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Impacts of Artificial Reefs on Surrounding Ecosystems

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Impacts of Artificial Reefs on Surrounding Ecosystems

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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Dedication

I dedicate my dissertation to my family and many friends. A special feeling of gratitude to my loving parents, Haroutioun Manoukian and Solina Minassian, my sister Gassia, my brother Razmik, and my brother-in-law Stefano, who never stopped encouraging me and believing in me. I hope you are all proud of me.
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Impacts of Artificial Reefs on Surrounding Ecosystems

Sarine Manoukian

Abstract

Artificial reefs are becoming a popular biological and management component in shallow water environments characterized by soft seabed, representing both important marine habitats and tools to manage coastal fisheries and resources. An artificial reef in the marine environment acts as an open system with exchange of material and energy, altering the physical and biological characteristics of the surrounding area. Reef stability will depend on the balance of scour, settlement, and burial resulting from ocean conditions over time. Because of the unstable nature of sediments, they require a detailed and systematic investigation.

Acoustic systems like high-frequency multibeam sonar are efficient tools in monitoring the environmental evolution around artificial reefs, whereas water turbidity can limit visual dive and ROV inspections. A high-frequency multibeam echo sounder offers the potential of detecting fine-scale distribution of reef units, providing an unprecedented level of resolution, coverage, and spatial definition. How do artificial reefs change over time in relation to the coastal processes? How accurately does multibeam technology map different typologies of artificial modules of known size and shape? How do artificial reefs affect fish school behavior? What are the limitations of multibeam technology for investigating fish school distribution as well as spatial and temporal changes? This study addresses the above questions
and presents results of a new approach for artificial reef seafloor mapping over time, based upon an integrated analysis of multibeam swath bathymetry data and geoscientific information (backscatter data analysis, SCUBA observations, physical oceanographic data, and previous findings on the geology and sedimentation processes, integrated with unpublished data) from Senigallia artificial reef, northwestern Adriatic Sea (Italy) and St. Petersburg Beach Reef, west-central Florida continental shelf. A new approach for observation of fish aggregations associated with Senigallia reef based on the analysis of multibeam backscatter data in the water column is also explored.

The settlement of the reefs and any terrain change are investigated over time providing a useful description of the local hydrodynamics and geological processes. All the artificial structures (made up by water-based concrete for Senigallia reef and mainly steel for St. Petersburg Beach reef) are identified and those showing substantial horizontal and/or vertical movements are analyzed in detail. Most artificial modules of Senigallia reef are not intact and scour signatures are well depicted around them, indicating reversals of the local current. This is due to both the wind pattern and to the quite close arrangement of the reef units that tend to deflect the bottom flow. As regards to the St. Petersburg Beach reef, all the man-made steel units are still in their upright position. Only a large barge shows a gradual collapse of its south side, and presents well-developed scouring at its east-northeast side, indicating dominant bottom flow from west-southwest to east-northeast. While an overall seafloor depth shallowing of about 0.30 m from down-current deposits was observed for Senigallia reef, an overall deepening of about 0.08 m due to scour was observed at the St. Petersburg Beach reef.

Based on the backscatter data interpretation, surficial sediments are coarser in the vicinities of both artificial reefs than corresponding surrounding sediments. Scouring reveals this coarser layer underneath the prevalent mud sediment at
Senigallia reef, and the predominant silt sediment at St. Petersburg Beach reef. In the ten years of Senigalia reef study, large-scale variations between clay and silt appear to be directly linked to large flood events that have occurred just prior to the change.

As regards the water column investigation, acoustic backscatter from fish aggregations gives detailed information on their morphology and spatial distribution. In addition, relative fish biomass estimates can be extrapolated. Results suggest that most of the fish aggregations are generally associated with the artificial modules showing a tendency for mid- and bottom-water depth distribution than for the surface waters.

This study contributes to understanding the changes in artificial reefs over time in relation to coastal processes. Moreover, the preliminary results concerning the water column backscatter data represents progress in fisheries acoustics research as a result of three-dimensional acoustics. They demonstrate the benefits of multibeam sonar as a tool to investigate and quantify size distribution and geometry of fish aggregations associated with shallow marine habitats.

1.1 Introduction

An artificial reef is “one or more objects of natural or human origin deployed purposefully on the seafloor to influence physical, biological, or socioeconomic processes related to living marine resources. Artificial reefs are defined physically by the design and the arrangement of materials used in construction and functionally according to their purpose. Items used in reef construction add vertical profile to the benthic (sea floor) environment” (Seaman and Jensen, 2000, p.5). Artificial reefs range in structure and complexity from sunken ships to custom-made objects from a wide range of materials (Brown and Harper, 2006). At the beginning, artificial reefs represented a means to provide additional critical habitat to aggregate and attract fish or to increase biomass, enhancing the probability of fish catches and the collection of benthic organisms. Later, however, with the development of new technologies, their employment has also been extended to other applications with more ecological purposes.

Artificial reefs potentially can enhance marine environments by providing hard surfaces onto which sessile marine organisms can attach, grow and act as food sources for higher trophic levels (thereby increasing feeding efficiency), recruitment habitats for individuals that would otherwise be lost from the population (Chou, 1997), shelters for juveniles and adults from predation or currents (Relini et al., 1994a, 1994b; Spanier, 1996), and a reduction of harvesting pressure on natural
reefs (Harmelin and Bellan-Santini, 1996). Besides enhancing the habitat in terms of “replacing the original ecosystem with a different ecosystem” (Svane and Petersen, 2001), artificial reefs can also protect fish spawning and nursery areas from illegal trawling fishery (Fig. 1.1).

Other purposes for artificial reefs include management of the different fishing activities whether commercial or recreational, conservation concerns such as habitat protection, conservation of biodiversity, mitigation of habitat damage and loss, restoring and enhancing water and habitat quality (Seaman, 2000), and providing deeper knowledge and understanding of marine environments from both scientific and popular points of view. Moreover, recreational diving sites and submarine tourism sites are also factors driving the deployment of artificial reefs. Nowadays, they have been deployed around the world for a wide number of reasons including coastal erosion prevention, fisheries protection and enhancement, and environmental rehabilitation (Harris, 2006).

Figure 1.1. Example of a trawl being dragged over concrete blocks of an artificial reef and how the artificial reef provides protection for spawning and nursery areas.
An ongoing argument concerning the efficacy of artificial reefs in enhancing fish populations concerns the source-sink dynamics, which may define the patterns in distribution and abundance of many marine species. Do artificial reefs serve primarily to aggregate fishes (sink) or actually become sites of primary and secondary productivity comparable to natural reefs (source; Bohnsack, 1989; Lindberg, 1997)? As reviewed by Brickhill et al. (2005), the attraction hypothesis suggests that artificial reefs simply attract fishes from surrounding habitat as a consequence of fish behavior (Bohnsack, 1989). Fishes moving onto artificial reefs are unable to be replaced due to limits on the abundance of fishes in the area (e.g., predation, finite larval or food supply). Thus reefs do not significantly increase local populations. Alternatively, the production hypothesis proposes that artificial reefs provide additional habitat, increasing the carrying capacity of an area (Bohnsack, 1989). Besides the increased food supply and shelter opportunities, and possible decrease of predation rate that encourage fish settlement at reefs, a greater number of juveniles are able to settle and survive to spawn as adults and contribute new individuals to local populations. The artificial reef promotes a net increase in local abundance of fishes. Hypotheses based on source-sink dynamics implicitly incorporate recruitment processes, physical transport mechanisms, dispersal behavior, post-settlement demography, food supply, predation rate, and habitat heterogeneity across various scales of space and time.

The first evidence for deployment of artificial reefs dates back to the end of seventeenth century in Japan, where natural rocks were intentionally placed to increase the production of the brown algae Laminaria spp. (Mottet, 1986). The modern concept of “artificial reef” originated in Japan during the following century, and spread to the USA at the beginning of the nineteenth century. During the second half of the nineteenth century, artificial reefs were deployed off the coast of South Carolina, where piles of logs and stones were used to attract and increase
abundances of some fish species (Stone, 1985). In the twentieth century, the employment of these structures increased rapidly and it was adopted in Europe during the second half of the twentieth century. By 1991, about 40 countries were using artificial reefs (Seaman and Sprague, 1991; Fig. 1.2). To date, this number increased to 50, with the greatest concentrations in southeast Asia, Japan, Australia, the Atlantic coast of North America, the Caribbean Sea and the Mediterranean.

![Figure 1.2](modified from Seaman and Sprague, 1991)

**Figure 1.2.** Use of artificial reefs in the world (modified from Seaman and Sprague, 1991).

### 1.2 Artificial Reefs in Italy

In 1995, a census of artificial reefs within the European Artificial Reef Research Network (EARRN) project reported the existence of about 75 artificial reefs in Europe, mainly located in Italy and along the Mediterranean coast of France and Spain (Jensen and Collins, 1995; Jensen, 1998). Most of those located in the
Mediterranean Sea are used for fishery management by protecting the coastal areas or other sensitive habitats against illegal trawling, enhancing the small-scale fisheries, and decreasing the conflicts among different fishing activities.

Unlike other countries, Italy did not have a national program for the regulation and rationalization of deployment of artificial reefs according to the ecological and socio-economical requirements of the different coastal areas. Over the past several years, the construction of artificial reefs has been controlled by regional authorities and may become included in the annual or multi-year Regional Plans for Fisheries and Aquaculture. Bureaucratic procedures and regulations can vary from region to region, but common restrictions exist regarding the materials in order to prevent dumping of waste materials and release of contaminant substances. No specific management plans are applied after reef deployment in the case of reefs constructed with public funds.

Most of the present reef systems have been constructed with the financial help of the European Community. However, projects can be also proposed and constructed by local authorities and/or private associations (diving clubs, recreational fishers, professional fishers, etc.), which support the project with their own funds. When the reef is privately constructed, the organization must submit a proposal for the project and seek permission from the Regional Authority and to lease a seabed area.

The first artificial reef in Italy was deployed in 1970 (Relini, 2000a). To date, more than 70 reefs have been constructed along the Italian coasts. Most of them are medium- or large-scale reefs, while only few are small-scale experimental reefs used for research.

Fisheries management is the main purpose for artificial reef construction. Such reefs are considered tools for protecting the coastal nursery areas or other critical habitats (e.g., coralligenous benthos, seagrass beds, and submerged caves).
from illegal trawling, reducing conflicts between different categories of fishers (e.g., small-scale fishers and trawlers), enhancing small-scale fisheries by increasing local finfish populations, and in eutrophic waters, by developing new populations of edible bivalves (e.g., mussels).

Within their numerous applications, artificial reefs can be described as "soft technology" interventions intended both to increase the marine productivity and, associated with other managerial measures, to contribute in the solution or attenuation of all the biological and socio-economical problems concerning marine resource exploitation. From this point of view, they represent a different approach (though complementary) with respect to fish resource management and preservation strategies carried out in many countries. Previous strategies, typically, include actions to reduce the fishing capacity by reorganizing the fleet, by prohibiting some fishing activities and by applying other technical restrictions without considering any direct intervention on the resources that could allow productivity and employment levels to be maintained or even increased. Protecting the spawning and nursery areas of demersal species can reduce fish mortality, natural and by fishing, with consequent direct or indirect benefits for all the fisher groups (Bombace et al., 1993, 1994). Moreover, artificial reefs can constitute an administrative tool to reallocate resources and fishing activities, affect the use of fishing gears and increase the selectivity in terms of individuals’ species and size in addressing the catches to target species.

Many different materials have been used to create artificial reefs, including specific anti-trawling bodies such as tripods, car bodies, vessel wrecks, construction debris, and finally production of mixed concrete modules (Bombace et al., 2000; Fabi, 2006). Some materials were not successful due to pollutant leaching and paint flaking, which reduced the number of organisms capable of attaching and/or maintaining a permanent foothold on certain material (e.g., fouling organisms; Relini
and Orsi Relini, 1971; Relini and Wurtz, 1977; Relini, 1979, 1983a, 1983b), or to the destructive action of perforating organisms. Other problems include quick burial of the structures associated with limited supporting surfaces (CONISMA, 1999). Also some of the modules specifically designed for artificial reefs did not give satisfactory results. Some artificial structures broke up under the action of the waves or partially sank in the soft sediment bottom (Bombace et al., 2000).

On the other hand, the water-based concrete (WBC) blocks planned by the Italian National Research Council - Maritime Fishing Research Institute (now Marine Science Institute) of Ancona worked properly for certain specific purposes. These modules (2x2x2 m) have a weight of 13,000 kg, rough surfaces favoring the settlement of sessile organisms and holes of different diameters offering shelters to fish and other macrofauna (Fig. 1.3a, 1.3b and 1.3c). They provide good stability, effective protection against illegal trawling, and a considerable flexibility in reef planning due to numerous assembly possibilities (Bombace et al., 2000). They were employed for the first time in 1974-75 off the coast of Porto Recanati (northwestern Adriatic Sea) for the purposes of building the first scientifically-planned artificial reef. The reef served several purposes including protection of the coastal area against illegal trawling, fish repopulation, and development of new mussel (Mytilus galloprovincialis) and oyster (Ostrea edulis and Crassostrea gigas) beds. In this particular case the modules were assembled in 3-layer pyramids placed on gravel “mattresses” to spread the weight and prevent subsidence, and were deployed in a rectangular arrangement about 50 m apart.

Stone piles were placed among the pyramids to make the reef system continuous and two old vessels were sunk at the centre of the oasis, whereas all around it small anti-trawling bodies were randomly scattered.
Figure 1.3. Water-based concrete blocks used for the construction of most artificial reefs in Italy. (a) The basic module is an 8 m$^3$ concrete block, weighing 13,000 kg with rough surfaces to facilitate the settlement of benthic organisms and different shape and size holes to provide habitats for marine biota. The cuboid shape allowed stacking of the blocks to create "pyramids" to increase reef height. (b) Example of 2-layer module located in north-western Adriatic Sea, Italy (Senigallia artificial reef). (c) Example of 3-layer module located in north-western Adriatic Sea, Italy (Porto Recanati artificial reef).

Subsequently, considering the ecological results (Bombace, 1977, 1982, 1989) and the qualified technical characteristics of the concrete blocks, these modules were widely employed to build most of the artificial reefs present today along all the Italian coasts (Fig. 1.4). At the beginning, 2- or 3-layer pyramids were created and placed at 25-50 m from each other in 15 m to 20 m water depth, depending on the local environmental characteristics (Ardizzone et al., 1989; Badalamenti et al., 2000; Bombace et al., 2000; D'Anna et al., 2000; Relini, 2000a; Riggio et al., 2000). The main reasons driving the creation of these artificial reefs were protecting the coastal area and other ecologically critical habitats (e.g., *Posidonia oceanica* meadows) and promoting small-scale fishing.
Concrete has been found to be very favorable for artificial reef construction. It does not degrade in seawater, can be made to have neutral pH, is easily molded and is not easily moved once in place. However, concrete structures can be difficult to transport to a deployment site. Concrete can be made to have a texture comparable to natural reefs and develops very similar communities as natural reefs (Pickering, 1997). Although concrete is the primary material employed in building artificial reefs in Italy since the late 1980s, research has been carried out to investigate the possible use of waste materials such as coal ash from the power stations, already tested and used in artificial reefs in the USA (Woodhead et al., 1982, 1985; Livingstone, 1994), Taiwan (Chen, 1987; Shao et al., 1994; Kuo et al., 1995), Japan (Suzuki, 1985, 1995) and United Kingdom (Collins et al., 1990, 1991, 1994a, 1994b; Jensen et al., 1994).

Following positive experimental results obtained in laboratories and tanks (Relini and Patrignani, 1992; Sampaolo and Relini, 1994; Relini, 2000b), sea trials began in 1992 when some blocks containing a mixture of coal ash and lime were immersed inside the Loano artificial reef, Ligurian Sea, and the Senigallia artificial reef, northwestern Adriatic Sea (Relini, 2000b). The sea trials confirmed that such material does not release harmful elements into the marine environment or to
aquatic organisms, and favors a good settlement of benthic fauna. Ash mixtures are not useful for the construction of anti-trawling reefs because of the greater brittleness as compared to concrete (Bombace et al., 1997a; Relini, 2000b). On the other hand, just for this ‘brittleness’ characteristic, the coal ash-lime mixture modules deployed in Adriatic Sea were extremely suitable for the settlement of *Pholas dactylus* larvae (common piddock; Fig. 1.5). This stone-drill bivalve lives inside of soft rocks (e.g., sandstone, schistose, and marl) down to about 20 m of water depth (Bombace et al., 1995a; 1997a) and is very valuable in some markets. Although fishing for *P. dactylus* is forbidden by Italian law (Cabinet Order of October 20, 1988) because it requires the destruction of the natural rocky habitat. *P. dactylus* is presently still the object of intense illegal harvesting.

**Figure 1.5.** Common piddock (*P. dactylus*) individuals colonized inside a coal ash-lime mixture module deployed in northern Adriatic Sea.
1.3 Artificial Reefs in Adriatic Sea

The large biomass of mussels settled on the concrete modules immersed in the Adriatic Sea led to the creation of more specialized reefs adapted for the development of an extensive mussel culture. The new specialized artificial structures were deployed on a large scale (7500–13000 m³ of immersed material) at the end of the 1980s and were placed close to the shoreline (between 10 m and 15 m of water depth) for better management of the mussel cultures. In such shallow waters, 2-layer pyramids were built associated with concrete cages (6x4x5 m; Fig. 1.6a, b and c), designed to increase available surface for the natural colonization of the mussels (Bombace et al., 1994, 1995b; Fabi and Spagnolo, 2001).

In recent years the creation of artificial reefs was referred to regional authorities, who considered their own local realities and built reefs on a much smaller-scale, organized in very simple spatial arrangements (e.g., single concrete cubes just scattered on the seabed) or made of low cost materials/modules not tested in advance either scientifically for possible ecological impacts or technically for the structural resistance to the marine environment. All these factors can limit the effectiveness of such artificial reefs. Thus, different studies were initiated to identify both the optimal spatial arrangement (in regards to the physical stability) of the artificial structures on the seabed and innovative modules to provide the best compromise between moderate price and the highest ecologically efficiency and structural stability of the new reefs. The studies carried out in the Adriatic Sea identified two new types of modules that together can satisfy the requirements listed above.
Figure 1.6. Water-based concrete cages employed in the deployment of artificial reefs in Italy. (a) Concrete cages (6mx4mx5m) for shellfish culture are placed among the pyramids to increase the ecological functionality of the artificial reefs. (b) Photograph before the deployment. (c) Photograph of mussels encrusting the cage.

The first module, defined as a "technoreef pyramidal group" (Fig. 1.7), has been designed with the specific purpose of fish repopulation and it is made up of 42 (or less) octagonal concrete plates with pH 9, constructed using only natural elements (e.g., washed sand or broken gravel) and without any debris or chemical additives. Every pyramidal group made up of 42 plates has a base surface of 12 m$^2$ and a height of 3.5 m, for a total surface of 43 m$^2$ and a weight of 3,000 kg. The module is structurally complex with a network of inner hollows that guarantee a constant water exchange while creating shelters and diverse habitats for different sessile and vagile marine organisms. Moreover, its microporous surfaces favor the settlement of the larvae of sessile organisms. Finally, these structures are stable and self-anchored, able to withstand the stresses of wave action, currents, burial, storms, and dragging by fishing gears.

The second type of module, defined as "plinth-stake" (Fig. 1.8), has a height of 4.2 m, a total weight of 8,930 kg, and consists of a hollow rectangular base
surface in which a stake with a 50 cm diameter is inserted. The entire structure is concrete. The main purpose of this module is to obstruct illegal trawling.

After scientific testing on a small-scale, these modules were employed for the first time on a large-scale in 2003 to build a multiple purpose, artificial reef about 5 km (3 nm) off the coast of Cattolica, in northwestern Adriatic Sea. The reef covers a rectangular area of 0.8 km$^2$ and it is made of 178 “plinth-stake” modules placed along the entire perimeter in an irregular arrangement about 35 m apart, while 78 “technoreef pyramidal groups” were placed in the central area. A second reef, organized in the same way, was deployed off the coast of Pedaso about 150 km south from Cattolica.

Multi-year monitoring programs are usually carried out before and after reef deployment to assess the effects of the structures on the environment and fishery resources. The investigations conducted after the placement of the structures assessed their stability, the natural soft-bottom benthic communities inside and outside the reef, the benthic community settled on the hard substrates, the finfish aggregation inside and outside the reef, and fishing yields.

In eutrophic conditions such as those found in Adriatic Sea, artificial structures are quickly and massively colonized by filter feeding organisms. The pioneer species are mainly hydrozoans, bryozoans, and serpulids. After a short period, depending on the season when the modules were immersed, mussels and their associated interstitial species (such as errant polychaetes and amphipods which find a suitable habitat in the bivalves’ byssus) dominate the benthic community. The abundance of the mussels decreases from the top to the bottom of the structures. Mussels are incrementally replaced by oysters with increasing depth of the structures (Bombace et al., 1994, 1995b; Fabi and Spagnolo, 2001). This is a typical ecological succession for artificial reefs in Adriatic Sea where biomass of mussels on the modules can reach 50 kg/m$^2$. However, high sedimentation can lead to
disappearance of the mussels and the benthic community becomes progressively dominated by deposit feeding and carnivorous species.

Figure 1.7. The “technoreef” module is the new type of artificial reef that is gaining popularity. (a) Octagonal concrete slabs composed of washed sand and broken gravel (pH 9) made up these structures. The continuous internal cavity system typical of the technoreef guarantees a constant water exchange favoring the nutrients supply and providing shelters for adult and juvenile fish and for benthic sessile organisms. Moreover the structure is self-anchoring able to resist against both the bottom currents and the dragging effects of the trawling fishery. (b) Example of 3-layer technoreef module. (c) Example of 2-layer technoreef module.

The physical presence of the modules and the benthic community colonizing them can also affect the soft bottom benthic populations in the surrounding area. In fact, the large abundance of mussels developed on the structures produce a biodetritus rain on the seabed favoring the proliferation of deposit feeders.

Fish aggregations associated with artificial reefs of the Adriatic Sea include thigmotactic species such as the sargo *Diplodus annularis*, the brown meagre *Sciaena umbra*, the shi drum *Umbrina cirrosa*, the European sea bass *Dicentrarchus labrax*, the mullets *Mugil cephalus* and *Liza* spp., the picarels *Spicara* spp., the bogue *Boops boops*, and the mackerels *Trachurus* spp. (Fabi and Fiorentini, 2004). This
aggregation shows seasonal changes due to both the eco-ethology of the different species and the environment. For example, numerous species migrate from the reef to the deeper and warmer offshore waters during the fall, and they swim back to the reef in spring or at the beginning of summer.

**Figure 1.8.** The “plinth-stake” module is another type of artificial reef that is gaining popularity. (a) A hollow rectangular base surface hosts a stake with 50 cm of diameter. The module is able to resist against the dragging effects of the trawling fishery. (b) Example of the plinth-stake module in northwestern Adriatic Sea. (c) Photograph of mussels encrusting the stake.

