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ABSTRACT

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The oceans incorporate three-quarters of the Earth's surface, and most of humanity lives in coastal regions. For example, more than half of the total U.S. population presently lives in coastal areas, and the coastal population is projected to increase by 7 million between now and 2015. Similar projections can be made for other developed countries many of which depend on the coastal zone as a major source of tourism-related income. The long-term ecological health and sustainability of the marine and coastal environments are obviously at risk. Coastal projects such as beach re-nourishment, housing developments, and pipe-line, harbor and marina construction can have negative impacts on the coastal environment that must be minimized and often mitigated. Typically, mitigation is done after the fact at considerable expense and often with a questionable return of ecosystem services. However, multiple research projects clearly show that species-specific and lifestage-specific habitat can be designed into artificial structure. Thus, with forethought, coastal construction can include structural designs that are not only ecosystem friendly but which also return ecosystem services impacted by construction. Structure incorporating fish and invertebrate habitat can often be integrated up front at little or no extra construction cost. This paper discusses the results of some of the artificial habitat research as well as recent examples of coastal construction and design that have incorporated these findings.

ADDITIONAL INDEX WORDS: *coast, ecosystem services, mitigation, artificial habitat.*

INTRODUCTION

Coastal Zone

The oceans incorporate almost three-quarters (71%) of the Earth's surface (NOAA, 2010), and most of humanity lives in coastal regions. In 1998 approximately 50% of the world's human population (about 3.2 billion) lived and worked within a coastal strip just 200 kilometers wide, and about two-thirds (4 billion) were living within 400 kilometers of a coast (Hinrichsen, 1999). Thus, the overwhelming majority of humans are concentrated along or near coasts on just 10% of the earth's land surface (Crossett *et al*, 2004).

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It is happening to much the same extent on every continent, and with the exception of Antarctica, only Africa still retains the majority of its population in the interior; although a similar trend towards increasing populations is emerging there as well (Hinrichsen, 1999).

This global trend of coastal population growth is anticipated to continue well into the foreseeable future. For example, more than half of the total population of the United States (US) currently lives in coastal areas, and the national coastal population is projected to encompass nearly three quarters of the total population by 2025 (Crossett *et al*, 2004). In addition, more than 75% of the entire global population is expected to live within 100 km of a coast by 2025 (EEA, 1999; Airoldi and Beck, 2007; Heip *et al*, 2009). Currently, from 10 of the world's most populous cities, 8 are in this coastal zone, and boast population densities that are 5 times greater than any other populated area (DATAR, 2004).

The phenomenon of “thalasso-tropism” (Doumenge, 2000), in which the populace is increasingly drawn to the coast, has already had a lasting impact on coastal landscapes. Airoldi and Beck (2007) stated that over 22,000 km^2 of the European coastal zone is covered in concrete and asphalt, with similar examples from California, Australia, and Japan.

Coastal ecosystems such as mangroves, seagrass beds, and coral reefs do not function as independent units, but rather as fundamental parts of a “seascape” network, interconnected by biological/ecological and physical/hydrodynamic processes. For example, it has been estimated that approximately 80% of all commercially or recreationally valued marine species in Florida, USA, depend upon the shelter and resources of mangrove estuarine areas at some point in their life cycles (Hamilton and Snedaker, 1984; Moberg and Ronnback, 2003). Consider, for example, the global market value of mangrove-related fisheries alone (non-aquaculture), which has been valued at US $800-12,000/ha mangroves annually (Ronnback, 1999; Moberg and Ronnback, 2003). To again use the US as an example, currently coastal states receive more than three quarters of overall tourist-related revenues, with beach-related visitations contributing over $250 billion to the national economy (Houston, 2008). Costanza *et al* (1997) estimated the global ecosystem to provide approximately US $$33x10^{12}$ to the global economy, of which aquatic ecosystems contribute some US $$21x10^9$; a value that exceeds that of any other terrestrial ecosystem tenfold. Although public concern about environmental issues and the effect(s) of human impacts is often the impetus for many coastal restoration efforts, the monetary values of ecosystem goods and services more than justify any restoration expense (Costanza *et al*, 1997; Gosselink *et al*, 1974). This clearly suggests that there are substantial economic benefits to be gained by preserving coastal ecosystems, not to mention social and aesthetic values that are harder to quantify.

