Integrated Management of Coastal Hypoxia in the Northern Adriatic Sea: the Case Study of the Province of Rimini

A. Luchetta[1], F. Alvisi[2], S. Cozzi[1], C. Cantoni[1], A. Russo[3], P. Serratore[4] , O. Bajt[5], P. Focaccia[2], C.R. Ferrari[6], G. Catalano[1], M. Ravaioli[2]
1, Institute of Marine Sciences, CNR, Trieste, Italy
2, Institute of Marine Sciences, CNR, Bologna, Italy
3, Dipartimento di Scienze della Vita e dell'Ambiente, Università Politecnica delle Marche, Ancona, Italy
4, Department of Veterinary Medical Sciences, University of Bologna, Bologna, Italy
5, Marine Biology Station, National Institute of Biology, Piran, Slovenia
6, DAPHNE Oceanographic Structure, Environmental Agency of Emilia-Romagna, Cesenatico, Italy
a.luchetta@ts.ismar.cnr.it

Abstract

An integrated monitoring network aimed at the management and mitigation of environmental and socio-economic costs of hypoxia was developed for the coastal zone of Rimini (Emilia Romagna - Italy).
This area was chosen for the presence of high anthropogenic pressure (416,000 equivalent inhabitants and tourist summer peak of up to 973,110), industrial and agricultural activities, as well as maritime traffic and nutrient river discharges (about 600 $t \cdot y^{-1}$ of N and 300 $t \cdot y^{-1}$ of P in 2002).
EMMA monitoring network was planned by linking scientific knowledge on hypoxia phenomenon with in situ experimental investigations. Its integration with existing environmental monitoring, available facilities and data resources was considered in order to increase the cost effectiveness of the project.
The structure of EMMA monitoring network was based on four main components:

- an instrumental monitoring network of the coastal zone, by means of an automated remote station coupled by traditional sampling at fixed stations, to provide a set of high resolution environmental data;
- a 3-D numerical model (ROMS) implemented to perform hydrological simulations and forecast of hypoxia in the area of interest;
- a Local Information Centre (LIC) devoted to the acquisition and exchange of data and model results among network components;
- a Decision Supporting System to bring scientific aspects of hypoxia phenomena into management requirements of local institutions and socio-economic operators.

1 Introduction

Eutrophication often causes symptoms of marine ecosystem stress ranging from elevated growth of algal biomass to low dissolved oxygen concentrations, massive mortality of marine organisms, defaunation of benthic populations, low quality of bathing waters, or even more serious problems connected to the occurrence of toxic algal blooms. Among these aspects, hypoxia and anoxia crises are common consequences of eutrophication in coastal zones. Over the past few decades both coastal eutrophication and hypoxia have become such widespread phenomena as to be regarded on a global rather than on a local scale [1, 2].

The causes of hypoxia are generally associated to an excess of continental nutrient loads, although the response of each marine ecosystem to this anthropogenic pressure is strongly modulated by the timing of water stratification, mixing and circulation at regional and local scales. Even global scale factors, such as climate change, may alter local ecosystem productivity therefore further exacerbate the problems related to anoxia and hypoxia. Microbial communities also affect the biogeochemical cycles of C, N and P, since nitrogen is considered the major limiting nutrient for marine primary production. An estimation of the abundances of bacterial groups specifically involved in the nitrogen cycle then results essential to understand the mechanisms acting in eutrophic ecosystems [1, 2, 3, 4].