### 1.4 Effects of Artificial Reefs on the Surrounding Terrain

The introduction of artificial reefs into the marine environment acts as an open system with exchange of material and energy, altering the physical and biological characteristics of the area where they are deployed. The reefs can modify flow velocity and create turbulent intensity in and around the vicinity of the
structures, which can lead to scour and changes in sediment accumulation in the surrounding area (Farmer et al., 1999; Rambabu et al., 2002; Rambabu et al., 2003; Quinn, 2006; Jenkins et al., 2007; Wolfson et al., 2007). The environmental changes on the adjacent seafloor can, in turn, physically affect the artificial structures. Thus the stability of a reef will depend on the balance of scour, settlement, and burial resulting from ocean conditions over time. Today’s artificial reefs are all designed with particular purposes, and to maximize these purposes some considerations must to be taken into account (Pickering et al., 1998). Will the structure withstand the bottom impact during free-fall deployment? Once in place, will it withstand the stresses of currents, burial, and storms? If the reef is placed in an area of strong currents, factors such as scouring must be taken into account along with potential movement of the reef. Scouring under the edges of artificial reefs can eventually result in the burial of the reef (Wolfson et al., 2007). The lateral movement of artificial reefs can destroy the area around the reef as well as the artificial reef itself. Therefore, the design of a reef is critical to the survival of the structure and preservation of desired species.

Although much research has been conducted on terrain change and scour processes operating around anthropogenic structures in the near-shore (Yu and Ura, 2002; Rambabu et al., 2002; Rambabu et al., 2003; Quinn, 2006; Wolfson et al., 2007; Mayer et al., 2007), only limited research has been conducted on horizontal movement, deepening, and scouring of unique ecological systems like artificial reefs (Shyue, 1998; Shyue and Yang, 2002; Stauble and Tabar, 2003; Stauble, 2003; Brown and Harper, 2006). Detailed quantitative information on seabed morphology and terrain changes around individual reef units were obtained by Shyue and Yang (2002), while Brown and Harper (2006) worked on an experimental artificial reef particularly suited for scientific studies, offering a replicated reef design. But there is still the lack of long term monitoring of the artificial reef systems and, moreover, a
detailed description of how the sedimentary and oceanographic conditions affect different types of reefs and the succession of reef communities over time.

Acoustic systems are efficient tools capable of monitoring the environmental (physical and biological) evolution around artificial reefs, whereas visual dive and ROV inspections can be limited by water turbidity. However, techniques such as single-beam echo sounder and side-scan sonar have spatial limitations and navigation uncertainties of the towfish as well as difficulty in three-dimensional positioning of the towfish during a survey. Conversely, high-frequency multibeam echo sounders offer the potential of detecting and defining the fine-scale distribution of reef units from a ship mount with good control of sonar positioning during a survey due to the very accurate navigation available from differential GPS or similar systems.

These high-resolution systems are able to acquire 100% coverage of seabed geology and geomorphology over relatively broad spatial scales, offering an unprecedented level of resolution, coverage, and spatial definition (Kenny et al., 2003; Berman et al., 2005). In recent years the application of acoustic-mapping methodology, in particular the use of acoustic ground-discrimination systems used in conjunction with bottom sampling, has become common practice in monitoring and mapping seabed habitats (Naar et al., 1999; Cochrane and Lafferty, 2002; Foster-Smith et al., 2004; Jarrett et al., 2005; Jordan et al., 2005; Freitas et al., 2008). Because acoustic data are less able to detect changes in the biological components of the seabed, classifications of different seabed environments tend to be driven largely by physical criteria (Kostylev et al., 2001; Freitas et al., 2003).

Since the end of the 1980’s, the Marine Environmental Management Unit of ISMAR Ancona has been carrying out studies on the management of demersal resources, benthic communities, and habitat mapping. Over the past ten years, high-resolution multibeam studies have investigated scour, settlement, and burial of
artificial reefs and have mapped benthic/fish habitat of marine protected areas in the Western Adriatic Sea. Before the advent of Kongsberg Simrad EM3002 echo sounder, studies on the geophysical evolution of artificial reefs and fish biomass changes were carried out separately by two different acoustic systems. The Kongsberg Simrad EM3000 multibeam echo sounder was used for seafloor mapping (Manoukian et al., 2004) and a stationary array of hydrophones was used for the evaluation of fish biomass (Sala et al., 2007). Moreover fish samplings were also collected and compared with a reference site.

The objective of this research is to map and investigate artificial reefs deployed in the Western Adriatic Sea (Italy) and in the Gulf of Mexico as part of University of South Florida and ISMAR-CNR (Istituto Scienze del Mare di Ancona – Consiglio Nazionale delle Ricerche, Italy) collaboration.

Specifically, the goal is to assess the geophysical and biological impact of selected artificial reefs on the seabed and the surrounding marine environment using Kongsberg Simrad EM3000 and EM3002 multibeam echo-sounders, which operate at 300 kHz. The data collected in a series of repeated surveys will be used to address the following questions:

1) How do artificial reefs change over time in relation to the coastal processes (geology, hydrodynamics, sedimentation, etc.)?
2) Do certain artificial reef designs work better than others in certain geologic or physical oceanographic settings?
3) How accurately does multibeam technology map different typologies of artificial modules of known size and shape?
4) How do artificial reefs affect the fish aggregations behavior? What are the limitations of multibeam technology for investigating fish aggregations distribution as well as spatial and temporal changes?
In regards to the last question, an attempt to investigate the fish aggregations at the artificial reef using a sophisticated multibeam sonar system designed exclusively for bathymetric mapping was made and the results are presented in Chapter 8.
2. Overview of the Northwestern Adriatic Basin

2.1 Introduction

The Adriatic Sea is an important continental basin, and one of the most productive, in the oligotrophic Mediterranean Sea (Fonda Umani et al., 2005). The basin is elongated, with a long northwest–southeast axis of about 800 km long. The basin is approximately 150 km wide, is extremely shallow with a mean depth of about 35 m, and receives strong river runoff (Figure 2.1). This epicontinental sea lies between the Italian peninsula and the Balkans (Artegiani et al., 1997a), covering 138,600 km$^2$ and occupying a volume of 35,000 km$^3$. It is surrounded by several mountain ranges such as the Alps, the Apennines, and the Dinaric Alps, which strongly influence the wind system and the climate. Water exchange with the Mediterranean Sea takes place through the Otranto Channel, whose sill is 800 m deep.

The Adriatic basin has complicated morphology and bathymetry. The western coast is low and mostly sandy, whereas the eastern coast is generally high and rocky, rugged, with multiple islands and coves. It shows clear morphological differences along both the longitudinal and the transversal axes and has been divided into northern, middle and southern sub-basins (Artegiani et al., 1997a; Fig. 2.1). The northern Adriatic is very shallow (<100 m) with an average bottom depth of about 35 m and has a very gradual topographic slope (~0.02°) along its major axis. The middle Adriatic is a transition zone between northern and southern sub-
basins, with an average depth of 140 m, and contains the two Pomo Depressions (approximately 260 m). The southern section is characterized by a wide depression more than 1200 m deep.

**Figure 2.1.** Adriatic Sea coastline and bathymetry. Lines a and b define the north, middle and south sub-basins (*modified from http://ancona.ismar.cnr.it/dataset/atos.html that was kindly provided by colleagues of the Oceanographic Lab of CNR-ISMAR Ancona*).

A large number of rivers discharge into the basin with an estimated mean load of 5,700 m$^3$/s, and with significant influence on circulation in the Sea. About 28% of the river supply is due to the Po River (1,525 m$^3$/s; Syvitski and Kettner, 2007), particularly relevant in the northern basin. The Po River and the other
northern Italian rivers are believed to contribute about 20% of the total river runoff into the Mediterranean Sea (Hopkins, 1992).

The northern Adriatic constitutes a unique ecosystem and it is the most biologically productive part of the Adriatic, and one of the most productive Mediterranean regions at several trophic levels, from phytoplankton to fish. Indeed this sub-basin is one of the major fishing grounds of the Mediterranean Sea, thus having great socio-economic importance. This continental shelf shows wide inter-seasonal and inter-annual variations in environmental parameters (e.g., temperature and salinity) and circulation, which are strongly influenced by atmospheric forcing and river inputs (Russo and Artegiani, 1996). The huge nutrient loads discharged by the Italian rivers, particularly the Po River, that drain highly anthropogenically-modified basins with high-population densities, tourism, extensive agriculture, and livestock, result in coastal pollution and eutrophication (Fig. 2.2). These strong anthropogenic pressures can lead to anoxic conditions (during reduced circulation) and fish kills, as were reported mainly in the 1980s (Vollenweider et al., 1992; Caddy, 2000). Moreover, this ecosystem is also heavily stressed by the intensive commercial fishing, which cannot be disregarded. Because of the strong overexploitation and the great environmental variability that have coexisted since ancient times (Barausse et al., 2009), it is very difficult to quantify the magnitude of the human impacts on this ecosystem compared to its natural state.
2.2 Physical Oceanography

The first studies investigating the general circulation of the Adriatic Sea go back to the end of the nineteenth century. Over the last twenty years, hard work was done to consolidate the knowledge already acquired.

Figure 2.2. Adriatic Sea trophic conditions (from Rinaldi et al., 1995).
The Adriatic Sea plays a fundamental role in the water mass dynamics of the whole Mediterranean, being one of the main sources of the Eastern Mediterranean’s bottom waters. These deep-water masses, formed in both the northern and southern sub-basins, together with a surface current, run along the western Italian coast and flow into the Ionian Sea across the Otranto Channel (Fig. 2.3). On the other hand, the Adriatic Sea receives Ionian surface waters along the eastern coast and the intermediate Levantine waters formed in the far Eastern Mediterranean basin at intermediate water depths forming an intermediate layer.

The Adriatic Sea has, in general, a cyclonic (counterclockwise) circulation with current flowing towards northwest along the eastern coast (Albanian-Croatia coast), and a current flowing towards the southeast along the western coast (Italian coast). Circulation in the Adriatic is characterized both by positive and negative thermohaline circulations, called estuarine and anti-estuarine circulation, respectively (Fig. 2.3).

Figure 2.3. Adriatic Sea baroclinic circulation (from Arregiani et al., 1997b).
2.2.1 Thermohaline Circulation

Thermohaline circulation in a basin is determined by the water density gradient. In a semi-enclosed basin such as the Adriatic Sea, the density gradient may be caused by either an increase of the buoyancy due to rainfall and river input, or a decrease of the buoyancy due to cooling and evaporation. The Adriatic Sea, indeed, is subject to an intense winter air-sea heat losses due to the Bora winds that occur mainly in the north sub-basin. The northwestern Adriatic shelf is the formation site of cold and dense water masses. The process begins in late autumn with a preconditioning phase when the entire water column becomes completely homogeneous. In fact, during the winter, the Bora winds cause strong heat losses and the consequent considerable evaporation leads to an increase in salinity. Under these conditions, the cold and dense water mass called North Adriatic Dense Water (NAdDW) is formed and represents the densest water mass formed within the entire Mediterranean Sea. The entire water column is completely homogeneous from November through March; afterwards, spring heating and increasing river input isolate this more dense water mass in the bottom layer between the Po River Delta region and Istria (Fig. 2.1). The NAdDW is one of the two dominant water masses present in the north-western Adriatic shelf and flows southwards along the Italian coast as a density-driven western bottom current that then becomes what is called the Dense Water Outflow Current (DWOC). During its flow, it bifurcates and becomes two currents, one entering in the Pomo Depressions and the other continuing towards the southern sub-basin where additional deep water forms. This sub-basin is where Adriatic Deep Water (ADW) originates and flows out from the Otranto Channel during the summer. These deep currents together with the water flow coming from the Ionian Sea contribute to the anti-estuarine circulation.

Artegiani et al. (1997b) used the temperature and salinity ATOS (Adriatic Temperature, Oxygen and Salinity) data set to calculate the system of surface
currents, describing in detail the baroclinic components of flow during all the four seasons (Fig. 2.3). With regard to the north sub-basin, the accumulation of fresh water from rivers and heating cause the formation of the Western Adriatic Current (WAC), which is part of the estuarine circulation and it is the second dominant water mass present on the northwestern Adriatic shelf. The WAC, which is mainly characterized by relatively cold water and reduced salinity, is a western sector intensified current (10–50 km wide) flowing southwards along the Italian coast with long-term average speeds that reach 0.20 m/s at some locations (Poulain, 2001).

The WAC exports fresh water and related substances from the north sub-basin toward the central and southern Adriatic and the exchange reaches a maximum in the colder seasons when cyclonic water circulation prevails. Along the eastern edge of the Adriatic Sea, in fact, a compensation inflow carrying warmer and saltier waters from the southern Adriatic and Ionian Sea occurs (Zore-Armanda, 1963; Artegiani et al., 1997a; Cushman-Roisin et al., 2001) and is called Eastern Adriatic Current (EAC). Its formation takes place along the eastern coast in the north direction and two different water masses come into play, Ionian Surface Water (ISW) and Levantine Intermediate Water (LIW) flowing at depths of about 200 m.

In spring and summer this circulation is sometimes replaced by a gyre and transverse currents may reduce the rate of water exchange. Low salinity waters, formed by mixing with fluvial waters in the western coastal zones, are dispersed over the entire north shelf, advancing the process of water column stratification.

This two-fold thermohaline circulation is susceptible to climatic changes on both seasonal and annual scales (Orlic et al., 1992, 1994). In addition, atmospheric disturbances due to the average wind system have to be also taken under consideration even if they are less intense on spatial-temporal scales compared to the general Adriatic circulation (Malanotte-Rizzoli and Bergamasco, 1983).
2.2.2 Wind-driven Circulation

Three factors come into play in the dynamics of wind-driven circulation: the wind stress on the sea surface, the vertical pressure gradient generated along the entire water column, and the bottom friction. The northwestern Adriatic shelf is the area most influenced by the wind system, which uniformly mixes the water column in winter time (Zavatarelli et al., 1998).

Two distinct wind regimes, Bora and Sirocco, influence basin-wide circulation in the Adriatic (Fig. 2.4). The Bora is a strong, cold, dry, continental wind blowing from north-northeast towards the sea. It is a katabatic wind whose source is so cold that when the air reaches the coast, the dynamic warming caused by subsidence is insufficient to raise the air temperatures of the region to the level normally experienced.

The Bora occurs when a cold and dry mass of air accumulates over the Balkan Peninsula, especially over Slovenia, Croatia, and the former Republic of Yugoslavia. The depth of the cold air reservoir has to reach at least up to the mountain passes for the Bora to commence streaming along the valleys of the Dinaric Alps and blowing violently on some Adriatic areas (Poulain and Raicich, 2001). On the average it is most violent to the North along the eastern Adriatic coast from Trieste to the Albanian border, with decreasing intensity southward and over the open sea (Fig. 2.5). The strength depends to a great extent on topographical features adjacent to the coastline. Over the open water of the Adriatic Sea, its average speed is 15 m/s reaching maximum peak value of 50 m/s. Sometimes the Bora is very localized, extending only a few miles seaward from the eastern coast. At other times, the Bora covers the entire Adriatic Sea. Its normal southward extent, however, is about 111 km (60 nm) south of the Strait of Otranto.
Figure 2.4. Main wind pattern in Adriatic Sea (from Cushman-Roisin et al., 2001).

Bora winds are most common during the cold season (November through March). Generally, the frequency of gale force winds of at least 15 m/s varies from one day or less per month during the summer to six days or more per month during the winter. The average duration of a continuous gale force Bora over the Adriatic Sea is about 12 hours, but the winds sometimes will last up to two days.
There are two types of weather patterns which produce the Bora: an anticyclonic weather pattern characterized by strong high pressure over Central Europe (Dorman et al., 2007), but with no well-developed low to the south ("katabatic" pattern), and a cyclonic weather pattern characterized by a depression in the southern Adriatic Sea or in the Ionian Sea ("dynamic" pattern). In each case the pressure is higher on the European side of the mountains and lower over the Mediterranean.

Bora winds typically induce sea surface to rise near the coast and this intensifies the WAC and causes a plume of freshwater and suspended sediment to extend from the Po River region past the Gargano Peninsula (Orlic et al., 1994). The winds may produce a cyclonic (counterclockwise) gyre in the northern third of the Adriatic that transports freshwater from the Po River toward the northeast (Franco and Michelato, 1992; Orlic et al., 1992, 1994; Artegiani et al., 1997b; Hopkins et al., 1999; Cushman-Roisin et al., 2001; Mauri and Poulain, 2001), with an intensified EAC along the eastern coast. Historical data and numerical simulations have demonstrated that Bora winds can cause the formation of a double gyre structure consisting of a larger one in front of the Po River Delta region and a smaller anticyclonic one just below (Poulain et al., 2001).

The Sirocco is a tropical, continental, southeasterly wind that originates in North Africa and Arabia and blows over the Mediterranean (Fig. 2.4). These source regions are over deserts and thus the Sirocco is extremely dry and warm at the beginning, but crossing the relatively cool water of the Ionian Sea, the mass of air induces evaporation. As the air continues its long trajectory, streaming along the Adriatic basin’s major axes, it becomes saturated with water vapor in the lowest layers.
Figure 2.5. Regional Ocean Modeling System results. (a), (b) and (c) current vectors at surface and sea surface temperature; (d), (e) and (f) current vectors and temperature at bottom. (a) and (d) before bora event; (b) and (e) during bora event; (c) and (f) after bora event (from Boldrin et al., 2009).

The Sirocco can occur in any month or season. In autumn and in winter the whole Adriatic is affected by Sirocco events preceding cyclonic systems that move towards the north or east from the western Mediterranean. The gale force Sirocco has an average intensity of 10 m/s, but can exceed 15 m/s, especially in winter and in spring reach 30 m/s. The Sirocco is in part responsible for the sea level rising in the North Adriatic sub-basin (even tens of centimeters). Coming from the southeast over the sea, it is less subject to local variations than the Bora, but it does show some geographical variations due to the coastal orography (Pasarić et al., 2007).
Sirocco winds tend to be southerly in the Strait of Otranto and off the Istrian Peninsula (Pula), and more easterly at some places along the northern Adriatic near Ravenna and Pesaro (Poulain and Raicich, 2001).

Sirocco winds may reduce, or even reverse, the WAC (Artegiani et al., 1983), and confine discharge from northern Adriatic rivers, such as the Po and Adige, to the north (Orlic et al., 1994; Zavatarelli and Pinardi, 2003).

Both Bora and Sirocco winds generate energetic waves in the western Adriatic, particularly near the Po Delta. Sirocco winds are aligned with the long axis of the Adriatic Sea, with approximately 800 km fetch, and generate waves that exert large shear stresses on the seabed in the shallow northern Adriatic. Bora winds have a shorter fetch than Sirocco, but are strong enough to create waves capable of suspending sediment, especially along the northwestern coast (Fain et al., 2007; Traykovski et al., 2007; Wang et al., 2007). More details are described in Section 2.3.

### 2.2.3 The Temperature/Salinity Distribution

Surface heat and water fluxes (evaporation and precipitation) and a considerable Po River runoff characterize the northwestern Adriatic shelf. The wide Po River Delta strongly influences all the area's morphology and hydrodynamics. Some estimates of the surface climatological heat and water budgets have been attempted by Raicich (1996), Artegiani et al. (1997a), Maggiore et al. (1998), Cardin and Gačić (2003), Chiggiato et al. (2005), and Wang (2005). The surface mean heat budget shows a value of about -20 W/m² with a large interannual variability (Fig. 2.6). At the climatological time scale, this surface heat loss should be compensated by heat advection through the Otranto Channel (Chiggiato et al., 2005). The balance between evaporation and precipitation is estimated to range between 0.06 and 0.52
Evaporation results in water loss between 1.08 and 1.34 m/yr, while precipitation determines water gain ranging between 0.82 and 1.02 m/yr.

Temperature and salinity show homogeneous vertical values along the entire water column in winter and the minimum sea surface temperature is about 8°C (off the Po River Delta; Gačić et al., 1997; Maggiore et al., 1998). The Po River affects the sea surface temperature bringing basically colder water than the ambient seawater by several degrees (Sturm et al., 1992). In summer the water column is strongly stratified with a thermocline at about 10-15 m depth. Sea surface temperatures are maximum along the Italian coast (23-25°C) and minimum on the other (eastern) side (19-20°C) where upwelling events prevail. The Po river water is slightly warmer than the seawater (Sturm et al., 1992). Salinity ranges from 0, at the river mouth, to about 38.5 along the eastern coast where saltier water mass flows from the south in the cyclonic circulation. Very low salinity values can be found far from the river mouth where the fresh water is confined to the surface turbid plume carrying its nutrient and sedimentary loads. These events occur mainly in summer.

As already mentioned above, the Po River represents the major buoyancy input in the northwestern Adriatic shelf with an annual mean discharge rate of 1,525 m³/s, accounting for about one-third of the total riverine fresh water input in the Adriatic (Raicich, 1996; Svytski and Kettner, 2007; Figs. 2.7 and 2.8). Its runoff is particularly strong in winter and the Po River plume flows predominantly southward confined along the Italian coast feeding directly a buoyant Western Coastal Layer (WCL; Malanotte-Rizzoli and Bergamasco, 1983; Poulain et al., 2001). The WCL shows peculiar hydrological properties, completely different for example from the water masses coming from the center of the sub-basin. Moreover, it is associated with the WAC, which flushes the nutrient-rich water out of the northern Adriatic along the Italian coast (Hopkins et al., 1999; Marini et al., 2002; Campanelli et al.,
2004). During summertime this fresh water input is restricted to the surface layer, which is often a few meters thick (~5 m). It sustains itself and flows above the lower layers reaching great distances from the mouth. Besides forming the WCL it also spreads offshore over the entire northern sub-basin. Water column homogeneity, weak wind stress, and low Po River discharge rates cause generally a wider WCL restricted along the coast, whereas stratified water column, Bora and Scirocco events, and strong Po River discharges favor a thinner WCL spreading offshore (Grancini and Cescon, 1973; Malanotte-Rizzoli and Bergamasco, 1983; Barale et al., 1986; Kuzmic and Orlic, 1987; Zore-Armanda and Gačić, 1987; Kuzmic, 1991; Sturm et al., 1992; Orlic el al., 1994; Bergamasco et al., 1996; Kourafalou, 1999).

The Po River plume is characterized by horizontal vortex structures with time scales of one or two days and length scales of about 10 km. In fact, satellite observations of surface chlorophyll-a concentration and sea surface temperature revealed very complex mesoscale dynamics including the meandering and instability of WCL, jets/filaments, and eddies (Mauri and Poulain, 2001; Fig. 2.9).

In summary, a temporal succession of two different hydrodynamic patterns has been recognized: between November and March, the westernmost waters are diluted mainly by the Po River outflow and remain separated from the highly saline and vertically-mixed offshore waters thanks to a frontal system located 8–16 km from the coast. The dissolved and particulate matter, coming from the land, therefore remains more or less confined. Between April and October, warmer waters diluted by freshwater inflows are confined to the surface layer and reach almost all of the Northern sub-basin. During that period, one or more pycnoclines separate the water masses of intermediate density, while the high-density waters are confined near the bottom.
Figure 2.6. Mean monthly sea surface temperature (°C) of Adriatic Sea obtained from Advance Very High Resolution Radiometer (AVHRR) from January 1998 (up left corner) to December 1998 (down right corner). Strong seasonal variability is recorded. A north-south gradient is well depicted due to both the entrance of warmer water mass from the Mediterranean and heat losses from the northern Adriatic mainly during winter time. The cyclonic circulation is also well evident with warmer water inflow northwards from the South Adriatic and Ionian Sea along the eastern coast and colder water flowing southwards along the western coast. During summer time the pattern reverses with colder water entering from the Mediterranean and relatively warmer water flowing down along the Italian coast out from the Otranto Channel.
Figure 2.7. Daily discharge in m$^3$/s of the Po River for the years 1989–2003 at Pontelagoscuro station, 91 km from the river mouth and 8 m above sea level (from Syvitski et al., 2007).