Whether on purpose or unintentionally the collective global society is dramatically impacting the majority of our coastal and ocean ecosystems (Airoldi and Beck, 2007). At the root of the problem are swelling human numbers and their ever-growing needs. Pressure on coastal ecosystems from activities such as beach re-nourishment, port expansion, land reclamation, offshore energy production, and construction (roads, marinas, houses and hotels, bridges, piers, seawalls, wastewater outfalls, cables, pipes, breakwaters, etc.) can all have significant negative impacts on the coastal environment. A chronic and pervasive trend of undervaluation of coastal ecosystems (e.g., mangroves, hardbottom, coral reefs, sea grasses) and their associated goods and services is integrally linked to the relative ease and frequency in which these systems have been converted to alternative uses. This tendency to undervalue ecological services is related to the inherent difficulty involved in accurately assessing and monetarily quantifying all relevant factors, in addition to the propensity for those performing the evaluation to lack sufficient ecological knowledge and/or a failure to incorporate a holistic approach in their assessments (Ronnback, 1999).

Even though most major accounting systems still do not include coastal ecosystems among the list of relevant socioeconomic assets, the importance of effective coastal restoration and mitigation management plans is now recognized and enacted in federal laws such as the US Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) (Steyer and Llewellyn, 2000). In recent years the majority of US and Canadian federal, state, and provincial wetland policies have incorporated a “sequencing” process, in which wetland permit applicants are required to avoid wetland impacts if possible, minimize unavoidable wetland impacts to the maximum extent “realistically possible”, and mitigate any remaining wetland impacts (Austen and Hanson, 2008; EPA, 2008; King and Price, 2004).

All this demonstrates that a standardised colour assessment procedure must be developed making it possible to analyse sand colour and to evaluate colour difference between native and borrowed sediments, possibly giving values within which human perception sees them as equal.

Mitigation

Historically, damage to the marine environment resulting from construction projects has been offset by compensatory mitigation efforts after the fact, and often at considerable expense and with minimal thought given to how ecologically effective the results would be. Typically compensation is incorporated into the project only to fulfill legal obligations and minimum requirements put forth by governmental permitting agencies responsible for overseeing the output, as opposed to well intentioned scientifically designed attempts at creating something truly beneficial for the environment. Consequently, many mitigation projects have resulted in a questionable return of ecosystem services, or have fallen short of or failed to achieve their intended goals of replacing or repairing the impacted ecosystem(s) (Young, 2000; Naughton and Jokiel, 2001; Freeman, 2007; Sonntag and Cole, 2008; Murphy *et al*, 2008).

Certainly the idea of mitigating for the effects of coastal ecosystem loss and damage is a sound one, as the services provided by these systems are invaluable. Coastal development is not going to cease, and something obviously must be done to counterbalance its effects. However, reviews of wetland mitigation success over the past two decades are less than encouraging. The vast majority of these reviews have shown a distinct disparity between overall wetlands gains resulting from mitigation projects and overall wetland losses resulting from permitted wetland developments (King and Herbert, 1997; NRC, 2001; OPPAGA 2001). Even in those infrequent cases when mitigation has resulted in at least “one-for-one replacement” of wetland acreage, a net loss of wetland functions and services has been observed as a result of differences in wetland quality between the original and replacement wetlands. In addition, with respect to wetland services, this policy, in its current application, is failing to achieve the desired U.S. national goal of “no net loss” (Mitsch and Gosselink, 2000; NRC, 2001; King and Price, 2004). To add further depth to the issue, one must also consider how wetland mitigation markets and mitigation banks are affected by pervasive economic incentives that regulators are finding difficult to combat. Mitigation is unquestionably expensive (Naughton and Jokiel, 2001; Lirman and Miller, 2003; NERRS, 2010), and mitigation providers who deliver their products/services at the bare minimum limits of quality that regulations will allow often do so under the lure of strong economic incentives (Murphy *et al*, 2008). Counterbalancing economic incentives that would otherwise encourage or support the creation of mitigation products at the highest standards of quality have proven elusive to regulating agencies, as have the requisite tools needed to impose adequate quality control on the final products (King and Price, 2004).

In some cases the mitigation does not attempt to return the lost ecosystem services but rather replace them with services of equal value. The use of dissimilar habitat, (e.g., artificial reefs) away from the impact site, as mitigation is a controversial topic. Attempting to replace like-for-like habitat is difficult enough, especially functionally. This problem is compounded when dissimilar habitat is constructed to compensate for losses of natural coastal habitat types, even when there are no feasible alternatives (NOAA, 2007).

If current population trends and destruction of natural coastal resources continue, it is easy to visualize a bleak future for the long-term health and sustainability of marine and coastal environments worldwide. Aside from drastically curbing population growth, the largest hurdle for coastal resource managers in the coming century will be balancing coastal development with the maintenance of clean and functional coastal ecosystems.