Bottom water oxygen deficiency influences the living species and affects the biogeochemical processes controlling nutrient concentrations in the water column too. The importance of the benthic-pelagic coupling increases with decreasing water depth and nutrient load. The knowledge of sea floor characteristics is therefore crucial to study hypo-anoxia, as they can determine conditions favourable to local development of such phenomena. In addition to this, the sedimentary records provide information on the evolution of organic matter degradation, nutrient cycling and hydrodynamics over different spatial and temporal scales [5]. Northen (N) Adriatic Sea is highly productive and characterized by a trophic gradient decreasing from West to East. Nevertheless, production processes in this basin are highly variable, as a result of the interactions between meteorology, river inputs, nutrient dynamics and water circulation. These different factors play a role in the occurrence of large offshore anoxia and hypoxia and mucilage appearance. Hypoxia and anoxia in N Adriatic mainly occur in the western area where they were reported since the beginning of the last century. However, the analysis of their evolution, triggering mechanisms and consequences was often episodic, since most of the historical oceanographic data were collected at few coastal stations. More recently, specific observations on mass mortality of marine organisms, temporary cyst formation, unusually high catches of fish and invertebrates stressed by low oxygen concentrations and disturbance of meiobenthic copepod communities were reported at different locations as a consequence of the intensification of hypoxia and anoxia [1, 6, 7, 8, 9]. At regional scale, the coastal zone of Emilia Romagna plays a considerable role in the demographic and socio-economic perspective at national and European levels. Tourism, industry, fishing and aquaculture provide important contributions to the economy of this region. Here, the scientific community, local authorities and socio-economic operators often debated problems related to eutrophication and hypoxia since the 1970s. As a consequence, regular marine monitoring programmes, supported by regional institutions, was implemented since 1977. For these reasons, EMMA research project (Environmental Management through Monitoring and Modelling of Anoxia LIFE04ENV/IT/0479) operated from 2004 to 2007, with the aim of building an integrated monitoring/forecasting network to manage and possibly reduce the impact of hypoxia on the coastal zone of Rimini. EMMA was the first attempt in Italy to create an integrated network specifically dedicated to hypoxia and anoxia, through the combined efforts of scientific institutions, monitoring EPA, local and regional authorities and socio-economic actors. The project was carried out in collaboration with the National Institute of Biology of Slovenia (NIB), which is also involved in the monitoring program of marine eutrophication and hypoxia events in Slovenia. The aim of this paper is to present scientific background, planning activity and experimental investigations performed in the area of interest to define the operational characteristics of the monitoring/forecasting network.

2 Experimental activities

2.1 Study site

Within the 150 km long coastal zone under Emilia Romagna Region jurisdiction, the province of Rimini was chosen to implement the EMMA project (Figure 1). Very shallow waters characterize this 40 km long area, lying between Cesenatico and Cattolica. The water column structure is strongly influenced by the inputs of Po River and of other regional streams, which induce a complex circulation mostly dominated by a southward flowing current (Western Adriatic Current). High levels of nutrients, dissolved organic matter and suspended particulate matter are supplied to the coastal zone in concomitance with the spreading of the coastal front, their dynamics being modulated both by continental inputs and by in situ production/assimilation processes. Primary production and chlorophyll-a concentrations are high, particularly in a narrow belt within few miles from the coast [1, 10, 9, 11]. Temporal variations in the extension of low-salinity coastal waters also exert a strong influence on the deposition and biogeochemistry of sediments. Despite lateral transport and periodic resuspension, a net sediment accumulation characterizes the benthic compartment along the Italian coast South of the Po delta [5].

2.2 Field activity, data acquisition and elaboration

The EMMA monitoring network was set up taking into account the available monitoring activity in the area carried out by the Regional Environmental Protection Agency (ARPA Daphne). In details, it was integrated by:

- one fixed automated station (buoy) with real time data transmission;
- a new monitoring network of microbial communities, including some species potentially harmful for human health;
- a bulletin reporting about unusual catches of fish and other benthic organisms.

Ongoing environmental monitoring activities carried out by the Municipality of Rimini were also used to provide infor-

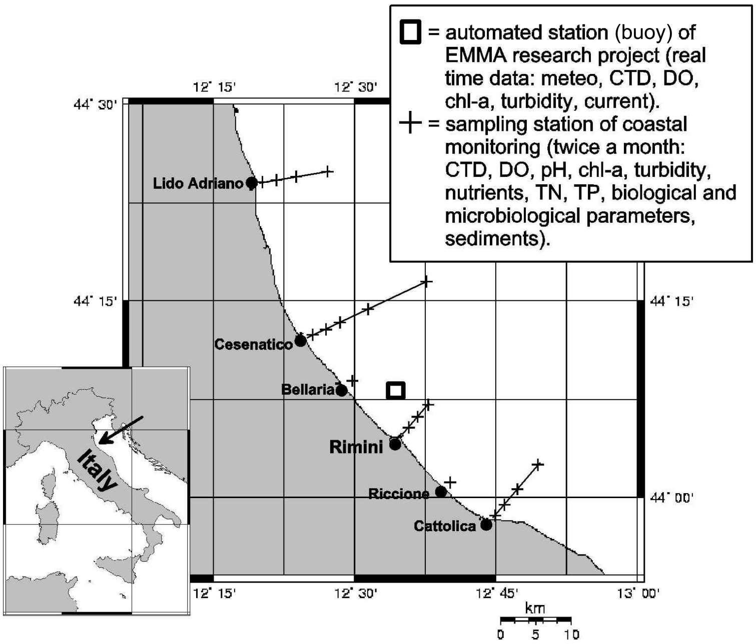

Figure 1: Study area: coastal zone of Rimini Province (NW Adriatic Sea), location of the automated station (buoy) of the EMMA research project and of the sampling stations of the regional environmental monitoring network.