Figure 2.8. Daily averages of the Po River flow for the period 1989–2002 (modified from Marini et al., 2008).
Figure 2.9. Very complex mesoscale dynamics of the Po River plume. (a) MODIS image of chlorophyll-a concentration for 15 October 2005 at 1155 GMT; (b) Sea surface temperature map from the AVHRR-NOAA-17 for 15 October 2005 at 1155 GMT (provided by GOS-ISAC (Rome)-CNR).
2.3 Geological setting and sediment dynamics

The northwestern Adriatic Sea is a foredeep basin, Pliocene–Quaternary in age, that represents the most recent of a series of foredeep basins formed during the Apennine orogenesis and migrated eastwards with two distinct depocentres up to 8 km thick (Royden et al., 1987).

During the late Pleistocene five glacial periods followed each other and the glacial maximum occurred in the last one called Würmian glaciation (~21,000 year ago) dropping the sea level of about 120 m compared to the present one and causing the maximum regression of the Adriatic Sea. At that time the shoreline was located in correspondence of the city of Pescara and the entire northern sub-basin, the current Adriatic continental shelf, was a wide fluvial-marshy plain drained by paleo-riverbeds. The relative rivers’ increased change in elevation caused an increase of the erosional power caused the transport of an enormous quantity of alluvial sand in the plain. Simultaneously clayey mud and peat deposited in marsh environments. The Adriatic basin was filled mainly from the northwest in an axial direction, as testified by seismic reflection studies (Ciabatti et al., 1987; Trincardi and Correggiari, 2000).

During the late Pleistocene-Holocene relative sea level rise, a wide portion of the northern and central Adriatic alluvial plain of the Würmian Glacial period was progressively drowned, resulting in an eight-fold widening of the shelf area of the Adriatic (Trincardi et al., 1994; Correggiari et al., 1996; Cattaneo and Trincardi, 1999; Fig. 2.10). This drowning event is known as the Flandrian transgression occurred in two main episodes, the first one at 6,000 years ago and the second one at 2,000-3,000 years ago when the maximum sea transgression was recorded. The sediments previously deposited in the alluvial plane were reworked in situ and they are still identifiable offshore. They are called “relict sand” since they are not in balance with the present hydrodynamic conditions. During the late Holocene the high
uplift rates of the Apennines led to high sediment supply rates. The deposits recording the late Pleistocene–Holocene sea level shift can therefore be subdivided into lowstand, transgressive and highstand systems tracts (Cattaneo and Trincardi, 1999; Correggiari et al., 2001; Ridente and Trincardi, 2005). Geophysical surveys indicate that about 180 km$^3$ of sediment have accumulated along the western margin of the Adriatic in elongate depositional accretionary features termed clinoforms (Palinkas and Nittouer, 2006; Cattaneo et al., 2007), with the locus of deposition in 40 to 50 m water depths (Cattaneo et al., 2003; Cattaneo et al., 2004) and reaching up to 35 m in thickness (Cattaneo et al., 2003; Trincardi et al., 2004; Fig. 2.11). The dimensions and shape of a clinoform are determined by factors such as relative sea level, sediment supply, depositional regime, accommodation space, and sediment type.

Successively, the current sedimentation regime on continental shelf began. Rivers are the primary source of sediments transported to the sea. Once sand and suspended mud are delivered, waves and currents play a critical role in sediment re-suspension and dispersion.

Three types of terrain are drained by the rivers discharging sediments to the Adriatic Sea. The Croatian coast is dominated by karst topography, and this coastline’s sediment input to the Adriatic Sea is negligible (Cattaneo et al., 2003). Northern Adriatic rivers drain Alpine watersheds that have relatively low sediment yields and contribute much of their sediment during spring snowmelt. Finally rivers on the east coast of Italy drain the more erodible Apennine Mountains, and supply sediment to the Adriatic Sea during river discharge pulses associated with precipitation. Therefore the Adriatic Sea is strongly asymmetric in terms of sediment supply.
Figure 2.10. Seismic–stratigraphic units of the western Adriatic shelf: Pleistocene sequences are separated by regional erosion surfaces (ES1 to ES4) and reflect ca. 100 kyr glacio-eustatic cycles; deposits above ES1 record the last sea level lowstand, rise and modern highstand (LST, TST and HST). Pleistocene sequences are internally composed of progradational units recording prolonged sea level falls during each cycle (forced regression deposits; from Ridente and Trincardi, 2005).

Tributaries draining both Alpine and Apennine mountain areas contribute to the Po River. The Po River carries a sediment load of 13–15 million ton per year (Mt/yr; ~30% of total; Frignani et al., 2005) with an average discharge of 1,525 m$^3$/s and represents the largest single source of sediment to the Adriatic Sea (Cattaneo et al., 2003; Syvitski and Kettner, 2007; Figs. 2.7 and 2.9). Discharge peaks in the early spring (from melting snow and glacial ice) and in fall (October-November) because of high precipitation. Flood events last for 1-2 weeks and are typically in the order of 3000-5000 m$^3$/s (Fig. 2.12). The mean grain composition of the discharged sediments is 7% clay, 23% sand and 70% silt (Nelson, 1970).

The sediment input to the northwestern Adriatic margin has formed a mud deposit (Correggiari et al., 2001; Cattaneo et al., 2003) with a sand-mud transition at 5-15 m water depth (George et al., 2007). The sand-mud transition is a nearshore boundary on the seafloor where the dominant sediment size changes from sand (>63 µm) to silts and clays (0.24-63 µm), known collectively as “mud” (McCave, 1972).
Figure 2.11. Thickness and depocentre distribution of the late Holocene highstand mud wedge. The central Adriatic mud wedge and the Gargano subaqueous delta represent progradational systems not directly connected to the Po delta and prodelta, on the north Adriatic shelf (from Cattaneo et al., 2003).
Mud is an important biological, physical, geological and chemical boundary in the sea, separating distinct benthic habitats, causing a significant change in acoustic backscatter, representing a key facies change, and delimiting more surface-reactive mud from less surface-reactive sand. Over time this material either accumulates close to the source area or is transported to the southwest by the WAC (Correggiari et al., 2001; Fain et al., 2007; Puig et al., 2007; Palinkas and Nittouer, 2007). Frignani et al. (2005) have estimated that the majority (~62% of total) of sediment entering this specific Adriatic region does so north of Ancona, and that sediment supply decreases markedly to the south (Ancona to Gargano, ~31% of total).

In the relatively low-energy epicontinental northwestern Adriatic shelf, storm events are the major mechanisms that cause sediment re-suspension and advection on the Po River subaqueous delta and are generally forced by Bora and Sirocco winds (Sherwood et al., 2004; Figs. 2.13, 2.14, 2.15 and 2.16). The subsequent transport controls the redistribution of sediment from its initial flood deposition site to its ultimate site of long-term accumulation. Thus, the event-driven sediment transport
compressed into shallow water and with a high inter-annual variability, has a major influence on the formation and maintenance of sedimentary deposits on the Adriatic shelf, as also reproduced by numerical models (Harris et al., 2008). In general, the sediment deposit is the result of rapid initial deposition near the river mouth during high discharge events (Fox et al., 2004; Palinkas et al., 2005; Milligan et al., 2007). Part of this initial deposition is subsequently transported in the along-shelf direction and successively redistributed along the entire shelf. Across-shelf sediment transport occurs by bottom Ekman transport, which results in a counter clockwise rotation of the currents from the bottom up due to frictional and Coriolis along-shelf transport, but is significant during Bora storms, which strengthen the WAC, increase wave shear stresses, and re-suspend sediment (Fain et al., 2007; Puig et al., 2007).

The along-shore sedimentary belts forming during the transportation process are hydraulically sorted in grain size in accordance with the classic model of modern sedimentation on continental shelves. Coastal sands, mud, and shelf relict sand farther offshore are, indeed, observed. Sediment transport induced by Bora winds is highly variable in terms of magnitude and direction, probably due to the interaction between bathymetry and the wind-driven circulation that generates gyres and mesoscale circulation features described in the previous chapter. Records from the Po region show that the sediment flux is strongly storm-driven along the 12-m isobath (Fain et al., 2007). A relatively continuous band of fine-grained sediment is created along the coastline between 0 m and 30 m depth, which extends from the Po Delta southward for a distance of over 600 km (Correggiari et al., 1996; Cattaneo et al., 2003). Little sediment accumulation is found at water depths greater than 30 m (Palinkas et al., 2005).
Figure 2.13. Conditions averaged during a Bora from 15 to 20 February 2003. (a) Wind stress (arrows; see scale for magnitude) and wave height (color); (b) Depth- and time-averaged sediment concentration (color) and velocity (arrows; see scale for magnitude); (c) Time-averaged, depth-integrated flux ($t \, m^{-1} \, d^{-1}$). Arrows show direction where flux exceeds $0.1 \, t \, (m \, d)^{-3}$. Contours every 25 m up to 200 m water depth (from Harris et al., 2008).

Figure 2.14. Bed shear stresses averaged during the Bora from 15 to 20 February 2003. (a) Combined wave-current skin friction shear stress; (b) Wave component of shear stress and (c) current component of shear stress. Colors shown in log scale. Contours drawn every 25 m up to 200 m water depth (from Harris et al., 2008).
Figure 2.15. Conditions averaged during a Sirocco from 14 to 19 November 2002. (a) Wind stress (arrows; see scale for magnitude) and wave height (color); (b) Depth- and time-averaged sediment concentration (color) and velocity (arrows; see scale for magnitude); (c) Time-averaged, depth-integrated flux (t m\(^{-2}\) d\(^{-1}\)). Arrows show direction where flux exceeds 0.1 t (m d\(^{-1}\)). Contours every 25 m up to 200 m water depth (from Harris et al., 2008).

Average Bed Shear: 11/14-19

Figure 2.16. Bed shear stresses averaged during the Sirocco from 14 to 19 November 2002. (a) Combined wave-current skin friction shear stress; (b) Wave component of shear stress and (c) current component of shear stress. Colors shown in log scale. Contours drawn every 25 m up to 200 m water depth (from Harris et al., 2008).
3. Methods

3.1 Data Acquisition

3.1.1 Study Area

The Senigallia artificial reef is located approximately 28 km (~15 nm) northwest from Ancona, Italy (Latitude: 43°45'17.41" N, Longitude: 13°12'32.92" E). The reef was deployed in 1987 about 2.3 km (~1.2 nm) offshore at a mean depth of 12.0 m on a sandy mud seabed, far from natural hard substrates.

The reef consists of 29 pyramids, each of them built with five water-based concrete (WBC) cubic blocks (2x2x2 m). Each block weighs 13,000 kg and is characterized by rough surfaces to facilitate the settlement of benthic organisms and holes of different shape and size to provide habitats for marine biota. The 4-m high pyramids were placed on gravel “mattresses” to spread the weight and prevent subsidence, and were deployed in a rectangular arrangement about 15 m apart. Ten concrete cages (4x5x6 m) for shellfish culture were also interspersed among the pyramids making a reef a continuous system and increasing its ecological functionality (Fabi and Fiorentini, 1994; Fig. 3.1).

Some special modules were also introduced in the reef system: experimental concrete and ash mixture cubic blocks, a structure employed for common piddock (P. dactylus) culture (Fig. 3.2), a fish cage for gilthead bream (Sparus aurata) culture, (Fig. 3.3), experimental 'technoreef’ modules (Fig. 3.4), and a structure employed for lobster (Homarus gammarus) culture.
Figure 3.1. Location and arrangement scheme of Senigallia artificial reef.

The technoreef module is the new type of artificial reef that is gaining popularity. Octagonal concrete slabs composed of washed sand and broken gravel (pH 9) make up these structures. The continuous internal cavity system typical of the technoreef guarantees a constant water exchange and providing shelter for adult and juvenile fish and for benthic sessile organisms. Moreover the structure is self-anchoring, able to resist both the bottom currents and the damaging effects of the seafloor trawling.

The area is exposed to winds between northeast and southeast. As previously seen, two distinct wind regimes, Bora and Sirocco, influence basin-wide circulation in the northwestern Adriatic Sea (Fig. 3.5). Kovačević et al. (2000) investigated the seasonal variability of the flow related to this particular sub-basin area of the Adriatic Sea. A southeastward current with a variable speed of 15-35 cm/s occupies the 10-15 km wide coastal band, clearly showing the permanent presence of the WAC (Fig. 3.6). Beyond this coastal band, the current is less organized, with lower speeds (below 10-15 cm/s) and variable directions. The WAC is stronger during most of
autumn and winter (November-February) and weaker during spring and summer (March-August). The current flow is more evident in the November-February period when the WAC is well developed. But at local scales, the wind may remarkably influence the coastal circulation. While the northeast Bora wind contributes to the intensification of the WAC, responding promptly and directly to the wind, southeast Sirocco wind, after blowing over the major portion of the Adriatic Sea, induces a current reversal (Fig. 3.7). Since the current response to Sirocco forcing along the western Adriatic coast is northwestward, opposed to the prevalent southeastward flow, the current reversal has some delay to the southeastern wind.

The prevalent southeastward current is mainly driven by the horizontal density gradient with a direct connection between the intensity of the monthly current field at the study area and the spreading pattern of the fresh water from the Po River (Franco and Michelato, 1992; Artegaian et al., 1999; Kovačević et al., 2000).

Both currents and fluvial input, mainly from the Po River and the local Cesano River, induce sediment suspension making poor visibility a common condition. The water temperature ranges from 7°C in winter to 26-27°C in summer.

**Figure 3.2.** (a) Structure employed for common piddock (*P. dactylus*) culture; (b) submersion of the common piddock special module.
Figure 3.3. (a) Fish cage for gilthead bream (*S. aurata*) culture; (b) mussel beds encrusting the submerged fish cage.

Figure 3.4. (a) 2-layer technoreef module; (b) submersion of a 2-layer technoreef module in the Senigallia artificial reef.
Figure 3.5. Mean daily surface wind over the northern and central Adriatic Sea. (a) Bora wind from northeast; (b) Sirocco wind from southeast. Red rectangle delimits the study area (modified from Kovačević et al., 2000).
**Figure 3.6.** Mean monthly current field from September 1997 to August 1998 at the study area. A remarkable seasonal variability is well depicted (*modified from Kovačević et al., 2000*).
Figure 3.7. Low frequency current flow sub-sampled at the study area during (a) Bora wind from northeast and (b) Sirocco wind from southeast (*modified from Kovačević et al., 2000*).
3.1.2 Geophysical Survey

Multibeam surveys of Senigallia artificial reef were conducted between November 2001 and July 2008. The 2001, 2002 and 2004 geophysical surveys were carried out using a Kongsberg-Simrad EM3000 Multibeam echo sounder. For the subsequent 2005, 2007 and 2008 surveys, the acoustic system was upgraded to the EM3002 Multibeam echo sounder. In all the surveys, the transducer was hull-mounted on the CNR-ISMAR (Ancona) R/V “Tecnopesca II” (Fig. 3.8 and 3.9), and the tracks were positioned so as to ensonify 100% of the seafloor with a ~20% of overlap.

![R/V Tecnopesca II of CNR-ISMAR Ancona.](image)

**Figure 3.8.** R/V “Tecnopesca II” of CNR-ISMAR Ancona.

In addition to the high resolution multibeam bathymetry data, the backscatter signal was recorded. Neither multibeam or backscatter data from 2001, 2005, and 2007 cruises are displayed here because of poorer quality resulting from navigation problems and sonar malfunction, respectively.
3.1.2.1 Multibeam Bathymetry Data

The Kongsberg Simrad EM3000 system maps the shallow ocean floor using a 300 kHz acoustic frequency and fanning out up to 127 acoustic beams at a maximum ping rate of 25 Hz and an angle of 130° (1.5° × 1.5° beams are spaced 0.9° apart; http://www.kongsberg.com). This yields swaths that are up to ~4 times the water depth. The position and orientation of the vessel was obtained via a 24-hour, differential global positioning system (DGPS) navigation connected to a geostationary satellite, while an Anshutz Standard 20 gyrocompass and a Seatex Motion Remote Unit 4.0 were used to compensate for ship attitude (roll, pitch, heading, and heave). This information is integrated with the multibeam echo soundings to eliminate the effects of vessel movement, and provide accurate position and orientation of the seafloor as mapped by the multibeam sonar. Angular misalignment among transducer, motion sensor, and gyrocompass, together with latency, was calibrated by a patch test at sea. Moreover, sound speed profile measurements were made using Smart SV & Pressure 4609 from Applied Micro-system Ltd.

The system is capable of centimeter-scale resolution with a depth accuracy of ~15 cm RMS and a horizontal positional accuracy of ~1 m after post-processing. The data were logged using Simrad Merlin software, using the same settings for all the surveys.
During the summer 2005, the new Kongsberg Simrad EM3002 replaced the EM3000 system. Besides the technical and operational improvements, such as the increment up to 254 acoustic soundings at a maximum ping rate of 40 Hz and an angle of 130°, the EM3002 system extends the functionality of multibeam echo sounders to cover three-dimensional imaging of the water column. In fact, 164 acoustic beams are sampled digitally with a spatial resolution of 15 cm for each ping, creating a digital image of a slice of the water mass under the transducer. With the EM3002 system, the data were logged using Kongsberg SIS software using the same settings of the previous surveys.

3.1.2.2 Multibeam Backscatter Data

Both EM3000 and EM 3002 systems provide the strength of the acoustic signal returning to the transducers. The multibeam systems determine the spatial variability of backscatter strength as a result of the interaction of the acoustic energy with the seafloor geometry and physical properties giving useful qualitative seabed information (seafloor structure and basic geology such as rock, gravel, sand and mud). The backscatter signal is a function of reflection and backscatter from the seafloor caused by the difference of acoustic impedance between sea water and the bottom materials, the angle of incidence of the acoustic pulse, the degree of scattering, and the portion of signal that is directed back to the transducer (Lurton, 2002). The physical properties of the seafloor have a direct influence in the attenuation and scattering processes. Main constituents in these processes are surface geometry and roughness as functions of the acoustic wavelength, as well as seafloor composition (e.g., grain size, porosity, density, sediment type, and/or biological composition).

The backscatter images are generally shown using a grayscale, although color scales have also been used. Backscatter images from this study will show lighter
areas as corresponding to a strong acoustic return (high-intensity backscatter) and
darker areas to a weaker return (low-intensity backscatter). Backscatter maps show
the geographic variations of backscatter intensity. There are several ways to display
backscatter intensity from a multibeam system. For this study, the mean backscatter
intensity per beam is shown. In qualitative terms, high contrast rock and sediment
types can be discernible (rock outcrops/boulders, coarse sand, silt, clay) especially in
flat seafloor surfaces. A seafloor with sediment characteristics of rocks, gravels,
coarse shells, or steep slopes, will exhibit a high backscatter. Areas with low
backscatter may represent fine sediments. In areas that are not flat, backscatter
may define structures that strongly reflect and/or cast acoustic shadows (i.e., where
a rock or ledge provides a strong reflection where it is ensonified and prevents sound
from reaching a portion of the seafloor behind it; Saleem, 2007). Nonetheless, these
gross scale classifications may require supplementary data to confirm the
interpretations, such as visual observations and/or bottom samples within the
different areas of backscatter intensity. The ability to predict bottom type is
improved with knowledge of the local seafloor geology, but backscatter data alone
could be insufficient to provide unambiguous interpretations without supplementary
information.

3.2 Data Processing

3.2.1 Multibeam Bathymetry Data

The multibeam bathymetry data were edited for spurious bathymetric and
navigational values and subsequently post-processed using Computer Aided
Resource and Information System for Hydrographic Information Processing System
and Sonar Information Processing System software package (CARIS HIPS & SIPS,
Fredericton, NB, Canada; Fig.3.10, 3.11, and 3.12).
After the survey, the multibeam bathymetry data are edited by flagging obvious depth outliers with automatic and manual software techniques. The flagged data are retained, but not used when gridding or displaying the data. Quality checks are also made on the speed of the vessel, positions, sound speed, and the calibration of the sonar, navigation and motion sensors. Corrections for the rising and falling of sea level during the survey are made (known as tide corrections) as well as providing a normalized chart datum. A flowchart of the order of applications used is shown in Figure 3.13.

Tidal corrections were applied to the depth soundings using verified downloaded tide data available for the study area from www.mareografico.it. For this study, we use the Mean Sea Level datum. The tide data are recorded every ten minutes referring to GMT time at the Ancona Station (Latitude: 43°37’29.16” N, Longitude: 13°30’23.46” E; Fig. 3.14) located inside the Ancona Harbor. The tide gauge station is equipped with altimetrical bench marks (Fig. 3.15). Each benchmark refers to the Mean Sea Level datum measured in Genoa using the ancient Thompson tide gauge. The bench marks are represented by metallic check tags that determine the altimetric level of the water with very high precision following the guidelines fixed by IGM (Italian Military Geography Institute).

Once edited, the data are gridded using a weighted mean gridding filter. The very high lateral resolution of the multibeam sonar in the shallow water depths (10-15 m) in this study justifies gridding with a pixel resolution of 25 cm. The gridded data were exported as ASCII files and imported into Interactive Visualization Systems (IVS; Fredericton, NB, Canada) associated programs used to generate, manipulate, and visualize the data (Fig. 3.16). IVS Fledermaus, a high-powered 3-D data rendering, visualizing and interactively exploring program, was used to generate digital elevation models and profiles of the artificial structures. Additional information follows in the Data Analysis section.
Figure 3.10. CARIS mean depth, interpolated, 2D relief shaded color bathymetry of 2008 Cesano-Senigallia artificial reef. Red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*Pholas dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*Homarus gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 3.11. CARIS mean depth, interpolated image of 2008 Cesano-Senigallia artificial reef. Red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*Pholas dactylus*) culture (C), 'technoreef' modules (D), fish cage (E), structure employed for lobster (*Homarus gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 3.12. CARIS shaded surface relief, interpolated image of 2008 Cesano-Senigallia artificial reef. Vertical exaggeration of 1 with an elevation of 46 degrees and an azimuth of 350 degrees. Red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*Pholas dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*Homarus gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 3.13. Workflow diagram showing the most important steps for processing bathymetric data (modified from CARIS HIPS and SIPS 7.0 User Guide, 2009).
**Figure 3.14.** Location of the Ancona tidegauge station. Red arrow show the exact position of the tidegauge inside Ancona Harbor (Latitude: 43°37’29.16” N, Longitude: 13°30’23.46” E).

**Figure 3.15.** Ancona tide gauge located inside the harbor.
3.2.2 Multibeam Backscatter Data

The backscatter data from the multibeam were visualized and analyzed using IVS FMGeocoder. The program is designed to process the source files into mosaics, performing radiometric and geometric corrections to maximize the information content within the backscatter signals (Fig. 3.17). Such corrections include the removal of the time varying and angle varying gains applied during acquisition, calculation of the true grazing angle (the angle between the acoustic beam and the surface normal, in other words 90° minus the angle of incidence) with respect to a bathymetric model, compensation for spherical spreading, attenuation in the water column and actual slope and area ensonification (Fonseca and Mayer, 2007). The resulting 2D representation of the seafloor is called a backscatter mosaic, and once it has been generated, various statistics can be calculated and exported along with the backscatter in a number of different formats. Moreover, angular range analysis (ARA) can also be performed to attempt an automated seafloor classification using advanced algorithms for sophisticated sediment angular response analysis capabilities. These algorithms are based upon thousands of direct measurements made in the laboratory, represented by a series of regression equations relating grain size to porosity, density and attenuation, and sound speed in the sediment to density and porosity. Additional information follows in the Data Analysis section.
Figure 3.16. Workflow diagram showing the most important steps for processing the exported X, Y, Z data into suite of IVS Fledermaus programs for terrain change analysis and images of study area.
Figure 3.17. Workflow diagram showing the most important steps for processing the backscatter data using IVS FMGeocoder for sediment class analysis and images of the study area.
3.3 Data Analysis

3.3.1 Multibeam Bathymetry Data

A comparison between the actual dimensions of the WBC blocks and cages (provided by independent measurement means prior to their deployment and by SCUBA divers just after the deployment (Fig. 3.18)) and the acoustics measurements of the two types of artificial modules, allowed to test the accuracy (95%) of the multibeam technology in detecting the different modules.

