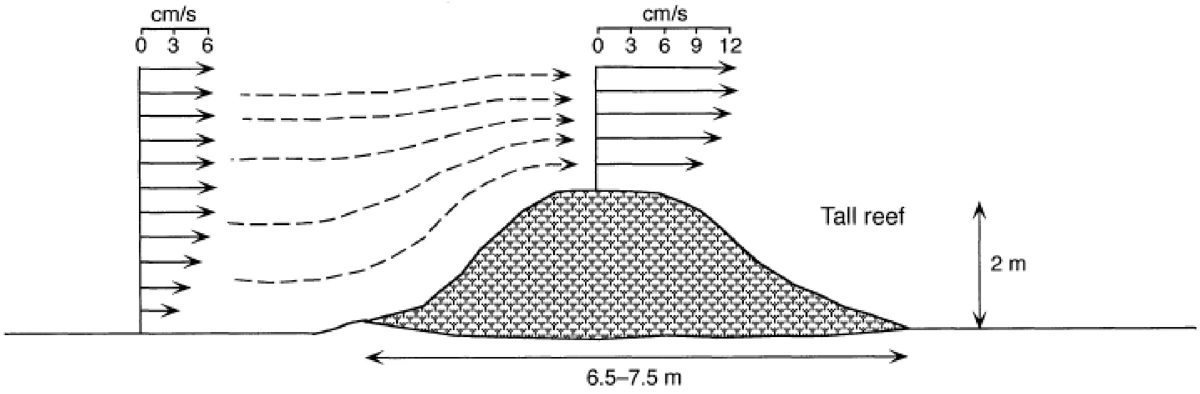


Figure 7. Current velocity increases as water flows over 3-demensional reefs. (From Lenihan, 1999).