mation on hypoxia events at very local scale. Meteorological data were obtained from the high resolution operational forecasts produced by COSMO-I7 model, operated by the Regional Servizio Idro-Meteorologico (ARPA Emilia-Romagna) in agreement with the Meteorological Office of the Italian Air Force. Flow rates of the Po River (mean daily discharge) and climatologic flow rates for the other local streams located along the coast were also used. Overall, the EMMA system was based on the activities described in the following.

2.3 Water quality investigations and pelagic/demersal resources

The automated station (Figure 2) was implemented for remote acquisition of meteorological data (wind direction and intensity, air temperature, air pressure, humidity, solar radiation) and CTD data (temperature, conductivity, dissolved oxygen, turbidity, Chl-a) at the water surface (0.5 m) and near the bottom (1 m above sea floor). A single-point Doppler Aanderaa DCS-4100 current meter measured current direction and speed in the deeper layer. The buoy was equipped with independent power supply and data transmission systems.

Environmental monitoring by ARPA

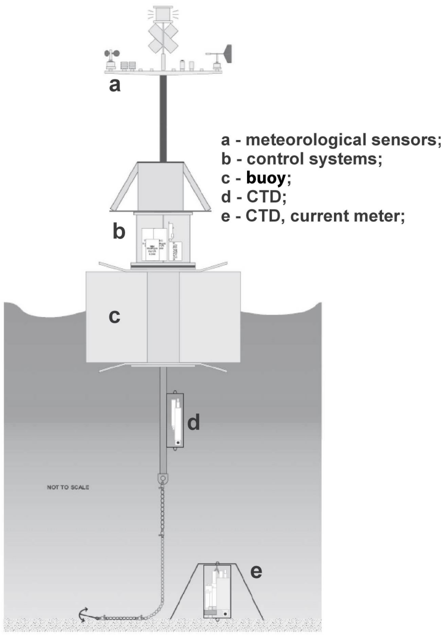

Figure 2: Schematic structure of the automated station of EMMA.

Daphne was periodically performed in the area by sampling 18 fixed stations located along 4 transects twice a month, whereas a higher frequency of sampling should be carried out in case of an early-warning for hypoxia. Profiles of temperature, salinity, dissolved oxygen, pH and chlorophyll-a are acquired by CTD downcasts. Bottle sampling is used for chemical (dissolved inorganic nutrients, ammonia, TN, TP) and biological (phyto and zooplankton) analyses, corer and box-corer for sediment sampling. ROV and photo camera for underwater environmental observation and record. Microbiological monitoring was carried out by collecting water samples north of the port of Rimini, with the aim of studying the microbial community involved in the nitrogen cycle [12], and those species that can be considered harmfull for human health under hypoxic conditions. *Nitrosomonas*, *Nitrobacter* and Total Denitrifying Bacteria (TDB) were determined by the MPN method. Total Heterotrophic Marine Bacteria (THMB), *Vibrio* spp., and *Pseudomonas* spp. were determined as CFU ml^{-1} using spread plate techniques. Presumptive *Vibrio vulnificus* strains were determined as previously reported [13]. Past monitoring, performed by the City of Rimini (2002-2004), has shown the occurrence of local events in canals and inland waters close to the coast. An analysis of physical, chemical and microbiological parameters of these brackish waters and sediments was performed to gain insight into the triggering factors and dynamics of these events. Since unusual catches of fish and demersal species may be the result of stressful conditions in the marine environment due to low oxygen concentration, these data were collected with the co-participation of local fisheries providing regular reports on catches including physical size and species abundances.

