BIODIVERSITY SMART MONITORING GUIDED BY HISTORICAL ANALYSIS OF COASTAL EVOLUTION

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Abstract – Environmental monitoring is aimed to measure biological, chemical, and physical parameters that characterize the environmental components. Recently, smart environmental monitoring has gained much attention from the technical and scientific community as it is recognized as a crucial tool for gaining insight into the state of the environment when the protection of biodiversity and ecosystems must be pursued. Indeed, it is one of the best means to understand the dynamics that develop, and any changes induced by anthropic activities upon the various environmental components/factors.

This paper is aimed to describe the architecture of the smart environmental monitoring system to be installed within the frame of the project BEST (Addressing joint Agro and Aqua-Biodiversity pressures Enhancing SuSTainable Rural Development) funded by the INTERREG VA Greece-Italy 2014/2020 Program, as well as the data analysis needed to synthesize the collected data. Particular attention is paid to the criteria behind the scene: the selection of the locations of monitoring stations, as well as the identification of the instrumentation and type of sensors. The use of low-cost sensors while keeping the smart features of the system management (i.e. the minimization of the role of human presence at the sensing stations) is also investigated.

The analysis of the evolutionary dynamics of the coasts, starting from a robust definition of the initial state based on previous studies and new analyses and monitoring activities, has been firstly carried out to characterize the areas and to inform the monitoring strategy. The latter is aimed to get a real picture of biodiversity (i.e. habitats and species) and to relate its spatial and temporal evolution to environmental parameters. Then, measurement of physical parameters (e.g. air temperature, air and soil humidity, atmospheric pressure, wind direction and speed, precipitation, etc) has been foreseen.

Introduction

Biota has exhibited worldwide steep declines in the years, largely due to human activities, and is also expected to change in number and distribution as the impacts of climate change play out in coming years. To meet the global challenges in monitoring and conserving biodiversity, scientists and resource managers must evaluate changes in species composition,

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distribution, abundance, and response to anthropogenic impacts [8]. This has traditionally been performed via standard surveying [5], [6], even if observation remains limited, especially in areas that are physically challenging to access, or when the focus is night-time behaviour [11].

With recent advances in technology, reductions in cost, and increased interest in wildlife images and sounds as an outreach and education tool, the use of remote cameras, microphones and hydrophones has grown exponentially for the past 10–15 year [1], [9]. However, modern remote monitoring stations carry out the automatic recording of audio and video but not the automatic detection of the species, based on the manual study of these recordings. With the current state of the art, the use of machine learning, albeit limitedly widespread, has shown great skill in monitoring biodiversity. Machine learning workflows use a “training set” of data from which the algorithm “learns,” a “validation set” used to determine when the learning has achieved a satisfactory level, and then a “testing set” which is used for the actual evaluation to estimate the algorithm’s typical performance on unseen data [10].

Remote sensing has become increasingly widespread for analyzing the effects of environmental changes on biodiversity, integrating in situ local data on biodiversity with environmental data available globally. However, in situ sensing of biodiversity provides insight into the levels of genes, species, and some ecosystems that remain hidden from remote sensing. It can also generate urgently needed time series of biodiversity observations, complementing remote-sensing time series of measures such as land cover and sea surface temperature that now span several decades [2]. The result is an interaction between the global scale of conservation needs and the localized availability of ecological data [3].

The environmental monitoring to be implemented within the frame of BEST project is intended over the years to be smart (Smart Environmental Monitoring – SEM). Indeed, this approach has been identified as an effective tool to solve both the spatial and temporal resolution of standard methods (i.e. [4], [11]) to be used to identify structural and environmental issues and the best management strategies to conserve as well as to restore biodiversity.

This paper discusses a new community engagement paradigm for the development of low-cost and smart environmental monitoring system and presents the latest developments for the BEST project from a physical and technological perspective. We review and refine the key goals for inexpensive biodiversity monitoring and propose the core hardware and software systems as well as the monitoring strategy informed by the evolutive dynamics of the coasts.