Figure 3.18. WBC blocks measurements by SCUBA divers after the reef deployment.

A subset of 30 blocks was selected, depending on their position in relation to both the ensonifying beams and the survey transect. Choosing the blocks ensonified by the outer beams, provides the worst-case scenario to test the accuracy which can only improve considering all the other beams closer to the nadir. Moreover, choosing the blocks with one side positioned as parallel as possible to a survey line avoids any confusion when referring to one of three dimensions of the cubic block: parallel track side, perpendicular track side, and height. As regards the WBC cages, all the
detected cages were considered for the comparison. For both types of modules, a set of three measurements was taken for each dimension: one in the central section and two at each border of the structure (Fig. 3.19). Median, mean, standard deviation and standard error were calculated for each set of measurements per each different type of module.

![Diagram showing three acoustic measurements for each considered dimension of the block module: track parallel (//) side, track perpendicular (⊥) side, and height. Parallel and perpendicular refer to the survey line.](image)

**Figure 3.19.** Set of three acoustic measurements (m₁, m₂, and m₃) for each considered dimension of the block module: track parallel (//) side, track perpendicular (⊥) side, and height. Parallel and perpendicular refer to the survey line.

For each survey, a survey line crossing all the other parallel survey lines was collected to verify the accuracy (95%) of the resultant depth across the swath of all the survey lines. In general, the vertical beam of a crossing survey line provides the most accurate depth to compare with all the other depths measured by the outer beams of the parallel survey lines. However, more sophisticated quality checks are now possible as described next. The HIPS Quality Control (QC) utility was used to assess the vertical accuracy and confidence measure of acoustically recorded depths. The QC process statistically compares soundings recorded from check lines against data points from the actual survey reading the cross-section profile data and longitudinal profile data, computing the intersection, and interpolating a depth from each input file. For each cross-section, the output file listed the beam number (as the soundings were chosen to be grouped according to across-track beam number), the
total soundings in range, the maximum and minimum distance of soundings above and below surface respectively, mean differences of soundings to surface, standard deviation of mean differences presented at 68% confidence interval, and percentage of soundings falling within the selected S-44 survey orders. In fact, to accommodate in a systematic manner different accuracy requirements for areas to be surveyed, four orders of survey are defined: Special Order, Order 1, Order 2, and Order 3. To calculate the error limits for depth accuracy, the following formula was used:

$$\text{Error limit for depth accuracy} = \pm \sqrt{a^2 + (bd)^2}$$

where:

- $a$ = constant depth error (i.e., sum of all constant errors)
- $b$ = factor of the depth dependent error
- $d$ = depth

For the present study, the surveyed area falls within the Order 1 hydrographic surveys intended for harbors, harbor approach channels, recommended tracks and some coastal areas with depths up to 100 m. For the Order 1 surveys the corresponding values of $a$ and $b$ to calculate depth accuracies at 95% confidence level are 0.5 m and 0.013 respectively. For more information and detail about the classification of surveys please refer to IHO Standards for Hydrographic Surveys (2008).

The maximum allowable bias for this study’s Order 1 surveys was 0.60 cm. Biases are often referred to as systematic or external errors and may contain observational errors (USACE, 2002). Examples of bias include a bar check calibration error, tidal errors, or erroneous squat corrections. Random errors are the errors that are present in the measurement system that cannot be easily minimized by further calibration. Examples of random error include uneven bottom topography, bottom vegetation, positioning error, and speed of sound variation (laterally and vertically)
in the water column. The depth accuracy estimate is determined from actual depth comparisons taken over the same terrain and computing the mean difference (MD), which are considered bias errors, and the standard deviation (SD), which are considered random errors between cross-line check comparisons. The two estimates are then combined to compute the Root Mean Square (RMS) error. The RMS error estimate is used to compare relative accuracies of estimates that differ substantially in bias and precision (USACE, 2002).

Taking into account all the examined surveys, a mean difference and a standard deviation are computed from a certain number of data points. Using the following formulas, a 95% depth accuracy was calculated:

\[
SE = SD / \sqrt{n}
\]

\[
RMS = \sqrt{MD^2 + SE^2}
\]

\[
RMS \text{ (95\%)} \text{ depth accuracy} = 1.96 \times RMS
\]

where:

- \(SE\) = standard error
- \(SD\) = standard deviation
- \(n\) = number of data points
- \(RMS\) = root mean square error
- \(MD\) = mean difference

Accordingly, changes in seafloor height comparing data sets from different survey periods may not be detectable if the depth difference between two surfaces taken at different times is greater than the calculated 95% depth accuracy. In other words, changes in seafloor height may be treated as a depth measurement error, rather than a real geological process such as scour or sedimentation.

Before analyzing changes in the seafloor morphology (scour, burial, and other vertical and/or horizontal changes), the data were exported from the CARIS program.
as an X, Y, Z ASCII file to be used by the suite of Fledermaus programs to test for temporal changes.

The X, Y, Z ASCII file of the study area was first imported into the IVS Average Gridder (“avggrid”). The Average Gridder is designed to produce a regular gridded surface from irregularly spaced points. Using a gridding algorithm controlled by input parameters, the Senigallia artificial reef data were exported as a “.dtm” (digital terrain model), and a “.geo” (geo-referenced information) file for use in another IVS program called “DMagic” (Data Magician). DMagic is an application designed to prepare objects for visualization in Fledermaus. Once the data are imported into DMagic, the Surface Shader tool is used to shade the surface based on mean depth by manipulating the shadow direction of the sun and lighting parameters. The Surface Shader can be used to visualize features and has the ability to create 3D surfaces with true cast shadows. Cast shadows highlight fine details on the surface and produce a much more realistic and intuitive 3D model of the surface. Six parameters of the illumination model were adjusted to the desired 3D image. These parameters are: light position, light direction, intensity of ambient light, specular component, shadow softness, and vertical exaggeration of heights. The artificial sun or illumination direction can be rotated to any azimuth from 0 to 360 degrees, while the shadow length can be adjusted changing the sun elevation value from 0 to 90 degrees (where 0 degrees indicates the sun would be at the horizon and 90 degrees would indicate the sun would be directly overhead). The illumination direction is from the northwest at an angle of 315°. The length of the shadows from the northwest was set changing the effective illumination angle to 7 degrees from the horizon. The ambient light control was set to 0.100, which affects the amount of light that appears in cast shadows. High ambient light makes that entire image brighter and shadows less distinct. The specular component was set to 0.106 (medium glossy-matte finish), which controls the extent of glossy highlight. High
specular content makes the surface appear to be very glossy, while low specular content provides a matte finish. Shadow softness controls the sharpness or softness of the shadow edges and it was set to 0.350. The vertical scale is the height of the surface that can be artificially increased or decreased to change the shadow length. The vertical scale was set to 0.500. Once the image was saved as a scientific data object (SD), the object was assembled in Fledermaus.

The assembled Senigallia artificial reef files were loaded into the Fledermaus and surface characteristics and statistics analysis were performed. Using the Map Sheet tool, a top down, plan view of each 3-D surface was created and saved as encapsulated postscript files. A map scale of 1:2500 was defined. Individual high-resolution 3-D snapshot from a portion of each surface were exported using the Screen Capture function.

Terrain changes (e.g., scour or burial) profile analyses were performed on artificial modules of particular interest. The terrain profiles were saved as text files and individual images of each analyzed module were once more exported using the Screen Capture function. Cross-sections profiles along the major and minor axes of the artificial reef area with a vertical exaggeration of 40:1 were made and utilized for terrain change analyses. In the text file each point in the profile is written out to the file as a distance along the profile and an x, y and height/depth (z) position.

Finally surface differences between different survey years were performed using the Surface Difference command. The new surfaces resulting from the differences were visualized and surface characteristics and statistics analysis were performed.
3.3.2 Multibeam Backscatter Data

In FMGeocoder, all work revolves around a session which defines what files are to be processed, what parameters are used in the processing, the geographic area to be processed, and what output (backscatter, statistics, ARA, etc.) is desired.

The raw multibeam data of the study area are first added to a new session. When files are first added the status will be 'New' meaning that they are not yet processed or, scheduled to be processed. Their status will change to 'Wait', then to 'Proc', and finally to 'Done' when they are being processed in the All Processing module. In the Processing Parameters section, the Apply AVG Correction function is toggled on applying an angle varying gain (AVG) to the data using a sliding window of normally 30 pings. The AVG corrections were applied to the data using the supported AVG algorithm 'Flat'. The 'Flat' algorithm is generally the best default and will smooth out small variations in backscatter level in an attempt to reduce noise in the signal. In the Starting Beam Angle and Cutoff Beam Angle options the values were set to 0 and 90 degrees, respectively, which processes all the beams. Finally, Linear Interpolation was selected in the Navigation Parameters section, which provides extra options for files that do not have good navigation or heading information. In the Mosaicking Parameters section the 'dB Mean' was set as the filter type, while the 'blending' was set at 50% as default value. As track lines of data are processed, their backscatter output are added to the overall backscatter mosaic. Using the Open Surface function, the bathymetric surface (saved previously as Fledermaus SD object) was loaded to assist the software in applying corrections to the resulting backscatter mosaic, because the seafloor geometry is important in adjusting backscatter values to represent intrinsic seafloor properties without the overprinting effects related to the seafloor geometry.

Statistical Analysis and ARA patch analysis together with the Use Formal Inversion function were computed for each surface to attempt an automated seafloor
classification (no coupling with in situ ground-truthing techniques). The Use Formal
Inversion function is very important for a full sediment analysis because it runs the
full Jackson model inversion for each patch of pings in the ARA patch analysis and
generates the results. Jackson’s model (Jackson et al., 1986; Jackson and Briggs,
1992; Mourad and Jackson, 1989) is a two-component model that treats interface
roughness scattering and volume scattering separately. The model characterizes the
seabed with six parameters, two of which describe the interface roughness and three
of which describe acoustic propagation through the sediment, modeled as an
acoustic fluid. The remaining parameter is an empirically determined quantity, which
specifies the level of volume scattering within the sediment. The ARA patch analysis
divides and analyzes the returned backscatter into discrete angular regimes (Fonseca
and Mayer, 2007). It works by combining a set of multibeam pings together
(normally 30 consecutive pings along track) and analyzing the backscatter response
as a function of grazing angle (Fig. 3.20). The results of the patch analysis are a set
of points, one each for the port and starboard of each patch. The sediment
parameters are evaluated for each side of the patch. The key sediment parameters
from the iterative model include the grain size, impedance, and roughness estimates.
The grain size is used to generate the classification for the sediment type. The
resulting ARA points were saved as both a Fledermaus SD Object and an ASCII
multi-column file containing information such as geographical coordinates, slope of
the backscatter intensity versus the grazing angle, overall mean backscatter value,
mean backscatter value for the near nadir, far angle, and outer beams, impedance,
roughness, and grain size computed from the Jakson model, classification for bottom
type, etc. (for a complete and detailed description of ARA parameters see Fonseca
and Mayer, 2007). The classification value is an integer based on mapping ranges of
grain size to table of classifications as shown in Table 3.1. Finally the ARA patch
analysis results were extrapolated to the backscatter mosaic providing an attempt of sediment texture map.

**Figure 3.20.** ARA patch analysis dialog box. The graph of the backscatter intensity vs grazing angle (the corrected angle by which the sound wave impacts the seafloor) is shown. The range of angles is broken up into three sections, the near range (closed to the nadir), the far beams, and the outer beams. Linear fit is computed for the total graph, the near region, and the far region, giving a slope and intercept. The intercept is just the backscatter value for the linear fit. These values among other are the attributes of the port or starboard portions of the swath, which are then fed into the sediment model in an attempt to classify the type of sediment contained within the two patches.
Table 3.1. FMGeocoder sediment type classification based on Jackson’s model. The right column shows the Udden-Wentworth grain-size classification of terrigenous sediments (Wentworth, 1922).

<table>
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<tr>
<th>Grain Size Range</th>
<th>Classification</th>
<th>Wentworth Size Class</th>
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</thead>
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<tr>
<td>&lt; -0.8</td>
<td>Gravel</td>
<td>Boulder</td>
</tr>
<tr>
<td>[-0.8, -0.3]</td>
<td>Gravelly Coarse Sand</td>
<td>Cobble</td>
</tr>
<tr>
<td>[-0.3, 0.0]</td>
<td>Coarse Sand - Sandy</td>
<td>Pebble</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Granule</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Very Coarse Sand</td>
</tr>
<tr>
<td>[0.0, 1.0]</td>
<td>Coarse Sand - Gravelly</td>
<td>Coarse Sand</td>
</tr>
<tr>
<td>[1.0, 1.5]</td>
<td>Medium Sand - Gravelly</td>
<td>Medium Sand</td>
</tr>
<tr>
<td>[1.5, 2.0]</td>
<td>Medium Sand</td>
<td>Fine Sand</td>
</tr>
<tr>
<td>[2.0, 2.5]</td>
<td>Fine Sand</td>
<td>Silty Sand</td>
</tr>
<tr>
<td>[2.5, 3.0]</td>
<td></td>
<td>Medium Silt</td>
</tr>
<tr>
<td>[3.0, 3.5]</td>
<td>Muddy Sand</td>
<td>Fine Silt</td>
</tr>
<tr>
<td>[3.5, 4.0]</td>
<td>Very Fine Sand</td>
<td>Clay</td>
</tr>
<tr>
<td>[4.0, 4.5]</td>
<td>Clayey Sand</td>
<td>Coarse Silt</td>
</tr>
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<td>[4.5, 5.0]</td>
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<td>Medium Silt</td>
</tr>
<tr>
<td>[5.0, 5.5]</td>
<td>Sandy Silt</td>
<td>Fine Silt</td>
</tr>
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<td>Medium Silt</td>
<td>Clay</td>
</tr>
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<td>Sandy Mud</td>
<td>Very Fine Silt</td>
</tr>
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<td>Sandy Clay</td>
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</tr>
<tr>
<td>[7.5, 8.0]</td>
<td>Very Fine Silt</td>
<td></td>
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<td>[8.0, 8.5]</td>
<td>Silty Clay</td>
<td></td>
</tr>
<tr>
<td>≥ 8.5</td>
<td>Clay</td>
<td></td>
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4. Results

4.1 Multibeam Bathymetry Data

The Senigallia artificial reef extends approximately 170 m x 80 m with the major axis in NW-SE direction (Fig. 4.1). The rectangular arrangement was almost correctly deployed and is still well preserved.

All the 29 2-layer WBC pyramids and the ten WBC cages were identified and localized (Table 4.1 and 4.2). Only four pyramids are nearly intact with every single 2x2x2 m block well depicted; in regard to the remaining pyramids, in some cases the top block still preserves its higher position but one or two bottom blocks are shifted away, and in other cases all the five blocks are completely spread out on the seabed (Figs. 4.2a, 4.2b and 4.2c). Interpretation of the actual condition of the cages through the acoustic images was much more difficult. During the 2008 survey, indeed, they appear almost completely missing compared to the previous surveys (Fig. 4.3a and b). However, verification by scuba divers showed that most of the cages are still sitting in their upright position.

In the northwestern portion of the reef the other artificial modules different from the standard BWC pyramids and cages were identified and located (Table 4.3). The same difficulty of acoustic detection occurs for some of these modules like the fish cage, the common piddock culture structure, and the technoreef units (Figs. 4.3c and 4.3d). Therefore, verification by SCUBA divers was performed, which revealed that they are all upright, except for the technoreef modules. The latter were completely crushed sometime after their deployment.
The concrete and ash mixture blocks were also located at about 25 m northwest of the reef. The former meteorological station pole and its anchor log were found lying 62 m from each other, about 10 m north and 30 m northeast of the closest pyramids, respectively (Table 4.3).

Tables 4.4 and 4.5 show the acoustic measurements for the selected 30 blocks and the seven detected cages respectively. Track parallel side, track perpendicular side, and height are considered for the blocks. Length, width, and height are considered for the cages. For each dimension, a set of three measurements is shown for a total of 90 acoustic measurements for the blocks, and 21 for the cages.
Figure 4.1. 2008 Senigallia artificial reef. Mean depth, interpolated shaded color bathymetry. Red roman numbers (I-XXIX) denote the location of the 29 BWC pyramids. White roman numbers (I-X) denote the location of the ten BWC cages. Red dotted window indicates special area of interest showed in detail on the left side. Red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), 'technoreef' modules (C), structure employed for common piddock (P. dactylus) culture (D), fish cage (E), structure employed for lobster (Homarus g.) culture (F), and anchor log of the previous meteorological station pole (G).
Table 4.1. Geographical location (latitude and longitude in WGS84) of each WBC pyramid of Senigallia artificial reef. Roman numbers correspond to those showed in Figure 4.1.

<table>
<thead>
<tr>
<th>Target</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
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<td>PYRAMID I</td>
<td>43°45’18.31” N</td>
<td>13°12’30.20” E</td>
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<tr>
<td>PYRAMID II</td>
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<td>43°45’18.84” N</td>
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<td>43°45’17.82” N</td>
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Table 4.2. Geographical location (latitude and longitude in WGS84) of each WBC cage. Roman numbers correspond to those showed in Figure 4.1.

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<td>CAGE VIII</td>
<td>43°45’16.14” N</td>
<td>13°12’33.36” E</td>
</tr>
<tr>
<td>CAGE IX</td>
<td>43°45’16.10” N</td>
<td>13°12’34.53” E</td>
</tr>
<tr>
<td>CAGE X</td>
<td>43°45’16.23” N</td>
<td>13°12’34.77” E</td>
</tr>
</tbody>
</table>

Figures 4.4, 4.5, and 4.6 compare the actual dimensions for the blocks and the cages with the acoustic measurements, showing the variability of the multibeam measurements.

Median, mean, standard deviation, and standard error of the acoustic measurements are reported in Table 4.6 and 4.7 for the blocks and the cages respectively. In case of the blocks, a 95% detection accuracy of ±0.02 m for both track parallel and track perpendicular sides was calculated, while an accuracy of ±0.00 m was calculated for the height. In regard to the cages, 95% detection accuracies of ±0.32 m, ±0.27 m, and ±0.31 m, were calculated for length, width, and height respectively.
Figure 4.2. Three-dimensional acoustic images of 2008 Senigallia artificial reef’s pyramids. (a) Integral 2-layer pyramid; (b) 2-layer pyramid with one bottom block shifted away; (c) fallen apart pyramid with all the five blocks spread out on the seabed.
Figure 4.3. Three-dimensional acoustic images of a detail of Senigallia artificial reef. (a) and (b) Area with WBC cages surveyed in 2008 and 2004 respectively. Yellow letters denote the WBC cages. Fallen and almost buried cages (A); standing up cages (B). (c) and (d) Area with artificial modules different from the standard WBC pyramids and cages surveyed in 2008 and 2004 respectively. Yellow letters denote the special artificial modules. Standing up fish cage (A); standing up common piddock culture structure (B); crumbled technoreef modules (C).

Table 4.3. Geographical location (latitude and longitude in WGS84) is shown for each module different from the standard WBC pyramids and cages.

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<tr>
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</tr>
<tr>
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<td>F - LOBSTER STRUCTURE</td>
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<td>13°12’31.35” E</td>
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<td>G - FORMER MTG ST. ANCHOR LOG</td>
<td>43°45’18.70” N</td>
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Table 4.4. Acoustic measurements of the 30 blocks. For each dimension, three measurements ($m_1$, $m_2$, and $m_3$) are shown. T = survey track

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Table 4.5. Acoustic measurements of the seven cages. For each dimension, three measurements ($m_1$, $m_2$, and $m_3$) are shown.

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<th>Height (m)</th>
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Figure 4.4. Comparison between the actual track parallel side dimension of the blocks (2.0 m) or the length for the cages (6.0 m) with the respective acoustic measurements. MBES = multibeam measurements.
Figure 4.5. Comparison between the actual track perpendicular side dimension of the blocks (2.0 m) or the width for the cages (4.0 m) with the respective acoustic measurements. MBES = multibeam measurements.

Figure 4.6. Comparison between the actual height of the blocks (2.0 m) and the cages (5.0 m) with the respective acoustic measurements. MBES = multibeam measurements.
Table 4.6. Statistical parameters calculated for the acoustic measurements of the 30 WBC blocks. T = survey track

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<th>Height (m)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
</tr>
<tr>
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<td>1.99 1.97 0.09 0.01 1.99 1.97 0.11 0.01 2.00 1.99 0.02 0.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7. Statistical parameters calculated for the acoustic measurements of the seven WBC cages.

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<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAGGE</td>
<td>median mean std. dev. std. error median mean std. dev. std. error median mean std. dev. std. error</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>6.05 5.95 0.74 5.96 4.25 4.31 0.63 0.14 4.95 4.66 0.72 0.16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The ambient seafloor depth surrounding the artificial reef is about 12.0 m below Mean Sea Level (MSL), while the whole area hosting the reef experienced nearly 1.0 m of scour so that resulting seafloor depth is about 13.0 m below MSL. The maximum recorded depth of 13.6 m corresponds to the scour near of one of the pyramid blocks. The minimum recorded depth of 7.9 m represents the crest of one BWC cages in the NW portion of the reef (the depth values refer to the 2002 cruise when most of the cages were mapped in their correct upright position).

Figures 4.7, 4.8, and 4.9 show detailed bathymetry relief images of 2002, 2004, and 2008 surveys, respectively. The surface characteristics from each survey are listed in Table 4.8, while the statistics relative to each surface are described in Table 4.9. To perform both the surface characteristics and statistics for each survey, an area of almost the same size was extracted from the original surfaces.

As previously mentioned, the use of the more advanced EM3002 echo sounder during the 2008 survey allowed higher definition images of the seafloor compare to the previous surveys. A first look of the three survey bathymetry maps does not show any obvious changes over time except for the deepening of the central part of seafloor hosting the reef (Fig. 4.9). But further inspection reveals additional focused scouring near the artificial modules (most evident in a southeast direction within the data collected during the 2008 survey; Fig. 4.9).

Both the 2004 and 2008 bathymetry maps do not show a preferential location of the well-developed scour hollows associated with the reef modules. Sometimes they are found to the south and southeast of the modules indicating a bottom flow from north to south and from northwest to southeast. Some scour hollows are located northwest of the modules indicating a localized bottom current flowing from a southeast direction.

A mean difference of –0.081 m and a standard deviation of 1.27 m were computed from 85 data points using the method described in section 3.3.1. A 95%
depth accuracy of ±0.31 m was calculated. Accordingly, deepening of a unit may not be detectable if the depth difference between two surveys is <0.31 m.

Figures 4.10 and 4.11 show the difference between the 2002 and 2004 survey surfaces and the 2004 and 2008 survey surfaces respectively, highlighting possible erosion or sedimentation. The mean change values in seafloor depth were 0.02 m ± 0.29 m and 0.05 m ± 0.31 m for the 2004-2002 and the 2008-2004 comparisons, respectively (Table 4.10). Between 2002 and the 2004 surveys, slight erosion occurred SE of the reef (Fig. 4.10; bluish part of the color scale) while sediment accumulated NW of it (Fig. 4.10; reddish part of the color scale). An overall accumulation of sediment took place at the site for a total amount of 166.42 m$^3$ (Table 4.10). Between 2004 and 2008 (Fig. 4.11), a total loss of sediment of 2,414.52 m$^3$ was calculated (Table 4.10). Overall, no significant difference was recorded in either case, but profile maps may still help to identify location, orientation, and amount of deepening of both the entire reef and the individual units.