2.4 Sea floor characterization

Sea floor and sediment characterization of the area was carried out during a preliminary cruise in September 2005. Sediments were sampled by box coring at 14 stations located along three transects coinciding with the regional water quality monitoring (Cesenatico, Bellaria, Rimini). Sediment sections were photographed and their lithostratigraphy described. Sub-samples for pH, redox potential (Eh) and temperature were immediately measured after collection. Analyses of short-lived radioisotopes (^{210}Pb,^{137} Cs,^{7} Be,^{234} Th), organic carbon, $\delta^{13}C$, C/N ratio of the organic matter and mineralogical characterization were also performed at CNR-ISMAR laboratories.

2.5 Data collection and management

Meteorological forecasts, river discharges, in situ observations and hydrological and chemical data acquired by the automated station and by traditional sampling fed the Local Information Centre (LIC) and are organized on a database server with the utilization described in the following.

2.6 Modelling and processing

A 3-D numerical model, the Regional Ocean Modelling System [5], which includes a biogeochemical module, was used for short-term forecasting and early warning of hypoxia. ROMS model is a primitive equation, finite difference, hydrostatic, free surface model using generalised terrain following s-coordinates and a staggered Arakawa C grid on the horizontal, using a split-explicit, non-homogeneous predictor/corrector time stepping. The biogeochemical module is a relatively simple representation of nutrient cycling processes in the water column and organic matter remineralisation at the water-sediment interface that explicitly accounts for sediment denitrification. It incorporates only one phytoplankton class and one zooplankton class. The minimum set of equations is adapted from the Fasham plankton dynamics model [14]. Data provided by LIC was used for initialization and verification of the model. The model provides hindcasts and forecasts of circulation and dissolved oxygen content of the water in the area of interest every day for the following 3 days (limit imposed by the COSMO-I7 forecast) as daily averaged and 3 hour instantaneus fields. The Decision Supporting System implemented by EMMA assimilates all information and data provided by the forecasting model and by in situ observations. It is designed as a tool to help local authorities in the management of hypoxia crises.

3 Results and Discussion

3.1 Analysis of hypoxic/anoxic events in the coastal zone of Rimini

The coastal waters of the NW Adriatic are generally eutrophic, particularly along the coast of the Emilia Romagna and Marche down to Ancona. Here, high production events and stable meteorological conditions often lead to hypoxia or anoxia in deeper waters, which can extend over hundreds of square kilometres. Usually, the major events break out in proximity of the Po Delta then spreading southward, showing dynamics related to river discharge and water circulation. The analysis of the data provided by ARPA confirmed that wide hypoxia almost never originate in the area between Cesenatico and Cattolica, but are here advected from north. Concentrations of dissolved oxygen less than 3 mg$\cdot$l^{-1} are here considered the limit for hypoxia since critical for marine benthonic organisms, which slow their metabolism below these values, suffer and are in danger of life [2]. In the North Adriatic, massive mortality of benthonic communities starts at values around 0.7 mg$\cdot$l^{-1}, while the mortality of more sensitive and weaker individuals was already observed at values less than 1.4 mg$\cdot$l^{-1}.

Historical data show that the frequency of hypoxia increased since the 1970s, progressively losing its characteristics of being a merely occasional phenomenon, and becoming chronic. Studies on local benthic foraminifera associations in Po delta sediments showed a steadily increase of eutrophication since 1900, with a more frequent occurrence of hypoxia/anoxia during summer since the 1960s [1]. On a local scale, the analysis of data gathered by the regional EPA monitoring showed that oxygen deficiencies occurred quite often in the period 1994-2004. Hypoxia affected waters extending from the beach to 6 km offshore. These events often occur in June - September and in October - November. Other events were reported on a very local scale, within the bathing belt (500 m from the coast) or in the inner brackish canals connected to the sea. They were caused by the degradation of huge algal biomasses, developed thanks to strong runoff and scarce circulation.