Materials and Methods

Within the frame of the BEST project, a specific analysis of the evolutionary dynamics of the beaches belonging to an Adriatic coastal stretch and the implementation of a smart monitoring system, to be extended to a nearby enclosed basin, are foreseen. The project, as a whole, aims to protect the natural and cultural heritage and restore biodiversity and rural and coastal natural habitats. It involves local stakeholders in cross-border projects and joint pilot actions also through the use of new technologies with low environmental impact, with the final goal of improving the quality of life of the citizens of the regions concerned. The activities concern two main aspects, mutually correlated and analyzed in detail in the following, i.e. (i) monitoring of the areas, and (ii) analysis of the evolutive dynamics of the coasts.

The project has identified a series of pilot areas for the implementation of a monitoring network aimed at the protection and conservation of biodiversity. As part of the activities related to the development of a smart network, the preliminary recognition of existing knowledge aimed at defining the initial "zero point" reference framework plays an "information" role in the monitoring strategy. This activity concerned (i) the analysis of the biodiversity of habitats and species present in the pilot areas, concerning particularly the data available in the European network of NATURA 2000 sites, (ii) the identification of environmental factors, with particular regard to abiotic ones, to be monitored both in the terrestrial and in the aquatic environment, (iii) the definition and mapping of the areas and environments of greatest naturalistic importance in the pilot areas of the project.

The considered coastal areas fall within the Apulia Region, south Italy, respectively (i) the territory of the municipalities of Polignano a Mare, Monopoli, Fasano, and Ostuni on the Adriatic coast (hereinafter referred to as Area 1.1, Fig. 1), (ii) the territory included in the proposed perimeter for the establishment of the "Mar Piccolo" Regional Natural Park, Taranto (hereinafter referred to as Area 1.2, Fig. 1). A further area, where three natural parks are present, affected by the *Xylella fastidiosa* will be monitored.

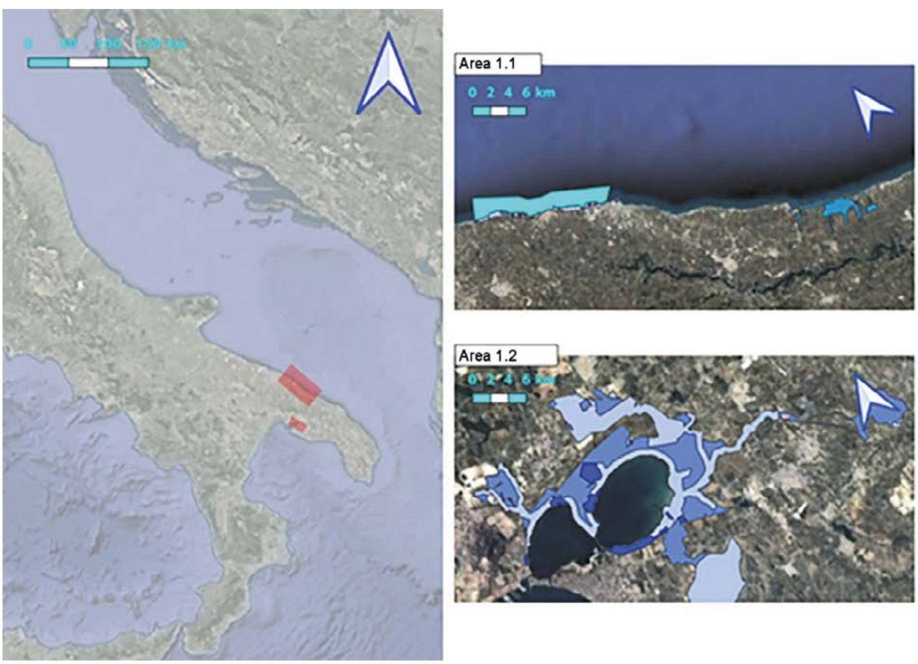

Figure 1 – Localization of the selected Areas 1.1 and 1.2. The shaded zones on the right panels refer to the Regional Parks in the areas.