Two cross-section profiles (Figs. 4.12 and 4.13) oriented in a NW-SE direction, parallel to the main current direction, and in a NE-SW direction, perpendicular to the main current direction, point out a certain amount of deepening experienced by the whole area hosting the reef. A gentle slope of about 1° at the beginning becomes abruptly 3°-4° mainly along the NE-SW direction. In 2008 survey the central part of the reef area became deeper by about 15-20 cm since 2004.
Figure 4.7. 2002 Senigallia artificial reef. Mean depth, interpolated shaded color bathymetry. Red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 4.8. 2004 Senigallia artificial reef. Mean depth, interpolated shaded color bathymetry. Red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 4.9. 2008 Senigallia artificial reef. Mean depth, interpolated shaded color bathymetry. Red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
**Table 4.8.** Surface characteristics for Senigallia artificial reef surveyed in 2002, 2004, and 2008.

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<th>Dimensions</th>
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<tr>
<th>Surface</th>
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<th>Std. Dev.</th>
<th>Height Range</th>
<th>Total Area (m²)</th>
<th>Negative Area (m²)</th>
<th>Total Volume (m³)</th>
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<td>54,623</td>
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<tr>
<td>Reef 2008</td>
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<td>61,252</td>
<td>61,252</td>
<td>-752,399.6</td>
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Figure 4.10. Surface difference between 2004 and 2002 surveys of Senigallia reef. Mean depth of surface difference; red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 4.11. Surface difference between 2008 and 2004 surveys of Senigallia reef. Mean depth of surface difference; red letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
### Table 4.10. Statistics for the surface differences between 2004 and 2002 surveys, and 2008 and 2004 surveys of Senigallia artificial reef.

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<th>Total Volume (m³)</th>
<th>Positive Volume (m³)</th>
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<td>0.05</td>
<td>±0.31</td>
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<td>20,092.75</td>
<td>-2,414.52</td>
<td>6,315.33</td>
<td>-3,900.81</td>
</tr>
</tbody>
</table>
Figure 4.12. Major axis cross section of Senigallia artificial reef. (a) Cross section along the major axis of the reef (white line M-M’) in the NW-SE direction. The multibeam map is not to scale. (b) Cross section profiles along the M-M’ section obtained from the three surveys. The distance of each profile measures 240 meters across with a vertical exaggeration of 40:1.
Figure 4.13. Minor axis cross section of Senigallia artificial reef. (a) Cross section along the minor axis of the reef (white line m-m') in the SW-NE direction. The multibeam map is not to scale. (b) Cross section profiles along the m-m' section obtained from the three surveys. The distance of each profile measures 160 meters across with a vertical exaggeration of 40:1.
Very pronounced scouring with a slope of almost 5° and sediment accumulation on the margin is evident NW of the fish cage (Fig. 4.9). The seafloor becomes deeper by about 80 cm in 2002 and 2004, and by about 70 cm in 2008 when all the reef area exhibited deepening. This cage lies with one of the four corner pointing NW from where the main current flows. Less pronounced is the scouring on the SE corner of the fish cage and around the WBC cages, which are lighter modules (Figs. 4.9 and 4.10). Note that the fish cage profile is completely missing in 2008 survey (Fig. 4.9) as previously noted, while the profiles of the WBC cages are extremely reduced or again missing (Figs. 4.9 and 4.10 respectively).

4.2 Multibeam Backscatter Data

The backscatter maps of Senigallia artificial reef from the 2002, 2004, and 2008 surveys are visualized in Figures 4.14, 4.15, and 4.16 respectively. In all three maps a lighter area (high backscatter intensity) corresponding to the reef is clearly distinguishable from the darker (lower backscatter intensity) surrounding seafloor, highlighting that coarser sediments characterize the reef seafloor while finer sediments are distributed all around it. The 2002 map shows a lighter grey tone compared to 2004 and 2008 maps, indicating that coarse grains exist in the area of the reef, suggesting that a shift in the sediment composition occurred, such that the fine sediments were winnowed from the reef area.

The individual reef modules are characterized by high-medium backscatter. They are surrounded by darker areas representing acoustic shadows where the concrete blocks prevented sound from reaching the seafloor behind the blocks. The cages appear much darker because their "cavity" structure retains the sound waves and reduces the amount of sound being reflected and backscattered to the sonar.

The backscatter images also reveal some scouring. The steep slopes due to the scouring around some of the reef modules are represented by light grey areas
with semicircular darker contours. In the 2004 maps for example, the scouring on
the NW side of the former meteorological station pole and its anchor log are as
distinctly marked as the single concrete block SE of them (Fig. 4.15). Scouring is
also depicted around some pyramids in the 2008 backscatter image (Fig. 4.16) in
which the steep slope between the reef area and the surrounding seafloor on the SW
portion is clearly evident.

In the right corner of each backscatter image (Figs. 4.14, 4.15, and 4.16), the
ARA analysis is visualized. The ARA points were grouped in three main sediment
classes represented by different colors: orange for sand, green for silt, and blue for
clay. The distribution of the colored ARA points shows a good match with the grey
scale backscatter images and SCUBA observations.

An automated extrapolation of this analysis was applied to all the data points,
generating predicted seafloor sediment classification maps for the three surveys
(Figs. 4.17, 4.18, and 4.19). The sediment maps for both the 2004 and 2008 survey
confirmed the shift in sediment distribution already observed qualitatively in the
bathymetry and backscatter figures. The 2002 seafloor is characterized by coarser
sediments like sand in the reef area and silt in the surrounding seafloor (Fig. 4.17).
In 2004 the silt was found mainly in the reef area and SE of it along the main current
direction, while clay was the predominant sediment. In 2008 the silt was confined to
the reef area like an island within a "sea of clay". Patches of sand were still present
close to some reef modules in both the 2004 and 2008 surveys.
Figure 4.14. Backscatter image of Senigallia artificial reef during the 2002 survey. Light gray to white areas may represent gravel, coarse shell or steep slopes (high backscatter). Dark gray to black areas may represent fine sediments especially mud or acoustic shadows (low backscatter). Yellow letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (P. dactylus) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (H. gammarus) culture (F), and anchor log of the previous meteorological station pole (G). Yellow arrows show some of the WBC pyramids and cages forming the artificial reef. On the upper right corner ARA points overlap the backscatter mosaic. Three sediment classes are defined by color: sand, silt, and clay.
Figure 4.15. Backscatter image of Senigallia artificial reef during the 2004 survey. Light gray to white areas may represent gravel, coarse shell or steep slopes (high backscatter). Dark gray to black areas may represent fine sediments especially mud or acoustic shadows (low backscatter). Yellow letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (P. dactylus) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (H. gammarus) culture (F), and anchor log of the previous meteorological station pole (G). Yellow arrows show some of the WBC pyramids and cages forming the artificial reef. On the upper right corner ARA points overlap the backscatter mosaic. Three sediment classes are defined by color: sand, silt, and clay.
Figure 4.16. Backscatter image of Senigallia artificial reef during the 2008 survey. Light gray to white areas may represent gravel, coarse shell or steep slopes (high backscatter). Dark gray to black areas may represent fine sediments especially mud or acoustic shadows (low backscatter). Yellow letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Yellow arrows show some of the WBC pyramids and cages forming the artificial reef. On the upper right corner ARA points overlap the backscatter mosaic. Three sediment classes are defined by color: sand, silt, and clay.
Figure 4.17. Extrapolated surficial sediment map of Senigallia artificial reef during the 2002 survey. On the basis of ARA analysis (backscatter response as a function of grazing angle), three color-based sediment sizes are indicated: sand, silt and clay. White letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), 'technoreef' modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 4.18. Extrapolated sediment map of Senigallia artificial reef during the 2004 survey. On the basis of ARA analysis (backscatter response as a function of grazing angle), three color-based sediment sizes are indicated: sand, silt and clay. White letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
Figure 4.19. Extrapolated sediment map of Senigallia artificial reef during the 2002 survey. On the basis of ARA analysis (backscatter response as a function of grazing angle), three color-based sediment sizes are indicated: sand, silt and clay. White letters (A-G) denote the location of artificial modules different from the standard BWC pyramids and cages. Concrete and ash reef blocks (A), former meteorological station pole (B), structure employed for common piddock (*P. dactylus*) culture (C), ‘technoreef’ modules (D), fish cage (E), structure employed for lobster (*H. gammarus*) culture (F), and anchor log of the previous meteorological station pole (G). Red arrows show some of the WBC pyramids and cages forming the artificial reef.
5. Discussion

The marine environment worldwide is under increasing pressure from anthropogenic activities. With the collapse of many offshore fisheries, and increasing competition amongst industries for resources such as oil, gas, and marine aggregates, there is a growing need for improved understanding of seafloor ecosystems to facilitate sustainable management of offshore resources. Human activities can cause a wide variety of impacts on the seabed environment. The need to identify and map different types of benthic habitats and associated biological communities to protect vulnerable, rare or ecologically important areas is now widely recognized (Pickrill and Todd, 2003; Beaman and Harris, 2005). Since artificial reefs have become a popular biological component in shallow-water environments characterized by a soft seafloor, they represent important marine habitats. Because of the unstable nature of sediments, they require detailed and systematic investigations that acoustic systems can provide.

Besides the ecological role played by artificial reefs in the marine environment, the lack of information on their post-deployment arrangement has been recognized for decades (Shyue, 1998; Shyue and Yang, 2002; Brown and Harper, 2006).

The introduction of an artificial reef to the seafloor induces a change in the local hydrodynamics increasing the flow velocity and the turbulent intensity. Due to the unstable nature of the sediments, many artificial reefs can undergo different geophysical processes such as scouring, deepening, sinking, and destabilization of the artificial structures at a wide range of temporal and spatial scales, with consequent reduction of the reef’s key role in attracting finfish and other living organisms. The spatial extent of scouring depends on the interaction between the
geometrical and physical characteristics of the artificial units (e.g., orientation, shape, size) and the marine environmental factors such as seafloor morphology, underlying geology, water depth, wave turbulence, bottom currents, and turbulence from bottom currents. Biological and chemical processes can also affect scouring. Moreover, some reef units can be partially or totally covered by sand and disappear, unless seismic, magnetic, or excavation techniques are used. Monitoring the spatial distribution of reef units and understanding the mechanism of scouring, subsidence, horizontal movements, and sand transportation involved in a local scale of an artificial reef, could be a reference for the future site selection criteria as mentioned previously by Shyue (1998). Shyue et al. (2002) mapped an artificial reef on two surveys undertaken four months apart, before and after the occurrence of a typhoon, highlighting a variety of geomorphological changes.

Scour creates erosional and accretionary sedimentary patterns near objects on or near sedimented areas (Inman and Jenkins, 2005). The eventual burial of objects in response to forcing by waves and currents has been widely studied (e.g., Farmer et al., 1999; Rambabu et al., 2002; Yu and Ura, 2002; Rambabu et al., 2003; Stauble and Tabar, 2003; Stauble, 2003; Inman and Jenkins, 2005; Quinn, 2006; Jenkins et al., 2007; Wolfson et al., 2007; Mayer et al., 2007). Different techniques ranging from SCUBA dive observations, AUV and ROV inspections, acoustic surveys to numerical models were developed and applied to investigate scour initiated by the intentional (e.g., submerged breakwaters; vertical piles; submarine pipelines; etc.; Rambabu et al., 2002; Vijaya Kumar et al., 2003; Rambabu et al., 2003; Stauble and Tabar, 2003; Stauble, 2003), or accidental (e.g., mines, wrecks, etc.; Inman and Jenkins, 2005; Quinn, 2006; Jenkins et al., 2007; Wolfson et al., 2007; Mayer et al., 2007) introduction of an object to the seafloor.

However, only limited research has been conducted on horizontal movement, scouring, sinking, deepening of the seafloor related to artificial reefs (Farmer et al.,
1999; Shyue, 1998; Shyue and Yang, 2002; Manoukian et al., 2004; Brown and Harper, 2006; Sala et al., 2007). As noted by Shyue (1998), acoustic systems are efficient tools able to monitor the geomorphological and geophysical evolution of artificial reefs, whose condition of settlement and scouring can be very hard to inspect by divers or ROV due to time-cost effectiveness for the former, motion-control difficulties for the latter, and water turbidity for both methodologies. Similarly, even an acoustic technology like side-scan sonar has navigation and tow-fish control difficulties in shallow water. Nevertheless, a single-beam echo sounder presents sounding spatial limitations. High-resolution multibeam echo sounders, instead, provide a detailed picture of the distribution of changes in depth, sediment type, and bedforms in the area hosting an artificial reef (Farmer et al., 1999; Shyue, 1998; Shyue and Yang, 2002; Manoukian et al., 2004; Brown and Harper, 2006; Sala et al., 2007).

In this study, I describe local geomorphology and seafloor sediment texture based on interpretation of multibeam data. The results presented above suggest that the multibeam echo sounder EM3002 is able to clearly locate and even identify individual reef modules, their condition, and any terrain change around them over time. The resolution of the multibeam system, combined with three-dimensional visualization techniques, provides realistic-looking images of not only the single reef modules but even the individual reef units such as each single 2x2x2 m concrete block.

More than twenty years after its deployment, the artificial reef of Senigallia shows its originally planned rectangular arrangement with the major axis in the NW-SE direction. Most pyramids have completely fallen apart, with each single concrete block well-depicted on the seafloor. This has been observed since the very first survey in 2002 and as recently as 2010, suggesting that the horizontal and vertical movements of the reef units happened sometime since the deployment in 1987,
perhaps during the actual deployment of the reef, but certainly before 2002.

Comparison with the first scientifically-planned artificial reef deployed in 1974-75 south of Ancona at 5.5 km (3 nm) from Porto Recanati shoreline at 12-15 m of depth, reveals the critical role played by the local hydrodynamics on the general settlement of the reef and the stability of the modules (Fig. 5.1). During the present research project, there was the opportunity in summer 2008 to acoustically map the Porto Recanati artificial reef for the first time after 33 years. The data were presented at the 9th International Conference on Artificial Reefs and Related Aquatic Habitats in November 2009 and a paper on it is in press on the Brazilian Journal of Oceanography (Manoukian et al., in press).

The reef appears in a very good condition with the planned rectangular arrangement still recognizable and, unlike Senigallia, most of the 3-layer pyramids made up of the same WBC 2x2x2 m blocks are still intact in their geometry (Fig. 5.2).
Figure 5.1. Porto Recanati artificial reef. (a) Location of Porto Recanati artificial reef. (b) Mean depth shaded color bathymetry of the reef investigated in Spring 2008.
Figure 5.2. High-resolution acoustic images of 3-layer pyramids of Porto Recanati artificial reef. (a) Intact 3-layer pyramid. (b) Fallen apart 3-layer pyramid.

With respect to the WBC cages, even though the 2008 multibeam relief image shows they have nearly completely sunk into the sediment compared to the 2002 survey, SCUBA dive observations show that they are all sitting in their full upright position except for those placed on the southwest side of the reef. The fish cage and the common piddock culture structures were acoustically undetectable. Once more SCUBA divers verified that they are completely intact. Their cavity structure probably
reduces the acoustic return so much that the multibeam sonar bottom detection algorithm cannot interpret it. For example, when the acoustic signal goes through the holes it could be then reflected a few times inside before going back if at all. Certain geometric shapes and location could be missed entirely. This kind of “undetectable” artifact is recorded more often using higher beam density system (e.g., 254 soundings of EM3002 compared to 127 soundings of EM3000). Why this is so could be an avenue for future research. Theoretical predictions of the beam “footprint”, “pulse width”, and “bandwidth” could be tested with such complex shape modules.

Technoreef units were also found to be acoustically undetectable, but for a different reason. In 2008, they were actually missing, and SCUBA diver observations found that the units were completely crushed.

In order to test the accuracy of the acoustic measurements, the total error propagation calculated by Wolfson et al. (2007) was considered. These authors used a similar multibeam system to observe mine burial near Clearwater (FL). They surveyed the area using the EM3000 and a very high-accurate RTK positioning system, compared to the DGPS one used for Senigallia reef surveys. The total error propagation for their entire system was 0.11 m. Considering the 1.0 m positioning uncertainty for the DGPS, the total error propagation for the system used for this study will increase to approximately 0.5 m. Accordingly, the 95% of detection accuracies calculated both for the single WBC blocks and the WBC cages, reveal how accurate are the acoustic measurements, with high resolution and repeatability. In addition, the sonar accuracy and detectability depends on the geometry and size of the targets, with higher accuracy for smaller and solid targets.

Over time the seafloor hosting the artificial reef was subject to a certain amount of deepening that was more pronounced in the 2008 survey, as also confirmed by the cross sections. The rate of scour has slowing down since the
deployment, from 0.073 m/yr to 0.025 m/yr (Table 5.1). However, the apparent changes observed in the 2008 survey and cross-sections are not statistically significant due to the relatively high standard deviations calculated for both the 2004-2002 and 2008-2004 surface differences. This is likely due to the positioning uncertainty of about 1.0 m for the DGPS used. The small horizontal shifting from one survey to the other of the artificial modules can cause a mismatching of the two surfaces in the bathymetric difference maps, leading to incorrect results. Moreover, the 2008 acoustic “ghost” images obtained for complex modules like the cages can cause errors due to the acoustically undetectable modules not being included in the surface calculations.

Table 5.1. Scour history at Senigallia artificial reef.

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth (m)</th>
<th>Elapsed time (yr)</th>
<th>Scour rate (m/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>12.0*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>13.1</td>
<td>15</td>
<td>0.073</td>
</tr>
<tr>
<td>2004</td>
<td>13.2</td>
<td>2</td>
<td>0.050</td>
</tr>
<tr>
<td>2008</td>
<td>13.3</td>
<td>4</td>
<td>0.025</td>
</tr>
</tbody>
</table>

* Assumed pre-deployment depth

Because scouring plays a major role in compromising the stability of man-made structures and leading to subsidence of those structures, many studies were previously carried out to understand the development of scour signatures around natural (Borg et al., 2007; Callaway et al., 2009) and artificial objects (Rambabu et al., 2002, 2003; Quinn, 2006; Jenkins et al., 2007; Mayer et al., 2007; Trembanis et al., 2007; Wolfson et al., 2007), but none of these studies considered investigating a network of objects that can interact with each other, affecting the local pattern of
bottom currents. Scour is well depicted around the artificial modules suggesting the presence of strong currents. Well-developed scour hollows are found at different sides of the reef modules even if the main current direction is along the NW-SE axis. This suggests that the reef itself is able to affect local circulation, changing the currents pattern and strength. As observed by Callaway et al. (2009), the bottom current can be obstructed by a reef module (or a single reef unit) causing the current to diverge around the reef module. This usually causes an increase in turbulent intensity and flow velocity around the systems, deflating the seabed in front of the module and leading to the formation of scouring hollows. The sediment lifted by the turbulent flow is deposited at some distance from the reefs, creating areas of raised seabed and mega ripples. But if the reef modules are placed close enough to each other, like at the Senigallia artificial reef site, the bottom current could be subject to more than one deflection that can completely reverse the initial direction due to turbulence. In such hypothetical case the scouring signatures will appear at different positions compared to what one would normally expect. Moreover, as already mentioned in Chapter 2, the area may be subject to a local current reversal due to reversing wind patterns. The outcome at Senigallia artificial reef could have been different if the reef configuration had taken prevailing current direction into consideration, and the modules had been deployed within optimal arrays in order to reduce the cross-sectional area perpendicular to the current, consequently decreasing the flow acceleration. A possible configuration would have been to place each module at a larger distance to each other and shifted in relation to each other along the axis parallel to the dominant current (and the coastline) in order to have one man-made module per each virtual transect perpendicular to the main current (Fig. 5.3). In addition, the orientation of the artificial modules can be also optimized to receive the large amount of nutrients transported by the current.
The same deepening phenomenon for the area hosting the reef was also observed for Porto Recanati (Fig. 5.1), while the scouring signals are more pronounced at the southeastern side of the pyramids parallel to the northwest to southeast prevailing current (Manoukian et al., in press). Moreover, peculiar features are formed in the interaction between these larger pyramids and, presumably weaker currents. In their process of seabed erosion, the scouring currents leave each pyramid on a 1 m height sediment pile. A comparison of the two reefs’ geomorphological maps provide information on the local hydrodynamics and currents pattern.

High-resolution representation of seabed morphology allowed the interpretation of dynamic characteristics of the local and regional water masses and,
furthermore, an interpretation of seafloor sediment distribution (useful for subsequent benthic habitat studies; Schiel et al., 2006; Balata et al., 2007; Ryan et al., 2007). This approach contrasts with the more traditional granulometric description, commonly based on grab samples. In this study, in fact, the interpretation of the backscatter images and the subsequent ARA analysis were used to extrapolate the sediment texture maps. The resultant estimate of sediment distributions contains reliable information on grain size in this small area of western Adriatic Sea, matching fairly well with historic information from the same area (Leder, 2004) and with more recent study conducted during the PRISMA 2 research project for the preservation of Adriatic Sea (Fig. 5.4; Magi et al., 2002; Artegiani et al., 2003). During this project, 12 sampling stations were located close to Ancona and the studied sediments were collected in September 1996 using a stainless steel grab, along transects perpendicular to the coast. Figure 5.3 shows some of the sampling sites. The site 1 corresponds approximately to the Senigallia artificial reef location. It is characterized mainly by clay confirming the predicted sediment distribution interpretation obtained from the 2004 and 2008 multibeam data automated analysis. In both the maps, clay is the dominant grain size of the seafloor, while coarser sediments are limited to the area hosting the reef.

A different situation is observed in the 2002 data. Silt is the dominant grain size of the seafloor, suggesting that sediment transport of unusually strong intensity and capacity occurred. The Senigallia artificial reef is located on the main current and sediment transportation path from northwest to southeast which represents also the main direction of the Po River discharge confined along the Italian coast (Malanotte-Rizzoli and Bergamasco, 1983; Poulain et al., 2001).
Recall the annual mean discharge rate of the Po River is 1,525 m$^3$/s (Raicich, 1996; Cattaneo et al., 2003; Syvitski and Kettner, 2007) carrying a sediment load of 1.4 x 10$^7$ tons/year (Fain et al., 2007) with a mean grain composition of 7% clay, 23% sand and 70% silt (Nelson, 1970). Thus, the Po River discharge is one of the major factors affecting the general circulation of the northern Adriatic Sea through the introduction of low salinity water at the western boundary of the basin (Artegiani et al., 1997a) and extreme events such as floods are important to understand the general circulation and sedimentological, chemical, and biological processes within the basin. During extreme events, transport and depositional processes may change the dispersion pattern of suspended sediment and the amount of sediment trapped in the estuary or transported offshore to the adjacent shelf (Hossain et al., 2001). As Palinkas and Nittrouer (2007) point out, a layer of coarser sediments such as silt layer usually corresponds to a flood deposit. A certain number of Po River flood
events characterizes the last decade with the October 2000 flood representing the largest one during the last century reaching a mean daily maximum of 9,650 m$^3$/s (Boldrin et al., 2005; Palinkas and Nittouer, 2007). Figure 5.5 shows the surface water salinity versus time along a Senigallia sampling transect perpendicular to the coast. The reduced surface water salinity resulting from the October 2000 flood shows up well (see left arrow in Figure 5.5). Another (or perhaps a continuation of the previous) low salinity plume occurred during the October 2002 multibeam survey when very low values of salinity were again recorded (second arrow from left in Figure 5.5). This low salinity was due to the increased the Po River discharge rate up to almost 8,000 m$^3$/s (ARPA, 2002), causing a larger amount of coarser sediments to be transported towards the southeast and temporally changing the type and rate of sediments being deposited. These changes help explain the different sediment texture pattern observed from the October 2002 multibeam mapping and sampling surveys.