3.2 Socio-economic relevance of the region and inventory of anthropogenic loads

From a demographic and socio-economic perspective, the Emilia Romagna Region is important for the European Community as a whole. The population in this region increased markedly up to the 1970s, stabilizing to around 4 millions inhabitants (6.9% of national population). Population density is 180 inhab. km^{-2}, especially high in the plain and along the coast, with peaks of 871 inhab. km^{-2} in Rimini. Industry employs 1.5 million people, and tourism shows a constant increment of visitors (+15% over the decade 1992-2001). Fishing contributed to the regional economy in 2001 with 14,587 t$\cdot$y^{-1} of fish, corresponding to a wholesale value of k€ 34,000, and with amounts ranging from 800 to 1,800 t$\cdot$y^{-1} over the decade 1994-2004, whereas aquaculture ranged from 1,500 to 3,000 t$\cdot$y^{-1} over the same period. From these data, it is clear that anthropogenic load in regional coastal waters is high. If estimated as equivalent inhabitants (eq. inhab. = resident population + tourism + industry), they peak at 6.7 millions in summer, corresponding to a 5.4 millions annual average, whereas sewage disposal plants operating in the area are able to treat loads corresponding to 6.2 millions eq. inhab. [7]. The Rimini Province increased its economic activities and population over the past few decades up to 416,000 eq. inhab., as its coastal area is able to attract 20% of visitors from the whole region. Fishing and aquaculture contribute to local and regional economies in a significant way (1,000 t·y^{-1}, 1,400 t·y^{-1}), while contributions from agriculture and industry cannot be neglected. The anthropogenic load into coastal waters is 1 million eq. inhab. in summer, and may not be completely treated by the available disposal plants corresponding to about 900,000 eq. inhab. The Municipality of Rimini and the regional authorities are aware of this environmental pressure, as it affects economic activities and the quality of life of their inhabitants. For these reasons, the area of Rimini may be considered as a case study exportable to other coastal zones affected by a similar combination of environmental problems.

3.3 Sediment characterization in the coastal zone of Rimini

Sediments play an important role as nutrient sink and/or source in the shallow pelagic environment, if the following four conditions are met:

- high input of fresh organic matter sinking to sea floor without undergoing a complete oxic degradation in the water column;
  - high input of fine inorganic particulate matter;
- scarce influence of (biological?, physical?) mixing processes on the sea floor;
- high sediment accumulation rates both on short and long timescales.

In the coastal area from Cesenatico to Cattolica, local rivers generally affect the onshore zone, whereas low salinity offshore waters are originated by Po River discharges. The circulation pattern determines a general land-to-sea gradient from sandy to silty-clay deposits. However, the present study evidenced a more complex grain size distribution of surface sediments, originated by small morphological irregularities of the sea floor which, in combination with those of the coastline, determine an inhomogeneous distribution of currents and an irregular transport and deposition of surface sediments. All stations showed increasing hydrated and oxidized surface-active layers from the coast to the open sea except for the centre of the study area. This indicated the accumulation of sediments in NE coastal area as probably due to Po River, whereas onshore sporadic transport from SW to NE is due to local rivers. The low content of ^{7}Be($<$17 Bq·kg^{-1}) and the sporadic presence of ^{137}Cs in surface near-shore sediments indicated that hydrodynamic conditions in the area prevent a regular alongshore sedimentation of riverine particulate matter, or that they periodically cause the resuspension of the sediments recently settled. Since the amount and quality of the sedimentary organic matter have a great influence on benthic degradation rates, the abundant presence of fresh highly degradable organic matter in concomitance with high temperatures and low hydrodynamics can lead to the development of hypoxic conditions on the sea floor. On the whole, the sea floor characterization showed that the hydrodynamic circulation in the area follows a complex pattern, which is not only dominated by the West Adriatic Current as previously thought. Locally derived sediments seem to be transported onshore and from South to North, whereas extra-local sediments (from the Po plain and northern Adriatic) offshore 6-10 km are mostly transported in a SE direction. Around 3-6 km from the coast, a clockwise gyre carries part of the offshore sediments toward the studied coastal zone. Moreover, several artificial infrastructures located more or less permanently in this shelf area cause changes in water circulation and sea floor morphology on a very local scale.

3.4 Microbiological monitoring

Hypoxia occurs when production processes and respiration are uncoupled. Under these conditions, monitoring of the "physiological groups" of bacteria involved in the nutrient cycles and of those considered hazardous for human health may be important to understand the quality of coastal waters.

Nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*) and TDB were considered as predictive factors for the development of eutrophic conditions. In fact, nitrifying bacteria oxidize ammonia compounds to nitrite and nitrate, whereas denitrifying bacteria reduce nitrate to nitrite or N_2. Ammonifying bacteria decompose organic nitrogen and produce NH_4+. Since inorganic nitrogen is regarded as the main factor responsible for eutrophication, nitrifying bacteria substantially act as promoters of algal blooms, while denitrifying bacteria act as competitors of algae. Moreover, given that autochthonous bacteria such as *V. vulnificus*, and some *Pseudomonas* spp., are well known to be human pathogens through contact [15], their monitoring was carried out together with THMB. The risks of exposure to waterborne pathogenic and opportunistic microorganisms for swimmers and fishermen include wound infections, otitis, conjunctivitis, sinusitis, gastroenteritis and respiratory diseases.