The territory of Area 1.1 is located on the Adriatic coast of the Puglia Region (Figure 1) and includes (i) the Regional Natural Park called "Coastal Dunes from Torre Canne to Torre S. Leonardo" (hereinafter referred to simply as "Coastal Dunes”), and (ii) the Regional Natural Park called "Costa Ripagnola", located in the municipalities of Polignano a Mare and Monopoli. The coastal stretch extends almost parallel to the NW-SE direction for a length of approximately 35 km, and is mainly rocky, with few sandy beaches, and some pebbly beaches. The rocky coast becomes high in correspondence with the built-up area of the Municipality of Polignano a Mare. Along this stretch, there are evident signs of erosion at the foot of the cliff and some cave collapses have also been recorded, on which a large part of the historic center of Polignano stands. The sandy beaches are affected by erosion due to the strong anthropogenic pressure. There are numerous habitats of community and priority interest, according to NATURA 2000 network. There are also numerous species of community interest and priority established based on the Habitats Directive and the Birds Directive of the EU. Other features of the site concern the landscape, consisting of weak hilly undulations that degrade towards the coast, with a substratum of Cretaceous limestone. The thermo-xerophilic climate favors the presence of vegetation along the slopes. The quality and importance reside in the area of recent coastal dunes, with the presence of Mediterranean scrub vegetation. The pseudo-steppe areas are rich in orchids, including some endemic ones.

The territory of Area 1.2 is located in the Mar Piccolo of Taranto. It consists of a confined water basin subject to fluctuations in the average level and surrounded by a coastline that is substantially fixed over time. There are two regional natural parks in the area, i.e. the "Palude La Vela" Regional Nature Reserve and the "Mar Piccolo" Regional Nature Park. It is observed that Area 1.2 is not characterized by a real evolutionary dynamics of the coasts (substantially lacking a morphodynamic modification of the boundaries of the water basin), therefore the study essentially concerns the analysis of sea levels that can influence biodiversity in the area. Likewise Area 1.1, in this area there are numerous species of community interest and priority, according to NATURA 2000 network, the Habitats Directive and the Birds Directive of the European Union. The site is also characterized by coastal depressions with water stagnation and high halophilia. The substrate is mainly made up of Pleistocene clays and silts. It is also characterized by the presence of coastal humid depressions with halophilous vegetation, by salt flats, and by a watercourse belonging to the group of short but characteristic Ionian rivers.

To complete the monitoring network covered by the BEST project, additional stations have been identified in three natural parks in the territory included in the Area 2. The first park is "Bosco delle Pianelle" Regional Nature Reserve, a protected natural area belonging to the wider Site of Community Interest "Murgia di Sud-Est". The reserve was established to conserve natural biodiversity and promote sustainable economic and fruition activities from an environmental point of view. The second one is "Le Cesine" Nature Reserve has been recognized as a Special Protection Area due to the nesting of various animal species and as a Site of Community Interest thanks to the presence in the area of habitats and animal and plant species listed in the Habitat Directive and the Birds Directive. The area also represents an extraordinary training ground for knowledge and respect for nature. Finally, "Aquatina" Coastal Basin Naturalistic Oasis is a humid coastal area. The basin of brackish water covers an area of 45 ha and extends for 2 km in a rear dune position. Among the plant species, there are shrubs of the Mediterranean scrub, the salt steppe, and various species of spontaneous orchids. Among the animal species, there is an abundant and valuable ichthyofauna.

The implementation of the smart biodiversity monitoring network has been the driving force of the whole study. The network does not require the presence of operators in the field, whilst it requires a remote transmission system of the acquired data, a monitoring system for the proper functioning of the stations for the definition of activities of maintenance, and a security system against vandal attacks. In identifying the configuration of the measuring stations for biodiversity monitoring, an attempt was made to identify the most appropriate strategy to define quality models of the instrumentation that at the same time can comply with the requirement of being low-cost.