**Figure 5.5.** Water surface salinity evolution over time along a Senigallia sampling transect perpendicular to the coast. Black arrows indicate extreme flood events (*unpublished data kindly provided by colleagues of the Oceanographic Lab of CNR-ISMAR Ancona*).
Another intense flood event occurred in November 2010 (Fig. 5.5), while a new dual-head multibeam dataset of Senigallia reef was being collected. Although these data are not part of this study, a preliminary ARA analysis on the backscatter data was done to test if there was a coarser grain distribution in relation to the unusual large sediment discharge. An odd output was obtained from the ARA analysis, which showed two completely different sediment patterns for the starboard and port sides of each single survey line with the starboard side having a considerable higher backscatter angular response near the nadir portion of the swath. Because it was the first time a dual head system was employed to survey the study area, it was suspected that probably something in the FMGeocoder ARA analysis was not running properly. Therefore, the data were sent to IVS Support Team. They discovered that the FMGeocoder incorrectly combined the data from the two sonar heads when creating a single virtual ping for mosaicking and for ARA analysis. IVS developers plan to fix this problem in the next release of their software. This experience points out the importance of cooperation between scientists and hardware/software developers. In the meantime, the supervisor of IVS Support Team created a corrected ARA analysis shown in Figure 5.6. This image corroborates that the flood events cause coarser grains (mainly silt) to be deposited, as observed on the seafloor of Senigallia reef area by multibeam data analysis. This further corroborates the reliability of the multibeam backscatter data interpretation as well.

A possible reconstruction of sedimentation history at the reef site is summarized in Figure 5.7.
Figure 5.6. Extrapolated sediment map of Senigallia artificial reef during November 2010 coinciding to the intense flood event. On the basis of ARA analysis supported by IVS team, three color-based sediment sizes are indicated: sand, silt and clay.

Figure 5.7. Proposed sedimentation history at Senigallia artificial reef.
6. Conclusions

This is the first dedicated long-term temporal study of an artificial reef, recording the exact location and orientation of each artificial module/unit with respect to others and providing a detailed description of the actual condition of each reef module.

Multibeam technology is a very accurate tool, with high resolution and repeatability, to investigate how well different types of man-made modules endure the elements over time. At the 95% confidence level, the detection accuracies for the single WBC blocks and the WBC cages was approximately of 0.01 m and 0.30 m respectively. However, misinterpretation of the acoustic images can occur in relation to complex shape modules with cavities or a large number of sharp corners (e.g., cages, technoreef) using high beam density systems such as the EM3002. Such objects should be investigated with more than one survey line. Several lines with different orientations (for example, four survey lines located at an angle of 45° from each other) should be run.

Our results show that multibeam data not only thoroughly define the extent of the reef, but also quantifies the horizontal and vertical movements of the artificial reef components, as well as the scour and/or the burial of the artificial reef units. Local hydrodynamics plays a critical role in the settlement and stability of artificial modules. At the same time, the entire reef system changes the local environmental hydrodynamic processes acting on the reef itself. At Senigallia artificial reef, we have
found that most pyramids have completely fallen apart, and several WBC cages have gradually sunk into the sediments.

At Senigallia reef, scouring has occurred on different sides of the reef modules without showing a preferential direction related to the direction of the main current. A micro-environment of unique hydrodynamics is created by the reef itself and, besides changing the settlement and stability of each module, it may affect the local sediment transport and deposition exerting a primary control on the associated benthic habitat.

On the other hand, the location in an area characterized by less intense hydrodynamics and current pattern, and the larger distance among the artificial modules, may explain why Porto Recanati reef appears to be in a very good condition 33 years after its deployment, with most pyramids still intact. We have found that scouring signals run parallel to the main current’s direction from northwest to southeast. The scour was 1.0 m deep surrounding the 6.0 m high pyramids, together with scouring tracks down current.

Furthermore, the large-scale bathymetric view of the seafloor gives useful information of the terrain changes in coastal shallow areas induced by the presence of the reef. Before the advent of the multibeam system technology, previous SCUBA diver inspections had depicted only single units without allowing any connection with the overall reef system. Although a deepening of about 1.0 m of the seafloor hosting the Senigallia reef was recorded since the first survey in 2002, over the 10-year period of this study the total seafloor depth change has on average resulted in a slight shallowing of about 0.30 m. However, overall changes of depth have been much more dramatic in local areas due to scour and then subsequent deposition away from the scoured areas. The rate of scour has been slowing down since deployment, from 0.073 m/yr to 0.025 m/yr. Imagining a polygon around the reef outermost edges, the observed shallowing occurs mainly outside the polygon from
down current deposits up to at least 60.0 m away which represents the limit of the surveyed area. In future, a wider area should be investigated to provide more detailed information about the degree to which the artificial reef affects the surrounding seafloor. Within the simulated polygon, 70% of the seafloor shows an average negative change of depth of -0.08 m due to scour.

Finally, the multibeam backscatter data provide a valuable tool for the interpretation of seafloor sediments and benthic habitats. As mentioned before, unlike all the previous studies, no grab samples were collected during this research. The new Geocoder technique showed a good match with the published sediment distribution characterizing the study area. A cross check with the dynamic conditions over the region through time confirmed the results obtained by the relatively new Geocoder technique for the different time periods analyzed. At Senigallia reef, we found that the predominate sediment type is clay (size fraction < 63 µm) but underneath this clay, scouring reveals a silt layer. In the ten years of the study, the sediment type at Senigallia reef shows only a minor variation from mud to silt, and these large-scale changes appear to be directly linked to large flood events that occurred just prior to the change. Therefore, the backscatter interpretation maps not only provide detailed information on the seafloor changes strictly related to the local hydrodynamics and geological processes of the study coastal shallow area, but allows one to predict what to expect around certain objects deployed in specific environmental settings. For example, in less energetic environments, larger and taller artificial modules show a greater resistance to the local oceanographic and geologic settings. Further developments of the use of multibeam sonar technology in such a field should include analysis and interpretation of high-resolution seabed stratigraphy, the multibeam signal in terms of habitat complexity, and other physical properties, which may be applicable to the cross-classification of acoustic and benthic data.
7. St. Petersburg Beach Reef

7.1 Introduction

An artificial reef deployed west of St. Petersburg Beach has been the focus of repeated high-resolution 300 kHz multibeam surveys since 1999. This artificial reef is made of much different materials compared to Senigallia artificial reef in Adriatic Sea, Italy, where a similar study has been undertaken. Beyond testing the accuracy of using multibeam technology for investigating underwater structures, this study investigates the ability of the multibeam system to map different types of artificial reefs and how they evolve over time in relation to the coastal processes (geology, hydrodynamics, sedimentation, etc.).

St. Petersburg Beach is located on Long Key, part of a barrier island along the western edge of Pinellas County, just north of the entrance to Tampa Bay (Fig. 7.1). Barrier island formation along this coast began in the Holocene (Evans et al., 1985). The barrier-inlet system is closely linked to the general geology of the shelf and coast, which is currently receiving essentially no new terrigenous sediment from the north or from the mainland (Hine et al., 2003). The modest amount of sand carried to the coastal zone by rivers is trapped by the numerous estuaries and does not reach the open coast. The only significant sources of sediment for barrier construction and maintenance are the reworking of older siliciclastic sediments and the production of carbonate skeletal sediments by marine organisms.
The west Florida continental shelf is the submerged extension of the Florida carbonate platform that extends westward into the Gulf of Mexico approximately 250 km from the barrier-island coastline. It consists of a limestone karst surface covered by a thin (<3 m) layer of unconsolidated sediments primarily of fine quartz sand and
coarse sand/gravel-size marine biogenic carbonates (Doyle and Sparks, 1980; Locker et al., 2003). Black, phosphorite-rich sand is locally abundant, but always subordinate to the quartz and carbonate sediment types. The distribution is patchy and the transition between sediment types is generally abrupt, indicating that although processes may redistribute sediments on a local scale, large-scale sediment redistribution, which would tend to mix sediment types, is unlikely (Brooks et al., 2003).

The west coast of Florida is a low wave-energy coastal system with a microtidal regime (Davis and Hayes, 1984) and is classified by Tanner (1960) as ‘low to moderate’ due to the combined effects of the broad, shallow continental shelf (<1:2000 gradient), dominance of offshore winds, and the limited fetch across the Gulf of Mexico. Inlet morphodynamics are controlled by the interaction of wave and tidal processes. The broad, gently sloping continental shelf, in fact, restricts the size of the waves that develop. Episodic tropical storms, hurricanes, and winter cold fronts generate higher energy conditions (relatively large waves and strong long-shore currents) and are largely responsible for redistributing sediments along the broad inner shelf (Davis and Barnard, 2000) and play a dominant role in producing strong seasonal variation of shelf circulation in water depths less than 50 m (Yang and Weisberg, 1999; Yang et al., 1999). The local variability of the orientation of the coast and the low relief create complex wave reflection patterns (Davis and Gibeaut, 1990).

The sediment transport direction is generally southwards with numerous local reversals, even though the prevailing weather condition is one of southerly wind moving sediment to the north. From October through March, in fact, the predominant winds are from the north associated with the passage of frontal weather systems across the barrier coast (Fig. 7.2). Although these northerly winds are present only about 5-10 % of the time, they are strong (15-20 knots) in comparison
with the low energy conditions associated with the prevailing winds with a southerly component. This relatively energetic system generates large waves that produce strong longshore currents transporting sediment at much higher rates, and thus helps explain why the net sediment drift is to the south in this area.

Average annual wave height along this coast is about 30 cm, while during passage of frontal systems in winter, waves of about 100 cm are common at the coast (Gibeaut, 1991). Even with a low tidal range (spring tidal range of approximately 0.7 m; Mehta et al., 1976), the rather large coastal bays produce sizable tidal prisms at many inlets. This results in swift currents; speeds of 80-100 cm/s are common and some reach 150 cm/s during spring conditions (Davis and Barnard, 2003), which form the large sedimentary delta deposits outside of the inlets and bays.

**Figure 7.2.** Generalized diagram showing the approach and passage of a cold front along the Gulf coast of the Florida peninsula. In panel A, the barometric pressure begins to fall and winds are from the southwest as the front moves near the peninsula. Panel B shows the same processes except that the wind velocity has increased due to lower barometric pressures. The front passes in panel C with an abrupt shift in wind direction, a rapidly rising barometric pressure and strong winds from the northwest and north. As the front moves toward the east coast, wind velocity decreases and barometric pressure becomes level. These frontal systems dominate the processes over the long term (from Davis and Barnard, 2003).
7.2 Methods

7.2.1 Data Acquisition

7.2.1.1 Study Area

The St. Petersburg Beach artificial reef is just over 8 km (5 miles) out from the Pass-A-Grille Channel Entrance Marker #2 and is located near 27°40’46.00” N and 82°51’45.00” W (Fig. 7.3). The reef was deployed in March 1976 when large concrete sections (slabs, pilings, culvert pipes) of the Old Corey Causeway and Skyway Bridge were sunk in about 8.3 m of water laying the “foundation” for further construction.

![Figure 7.3. Location of St. Petersburg Beach artificial reef.](image)

To augment the lower profile concrete rubble and culvert, in 1984 a “high-profile” steel barge was salvaged off Star Island in Saint Petersburg and scuttled east of the reef’s center. Finally, in April 1995 the U.S. Army sunk ten obsolete combat vehicles, Vietnam era M-60 tanks (Figs. 7.4a and b), to the west of the reef’s center, as successfully accomplished in 1985 off the coast of New Jersey (Figs. 7.4c and d). Under the joint military operation REEFEX, indeed, obsolete tanks were submerged as artificial reefs, attracting or producing sea life and increasing commercial and
recreational fishing and SCUBA diving opportunities off the coast of New Jersey and New York. Before any of the vehicles could be used to construct the reefs, all fluids were drained and components such as the engines, transmissions, and hydraulic systems removed. This way the vehicles would not pollute or cause any damage to the environment they were deployed to aid.

**Figure 7.4.** Vietnam era M-60 Army tank used to deploy artificial reef. a) M60 tank is fitted with a 105 mm main gun and manned by a four-man crew. (b) M60 tanks undergo a thorough cleaning before use as reefs. (c) An M60 tank is knocked tail-first off a barge into the water. (d) An M60 tank on the Axel artificial reef off Bayhead, New Jersey, USA.
Multibeam surveys of St. Petersburg Beach artificial reef were conducted between March 1999 and February 2007. All the geophysical surveys were carried out using a Kongsberg Simrad EM3000 Multibeam Echo Sounder pole-mounted to the R/V Bellows during the 1999 cruise and to the R/V Suncoaster during the 2004 and 2007 cruises (Figs. 7.5a and b). The tracks were positioned so as to survey 100% of the seafloor with a ~20% of overlap. The dataset show some lack of data due to an anchored boat. Although the coverage was variable from survey to survey, the area considered for this study is approximately the same. In addition to the high-resolution bathymetry data, the multibeam backscatter signal also was recorded.

![Research vessels used to carry out St. Petersburg Beach artificial reef surveys. (a) R/V Bellows used during the 1999 cruise; (b) R/V Suncoaster used during the 2004 and 2007 cruises.](www.marine.usf.edu www.gulfoceanservices.co)

**Figure 7.5.** Research vessels used to carry out St. Petersburg Beach artificial reef surveys. (a) R/V Bellows used during the 1999 cruise; (b) R/V Suncoaster used during the 2004 and 2007 cruises.

### 7.2.1.2 Multibeam System

The Kongsberg Simrad EM3000 system maps the shallow ocean floor using a 300 kHz acoustic frequency and creating 127 acoustic beams at a maximum ping rate of 25 Hz and an angle of 130° (1.5° × 1.5° beams are spaced 0.9° apart; [http://www.kongsberg.com](http://www.kongsberg.com) – for further details see Chapter 3). This yields swaths that are up to ~4 times the water depth.
The multibeam system was supplemented with an Applanix Positioning and Orientation System for Marine Vessels (POS/MV 320 system). The system is composed of an inertial motion unit (IMU) with global positioning system (GPS; horizontal positional accuracy of ~1 m after post-processing) azimuth measurement system (GAMS) integrated with real-time kinetics (RTK). When working properly, this combined system provides positioning accuracy on the order of ~15 cm, and roll, pitch, and yaw measurements accurate to 0.02 m. However, the accuracy of any given depth from the multibeam system is estimated to be about 1 m based on additional uncertainties related to installation parameters and water-column properties. The POS/MV system with RTK capabilities also provides real-time heave correction with a measurement accuracy of 5 cm or 5% of the heave amplitude (whichever is greater) for periods up to 20 s. This information is integrated with the multibeam echo soundings to eliminate the effects of vessel movement, and provide accurate position and orientation of the seafloor as mapped by the multibeam sonar.

Angular misalignment among transducer, motion sensor, and gyrocompass, together with latency, was calibrated by a patch test at sea. Moreover, sound speed profiles were collected at the start of each survey using a SeaBird Electronics Inc., Bellevue, WA, conductivity–temperature–depth sensor (CTD SBE 25) in order to correct for acoustic ray bending of the signal. The data were logged using Simrad Merlin software.

7.2.2 Data Processing

7.2.2.1 Multibeam Bathymetry Data

The multibeam bathymetry data were edited for spurious bathymetric and navigational values and subsequently post-processed using the CARIS HIPS & SIPS software package (CARIS, Fredericton, NB, Canada; Figs. 7.6a, b and c). Post-processing steps included editing, cleaning by removing the outliers with the
automatic and manual flagging option, and resolving position, tide, sound speed, and vessel attitude problems (See Chapter 3, Section 3.2.1 for more details).

The depth soundings were corrected for tidal and other long-term sea level fluctuations by using verified data downloaded from a nearby NOAA (National Oceanic and Atmospheric Association) tidal station 8726520 in Saint Petersburg, Florida, using a mean lower low water (MLLW is the chart datum based on the average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch). The tide data were recorded every six minutes using GMT (Greenwich Meridian Time). Once cleaned, the data were gridded using a weighted mean gridding filter. The very high lateral resolution and density of beam spacing of the multibeam sonar justified gridding with a pixel resolution of 50 cm. The gridded data were exported as ASCII files and imported into Interactive Visualization Systems (IVS; Fredericton, NB, Canada) associated programs used to generate and manipulate data. IVS Fledermaus, a high-powered 3-D data rendering, visualizing and interactively exploring program, was used to generate digital elevation models and profiles of the artificial structures.

7.2.2.2 Multibeam Backscatter Data

The backscatter data from the multibeam were visualized and analyzed using IVS FMGeocoder, as for Senigallia dataset. For detailed information see Chapter 3.

7.2.3 Data Analysis

7.2.3.1 Multibeam Bathymetry Data

For each survey, a survey track line crossing all the other track lines was undertaken to verify the accuracy (95%) of the resultant depth. HIPS Quality Control (QC) utility was used to assess vertical accuracy and confidence measure of acoustically recorded depths (see Chapter 3 for the detailed procedure).
As already seen for Senigallia dataset, before the seafloor morphology (scour, burial, and other vertical and/or horizontal changes) analyses were performed, the data were exported from CARIS as an X, Y, Z ASCII file to be used by the suite of IVS programs. The same procedures and setting parameters applied for Senigallia reef were used for St. Petersburg Beach data. The assembled St. Petersburg Beach reef files were loaded into the Fledermaus and surface characteristics and statistics analysis were performed. Using the Map Sheet tool, a top down, plan view of each 3-D surface was created and saved as encapsulated postscript files. A map scale of 1:5000 was defined. Individual high-resolution 3-D snapshot from a portion of each surface were exported using the Screen Capture function.

Surface differences between different survey years were performed using the Surface Difference command. The new surfaces resulting from the differences were visualized and surface characteristics and statistics analysis were performed.

Finally, terrain-changes profile analyses were performed on some artificial modules of particular interest. The terrain profiles were saved as text files and individual images of each profile were once more exported using the Screen Capture function. Cross section profiles with a vertical exaggeration of 40:1 were made and utilized for terrain-change analyses. In the text file each point in the profile is written out to the file as a distance along the profile and an x, y and height/depth (z) position.

7.2.3.2 Multibeam Backscatter Data

IVS FMGeocoder was used to analyze the backscatter data of the investigated area (refer to Chapter 3). Statistical Analysis and ARA (angular range analysis) together with the Use Formal Inversion function were computed for each surface. The ARA patch analysis results were extrapolated to the backscatter mosaic providing an attempt of sediment texture map.
Figure 7.6. CARIS processed 1999 St. Petersburg Beach reef. (a) Mean depth, interpolated, 2D relief shaded color bathymetry; (b) mean depth, interpolated image; (c) shaded surface relief, interpolated image. Vertical exaggeration of 2 with an elevation of 46° and an azimuth of 350°. (a), (b) and (c) Red arrows show the artificial modules forming the reef such as the steel barge, the U.S. Army tanks and the large concrete sections of the Old Corey Causeway and Skyway Bridge.
### 7.3 Results

#### 7.3.1 Multibeam Bathymetry Data

The surveyed portion of the St. Petersburg Beach reef system extends approximately 1,000 m x 200 m with the major axis in N-S direction (Fig. 7.7). All ten M-60 U.S. Army tanks and the steel barge were located and identified (Table 7.1). A large amount of concrete sections were found to extend all over the area and especially on the north side of the reef. The tanks are all sitting upright, scattered in an area 100 m x 65 m and their shapes are clearly distinguishable (Figs. 7.8 and 7.9). The steel barge lies about 40 m east of the closest tank, with its long axis oriented ~349 degrees.

The surrounding seafloor depth averages 8.3 m, with a maximum recorded depth of 10.3 m in a scour hollow associated with the barge and a minimum recorded depth of 6.4 m on the crest of one of the U.S. Army tank (the depth values refer to the 2007 cruise).

Figures 7.10, 7.11 and 7.12 show detailed bathymetry relief images of 1999, 2004 and 2007 surveys respectively. The surface characteristics from each survey are listed in Table 7.2, while the statistics relative to each surface is described in Table 7.3.
Figure 7.7. 1999 St. Petersburg Beach artificial reef. Mean depth, interpolated shaded color bathymetry. Red dotted windows indicate special areas of interest showed in detail on the right side. Red roman numbers (I-X) denote the location of the ten M-60 U.S. Army tanks all sitting upright. Red letters denote the location of the steel barge (A) and the large concrete sections of the Old Corey Causeway and Skyway Bridge (B).
Table 7.1. St. Petersburg Beach artificial reef. The geographical location (latitude and longitude in WGS84) is shown for each of the ten M-60 tank and the steel barge.

<table>
<thead>
<tr>
<th>Target</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>TANK M-60 I</td>
<td>27°40’44.01” N</td>
<td>82°51’48.48” W</td>
</tr>
<tr>
<td>TANK M-60 II</td>
<td>27°40’43.65” N</td>
<td>82°51’49.82” W</td>
</tr>
<tr>
<td>TANK M-60 III</td>
<td>27°40’43.23” N</td>
<td>82°51’50.21” W</td>
</tr>
<tr>
<td>TANK M-60 IV</td>
<td>27°40’42.96” N</td>
<td>82°51’49.06” W</td>
</tr>
<tr>
<td>TANK M-60 V</td>
<td>27°40’42.59” N</td>
<td>82°51’48.47” W</td>
</tr>
<tr>
<td>TANK M-60 VI</td>
<td>27°40’42.23” N</td>
<td>82°51’49.71” W</td>
</tr>
<tr>
<td>TANK M-60 VII</td>
<td>27°40’41.99” N</td>
<td>82°51’49.05” W</td>
</tr>
<tr>
<td>TANK M-60 VIII</td>
<td>27°40’41.66” N</td>
<td>82°51’49.58” W</td>
</tr>
<tr>
<td>TANK M-60 IX</td>
<td>27°40’41.04” N</td>
<td>82°51’50.51” W</td>
</tr>
<tr>
<td>TANK M-60 X</td>
<td>27°40’39.72” N</td>
<td>82°51’49.23” W</td>
</tr>
<tr>
<td>BARGE</td>
<td>27°40’42.30” N</td>
<td>82°51’46.50” W</td>
</tr>
</tbody>
</table>

Well-developed scour signatures are located to the northeast and east of the barge, indicating dominant bottom flow from west-southwest to east-northeast. Corresponding to this scouring hollow, the terrain has become approximately 1.3 m deeper than the surrounding seabed with a pronounced steep slope of about 3.5°. Scouring is also evident around some of the concrete sections placed in the north portion of the reef. Because these sections are located very close to each other, they tend to act like one single reef system, inducing an average deepening of the seafloor by 1.0 m, with a peak value of 1.3 m. Moats and other depressions are also recorded around the M-60 tanks and concrete sections to the south. These scour features have increased the irregularity of the seabed’s geomorphology compared to areas outside of the artificial reef.
The mean difference of –0.079 m of all three surveys and a standard deviation of 0.55 m were computed from a number of 123 data points. Using the formulas described in Chapter 3, a 95% depth accuracy of ±0.21 m was calculated. Accordingly, subsidence of a unit may not be detectable if the depth difference between two surfaces taken at different times is <0.21 m. Figures 7.13a and b show the difference between the 1999 and 2004 surveys’ surfaces and the 2004 and 2007 surveys’ surfaces respectively. No significant difference was recorded in either case (Table 7.4). Some erosion process occurred during the six years between 1999 and 2004, highlighted by the reddish color south of the barge and in the north-east section area of the map on the east side of the concrete objects (Fig. 7.13a). On the other hand some sedimentation took place on the west side of the surveyed area depicted by the bluish color among the U.S. Army tanks and towards south among the concrete sections (Fig. 7.13a). The situation was more stable during the following three years, without any particular area subject to a noticeable amount of erosion or sediment deposition (Fig. 7.13b). However, changes continued to occur in relation to the barge during this time period.