Two events of hypoxia were observed in the area of interest in September and November 2005. The abundance of *Nitrosomonas* and *Nitrobacter* did not show correlation with these events, whereas TDB showed a considerable increase. This observation suggested that terrestrial inputs of nitrate, which are reduced by denitrifying bacteria, were an important N source for bacterial community with respect to the decomposition of organic compounds. The abundance of THMB and *Vibrio* spp. were strictly correlated, *Vibrio* spp. representing the largest fraction of the total population of marine heterotrophs. During hypoxia events, *Vibrio* spp. and presumptive *V. vulnificus* increase their abundance, given that they are facultative anaerobes, whereas *Pseudomonas* spp., are strictly aerobes and thus not favoured under low oxygen conditions. These data showed that strong nutrient inputs and variable oxygenation of coastal waters affect the abundance and composition of the bacterial community.

3.5 Forecasting model

The forecasting system has to predict hypoxia events their spatial extension and duration. A low resolution ROMS model was implemented on the whole Adriatic Sea at 2 km horizontal resolution. Heat, water and momentum fluxes through the sea surface were computed interactively from the COSMO-I7 3-hourly outputs. In our application, shortwave radiation was taken from COSMO-I7, while the other fluxes were calculated interactively with ROMS using its own sea surface temperature and COSMO-I7 atmospheric data. Forty-eight rivers and springs were included as sources of mass and momentum using available daily discharges (Po, Pescara, Biferno rivers) and monthly climatological values otherwise. Biogeochemical input is defined for every river on the basis of published data. Further details and results are described in [16].

The hydrodynamic model was able to simulate the circulation and the dissolved oxygen dynamics in the North Adriatic Sea with good agreement with data for up to a few days. To reach an optimum resolution in the coastal zone, multiple nesting was afterward implemented. An intermediate model was defined in the Northern Adriatic with 0.5 km horizontal resolution. In the vertical, there are 20 s-levels, which in the shallow western coastal area correspond to a vertical resolution of less than 1 m.

3.6 Decision Supporting System (DSS)

The development of a DSS to manage hypoxia and anoxia crises was one of the most important tasks of the project. It was designed to provide a practical and easy-to-use tool for local authorities and socio-economic partners in order to reduce environmental and socio-economic costs of these events. DSS acquires and integrates a series of indicators derived from scientific community, monitoring activities and past knowledge, outputs of the forecasting models and other additional information in order to evaluate effectiveness and environmental and socio-economic impacts of different intervention strategies. It represents a sort of "manual" to drive public authorities toward a correct management of the coastal zone with regard to dystrophic phenomena.

DSS was planned to approach hypoxia/anoxia phenomena on two different spatial-temporal scales. In the short-term and for local events, it provides practical instructions and guidance to local authorities for the immediate management of the emergency. Over the long-term and in the case of basin-wide extended events, it contributes to the identification of major risks and concurrence of factors that may worsen the evolutionary trend of hypoxic events.

Since the aim of DSS was though as a tool user-friendly for decision makers and local authorities, it was planned to act at three levels:

- a scientific level: to produce and update knowledge for corrective actions of prevention, mitigation and recovery. These actions were evaluated on the basis of a cost/benefit analysis;
- a management level: to choose the best management options among various alternative proposals, on the basis of cost/benefit analyses as well as social acceptability. Such actions could represent a proposal to develop legislative and administrative measures;
- a communication level: to raise awareness through educational and informative actions on best management practices and derived decisions and measures, especially addressed to local and regional policy makers, public authorities and citizens.