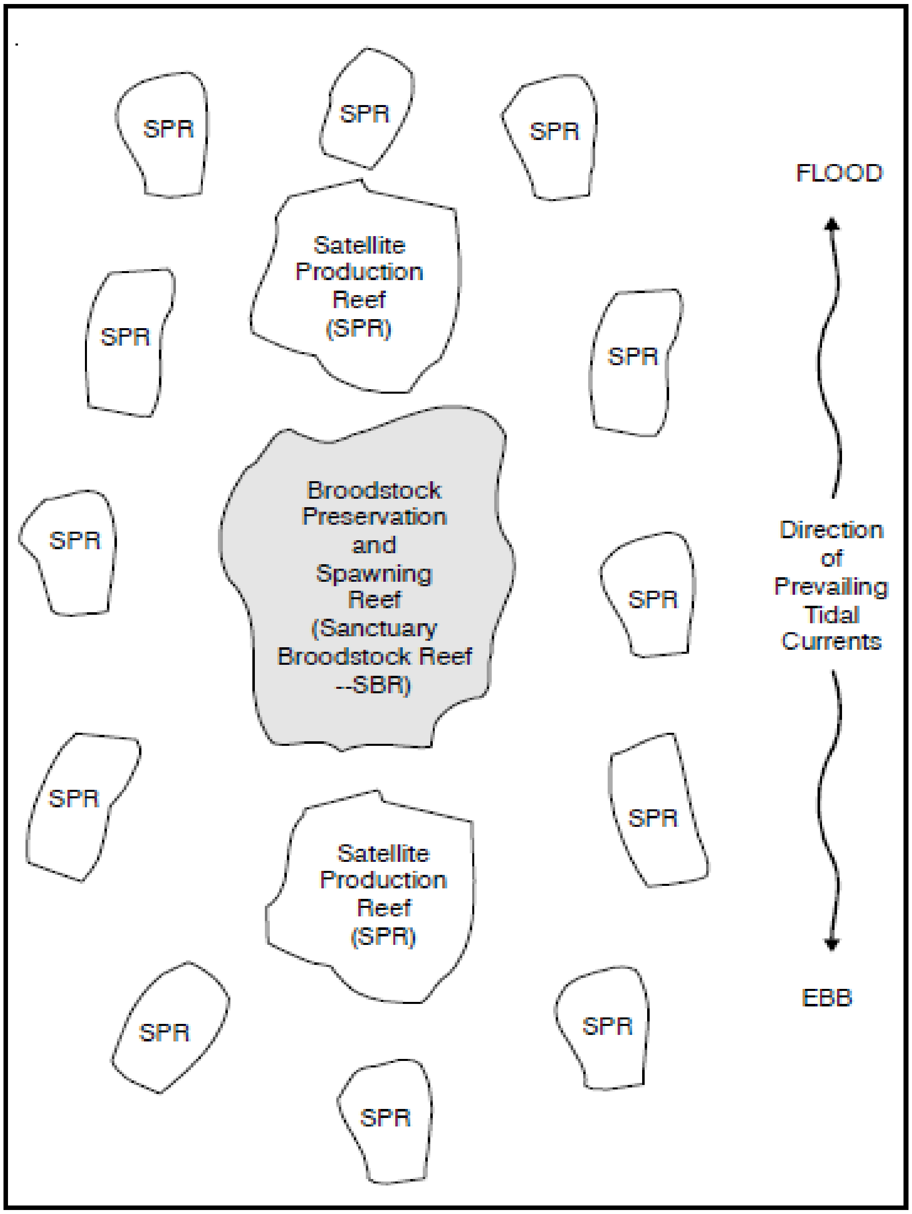


Figure 8. Diagram of a two-tier system of reef restoration. SPR = Satellite Production Reef. (From Hargis and Haven, 1999)