Figure 7.8. Three-dimensional detailed image of the ten M-60 U.S. Army tanks of 1999 St. Petersburg Beach artificial reef. Mean depth, N-S interpolated shaded color bathymetry. All the tanks are upright.
Figure 7.9. Three-dimensional acoustic image of one M-60 U.S. Army tank of 1999 St. Petersburg Beach artificial reef. Shaded surface gridded at 50 cm on the left. Wireframe surface on the right. The upright shape of the M-60 tank is clearly visible and comparable with a drawing of the tank.

As already mentioned in Chapter 4, even with a 1.0 m accuracy for the positioning system, slight shifting can occur from one survey to the other causing a mismatch during the surface overlapping process. Figures 7.14a and b show enlargements of the previous surface differences focusing on the barge area. In both cases it is possible to observe some accretion or a missing part of the barge. How much of this is real change versus missing pings is not fully certain. However, the degradation of a barge over time through several tropical and normal storm events in such shallow water is expected and not surprising.

A further analysis of the data (Fig. 7.15) integrated with cross section profiles (Fig. 7.16) can be very useful revealing in detail any physical change occurred to the target over time. For example, an aggressive interpolation of 1999 dataset relative to the east and south sides of the barge revealed in a surface loss in comparison with the 2004 dataset (reddish color in Fig. 7.14a); on the other hand an interpolation of 2004 dataset relative to the center of the barge resulted in a surface gain (bluish color in Fig. 7.14a). A surface gain is clearly detectable also at the north side of the barge when comparing the 2007 dataset with the 2004 due to lack of sufficient data coverage during the 2004 survey (bluish color in Fig. 7.14b). On the contrary a real loss of surface occurred gradually at the south side of the barge. Both the three-
dimensional images (Fig. 7.15) and the two-dimensional profiles across the major axis of the barge (Fig. 7.16) show the physical changes. The southern part of the barge was nearly intact in the 1999 data, partially collapsed in the 2004 data and completely collapsed in 2007.

Moreover, the cross-section profiles quantify the degree of scouring north and south of the barge. While the 1 m of scouring (from 8.0 m to 9.0 m) is already present in 1999, the less pronounced scour of 0.5 m (from 8.5 m to 9.0 m) south of the barge develops gradually with intermediate steps of 0.1 m in 1999 and 0.3 m in 2004.
Figure 7.10. Mean depth, interpolated shaded color bathymetry of 1999 St. Petersburg Beach artificial reef. Red arrows show the artificial modules forming the reef such as the steel barge, the U.S. Army tanks and the large concrete sections of the Old Corey Causeway and Skyway Bridge. Some track-parallel artifacts are evident in the image most likely to either a sound-velocity problem or roll-bias error.
Figure 7.11. Mean depth, interpolated shaded color bathymetry of 2004 St. Petersburg Beach artificial reef. Red arrows show the artificial modules forming the reef such as the steel barge, the U.S. Army tanks and the large concrete sections of the Old Corey Causeway and Skyway Bridge. Also some minor track parallel artifacts are visible in this image that appears as lightly colored streaks most likely related to a roll-bias error.
**Figure 7.12.** Mean depth, interpolated shaded color bathymetry of 2007 St. Petersburg Beach artificial reef. Red arrows show the artificial modules forming the reef such as the steel barge, the U.S. Army tanks and the large concrete sections of the Old Corey Causeway and Skyway Bridge. Some minor track parallel artifacts are visible in this image that appears as lightly colored streaks most likely related to a roll-bias error.
Table 7.2. Surface characteristics of St. Petersburg Beach artificial reef surveyed in 1999, 2004 and 2007.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Dimensions</th>
<th>Cell Size</th>
<th>Bound</th>
<th>Horizontal Coordinate System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1494 rows x 407 columns</td>
<td>0.50</td>
<td>X Range</td>
<td>Y Range</td>
</tr>
<tr>
<td>Reef 1999</td>
<td></td>
<td></td>
<td>316132 to 316335</td>
<td>3062515 to 3063262</td>
</tr>
<tr>
<td>Reef 2004</td>
<td></td>
<td></td>
<td>316132 to 316335</td>
<td>3062515 to 3063262</td>
</tr>
<tr>
<td>Reef 2007</td>
<td></td>
<td></td>
<td>316132 to 316335</td>
<td>3062515 to 3063262</td>
</tr>
</tbody>
</table>
**Table 7.3.** Surface statistics of St. Petersburg Beach artificial reef surveyed in 1999, 2004 and 2007.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Median depth (m)</th>
<th>Mean depth (m)</th>
<th>Std. Dev.</th>
<th>Height Range</th>
<th>Total Area (m²)</th>
<th>Negative Area (m²)</th>
<th>Total Volume (m³)</th>
<th>Negative Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reef 1999</td>
<td>-8.30</td>
<td>-8.36</td>
<td>±0.39</td>
<td>[-10.456; -6.171]</td>
<td>150,258</td>
<td>150,257</td>
<td>-1,301,653.40</td>
<td>-1,301,653.40</td>
</tr>
</tbody>
</table>
7.3.2 Multibeam Backscatter Data

The backscatter images of St. Petersburg Beach reef from the 1999, 2004 and 2007 surveys are visualized in Figures 7.17a, b, and c, respectively. As already noted for the Senigallia dataset (Chapter 4), the individual reef substrates are easily detectable because they are characterized by high-medium backscatter (lighter grey). They are surrounded by darker areas representing acoustic shadows where the tanks and the barge prevent sound from reaching a portion of the seafloor.

In all three maps, lighter areas (high backscatter intensity) represent concrete sections in: the north part of survey area, the east of the barge, around some of the tanks, and the south part of the survey area. These high-backscatter (lighter) areas clearly distinguish themselves from the lower backscatter intensity (darker) of the surrounding seafloor. This contrast is expected between man-made objects versus a seafloor of primarily sediments.

The observed backscatter pattern depicts areas where major geomorphological changes occur, primarily the scouring processes (e.g., high backscatter of the steep slope at the east side of the barge) and certain amount of seafloor deepening due to the very close location of the artificial units to each other (e.g., the concrete sections in the northern part of the survey area). Moreover, this pattern highlights the presence of coarser sediments (or partially exposed limestone) at these high-backscatter (lighter) areas compared with the general sediment distribution in the area for all the three surveys.

Following the methods described for the Senigallia artificial reef (Chapter 3), the ARA analysis resulted in three main sediment classes. They are represented by different colors: orange for sand (or limestone or artificial objects), green for silt and blue for mud. The distribution of the ARA groupings show a good match with the grey scale backscatter images for the three surveys. An attempt of automated
extrapolation of this analysis was applied to all the data, obtaining a general surficial sediment classification map of the investigated area (Fig. 7.18). The seabed is characterized by coarser sediments (or exposed or partially exposed limestone) in the areas hosting the artificial reef units, while silt grains surround the area. Most of the concrete sections and the U.S. Army tanks appear also covered by a layer of coarser sediments. This pattern is most likely the results of the winnowing away of the finer sediments due to the disruption of bottom currents by the artificial reef objects.

**Figure 7.13.** Surface differences of St. Petersburg Beach artificial reef. (a) Mean depth of 2004 and 1999 surface difference; (b) mean depth of 2007 and 2004 surface difference. (a) and (b) Red arrows show the artificial modules forming the reef such as the steel barge, the U.S. Army tanks and the large concrete sections of the Old Corey Causeway and Skyway Bridge.
### Table 7.4. Statistics for the surface differences between 2004 and 1999 surveys, and 2007 and 2004 surveys of St. Petersburg Beach artificial reef.

<table>
<thead>
<tr>
<th>Surface difference</th>
<th>Median depth (m)</th>
<th>Mean depth (m)</th>
<th>Std. Dev.</th>
<th>Total Area (m²)</th>
<th>Positive Area (m²)</th>
<th>Negative Area (m²)</th>
<th>Total Volume (m³)</th>
<th>Positive Volume (m³)</th>
<th>Negative Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2004-2002]</td>
<td>-0.01</td>
<td>-0.01</td>
<td>±0.18</td>
<td>135,362</td>
<td>62,728.30</td>
<td>72,633.87</td>
<td>-1,243.61</td>
<td>8,937.15</td>
<td>-10,180.76</td>
</tr>
<tr>
<td>[2008-2004]</td>
<td>-0.03</td>
<td>-0.02</td>
<td>±0.15</td>
<td>130,601</td>
<td>56,384.64</td>
<td>74,216.34</td>
<td>-2,770.89</td>
<td>6,323.74</td>
<td>-9,094.63</td>
</tr>
</tbody>
</table>
Figure 7.14. Surface differences corresponding to the steel barge of St. Petersburg Beach artificial reef. (a) Mean depth of 2004 and 1999 surface difference; (b) mean depth of 2007 and 2004 surface difference. (a) and (b) Black arrows depict some example of wrong difference calculation. Mismatch of the surveys’ surfaces and/or lack and consequently interpolation of data can result in misinterpretation such as not real accretion or missing parts.
Figure 7.15. St. Petersburg Beach artificial reef steel barge. Two different prospective view of 3D interpolated shaded color image of the steel barge surveyed in 1999, 2004 and 2007. The small panels in relief represent the acoustic images of the barge before the aggressive interpolation process for the three surveys respectively. A gradual breaking down occurred at the south side of barge, completely collapsed in 2007.
Figure 7.16. Cross sections along the longitudinal axis of St. Petersburg Beach artificial reef steel barge and corresponding profiles obtained from (a) 1999 survey, (b) 2004 survey and (c) 2007 survey. (a) and (b) Transparent blue boxes represent lack of data; transparent red boxes represent aggressive interpolation of data. (a), (b) and (c) Black arrows show scour allow at the north side of the barge; blue arrows show scour allow at the south side of the barge.
Figure 7.17. Backscatter images of St. Petersburg Beach reef. Light gray to white areas may represent gravel, coarse shell or steep slopes (high backscatter). Dark gray to black areas may represent fine sediments mainly mud or acoustic shadows (low backscatter). (a) 1999 survey; (b) 2004 survey (c) 2007 survey.
Figure 7.18. Extrapolated sediment map of St. Petersburg Beach artificial reef during the 2007 survey. On the basis of ARA analysis (backscatter response as a function of grazing angle), three color-based sediment sizes are indicated: sand, silt and clay.
7.4 Discussion

As noted in previous chapters, repeated artificial reef surveys provide an excellent illustration of how the seafloor changes in shallow water environments and what one might expect to occur around a very large object on the seafloor.

No previous studies have been carried out before to provide detailed mapping over time of an artificial reef. Thus, information on the condition and stability of the different man-made modules and any geomorphological change related to them and their surrounding terrain, is not available for comparison with the studies presented here.

All the ten U.S. Army tanks of St. Petersburg Beach artificial reef are still sitting upright and no significant change was recorded in the eight-year period of this study. On the other hand, a gradual collapse of the southern portion of the barge was well documented over this period. The smaller differences between seafloor surfaces obtained from the three different surveys need to be taken with caution, because two factors make these smaller changes less certain. First, the slight positioning mismatch of the considered targets investigated during different surveys may result in error in the calculation of the surface difference. Second, the lack of sufficient data density and resulting interpolation of data can cause additional error. However, the gradual demise of the barge and major changes in scour patterns are indeed reliable results.

The seafloor hosting the man-made units shows irregularity resulting from the moats and depressions around most of the tanks and concrete sections. The well-developed scour east-northeast of the barge indicates dominant bottom flow from the west-southwest to the east-northeast, typical of the low energy conditions associated with the prevailing winds with a southerly component (Davis and Barnard, 2003). The rate of scour has slowing down since the deployment of the artificial units. For example, for the north area of the reef where most of the concrete
sections were detected, the scour rate decreased from 0.059 m/yr to 0.006 m/yr (Table 7.5).

**Table 7.5.** Scour history at the north area of St. Petersburg artificial reef, where most of the concrete sections were detected.

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth (m)</th>
<th>Elapsed time (yr)</th>
<th>Scour rate (m/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>8.3*</td>
<td></td>
<td>0.059</td>
</tr>
<tr>
<td>1999</td>
<td>9.65</td>
<td>23</td>
<td>0.010</td>
</tr>
<tr>
<td>2004</td>
<td>9.70</td>
<td>5</td>
<td>0.006</td>
</tr>
<tr>
<td>2007</td>
<td>9.72</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

* Assumed pre-deployment depth

The backscatter mosaics show the scouring as lighter areas corresponding to their strong backscatter return. As previously described, scour processes occur during the interaction of the object with the seafloor on which it is placed and the local bottom currents. Turbulent flow, strong enough to lift and redistribute the sediments, is induced by the presence of the man-made substrate itself, which causes a local area of relative higher-energy hydrodynamics. The scour pattern clearly shows this relationship with the structures. The estimate of sediment distribution from backscatter data analysis in this small area west of Florida is consistent with the results of recent studies (Brooks et al., 2003; Finkl et al, 2007). These authors have found that the mean grain size ranges from -1.4Φ to 5Φ (31.3 µm < size fraction < 2000 µm; coarse silt) from Anclote Key, the northernmost barrier island, to Venice Inlet, and offshore to approximately 30 km (Fig. 7.19), but finest sediments are generally found close to shore with coarsest sediments more offshore.
Figure 7.19. Map of the patchy distribution of mean grain size ($\Phi$) of surface sediments from Anclote Key to Venice Inlet, and offshore to approximately 30 km. Contour interval = 1$\Phi$ (500 µm); darker shading denotes coarser sediment (from Brooks et al., 2003).
Multibeam technology is a valuable tool to investigate different types of man-made modules, including a large steel barge.

We found all ten U.S. Army tanks sitting upright, while the steel barge showed a gradual degradation of the south side until the complete collapse in 2007, probably due to the impact of high-energy events like tropical and winter storms in such shallow water. Slight positioning misalignment among different surveys and/or interpolation errors should be taken into account when using automated techniques to determine changes over different time frames.

The high-resolution acoustic images and the backscatter interpretation maps provide detailed information on the seafloor changes strictly related to the local hydrodynamics and geological processes of this wave-dominated coastal shallow environment. Although the net sediment drift is to the south due to the strong longshore currents related to seasonal northerly winds, most seas and swell arrive from the west-southwest, and tidally dominated bottom currents flow mainly to the east-northeast where we have found most scouring, above all related to the steel barge.

The large-scale view of the survey area shows an average deepening of about 1.0 m of the seafloor hosting the artificial units. However, over the 8-year period of this study the total seafloor change has averaged a slight deepening of about -0.03 m due to scour around the structures and subsequent deposition not so far away from them. The rate of scour has been slowing down since the deployment of the artificial units (i.e., from 0.059 m/yr to 0.006 m/yr for the north area hosting the concrete sections). Considering the area limited by the outermost edges of the reef, 55% of the seafloor shows an average negative change of depth of -0.07 m due to scour.
Finally, we have found that the predominant sediment size at the St. Petersburg Beach reef is coarse silt (31.3 µm < size fraction < 2000 µm) but underneath it scouring reveals limestone or some of the concrete sections.

The relationship between acoustic data, surficial sediments, seabed topography, and hydrographic regime allows large areas of the seafloor hosting artificial reef to be mapped cost-effectively using remote acoustic survey techniques with minimal ground-truthing. This approach will definitely provide a tool not only to assess the construction of artificial reef complex, but to find the key areas for future potential artificial reefs.
8. Water Column Investigation

8.1 Introduction

Newer versions of multibeam sonar can record backscatter responses from the water column, which extend the functionality of multibeam echo sounders to investigate and map possible fish aggregations and other acoustic reflectors such as suspended material (Fig. 8.1). The Kongsberg EM3002 system is one such system that we have used in this manner, as follows.

Over the long term, an artificial reef is supposed to resemble local natural environments as organisms associate with its surface, modules, and surrounding water column, and eventually increase biomass at the site (Seaman and Jensen, 2000). The increased biomass enhances the productivity of marine ecosystem, and in order to understand it, biological information integrated with relative marine environmental data should be considered. Other data, however, suggest that artificial reefs are very large carbon sinks (Pidgeon, 2009). Information about fish aggregations distribution in and around artificial reefs and the relationship between the reef environment and the marine organisms is essential.

The knowledge of fisheries acoustics has increased dramatically along with a remarkable progress of information and exploration technology. However, measurement and quantitative analysis of fish aggregation geometry and associated movements remain difficult to achieve, particularly in pelagic environments or shallow areas where strong hydrodynamics and/or river input can increase water turbidity.
Acoustic techniques have emerged as a valuable method in assessing fish populations. They provide a non-invasive sampling method to collect spatially continuous data on fish abundance and distribution (Fabi and Sala, 2002; Soldal et al., 2002; Brehmer et al., 2003; Sala et al., 2007) over large areas. In addition, avoidance reactions are minimized, except in the near-surface layer where organisms are outside the cone of sound (Soria et al., 1996; Gerlotto et al., 1999; Draštík and Kubečka, 2005). The response fish have to a noise disturbance is related to their habitat preference. For example, pelagic species are more likely to swim away while benthic species will hide close to the seafloor (Wardle et al., 2001). In presence of reefs (artificial or natural), fish aggregations will most probably move close to the reef structures where they can easily find a shelter.
However, sampling of acoustic signals using single, dual and split beam echo sounders (e.g., Simrad EK60, EY60, EK500, EY500, BioSonics Model DT200) is mainly performed in two dimensions, vertical and along track (Misund, 1997; Diner 2001; Freeman et al., 2004; Guillard et al., 2004). It is continuous in the vertical dimension through the water column, but it may be discontinuous in the horizontal one due to the distance in space and time between successive pings along the vessel track. Increasing the ping rate and/or the beam width, or slowing down the ship speed will help to avoid discontinuity in the along-track dimension. The across-track dimension is also discontinuous due to the cone-shape beam, requiring very close track spacing.

The fishery echo sounder beam angle is usually between 5 and 10°, implying that the sampling volume becomes quite wide even at a rather short distance from the transducer. Therefore, the spatial resolution decreases dramatically with distance (Gerlotto et al., 1998). This kind of scientific fisheries echo sounder is unable to provide a three-dimensional view of a fish aggregation.

Sufficient information on the internal structure of fish aggregations is critical when trying to understand the spatial behavior of fish and how it relates to the influence of environmental and biological conditions (Bertrand et al., 2004, 2006; Soria et al., 2007).

The water column functionality of EM3002 bypasses all the previous time and the logistic limitations related to sea condition, turbidity, and fishing gear to collect data on fish aggregation. The use of a multibeam system allows the addition of the third dimension providing a nearly full three-dimensional recording of the fish aggregation characteristics, enhancing the study of fish aggregation geometry and behavior. Moreover, it increases the sampling volume and provides a great improvement of fish aggregations’ descriptors as well as the underlying topographic features.
Some studies that describe the use of multibeam scanning sonar to identify fish aggregation were carried out in offshore environment (Gonzalez and Gerlotto, 1998; Misund and Coetzee, 2000; Gerlotto et al., 1999, 2003, 2004; Mayer et al., 2002; Melvin et al., 2002; Paramo et al., 2007). These studies investigated technical aspects of trying to use multibeam sonar systems for biological purposes providing information such as the three-dimensional spatial distribution of fish aggregations (Gerlotto et al., 1999), their morphology and classification (Paramo et al., 2007), and their abundance (Misund and Coetzee, 2000).

Most recently, multibeam technology is being adapted for fishery research. Initial efforts concentrated on the visualization and display of mid-water multibeam data to address issues of fish aggregation dynamics and vessel avoidance during acoustic surveys (Mayer et al., 2002; Melvin et al., 2002). Recent research is addressing further development of multibeam technology and its integration with new software and hardware to allow for real-time interactive three-dimensional display of acoustic targets in a large volume of water column created from multiple overlapping acoustic swaths from a typical seafloor survey (Wilson, 2005; Kang, 2006; Doucet et al., 2010).

Estimates of fish density in the water column and total fish biomass could eventually lead to direct assessment of fish stock abundance in a very thorough yet economical method compared to previous labor intensive visual methods.

Shallow, eutrophic areas like the northwestern Adriatic Sea have high primary productivity in the water column over a predominantly sedimentary seabed, which provide ideal conditions for the deployment of artificial reefs aimed at attracting fish aggregations. A preliminary investigation of fish aggregations at the Senigallia artificial reef was conducted using the same multibeam technology used to investigate the geomorphologic changes of the reef over time. The purpose of this study is to verify the possibility of using the EM3002 for investigating the water
column and the seafloor, simultaneously, and for understanding fish aggregation distributions around artificial reefs by addressing the following questions. Does the artificial reef affect the fish aggregation behavior in terms of its morphological characteristics, its distance from the artificial modules, and its vertical distribution along the water column (e.g., preferable depth)? What are the limitations of multibeam technology for investigating spatial and temporal distribution patterns in fish aggregations?

8.2 Methods

The water column data are from a Senigallia artificial reef survey carried out during November 2010. Prior to this survey, the EM3002 transducer was not completely functional to log backscatter data from the water column during this survey. A large amount of background noise was masking possible backscatter targets (Fig. 8.2). This precluded using water column data from the earlier surveys reported in the previous chapters. However, after a technical modification of the sonar head and software improvement that occurred in September 2010, an acceptable signal to noise ratio in the water column backscatter data was obtained. Also at that time, the multibeam system was upgraded to a dual head system (called an EM3002D). This dual head configuration provides a wider seafloor swath and hence, a larger water volume sampling. Both the bathymetry and water column dataset are logged simultaneously for each survey line storing them as separate .all and .wcd files, respectively (.all is short for seafloor data, .wcd is short for water column data). This storage separation keeps the file sizes from becoming too large during acquisition and post-processing.
A total of 164 acoustic beams were sampled digitally for each sonar head with a spatial resolution of 15 cm in beam direction for each ping, creating a digital image of an across-track slice of the water mass under the transducers. The Tasmanian Company Myriax has extended its Echoview software to reading and post processing the water column backscatter data, and to visualizing the extracted information as two-dimensional or three-dimensional images.

Figure 8.2. Screenshot of the previous multibeam sonar head echogram. Systematic noise rays are evident along all the water column slide, which impair or completely mask possible target detection.

After the conversion of the raw data, a detailed inspection of the bi-dimensional acoustic echograms relative to each survey line was performed. A bottom detection algorithm was applied to exclude the seafloor and the reef modules from the analysis. Unlike for single, dual and split beam data, it is not possible to use a user-specified backstep processing parameter which insures that the backscatter data being used are user-specified backstep value above the surface of the seafloor (or artificial reef). Very close to the artificial modules, the intense backscatter with a high scattering degree generated from them, prevents detection and identification of
possible fish aggregations due to a very strong acoustic masking (Fig. 8.3). In this case an underestimation of fish aggregations can occur.

Whenever a backscatter response clearly suggested a possible fish aggregation, the feature of school detection in Echoview was used to detect fish aggregations. Because the EM3002D is not calibrated for detecting and identifying any particular fish species, an average target strength of -44 dB was used (Goddard and Welsby, 1986). First, a ping subset was created selecting the ping numbers containing the target. Once the fish aggregation was detected, it was selected using the Echoview Target detection procedure choosing the cruise-scanning algorithm more qualified in moving-platform context (Fig. 8.4) and setting a minimum threshold of -65 dB and a maximum of -30 dB. This algorithm scans through the variable and discards any pings that cross the previous one or lie, in part or entirely, between the previous ping and the ping prior to it. For each remaining ping, it creates a virtual ping with data points set to either 1 (inside the defined thresholds) or 0 (outside the defined thresholds); identifies intervals in each beam and forms nearly rectangular prisms from each interval. These prisms span the distance between one ping and the next one. Afterwards, the algorithm triangulates the prisms and stores details of the vertices of the triangles that represent the visible surfaces. From the resulting data, after analyzing vertices and discarding non-visible surfaces, it defines groups of connected vertices and creates a three-dimensional region for each set of connected vertices and the triangles containing them.