Specifically, an attempt was made to frame the problem of quality by referring to solid and established cornerstones, in the context of the experience linked to decades of industrial software development activities. The modern vision has therefore been integrated which favors the culture of service over that of the product, considered more in keeping with the objectives set. The quality characteristics taken as a reference to determine the quality profile of the entire monitoring network are:

- usability, as the ability of the product/service to be understood, used, and appreciated (think of the quality of the data);
- functionality, as the product/service's ability to meet user needs;
- reliability, both as availability in absolute terms of the product/service and as fault tolerance to ensure product availability, through maintenance;
- the temporal efficiency, both in terms of product/service duration, and the ability to respond promptly to requests or response time (for example, the speed of intervention of a maintenance service activated due to an error message sent by a certain acquisition system).

The needed features of the network motivated a careful choice of monitoring stations components, considering different possibilities, compared in particular with maintenance costs. No matter how smart, the network needs management activities that are expressed in "monitoring the monitoring network" and with "ordinary maintenance" (with a frequency of 1-3 months depending on the growing season) and "extraordinary maintenance".

The aforementioned strategy was applied at the level of the individual components, managing to define different configurations of measuring stations (e.g., low cost controller, high cost sensor, medium cost power supply). Thus, an attempt was made to give the entire monitoring network a "fair" cost, which balances the choice of any higher cost components with maintenance costs, without ever interfering with the aforementioned quality parameters. In the next section, the details of the network architecture are detailed.

Results and Discussion

The present work focuses on the preparatory phase of the design of the biodiversity monitoring network. The preliminary results of this first phase are then presented, starting from the formation of a cognitive framework based on previous knowledge of environmental parameters, the definition of sampling stations, areas, and detection points depending on the characteristics of the territory, the presence of any sensitive areas (Natura 2000 sites, wetlands, protected natural areas, etc..). At the same time, the results of the analysis of the evolutionary dynamics of the coasts are shown in the light of the new analyses and new measures, which, together with existing data, aim to inform the monitoring strategy.

To describe the system architecture of the monitoring network, the OSI (Open Systems Interconnection) model was used: the separation of the levels is not sharp, on the contrary, the layers overlap each other to create efficient, light, capable communication protocols, to support advanced energy-saving features and flexible to changes in the network itself.

A simplified scheme of the structure defined for the biodiversity monitoring network consists of the following basic components (Figure 2): (i) a group of spatially distributed sensors for monitoring biotic and abiotic parameters (for a total of 27 measuring points and 75 monitoring stations), (ii) a transmission infrastructure for transmitting data to a server, (iii) a server for collecting data (images, video, audio and data related to environmental parameters), (iv) a collection of computational resources with medium-high performances on the data collection server's end aimed at archiving data, verifying data consistency, managing station malfunctions, data correlation analyses, data elaboration, biodiversity monitoring.

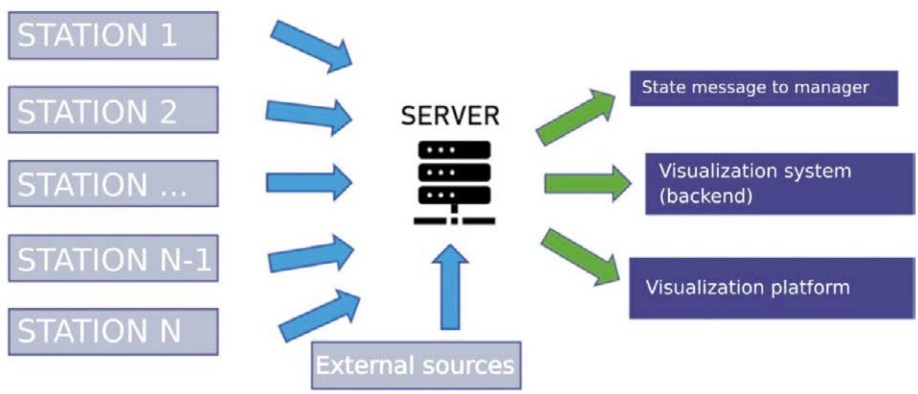

Figure 2 – System architecture of the smart ecosystem monitoring system.