In order for sustainable development to have any realistic chance of succeeding, it is imperative that targets reach well beyond the *status quo* and begin moving towards a net improvement of the coastal ecosystem. Reversing trends of diminished functionality will not be without difficulty, as current policies intended to deliver a “no-net loss” of wetlands have fallen short of their goals (NRC 2001; Diefenderfer *et al*, 2003) and the general status of coastal ecosystem health seems to be moving steadily towards less than optimal levels. Past deficiencies and future improvements are both centered on minimizing damage by constraining development, offsetting damage and losses by immediate compensation, and improving predictability of restoration effort outcomes. Healthy, thriving, productive natural areas cannot be completely replicated or re-created with current technologies, especially in the near-shore marine environment and on coral reefs. We still lack much of the fundamental knowledge to understand how these ecosystems function, and as such they are too ecologically diverse to try and re-create. At best, we can make replacement ecosystems that may or may not equate to the natural structure and function of the original. Consequently, in order for restoration projects to fully compensate for damages, it stands to reason that they must be designed in such a way that their size, quality, location, and viability more than adequately compensate for ecosystem losses and moderate any inherent uncertainties that may be present (Diefenderfer *et al*, 2003).

Public Opinion

In addition to the costs of mitigation, public pressure may subject the developer to further direct (i.e., legal) and indirect costs (i.e. lobbying) when initiating coastal projects. Public awareness of the importance and value of preserving the marine environment has been increasing in recent years. According to a 2006 survey (Woods Institute, 2007, just over half of the US population is under the assumption that the global environment will continue to deteriorate over the next decade, and the majority of consumers have serious concerns about this trend. Another survey indicates that most Americans expect the federal government to play a critical role in strengthening and enforcing “green” regulations, and that balancing economic growth and environmental protection is key (GfK Custom Research, 2007). Opposition from the general populace and special interest groups to environmentally unsustainable practices (including mitigation and coastal construction), as well as increased support for improved environmental ethical policies in the commercial/industrial sector, is on the rise (Greene, 1984; Payne and Raiborn, 2001; Save the Bahamas Coalition, 2008; Fleshler, 2010; Global Response, 2010; Hamilton, 2010; Rice, 2010). As the public becomes more educated, and the problems with mitigation are better understood, mitigation will appear to provide even less of a balanced response to coastal impact; a resulting increased public opposition to a specific construction projects is to be expected.

However, multiple research projects clearly show that species-specific and lifestage-specific habitat can be designed into artificial habitat. Thus, with forethought coastal construction can include structural designs that are not only ecosystem friendly but also return ecosystem services impacted by construction. Restoration costs are split into capital and operational costs. If green construction practices are used from the outset of a project and incorporated into ecologically sound structural designs, capital and operational costs of impact mitigation can be minimized by reducing or negating the loss of ecosystem services in the first place. Further, structure(s) incorporating fish and invertebrate habitat can often be integrated up-front at little or no extra construction cost. This paper discusses the results of some of the artificial habitat research, as well as recent examples of coastal construction and design that have incorporated these findings.

WHAT WE HAVE LEARNED FROM ARTIFICIAL HABITAT RESEARCH

Artificial reefs have been placed in the marine environment since at least 1655, which is apparently the date of the first recorded deployment (Mottet, 1985; Simard, 1995). However, it is likely that their habitat providing function was recognized by fishermen long before that. Currently, artificial reefs are used worldwide for diverse functions: primarily to enhance fishing and recreational diving, but also to prevent trawling, provide beach protection, mitigate marine construction, etc. (Seaman and Sprague, 1991, Thanner et al., 2006). For many years artificial reefs were constructed out of "materials of opportunity," i.e., used tires, old cars, construction rubble, derelict ships, and the like (Seaman and Sprague, 1991). However, it became obvious that all artificial reefs were not equal relative to habitat function and, as a result, there has been considerable research examining specific attributes of artificial habitat (AH) relative to functionality.

Concrete aggregate is the most common material for coastal construction due to its strength, durability, and cost. Concrete can also be readily engineered into artificial habitat and as such can quickly acquire a diverse assemblage of biota. Nonetheless, beyond question, design matters in the ecosystem functionality of artificial habitat. Below we point out the predominant criteria that must be taken into account in AH design, including some substantiating references. However, the literature related to artificial habitat design is voluminous and we have made no attempt to be exhaustive in our citations.

Species-specific Structural Design/Refuge

The Japanese, who did much of the early work on functional criteria in the 1970s, base their AH design on habitat usage by fisheries species. They categorize fishes as either Type A, B, or C. Type A species are benthic and prefer direct contact with the AH. They require internal spaces matching both the targeted species and their corresponding ontogenic stage. Type B species stay near the AH but not in direct contact with the structure. These animals will not enter spaces where they cannot fully visualize the size of the inhabitants within. Type C fishes stay in the vicinity of the AH, but in the water column well away. However, the turbulences in the water column generated by the AH must be adequate for Type C species to detect (Grove *et al*, 1991).