After performing extraction and geometric analysis of scattering features in the water column, the three-dimensional nature of the data lends themselves to analysis of size and shape of those features. Echoview provides the capability to extract and export to file the geometric and acoustic characteristics of the targets as well as to visualize them in a four-dimensional environment. The geometric and
acoustic characteristics considered for each detected fish school are described in Tables 8.1 and 8.2 respectively.

The geometric characteristics provide morphological and positional information of fish aggregations. The morphological features give a detailed description of the shape of the aggregations, while the positional ones allow examination of habitat preferences related to preferable distance from the reef, preferable vertical depth in the water column, and preferable reef unit type.

The acoustic characteristics provide energetic information of fish aggregations related to a mean volume backscattering strength of an aggregations ($S_v$), which can be used as acoustic density (Simmonds and MacLennan, 2005; Boswell et al., 2010).
Figure 8.3. Screenshots of the multibeam echogram. (a) Backscatter from a WBC pyramid; (b) Backscatter from a WBC cage. (a) and (b) White arrows indicate the bottom detection in Echoview. The intense backscatter due to the presence of the artificial module prevent from detecting possible fish aggregation very close to the structure or inside the WBC cages. Only targets clearly distinguishable from the strong background noise were taken into account. $S_v =$ Volume backscatter strength.
Figure 8.4. Screenshots of the water column data processing using Echoview software. (a) Fish aggregation detection during the echogram screening procedure. (b) Fish aggregation selection using the Target detection procedure. (a) and (b) White arrows indicate the bottom detection in Echoview. $S_v =$ Volume backscatter strength.
### Table 8.1. Geometric information of the 3-dimensional fish aggregations (3D regions) detected during the Echoview Target detection procedure.

<table>
<thead>
<tr>
<th>Geometric information</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area</td>
<td>m²</td>
<td>Surface area of the 3D region.</td>
</tr>
<tr>
<td>Length NS</td>
<td>m</td>
<td>Maximum length of the 3D region in the north/south axis.</td>
</tr>
<tr>
<td>Length EW</td>
<td>m</td>
<td>Maximum length of the 3D region in the east/west axis.</td>
</tr>
<tr>
<td>Minimum depth</td>
<td>m</td>
<td>Minimum depth of the 3D region.</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>m</td>
<td>Maximum depth of the 3D region.</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>Height of the 3D region (Maximum depth – Minimum depth).</td>
</tr>
<tr>
<td>Volume</td>
<td>m³</td>
<td>Volume of the 3D region.</td>
</tr>
<tr>
<td>Geometric center - latitude</td>
<td>degree</td>
<td>Latitude of the point at the geometric centre of the 3D region.</td>
</tr>
<tr>
<td>Geometric center - longitude</td>
<td>degree</td>
<td>Longitude of the point at the geometric centre of the 3D region.</td>
</tr>
<tr>
<td>Geometric center - depth</td>
<td>m</td>
<td>Depth of the point at the geometric centre of the 3D region.</td>
</tr>
<tr>
<td>Roughness</td>
<td>m⁻¹</td>
<td>Surface area of the 3D region divided by volume of the 3D region.</td>
</tr>
</tbody>
</table>

### Table 8.2. Acoustic characteristics of the 3-dimensional fish aggregations (3D regions) detected during the Echoview Target detection procedure.

<table>
<thead>
<tr>
<th>Acoustic characteristic</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sv mean</td>
<td>dB re 1 m⁻¹</td>
<td>S_v mean is the mean S_v within the domain.</td>
</tr>
<tr>
<td>Samples</td>
<td>-</td>
<td>Number of &quot;good&quot; data samples within the domain.</td>
</tr>
<tr>
<td>Pings</td>
<td>-</td>
<td>Number of pings in the variable being analyzed which intersect with the domain being analyzed.</td>
</tr>
<tr>
<td>Beams</td>
<td>-</td>
<td>Number of beams in the variable being analyzed which intersect with the domain being analyzed.</td>
</tr>
<tr>
<td>Sv min</td>
<td>dB re 1 m⁻¹</td>
<td>Minimum S_v value within the domain</td>
</tr>
<tr>
<td>Sv max</td>
<td>dB re 1 m⁻¹</td>
<td>Maximum S_v value within the domain</td>
</tr>
<tr>
<td>Density</td>
<td>Kg/m³</td>
<td>The volumetric density of fish expressed in mass units.</td>
</tr>
</tbody>
</table>
The density estimate (Table 8.2) is based on the theory of volume reverberation. Such a method employs the volume backscattering strength, which is a measurement of the backscattering of the acoustic wave caused by the organisms in each unit volume of the medium (Mitson, 1983; Johannesson and Mitson, 1983). The fish population density is obtained by dividing the volume backscattering strength by the scattering strength of individual fish. The volume backscattering strength is usually averaged over a certain depth interval, and over several pings (Johannesson and Mitson, 1983), and denoted by mean volume backscattering strength.

### 8.3 Results

Fourteen fish aggregations have been detected at Senigallia artificial reef in November 2010. Tables 8.3 and 8.4 show the geometric information and the acoustic characteristics of each identified aggregation.

Morphological characteristics (such as north-south and east-west length, height, area, and volume), positional depth, and energetic as mean $S_v$ of the 2010 fish aggregations at Senigallia artificial reef are shown using box plot in Figure 8.5.

The average lengths in the north-south and east-west directions of the fish aggregations are 2.42 m ± 1.24 m and 3.15 m ± 1.68 m, respectively, while the mean height of them is 0.35 m ± 0.26 m. The ratio between the length and the relative height of the fish aggregations reveals that they appear to be quite flat but almost evenly distributed in the horizontal plane. This behavior is confirmed from the three-dimensional images of the aggregations (Figs. 8.6 and 8.7). The mean area is 5.16 m² ± 3.40 m² and the mean volume is 0.29 m³ ± 0.23 m³.

The mean depth of all the fish aggregations (considering the geometric centre) is 9.00 m ± 2.51 m. Most of the fish aggregations were located at the top of the WBC cages or between the other modules, showing a tendency for a mid- and
bottom water depth intervals vertical distribution than for the surface waters (Figs. 8.6 and 8.7). Half of the aggregations have a preferable depth range of 6.73 m - 11.09 m.

The mean $S_v$ from all fish aggregations is $-49.24 \text{ dB} \pm 4.16 \text{ dB}$. Half of the aggregations appears in the mean $S_v$ interval between $-51.87 \text{ dB}$ and $-47.00 \text{ dB}$.

The three-dimension visualization (Figs. 8.6 and 8.7) helps to understand at a glance the relationship between fish aggregations and artificial reefs based on spatial location. Only three of them, Fish Aggregation 2, 3 and 7, are identified outside the reef at 98.12 m, 103.97 m and 64.91 m respectively from the nearest artificial module or unit.
Table 8.3. Geometric information of the 14 fish aggregations detected at Senigallia artificial reef.

<table>
<thead>
<tr>
<th>Fish Agg.</th>
<th>Surface area (m²)</th>
<th>Length NS (m)</th>
<th>Length EW (m)</th>
<th>Min depth (m)</th>
<th>Max depth (m)</th>
<th>Height (m)</th>
<th>Volume (m³)</th>
<th>Geometric centre (LAT)</th>
<th>Geometric centre (LONG)</th>
<th>Geometric depth (m)</th>
<th>Roughness (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.92</td>
<td>2.91</td>
<td>4.82</td>
<td>11.71</td>
<td>12.06</td>
<td>0.35</td>
<td>0.75</td>
<td>43° 45.28' N</td>
<td>13° 12.57' E</td>
<td>11.88</td>
<td>14.56</td>
</tr>
<tr>
<td>2</td>
<td>1.40</td>
<td>0.65</td>
<td>0.68</td>
<td>10.65</td>
<td>11.09</td>
<td>0.44</td>
<td>0.06</td>
<td>43° 45.25' N</td>
<td>13° 12.67' E</td>
<td>10.87</td>
<td>23.33</td>
</tr>
<tr>
<td>3</td>
<td>3.25</td>
<td>2.53</td>
<td>2.12</td>
<td>7.52</td>
<td>8.73</td>
<td>1.21</td>
<td>0.29</td>
<td>43° 45.27' N</td>
<td>13° 12.68' E</td>
<td>8.14</td>
<td>11.20</td>
</tr>
<tr>
<td>4</td>
<td>9.98</td>
<td>3.28</td>
<td>4.34</td>
<td>12.07</td>
<td>12.43</td>
<td>0.36</td>
<td>0.64</td>
<td>43° 45.28' N</td>
<td>13° 12.54' E</td>
<td>12.25</td>
<td>15.59</td>
</tr>
<tr>
<td>5</td>
<td>7.74</td>
<td>4.00</td>
<td>3.16</td>
<td>5.37</td>
<td>5.64</td>
<td>0.27</td>
<td>0.41</td>
<td>43° 45.30' N</td>
<td>13° 12.50' E</td>
<td>5.51</td>
<td>18.87</td>
</tr>
<tr>
<td>6</td>
<td>1.09</td>
<td>0.40</td>
<td>0.50</td>
<td>6.02</td>
<td>6.38</td>
<td>0.36</td>
<td>0.04</td>
<td>43° 45.25' N</td>
<td>13° 12.59' E</td>
<td>6.26</td>
<td>27.25</td>
</tr>
<tr>
<td>7</td>
<td>3.42</td>
<td>2.25</td>
<td>2.38</td>
<td>9.42</td>
<td>9.71</td>
<td>0.29</td>
<td>0.15</td>
<td>43° 45.31' N</td>
<td>13° 12.45' E</td>
<td>9.57</td>
<td>22.80</td>
</tr>
<tr>
<td>8</td>
<td>8.98</td>
<td>3.05</td>
<td>4.58</td>
<td>11.90</td>
<td>12.12</td>
<td>0.22</td>
<td>0.49</td>
<td>43° 45.33' N</td>
<td>13° 12.54' E</td>
<td>12.01</td>
<td>18.33</td>
</tr>
<tr>
<td>9</td>
<td>4.89</td>
<td>4.41</td>
<td>2.89</td>
<td>6.62</td>
<td>6.83</td>
<td>0.21</td>
<td>0.21</td>
<td>43° 45.30' N</td>
<td>13° 12.58' E</td>
<td>6.73</td>
<td>23.29</td>
</tr>
<tr>
<td>10</td>
<td>0.45</td>
<td>0.48</td>
<td>0.43</td>
<td>10.97</td>
<td>11.21</td>
<td>0.24</td>
<td>0.02</td>
<td>43° 45.28' N</td>
<td>13° 12.57' E</td>
<td>11.09</td>
<td>23.00</td>
</tr>
<tr>
<td>11</td>
<td>7.51</td>
<td>2.53</td>
<td>4.67</td>
<td>8.01</td>
<td>8.32</td>
<td>0.31</td>
<td>0.48</td>
<td>43° 45.27' N</td>
<td>13° 12.58' E</td>
<td>8.16</td>
<td>16.02</td>
</tr>
<tr>
<td>12</td>
<td>2.56</td>
<td>2.17</td>
<td>4.52</td>
<td>4.56</td>
<td>4.72</td>
<td>0.16</td>
<td>0.08</td>
<td>43° 45.28' N</td>
<td>13° 12.52' E</td>
<td>4.64</td>
<td>32.00</td>
</tr>
<tr>
<td>13</td>
<td>5.26</td>
<td>3.30</td>
<td>4.20</td>
<td>9.39</td>
<td>9.62</td>
<td>0.23</td>
<td>0.24</td>
<td>43° 45.29' N</td>
<td>13° 12.52' E</td>
<td>9.50</td>
<td>21.92</td>
</tr>
<tr>
<td>14</td>
<td>4.74</td>
<td>1.85</td>
<td>4.84</td>
<td>9.33</td>
<td>9.56</td>
<td>0.23</td>
<td>0.24</td>
<td>43° 45.27' N</td>
<td>13° 12.57' E</td>
<td>9.44</td>
<td>19.75</td>
</tr>
</tbody>
</table>
Table 8.4. Acoustic information of the 14 fish aggregations detected at Senigallia artificial reef. $S_v = \text{Volume backscattering strength}$

<table>
<thead>
<tr>
<th>Fish Agg.</th>
<th>$S_v$ mean (dB re 1 m$^{-1}$)</th>
<th>Samples</th>
<th>Pings</th>
<th>beams</th>
<th>$S_v$ min (dB re 1 m$^{-1}$)</th>
<th>$S_v$ max (dB re 1 m$^{-1}$)</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-44.84</td>
<td>963</td>
<td>12</td>
<td>132</td>
<td>-59.35</td>
<td>-37.08</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>-51.80</td>
<td>564</td>
<td>14</td>
<td>322</td>
<td>-57.29</td>
<td>-49.51</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>-51.87</td>
<td>847</td>
<td>8</td>
<td>288</td>
<td>-59.90</td>
<td>-45.63</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>-41.49</td>
<td>1434</td>
<td>8</td>
<td>172</td>
<td>-59.59</td>
<td>-34.55</td>
<td>0.71</td>
</tr>
<tr>
<td>5</td>
<td>-47.46</td>
<td>2874</td>
<td>34</td>
<td>706</td>
<td>-59.91</td>
<td>-43.41</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>-54.51</td>
<td>1131</td>
<td>24</td>
<td>852</td>
<td>-57.42</td>
<td>-51.27</td>
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</tr>
<tr>
<td>7</td>
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<td>145</td>
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<td>88</td>
<td>-59.52</td>
<td>-56.61</td>
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</tr>
<tr>
<td>8</td>
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<td>151</td>
<td>8</td>
<td>97</td>
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<td>-47.42</td>
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<tr>
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<td>-55.14</td>
<td>11840</td>
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<td>-59.63</td>
<td>-51.13</td>
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<tr>
<td>11</td>
<td>-43.15</td>
<td>81</td>
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<td>-35.47</td>
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<tr>
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<td>13</td>
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<td>-48.39</td>
<td>0.06</td>
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<tr>
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<td>-47.00</td>
<td>97</td>
<td>4</td>
<td>47</td>
<td>-54.65</td>
<td>-44.15</td>
<td>0.36</td>
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</tbody>
</table>
Figure 8.5. Box plot of various morphological, positional and energetic characteristics of the 2010 fish aggregations at Senigallia artificial reef. Fifty percent of the samples (box) and the first and third quartiles (bars) are shown. EW = east-west; SN = south-north; $S_v$ = Volume backscatter strength.
Figure 8.7. Three-dimensional zoom scene of Senigallia artificial reef environment. Two different prospective are visualized. White numbers denote some of the fourteen fish aggregations detected during the water column investigation. Red color identifies fish aggregations detected inside or at the boundary of the reef; yellow color identifies fish aggregations detected outside the reef.
Figure 8.6. Three-dimensional overview scene of Senigallia artificial reef environment. Two different prospective are visualized. White numbers denote the fourteen fish aggregations detected during the water column investigation. Red color identifies fish aggregations detected inside or at the boundary of the reef; yellow color identifies fish aggregations detected outside the reef.
8.4 Discussion

The single test survey does not allow for any general descriptions of reef fish aggregations, however the results described above are in agreement to those reported by Fabi and Sala (2002) and Sala et al. (2007) for the same Senigallia artificial reef. These authors assessed the biomass of fish assemblages inhabiting the reef through a stationary hydroacoustic technique, using a modified split-beam Simrad EY500 system. They detected fish aggregations just over or closely associated with the reef modules, with a preferential vertical distribution for mid- and bottom waters than for the surface ones, as observed in our test survey. Moreover, the distribution of fish aggregations clearly decreased at 80 m from the outer edge of the reef. Fabi and Fiorentini (1994) show that starting in early September, mobile pelagic species become dominant inside the reef, mainly due to the migration of the reef fish species from the coastal shallow waters to offshore, where the water temperature is about 10 to 12°C during the winter months. Historical fish net samplings (Fabi, unpublished data) clearly show an increment of fish density during the last three-month period of the year (Fig. 8.8) and the large density difference compared to control sites external from the reef (about 1.5 km).
The detected aggregations closer to the artificial modules may be mainly represented by partially and/or obligatory reef-dwelling species, such as sparids and sciaenids. In fact, Fabi and Fiorentini (1994) observed that higher mean catch rates were recorded for Diplodus annularis (annular sea bream, family Sparidae), Lithognathus mormyrus (striped sea bream, family Sparidae), Sciaena umbra (brown meager, family Sciaenidae), and Umbrina cirrosa (shi drum, family Sciaenidae). The most shallower aggregations may be included pelagic fish (Fabi and Fiorentini, 1994) mainly gregarious, transient non-attracted, such as Saridina pilchardus (European pilchard, family Clupeidae) and Engraulis encrasicolus (European anchovy, family Engraulidae), and partially-attracted, such as Mugil cephalus, Liza ramada, Liza saliens, Liza aurata, Chelon labrosus (family Mugilidae). Non-attracted and partially-attracted are defined on the basis of their behavior towards natural or artificial hard
substrates (Bombace et al., 1994). However, net samples taken during the water column data investigation would be critical to describe the composition of the observed aggregations.

Besides the studies conducted at Senigallia reef, other surveys carried out at different artificial reefs show a decrease in fish aggregations moving away from the reef. Boswell et al. (2010) conducted an acoustic survey on a petrol platform reef and found that fish aggregation density decreased 16 times at 30 m from the reef, while Ito (2011) found that Japanese mackerel density decreased starting from 65 m from a steel artificial reef.

In this study, 79% of fish aggregations are distributed inside or very close to the reef with an average density of $0.22 \text{ kg m}^{-3} \pm 0.22 \text{ kg m}^{-3}$. The mean fish density for the aggregations found outside the reef area is $0.02 \text{ kg m}^{-3} \pm 0.01 \text{ kg m}^{-3}$. However, direct density estimate of fish using the multibeam system is out of reach, due to the lack of a proper calibration, significant background noise, and the complexity of determining the intrinsic target strength of fish without the overprinting of geometric effects related to angle of detection. Although a few preliminary studies were conducted to find the most proper and accurate calibration technique for the EM3002 working in coincidence with a split-beam echo sounder (Huntting Howell, 2008; Gurshin et al., 2009), further research is needed to be carried out to provide calibration of all beams, single-target detections, target strength estimations, and quantitative estimates of biomass and target identification using a bathymetry multibeam system such as the EM3002.

The morphological “flat” shape of the fish aggregations (high length/height ratio) was observed by Gerlotto et al. (1999) comparing the fish aggregations detected in Adriatic Sea with those identified in the Catalan Sea. The three-dimensional images of the fish aggregations (Figs. 8.6 and 8.7) show the preferential
behavior of fish to stay together forming much wider than high aggregates close to the artificial units.

The acoustic three-dimensional scenes of the water column provide a full view of the detected fish schools in relation to the artificial modules with the ability to precisely locate the fish in position and depth below sea level and above the reef. The imaging of acoustic data in three dimensions (four dimensions if considering the temporal information available in the interactive software related to the time of collection) is an effective analytical tool for examining the fish aggregations’ distributions and behavior, providing a better understanding of their interaction with the surrounding environment. These results emphasize the importance of the detailed geometric and acoustic descriptors provided by the multibeam sonar and the need to spatially map the referenced information such as the relationship between fish aggregations and bottom topography. This approach is extremely valuable for designing artificial reefs. As already seen, beside attracting fish aggregations, the reef seems to play a key role in determining the location and size of the fish aggregations. Based on Table 8.3 and Figures 8.6 and 8.7, and taking into account that an underestimation of fish aggregations can occur very close to the artificial units, more aggregations and larger aggregations were detected among the artificial modules, while the only three small aggregations were identified outside the reef where background noise is very low (compared to background noise near the reef).

However, a limitation related to the use of multibeam sonar for biological purposes is the impact of side lobes on the images. As already observed by other authors (Gerlotto et al., 1999; Cochrane et al., 2003; Huge Clarke, 2006) the backscatter noise received through the side lobes is often equal to or higher than the fish backscatter signal. Depending on the settings and the nature of the bottom backscatter strength of the seafloor, seabed echoes will contaminate the water column data at distances exceeding than the depth and in fact, due to the spherical
spread of sound, will contaminate more of the water column at the outer edges of the swath. In other words, the water column data with the least amount of noise exist within a semi-circle of radius equal to the closest part of the seafloor to the sonar. This area above the semi-circle, although mostly noise free, is dramatically the smaller portion of the full water column. To properly use three-dimensional acoustics to estimate density in the full water column, this technical problem and related calibration issues (Cochrane et al., 2003; Foote et al., 2005) need to be addressed. Hardware improvements are still necessary to enhance the use of the most sophisticated multibeam systems designed exclusively for bathymetric mapping, normally gating-out water column signals as noise, for an accurate fisheries research.

8.5 Conclusions

This preliminary study addressed the following questions:

1. Does the artificial reef affect the fish aggregation behavior in terms of its characteristics, its distance from the artificial modules, and its vertical distribution along the water column (preferable depth)?

2. What are the limitations of multibeam technology for investigating spatial and temporal distribution patterns in fish aggregation?

The findings from this preliminary study shows that artificial reefs do affect the behavior of fish aggregations, not only in their geometrical shape but also in their spatial distribution in the water column. Most of the aggregation present a "flat" shape with a wider distribution horizontally than vertically along the water column. Larger and more numerous aggregations were detected inside the reef, at mid- and bottom-water, and especially close to the WBC cages than, outside the reef area.
Based on previous work, the detected aggregations are likely to be either reef-dwelling species (e.g., sparids and sciaenids) or transient pelagic species (e.g., mugilids and pilchards).

Further research is necessary to investigate the daily and seasonal behavior of the fish aggregations with systematic surveys as was conducted for the geomorphological studies.

The new water column functionality makes the EM3002 a remarkable tool for surveying fishery habitats, offering simultaneous and co-registered data collection of bathymetry, seabed backscatter imagery and water column backscatter, obtaining very detailed acoustic image of geophysical processes and fish aggregation around artificial substrates.

However, the EM3002 shows limitations where the signal-noise ratio near objects is too low. This lower signal to noise ratio makes detection of possible fish aggregations very difficult. One can increase the masking of noise, but if fish aggregations exist within the masked noise area, their size will be under-estimated. Moreover, additional research should include calibration of all beams, accurate target strength estimations, and quantification of the effect of overlapping beams on volume-backscatter measurements.
9. References


Gerlotto, F. and Paramo, J., 2003. The three-dimensional morphology and internal structure of clupeid schools as observed using vertical scanning multibeam sonar. *Aquatic Living Resources*, **16**: 113–122


Gonzalez, L. and Gerlotto, F., 1998. Observation of fish migration between the sea and a Mediterranean lagoon (Etang de l’Or, France) using multibeam sonar and split beam echo sounder. *Fisheries Research*, **35**: 15-22


Manoukian, S., Fabi, G. and Naar, F.D., (in press). Multibeam investigation of an artificial reef settlement in Adriatic Sea (Italy) 31 years after its deployment. *Brazilian Journal of Oceanography*


Relini, G., 1983a. Twelve years of experiments on artificial reefs in the Gulf of Genoa (Italy). Journée d’études sur les aspects scientifiques concernant les récifs artificiels et la mariculture suspendue, CIESM, Cannes: 73-75

Relini, G., 1983b. Esperienze di barriere artificiali in Mar Ligure. Il gazzettino della Pesca, 5: 20-23


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