The type of data depends on the type of station, function of the biotic or abiotic parameter under investigation, i.e. birds, mammals, insects, reptiles, flora, weather, water (Table 1).

The main and common characteristics of the planned components of each measuring point are described in Table 2.

The management of each subsystem is foreseen to allow the following minimal functions:

- integration of data flux management for data ingestion, addition, and configuration of new data source and related services;
- functionality and integrity control for the geospatial server through the resource and usage log;
- management of users and their access rights to services and resources;
- monitoring the proper functioning of the monitoring network and management of maintenance interventions.

Table 1 – Type of data associated with the type of station.

Type of station	Type of data
Birds monitoring	Images Audio track
Mammals monitoring	Images Audio track
Insects/reptiles monitoring	Images Numerical values
Flora	Images Numerical values
Weather	Numerical values
Underwater monitoring	Images
Underwater monitoring with water parameters measurement	Images Numerical values
Underwater monitoring with water parameters measurement and hydrophone	Images Numerical values Audio track

Table 2 – Characteristics of components for each measuring point.

Component	Characteristics
Power supply	photovoltaic panel with buffer battery, connection cable, solar charge controller, mounting brackets, installation box, assembly.
Data transmission	the measurement management system of one of the stations installed in the measurement point will act as an access point for all the others (installed in the same measurement point) consisting of an integrated circuit system, case with heat sink, gsm-gprs module, power supply for fans, sim subscription (flat rate, 2 years), assembly.
Installation	labor, equipment, any support structure compatible with the environment and with the relative constraints of the installation point (the structure must ensure the installation of the instruments up to a maximum height of 7.0 m, base and thickness adequate to support all the instruments anchored to it), possible foundation construction of the support structure.

For the analysis of biodiversity over time, which can be carried out as the final result of the monitoring through the network subject of this project, the algorithms must be reliable. Therefore, an experimental period is required during which the results obtained by the virtual operator (the algorithms) will be compared with those obtained by specialized operators.

To achieve this goal, monitoring protocol must be set up. It must be noted that pre-existing literature and legislation regarding biodiversity monitoring generally refer to in situ measurement techniques. The monitoring network discussed herein is smart, i.e. it will allow automated acquisition and cataloging of data which will then be further elaborated for providing useful information, comparable to what current legislation requires. In short, automated elaboration can be interpreted as the monitoring performed by a virtual operator.

Smart samplings through cameras/microphones/hydrophones are foreseen. All animals and vegetal species will be sampled through cameras (as will be sampled all animal species recognized through the use of microphones/hydrophones), taking special care of animals and vegetal species listed in the annexes to the Habitat Directive (Directive n.92/43/CEE) and the Birds Directive (Directive 79/409/CEE), especially noting non indigenous/alien invasive animal and vegetal species recognized by EASIN (European Alien Species Information Network).

As far as the environmental parameters are concerned, the temporal evolution of the monitored parameters will be crucial for the analysis of correlation with the results of the monitoring of biodiversity.

For the sampling of animal species (birds, mammals, reptiles, insects), algorithms will be implemented in order to identify, among all recorded video and audio on the server, samples that actually document the presence of animal species and a machine learning approach will be used to make the challenging attempt to define the type of animals so that they can be categorized. During the experimental phase for the system, results of unsupervised analysis of acquired data (obtained through algorithms) will be compared to those obtained in a standard way (through specialized biologists) with the goal of validating/improving/train the implemented algorithms.

For the sampling of vegetal species, long-term analysis of video footage is more effective to assess the variation of the specific composition (qualitative analysis) and variations in the extension of formations (quantitative analysis by employing well established parametric analysis, e.g. visible normalized difference vegetation index, vNDVI).