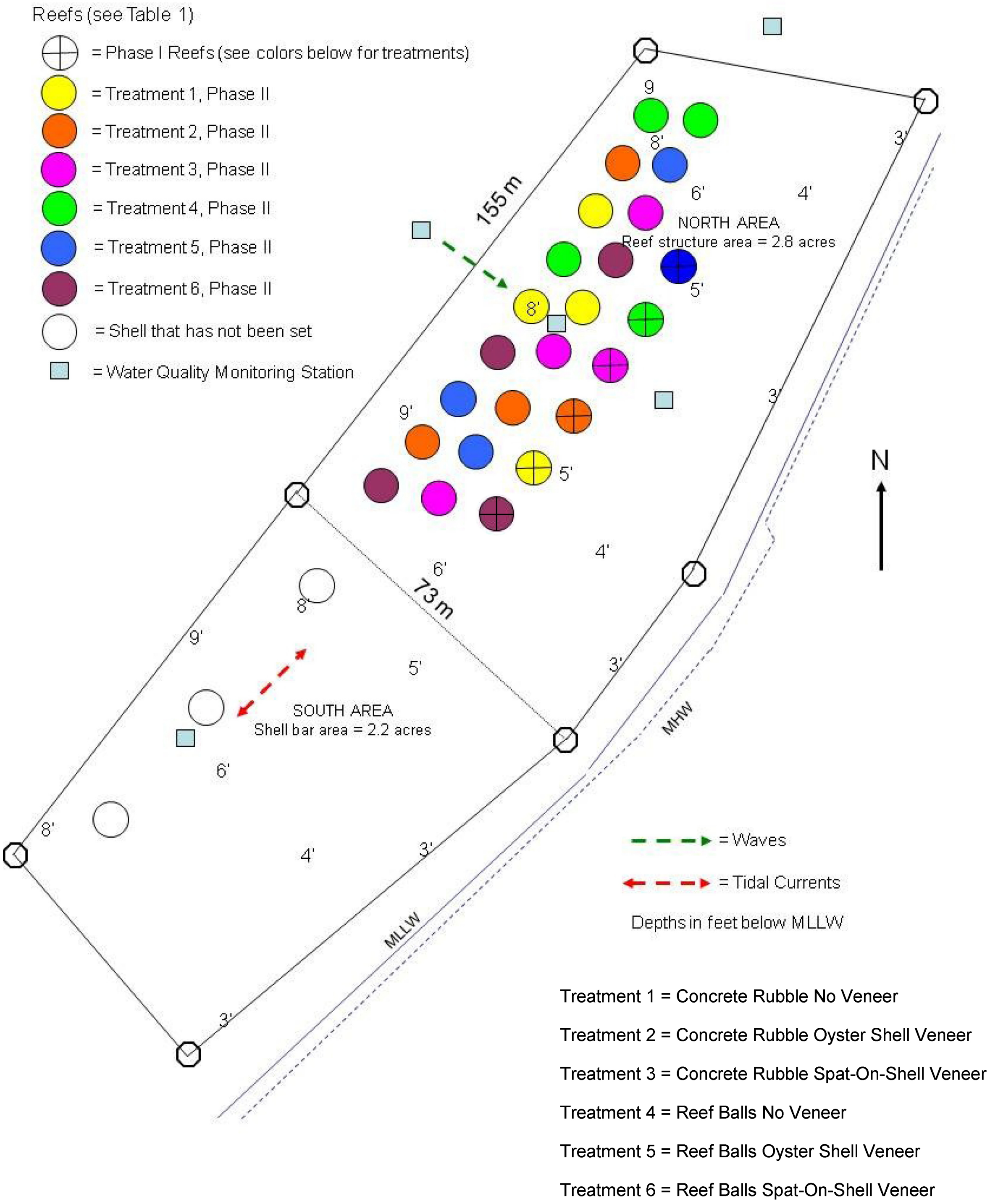


Figure 9. Proposed layout of reefs within the restoration site. See Table 3 for details on dimensions of reefs.

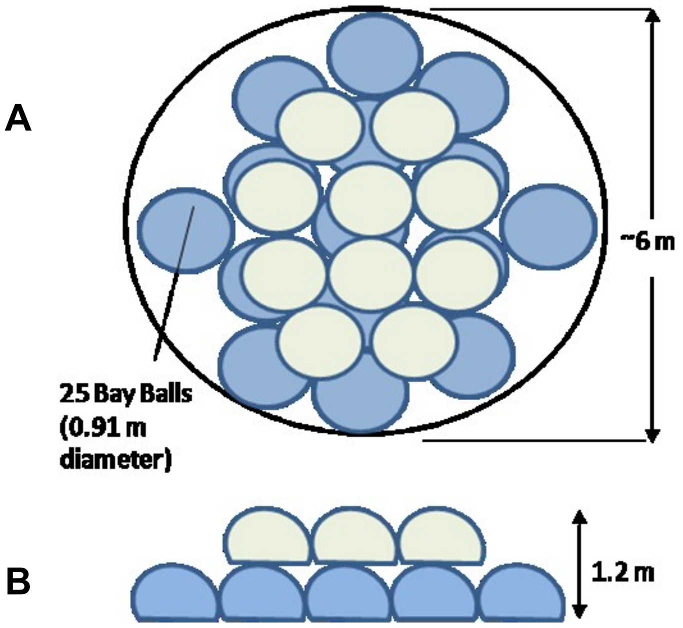


Figure 10. Design of ReefBall core treatment. A. ReefBall core . B. Stacking of ReefBall layers .

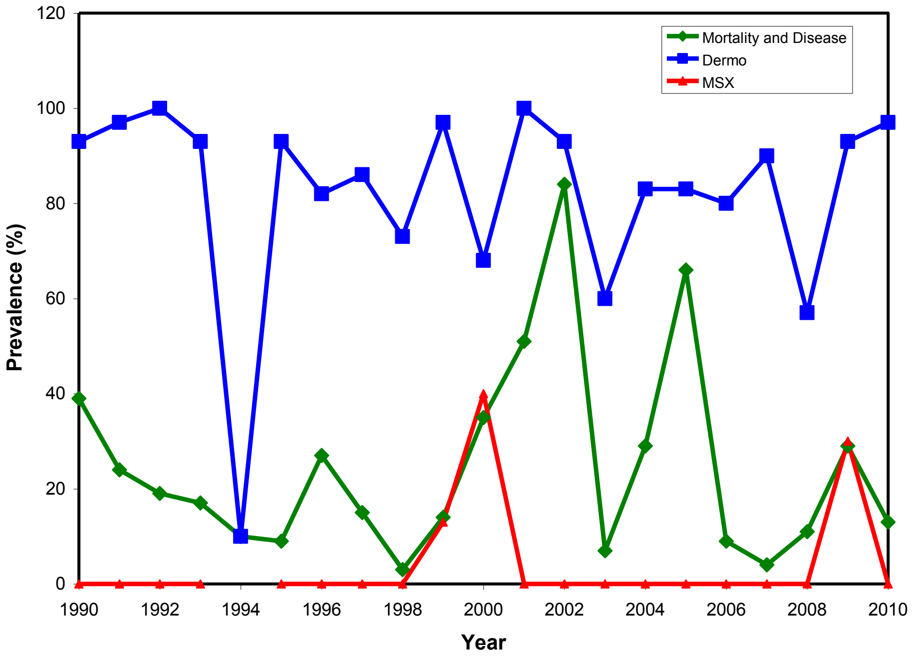


Figure 11. Oyster population mortality estimates and prevalence of the diseases Dermo and MSX on the Pagan Point oyster bar (Tarnowski, 2011).