Since that early work, there have been a host of reports examining the relationship between habitat complexity and shelter, or refuge, size and the associated assemblages of fishes. Most studies that have examined AH with varying hole sizes found a correlation between hole size and the size of the associated fishes. As would be expected, those studies, with few exceptions, where structural complexity is associated with diversely sized refugia, found a positive correlation between structural complexity and both species diversity and total numbers of fishes. For invertebrates, shelter can also be a major determinant of survival. For example, refuge scaling reduces predation on appropriately sized spiny lobsters. However, hole size is not the only concern for designing refugia, as other structural aspects are also important. For example, some blennioid fishes are found in blind-ended tunnels, while other fishes and spiny lobster appear to prefer ledges or complex structure with multiple escape routes. Thus there is a shelter-scaling effect as well as species-specific behavioral preferences that must be taken into account in species-targeted AH design (for references see Spieler *et al*, 2001; also Hunter and Sayer, 2009; Langhamer et al., 2009).

Predator Exclusion

The importance of refuge size has been confirmed for many fishes through experimentation with predator exclusion devices, primarily caging. There are more juvenile fishes on AH which have excluded large piscivores by caging than on habitats without caging (Doherty and Sale, 1986; Eklund, 1996; Gilliam, 1999, Jordan, 2010). Caging can protect a number of other taxa (algae, corals, sponges etc.) from predation as well, although the impact on population demographics may not be as clear. Because of fouling problems, caging material is not appropriate for long-term, unattended use. However, for short-term enhancement of settlement and survival of juvenile fishes, caging could be a valuable tool in monitored projects where cage cleaning could be a routine task (i.e., harbors and boat basins).

Hydrology

The impact of the structure on localized hydrology can be important and the interaction of the local current regime with the constructed habitat, regardless of size, is an important consideration. Eddy currents created by artificial structure can enhance food availability and feeding opportunities for planktivores and, in turn, predators (Lindquest and Pietrafesa, 1989; Arena et al., 2007).

Artificial structure can also provide shelter from currents which may be important in some cases (Lindquest and Pietrafesa, 1989; Arena et al., 2007). Although this work was done on large commercial artificial reefs or derelict ships, the same current responses in feeding behavior and shelter-seeking are apparent with early juvenile fishes on research modules of approximately 1 m^2 (R. Spieler, unpublished data).

Size and Deployment Configuration

Habitat size, in terms of volume and area coverage, also plays a role in AH functionality. A larger sized artificial habitat is not necessarily better; there may be a maximum effective size relative to resource availabilities or density dependent predator-prey interactions (Bohnsack *et al*, 1991, 1994; Frazer and Lindberg, 1994; Jordan *et al*, 2005). There have been several studies examining the role of spatial configuration of a given amount of habitat on the associated biota, primarily fishes, with different sized concrete modules or different spatial configurations among the modules. Close placement of artificial modules can result in a lower species abundance and diversity of fishes than the same number of modules more widely dispersed (reviews: Bohnsack *et al*, 1991; Grove *et al*, 1991; also Borntrager and Farrell, 1992; Bohnsack *et al*, 1994; Frazer and Lindberg, 1994; Seaman *et al*, 1994; Jordan *et al*, 2005). However, at this point, an ideal size or dispersion of artificial habitat cannot be recommended. The configuration of habitat modules used in any project will depend, at a minimum, on the goals (what biota) and limitations (site and amount of material) of that specific project.

Profile and Height

For many corals and a variety of fouling organisms vertically oriented surfaces are preferentially selected for settlement (Carleton and Sammarco, 1987; Harriott and Fisk, 1987; Tomascik, 1991). And some post-settled fishes do appear to be attracted by vertical aspects of small artificial reefs (Molles, 1978; Grove and Sonu, 1985). For some fishes the reef height relative to the water column height appears to be an important design criteria and this may be an important consideration for offshore construction (Grove and Sonu, 1985). However, substrate associated fishes typically stay within 3 m of the bottom (Bohnsack *et al*, 1991; Grove *et al*, 1991). Likewise, newly settled and early juvenile fishes often prefer benthic habitat (Baron *et al*, 2004). Thus, from a coastal construction perspective, although the vertical profile of artificial habitat is an important factor in habitat design, great height, apparently, is not.

In addition to structural design, such as complexity and refuge size; essentially all colonizing biota exhibit substrate-dependent settling preferences (Spieler *et al*, 2001). In general, these preferences are due to some physical or chemical aspect of the substrate surface, i.e. composition, texture, and color.