For the sampling of environmental, land and water parameters, temporal analysis will be useful for highlighting evolutionary trends and possibly relate criticality conditions for other analyzed biotic parameters.

All data can be compared to qualitative and quantitative indicators, which will allow to determine the presence of possible critical issues related to biodiversity conservation and, above all, the their temporal evolution. The system will thus represent a powerful tool aimed to support decision-makers.

The analysis of littoral dynamic evolution is aimed to inform the monitoring strategy of the areas by guiding their observation strategy.

First, a wind climate study has been carried out. The data from ERA5 database, recently developed by ECMWF (European Center for Medium-range Weather Forecast), have been used. In particular, 71 years (1950-2021) of observations have been considered, concerning the point located at: 41.00°N, 17.50 °E. According to the wind analysis, the wind rose reveals the existence of a prevailing wind sector (i.e. Mistral, NW – 345°N) from which the most intense and frequent events originate and a secondary wind sector related to Levant-Sirocco winds (i.e. ESE, 100-135°N). The wind data have been then analyzed considering the wind speeds following a Generalized Pareto Distribution (i.e. GPD). For the prevailing wind direction, the wind speed ranges between 13.9 m/s (return period TR = 2 year) and 25.6 m/s (TR = 200 years).

Then, a wave climate study has been performed. At first, a calibration with the wave data coming from the wave buoy installed in Monopoli and belonging to the National Wave Buoy Network has been carried out. The wave rose confirms the presence of a prevailing sector (N-NW) and a secondary sector (ESE). An extreme value analysis has been then performed. In this context, for the prevailing wave direction, the significant wave height ranges between 2.9 m (TR = 2 year) and 6.9 m (TR = 200 years). For the secondary direction, the significant wave height ranges between 2.1 m (TR = 1 year) and 5.0 m (TR = 200 years).

Lastly, a tidal analysis has been performed based on the tidal gauges installed in Bari (at the Ferry Port, Pier 12) and Taranto (at the S. Eligio Pier of the Taranto Port) for the time range from 01/01/1999 up to 12/31/2020 (sampling time equal to 1h). According to the superposition principle, the meteorological component of the level (i.e. storm surge, [7]) has been estimated as the simple difference between the observed levels and the (estimated) astronomical component. The extreme value analysis of the meteorological component has been then carried out. The achieved results show how the storm surge ranges from 0.52 cm up to 0.65 cm for Bari and from 0.50 cm up to 0.58 cm for Taranto, for a return period TR = 100 years, depending on the selected probability distribution function (i.e. GPD or GEV).

The littoral characterization also included the assessment of the shoreline evolution [2]. Within this context, the 2018 shoreline position has been compared to the shoreline location collected during a recent survey (2022). The stretch of the analyzed coastline (see Figure 3) is between the municipalities of Torre Canne (Fasano, BR) and Rosa Marina (Ostuni, BR). The results inspection revealed that 59 % (3.2 km) of the littoral is in retreat, the 18 % (1 km) is stable and the remaining 23 % (1.3 km) is in advancement. The sediment balance is negative with a medium annual loss equal to 10000 m^3/year. According to the dominant wave direction, the sediment transport is directed toward S-E.

Figure 3 – Recent littoral evolution trend. Comparison between shorelines of 2018-2022.

Concluding remarks

This paper aims to describe the design of a low-cost monitoring system for abiotic and biotic parameters that collect data remotely in near real-time with the final aim to assess the temporal and spatial evolution of biodiversity in coastal areas located in South Italy. The strategy of monitoring and the architecture of the network has been defined also based on the results of in-depth hydrodynamics and morphodynamics analyses of the coastal stretches to be monitored. These analyses are intended to "inform" the monitoring strategy. The data, along with their analysis and synthesis, are intended to support decision-makers. Indeed, smart environmental monitoring has gained much attention from the technical and scientific community as it is recognized as a crucial tool for gaining insight into the state of the environment when the protection of biodiversity and ecosystems must be pursued.

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