3.7 Structure of EMMA monitoring network

The structure of the monitoring/forecasting network of EMMA is shown in Figure 3. Available resources and facilities are integrated into a network specifically designed to manage hypoxia and anoxia. EMMA network has four main components:

1. the Local Information Centre operates as a centre for collection and exchange of data and model results among the different parts of the network;
2. the coastal monitoring system provides the high-resolution environmental data, which are needed to define hypoxia scenarios and to implement the early-warning system. These data are col-

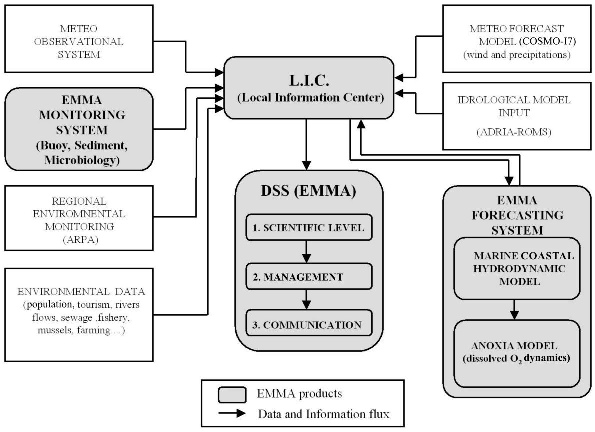

Figure 3: Components of the monitoring network of the EMMA research project (grey) and available environmental data, monitoring activities and model processing used by the project.

lected by means of an automated remote station (buoy) and by traditional monitoring activity in fixed sampling stations;

3. the forecasting model provides hydrological simulations and oxygen budgets in the area of interest with high temporal and spatial resolutions;
4. the Decision Supporting System acts as an interface between the scientific knowledge of the hypoxia phenomenon and the operative needs of local institutions and socio-economic operators.

4 Conclusions

The coastal zone of Rimini was chosen among others to study hypoxia in the coastal marine environment because of several scientific, socio-economic and logistic reasons:

- previous studies and time series of environmental data showed the presence of various and complex mechanisms at the basis of hypoxia phenomenon;
- the Province of Rimini provides an important contribution to the economy of the region based on marine resources;
- the environmental impact of hypoxia on the economy of this area is considerable;
- the integration with existing monitoring activities, meteorological forecasting systems and available facilities may improve the cost effectiveness of the network.

The application of the monitoring network of EMMA is expected to be a "case study", which could be used in other national and European coastal zones with similar characteristics.

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Thermal Fluid Discharges from Submarine Springs at the Formiche di Grosseto Islets (Tyrrhenian Sea, Tuscany, Italy) and their Relation with Regional Anti-Apennine Tectonic Lineaments

G. Fasano[1], G. Gabbani[2], F. Tassi[2], O. Vaselli[2]
1, Institute for Biometeorology, CNR, Sassari, Italy
2, Department of Earth Sciences, University of Firenze, Firenze, Italy
g.fasano@ibimet.cnr.it

Abstract

The Formiche di Grosseto (southern Tuscany, Italy) islets are a reef system of about 1,500 m^2, 9 nautical miles offshore the outfall of the Ombrone river and are constituted by Liassic carbonate rocks of the Tuscan Series (Calcare Massiccio, and are part of the Giannutri-Formiche di Grosseto (GFR) ridge separating Neogene basins of the Tuscan Shelf.
In 2005, during a monitoring survey several thermal springs discharging from the sea bottom close to Formiche islets were noticed. Thermal fluids discharge from several points mainly located along the N-NE scarp bordering the main reef at depths varying from 6 to 32 m. and an outlet temperature of about 41 °C was measured. Accordingly, continental Tuscany is characterized by a large amount of Ca-SO_4 thermal water discharges, such as Bagni Osa and Roselle located inland in the proximity of the Formiche di Grosseto area, whose chemistry is to be related to mixing of fluids from different sources, i.e. hydrothermal and seawater (Bagni Osa) and/or hydrothermal and meteoric (Roselle). For these considerations, the occurrence of CO_2-rich submarine thermal discharges at Formiche di Grosseto may conveniently be related to the regional anti-Apennine tectonic lineaments.

1 Introduction

The Formiche di Grosseto (southern Tuscany, Italy) islets are a reef system of about 1,500 m^2, 9 nautical miles offshore the outfall of the Ombrone river. They are constituted by Liassic carbonate rocks of the Tuscan Series (Calcare Massiccio, [2, 3]) and are part of the Giannutri-Formiche di Grosseto (GFR) ridge separating Neogene basins of the Tuscan Shelf [4].

In 2005, during a monitoring campaign aimed to investigate the effects of polluted sea water on local submarine vegetation several thermal springs discharging from the sea bottom close to the Formiche di Grosseto were noticed . Thermal fluids discharge from several points mainly located along the N-NE scarp bordering the main reef (Figure 1) at depths varying from 6 to 32 m.