Composition

The composition of the substrate can be an important determinate of the species using the artificial habitat (Fitzhardinge and Bailey-Brock, 1989; Burt *et al*, 2009). Further, differences in composition among similar substrates may also be important. For example, not all concrete aggregate is the same from a habitat perspective. Scott and coworkers (1988) found differences in endolithic fauna between limestone and a concrete aggregate, and Miller and Barimo (2001) found differences in coral recruitment to concrete and limestone. Limestone is a natural component of marine bio-construction present in mollusk shell, coral etc.; it is an effective natural substrate for marine colonization. Concrete is a basic pH substrate which provides a chemically mono-specific surface. To decrease the pH, as well as to diversify the surface of concrete, several studies have examined a bio-concrete with added marine limestone of shell or dead coral (Yoon *et al*, 2004; Devillers *et al*, 2009). A subjective examination indicated concrete with shell aggregate provided a better substrate for rapid colonization than shell-less concrete (S. Pioch, unpublished data).

Texture

There has been extensive work on the texture of the preferred substrate for settling organisms (Luckhurst and Luckhurst, 1978). In general, benthic assemblages (the fouling community, corals, and fishes) are more abundant and diverse on textured surfaces. Many corals, as well as other invertebrate larvae, prefer to settle on a rugose substrate rather than on a flat surface (for references see Carleton and Sammarco, 1987; also Thomason *et al*, 2002; Steinberg *et al*, 2008; Neo *et al*, 2009). It appears a rough, irregularly contoured surface is appropriate for artificial habitat.

Colour

The color of the artificial substrate also influences the functionality of the habitat. Fishes, as well as a variety of invertebrates and algae, are reported to prefer darker colored (e.g., dark red and black) rather than lighter colored artificial substrate (Long, 1974; Grove and Sonu, 1985; Swain *et al*, 2006; Zhenxia *et al*, 2007; Zhang *et al*, 2009; Dong *et al*, 2010).

Shading

The amount of shading artificial habitat provides may be critical. Some shallow water corals preferentially settle on shaded substrate (Wallace, 1985; Maida *et al*, 1994). Apparently, for spiny lobster refuge, shading is even more important than physical contact with the substrate (Spanier and Zimmer-Faust, 1988). Fishes often congregate in and prefer shaded areas (Helfman *et al*, 1997; Cocheret de la Morinière *et al*, 2004) and incorporation of structural elements that produce shadow has been recommended for fisheries reefs (Grove *et al*, 1983).

Location

Differing locations have differing biota and differing biota, in turn, have differing habitat requirements. Thus it is not surprising that the animals that associate with replicate artificial habitats will differ depending on where the AH is sited. Although it might be expected that differing biota would associate with habitats located hundreds of kilometers apart, the distance can be much shorter especially when there are differences in aspects of the physical ecosystem known to affect animal distributions i.e., water depth, (Sherman *et al*, 1999, 2001; Burt *et al*, 2009). Clearly then, the design and construction of the artificial habitat must be appropriate for its location and intended purpose.

Aesthetics

Typically AH is purposefully deployed with intended consequences. In most cases this involves enhancing fisheries, although they have also been used for coastal hardbottom mitigation and coral reef restoration (Seaman and Sprague 1991, Spieler *et al*, 2001). There are also AHs intended to enhance tourism as it relates to recreational diving. Nonetheless, few AHs take aesthetics into consideration and even when so the result may be alien (statues, mock ruins, etc.) to the natural underwater seascape. Excluding these special cases, although habitat considerations should be paramount in artificial habitat construction, any marine structure that is going to be seen by divers should ideally be integrated with the seascape and mimic the adjacent environmental substrate (Spieler *et al*, 2001; Tallman, 2006; Morley *et al*, 2008). This is especially important in coastal marine environs to buffer the often strong public criticism of coastal construction.

To summarize this section, artificial habitat research has shown that species-specific habitat can readily be constructed and the primary determinants of the species-specificity of the constructed habitat are: substrate, refuge size, location, module size and distribution, and predator avoidance (caging, escape routes).

THE WAY FORWARD

We begin this section with three basic assumptions: 1) coastal construction impacts the local ecosystem, 2) coastal construction will continue, 3) Public opposition will not abate.

From these assumptions, we conclude that there is the need to move to ecosystem friendly construction: a green approach. That is, not just do minimal damage but also to take a proactive approach to incorporate positive ecosystem benefits into the construction design from the onset. It was clearly demonstrated that land-use decisions may increase or decrease the number of niches in habitats available to species, and so may either increase or decrease the level of biodiversity (Brock, Kinzig, et Perrings 2010). Assessment of several habitat restoration projects showed that when integrated approaches were adopted, human intervention could in some cases help nature recover (Benayas *et al*, 2009). The goal of the green approach should be to return some anticipated loss of ecosystem services due to construction into the design. The result would be a pro-active move toward restoration of these services and a reduction of non-equitable mitigation.

Much of the anticipated loss of ecosystem services is currently documented in the Environmental Impact Statement, or similar, required in most countries prior to construction. Thus, to some extent the requisite replacement habitat is already established. In those cases where it is not feasible to replace a lost species habitat, then non-equitable habitat could be substituted. This would provide some return of lost ecosystem services.

It is critical to understand that a green approach to construction requires a close Engineering/Biology partnership to meet management goals. Biologists are not typically trained or licensed for the requisite engineering involved in construction. Likewise, non-biologists designing habitat often can lead to egregious results. For example, unintentionally constructing the wrong habitat, i.e., refuge for predators in a nursery area, or habitat that facilitates the spread of non-desirable species can increase, rather than ameliorate, the impact of construction (Bulleri and Airoldi, 2005; Freeman 2007).

Success Stories

In recent years, Pioch and co-workers (unpublished) developed an alternative to the classic engineering approach to marine construction. This new approach, "green marine construction," is now operational or in the planning stages for marinas, harbors, seawalls, dikes and pipelines.

In Mayotte (France, West Indian Ocean), a project in 2008 established a 2,600 m underwater pipeline for around US $8.8 million (6.8 M€), linking Grande Terre island to Petite Terre island, in a coral lagoon (marine protected area). The construction took place in shallow tropical coastal water, with an extremely sensitive coral reef ecosystem known for its high degree of biodiversity (Amaud, 2009). However, the pipeline was a social priority: bring fresh water to 6,000 people.

We will first describe the ecosystem, the social interest in maintaining a healthy ecosystem, and then the methodology to create an eco-engineered construction. The Mayotte lagoon encompasses approximately 1,500 km², including 200 km of barrier reef and one of the largest closed lagoons in the world (Arnaud 2009). A biological inventory of the area recorded 239 fish species, 400 shellfish species, and more than 270 seaweeds (Rolland, 2005). The internal reef is a nursery area with a high concentration of juvenile fishes. Since the 1960s the local population has risen from 25,000 to 200,000 people. The high anthropogenic pressure created by this population has resulted, in part, in ecosystem damage through overfishing, pollution, and sedimentation (erosion due to construction of houses). Further, natural impacts (i.e., hurricanes) have impacted the area. Together, the anthropogenic and natural impacts have resulted in a destruction of 40% of the coral reef habitats (Quod and Bigot, 2000; L. Bigot, personal communication). The main consequence of the habitat loss is a decrease in refuge for juvenile fishes and a diminution of biodiversity. From a social aspect, the lagoon is an important source of protein for local citizens. Traditional fisheries were the second largest economic activity in the region in 2000, supporting 3,600 boating fishermen (Wickel, 2000). The environmental agency (DIREN) asked the pipeline construction applicant, SIEAM (a public company), to discuss the ecosystem risks and to provide a construction solution to minimize impact as part of their bid. The impact study resulted in 3 suggestions to avoid or reduce damage: choosing a minimum-damage pipeline track relative to coral stands (even if this kind of work is usually difficult to realize), ecological assessment, and a quick completion of construction (less than 8 months). However, it did not address the loss of habitat due to construction. The green approach was chosen as an exclusive and original solution. Specifically, actions to create (restore) habitat in the lagoon as part of the requisite pipeline construction were outlined. It was proposed that "green" weights be used to stabilize the pipeline on the seabed, as well as to create and restore habitat and biodiversity in the lagoon. It is particularly noteworthy that by incorporating green techniques, the total construction cost was increased by less than 1%.

The project area started at the beach of Mamoudzou city on Grande Terre and ran across the lagoon to Dzaoudzi city on the island of Petite Terre, with a maximum depth in the lagoon around 26 m (figure 1).

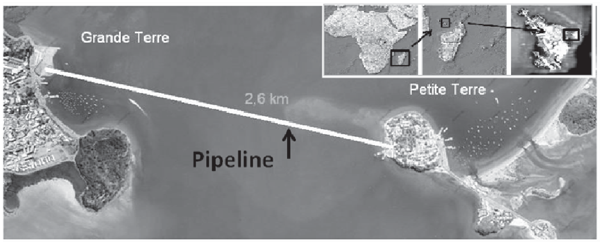

Figure1. Map of the project between Mamoudzou and Dzaoudzi.

An ecological survey was done on the track of the pipeline using the methods of English (*et al*, 1994) and Conand (*et al*, 2000). The survey identified: community structure (by families and species), biotopes (geo-morphological), habitats, and fishes relationships using the classification of Nakamura (1985), i.e., A= benthic, B = demersal, and C = pelagic fish species as juveniles or adults (Bigot, 2008).

Four biotopes were found and mapped in which 8 communities existed with both A and B species. Juveniles of these species were found in shallow water and adults in deep water. This survey was used to define the ecological sensitivity (ES) of specific areas based on the associated communities and biotopes. Three levels of sensitivity were determined (low, medium, or high) by examination of 1) species richness of communities (family level), 2) taxonomic diversity (family level), 3) kind of substratum: mud, sand, rock, or coral, 4) endangered or threatened species (species level), 5) function of habitat: nursery (juveniles), spawning, breeding (adults), or feeding (juveniles or adults).

The ecological vulnerability (EV) included also stakeholder usage (Utilization Factors, UF) and Environmental Risks (ER). For this study ER was defined by coastal construction both emerged (breakwater, dike, pontoon, boat-ramp) and submerged (pipeline, energy cable, phone cable), as well as boat navigation and current (direction and speed). Thus EV was determined with the formula: EV = ES + (UF and ER. The vulnerability was categorized as positive (high vulnerability) or negative. These factors were then used to define the environmental priorities and the construction design for different areas (Table 1). Two main habitat and species relationships were defined: 1) shallow water, juveniles from benthic and demersal species with low sensitivity and vulnerability to construction impact and 2) deep water, adults, from mainly benthic and also demersal species with medium and high sensitivity and vulnerability.

Table 1: *Sites, associated ecological parameters and the module type used for weighting the pipeline.*

Biotopes	Communities	Fish Type	Juvenile or Adult	Ecological Sensitivity	Ecological Vulnerability	Model Type
N°1 Shallow water by beaches	1	A, B	J	low		Rock
	8	A, B	J	low	-	
N°2 Sand with scattered coral	2	A, B	A	medium	+	Tile with rugosity
	3	A, B	A	**high**	+	
	4	A, B	A	low	-	Tile
N°3 Muddy-sandy channel	5	B	A	medium	+	Tile with rugosity
	6	B	A	low	-	Tile
N°4 Muddy with sand + coral	7	A, B	A	medium	+	Tile with rugosity

The engineering part of the project consisted primarily in conducting physico-oceanic surveys to design the pipeline. The main parameters were 1) morpho-bathymetric features, 2) climatic events in the lagoon: maximum waves and surfaces / bottom currents for a once-in-500 year occurrence (hurricanes), and 3) sediment type (sand, bottom, rocks) and coverage.

Affixing the pipeline to the substrate was required to minimize damage to the pipe and surrounding habitat due to movement. Typically this has been done with sand anchors and weights that are concrete squares or rings (ring weights are needed to minimize the effect of scouring). For the project, the pipe line PEHD PN16 (diameter is 400 mm) was chosen. It required an anchor in the sediment every 10 meters, with a total of 206 concrete weights of between 1 and 3 tons each.

It was hypothesized that these weights, which have a strong impact on seabeds because of their volume and shape, could be used to create an artificial habitat that would enhance biodiversity: green weights. Technical feasibility had to be considered: their weight needed to be 1-3 tons, a linkage system with sand anchors was required, as was a ring design, serial fabrication, and easy transportation. Further, they needed to be manufactured and deployed with the usual tools for this kind of work. Cost was also a major consideration. Out of 5 designs initially tested, only 2 of them were acceptable due to technical, economic, and ecological concerns.

The first module, called Rock, was designed to create effective habitat for juvenile fishes of species A (figure 2). This design mimicked shallow biotopes of area 1 containing communities 1 and 8. It consisted of 2 half-rings joined like a sandwich on the pipe. They are separated by 4 pods, 2 for each side of the pipe, creating space between each part. Porous rocks (local basaltic rocks) were inserted on top to add species-specific structural design/refuge. All shelters were appropriately sized to be suitable for benthic and demersal juveniles based on past AH research. The insertion of natural rocks and the soft curve of the shape (half-ring) will add to the future integration with the natural seascape.

The second module, called Tile, was designed to create effective habitat for adult fishes of species A and B. It was designed to mimic deeper biotopes of areas 2, 3, and 4, with added treatment to accentuate the rugosity for sensitive communities 2, 3, 5, and 7. No treatment was made for the non-sensitive communities 4 and 6. The rugose surface was incorporated to enhance corals, as well as other invertebrate larvae and algal settlement. It is the same shape of the Rock model, but the space between the half-ring is an important difference. All the shelters are shelter-scaled and provide refuge suitable for benthic species on the upper surface of the weight with a tile-like system (4 half-tunnels), and demersal species between the half-rings. Rugosity was accentuated to accelerate colonization of faunal assemblages. The shape (half-ring) and the tile-linked half-tunnel are all non-angular soft shapes which also should enhance future seascape integration.

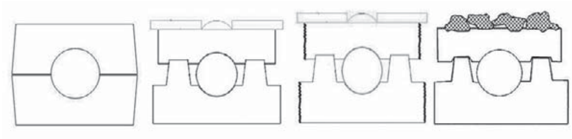

Figure2. Depiction of a vertical face of the pipeline weights described in the text. A = normal weight, B-D = “green” weights. B = Tile, C= Tile + rugosity, D = Rock. The center circle represents the pipeline.

RESULTS

Efforts to install the pipe began in mid-December 2009 and were finalized in March 2010. The original timeline of five months had been calculated based on previous pipeline construction projects. This timeline was met; thus, it took no longer to construct and deploy the pipeline using green technology. There were also no work interruptions or other problems related to the green weight modules. An ecological assessment began in March 2010 and the first video survey was done one month later (Wickel *et al*, 2010). Juveniles were noted in the first assessment under the Rock models for A and B commercial species (*Panulirus versicolor* and *Epinephelus flavocaeruleus*). Several different adult species were present around the Tile models, both under the tile-like habitats and between the half-rings. On the video a first semi-qualitative assessment showed families belonging to Pomacentridae, Labridae, Chaetodontidae, Holocentridae and Acanthuridae (other species identified on the video: *Pterois volitans, Cheilodipterus quinquelineatus, Neopomacentrus cyanomos, Pomacentrus pavo, Amblyglyphidodon leucogaster, Pomacentrus caeruleus, Anthiinae spp., and Pseudochromis spp.)*. Invertebrates (e.g. colonial hydroids) were also seen on the rugose models. Fish abundance on the old pipeline, still in use and located 5 m away from the new construction, was insignificant. In contrast, schools of 15+ fishes from 3 to 5 different families were seen on the new pipeline (L. Bigot, personal communication). Monitoring of the biota on the new construction will continue for 3 years. The first video was shown to the stakeholders (artisanal fishermen, scuba divers) and policy makers. They were pleased to see that the project did return technical and ecological services with socio-economic benefits. After this first construction, the Saint Leu (Reunion Island, West Indian Ocean, France) authorities asked that the pipeline of their water treatment plant effluent be constructed with green weights and work is scheduled to begin December 2010.

A number of other green marine construction projects are either in development or in process. A green marina with the harbor designed to attract and concentrate juvenile fishes by providing them safe and effective refuge (Pastor 2008) is in development, as are docks of a new material designed to enhance bio-filtration of harbor water to reduce pollution and organic matter (S. Pioch, unpublished data). Creating heterogeneity of habitat inside dikes will provide an increase in biodiversity associated with those structures (Moschella *et al*, 2005). Further, an enhancement of the structure associated with the submerged portions of offshore windmills has been proposed (Langhamer, *et al*, 2009). Artificial habitat could increase diversity along the pole from the sea surface (for post-larvae and juveniles) to the bottom (for adults). And, to complete the circle back to artificial reefs, artificial habitats have been developed and deployed with a green marine concept in September 2009 in the Mediterranean city of Agde (France). These structures are designed to mimic the natural hardbottom landscape by combining effective habitats designed for each targeted species, a biological concrete to enhance colonization, and a seascape integration approach. The ecological assessment of these structures has just begun, but the first results are positive and link the targeted species and designed habitat (S. Pioch, unpublished data).

CONCLUSIONS

We have presented here an approach to marine construction that would provide added ecosystem value directly to a construction site. However, clearly we are not advocating coastal development. We agree that impact to coastal ecosystems should ideally be avoided and when unavoidable, minimized. What we propose here is a way to minimize the impact by improving current technologies used to return some ecosystem services at the site of impact, as well as to decrease mitigation costs. Eco-design should be incorporated in all engineering of coastal structures to ameliorate some of the infrastructure impact to marine ecosystems. We are aware of the inertia that must be overcome to see the fruition of this concept. Insurance and construction companies, as well as resource managers, trust what they know and find safety from criticism, or legal repercussions, by repeating historically approved methods. Nonetheless, beyond question, coastal areas need to be considered from an ecosystem services standpoint. To preserve as much of these ecosystems as possible and insure continued well-being and socio-economic returns for human society delivered by the natural services, our future demands we “think green.”

Colour analysis of native and borrow sediments at Poetto shows the reasons argued by opponents to the project: ΔE^*ab equals 12.51 and most of this difference is due to Lightness values; 55.40 for fill sand and 67.38 for native sediment.

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