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A TECHNICAL SOLUTION TO ASSESS MULTIPLE DATA COLLECTION ON BEACH DUNES: THE PILOT SITE OF MIGLIARINO SAN ROSSORE REGIONAL PARK (TUSCANY, ITALY)

Abstract - *A technical solution to assess multiple data collection on beach dunes: the pilot site of Migliarino San Rossore Regional Park (Tuscany, Italy).* Coastal dunes are a complex environment characterized by several biotic and abiotic factors that concur to their evolution and development. A whole comprehension of the interplay between those factors is paramount to a wider definition of dune systems: in some cases focusing on a factor at once is not suffice to get satisfying insights. Here is proposed an integrated solution involving different disciplines in order to collect in-depth datasets within a short span of time on a selected site located in the Migliarino – San Rossore – Massaciuccoli Regional Park (Tuscany, Italy). Geological (geomorphology, sedimentology, and geophysics) and biological aspects of the coastal dunes will be assessed using traditional survey analyses and integrated with state-of-the-art technologies (UAV flights, wireless sensors) to get an all-around characterization of the ecosystem. A Wireless Sensor Network will be set up on the selected site to measure in real-time physical parameters such as wind speed and direction, soil moisture and sand dune volume and height variations. The ensuing data will be stored to create a database that might be used for management purposes. The aim of the paper is to provide a modern, inexpensive, and easy to reproduce system to monitor the evolution of any coastal dune field.

Keywords - beach dune; grain size; geomorphology; vegetation; GPR; aerophotogrammetry; wireless sensor, Tuscany, Italy.

Riassunto - *Una soluzione metodologica per acquisire un dataset multiplo sulle dune costiere: il sito pilota del Parco Migliarino - San Rossore (Toscana, Italia).* Le dune costiere sono un ambiente complesso caratterizzato da diversi fattori biotici e abiotici che determinano la loro evoluzione e sviluppo. La comprensione dell'interazione tra questi fattori è fondamentale per una caratterizzazione più profonda dei sistemi dunali. Approcci eccessivamente puntuali, seppur molto dettagliati, non sono sempre sufficienti a garantire un quadro conoscitivo adeguato ad una corretta gestione. È qui proposta una soluzione integrata che coinvolgendo diverse discipline permette di acquisire più dataset complementari, in modo economico e facili da essere riprodotti per il monitoraggio di qualsiasi sistema costiero dunale.
Il sito pilota scelto per testare questo nuovo approccio è situato nel Parco Regionale Migliarino - San Rossore - Massaciuccoli (Toscana, Italia). Gli aspetti geologici (geomorfologia, sedimentologia e geofisica) e biologici (copertura vegetale) delle dune costiere sono stati affrontati attraverso metodologie tradizionali di terreno integrate con approcci tecnologici specifici (voli UAV) o innovativi (rete sensori wireless). La misura dei parametri fisici, come velocità e direzione del vento, umidità del terreno, variazioni del volume di sabbia delle altezze delle dune è stata misurata in tempo reale tramite una rete di sensori wireless. I dati memorizzati da remoto sono implementati in un database utile anche a fini di gestione e monitoraggio dell'area di studio.

Parole chiave - dune costiere; granulometria; geomorfologia; vegetazione; GPR; aerofotogrammetria; sensori wireless; Toscana.

1. Introduction

Coastal dune systems are arguably one of the most dynamic environments because their evolution is controlled by many factors, either natural (river sedimentary supply, wave motion, longshore currents, wind action, type and density of vegetation cover) and anthropogenic (proliferation of protection structures, anthropization of backdune areas, poor management). The interaction between all these aspects makes coastal dunes vulnerable to any minimal change, which easily leads to alterations of such an instable equilibrium (Hesp, 2002). The variations often have a negative impact on the environment, ultimately triggering erosion processes that constitute a major threat to the development of coastal dunes (Masselink & Hughes, 2003). Since this ecosystem has a high value in terms of biodiversity (several habitats are included in the European Habitats Directive 92/43/EEC; European Commission, 1992) and economy (dunes serve as a form of natural protection also where human activities are present inland; Masselink & Hughes, 2003), the need to preserve each aspect is usually considered as one of the most important element when dealing with coastal zone management (Martinez *et al.*, 2013): as a matter of fact, 85% of protected areas in Europe are currently endangered (Muñoz Valles *et al.*, 2011), while according to recent estimates dune fields recorded a reduction of about 70% during the last century (McLachlan & Brown, 2006).
In this regard, an exhaustive understanding of the pro-

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cesses that concur to steer coastal dune evolution is paramount to better define the environment. Therefore, coastal dunes have been extensively studied in the last decades using a large variety of analyses and approaches. Traditional investigations such as grain-size analysis (e.g. Hesp *et al.*, 2007; Bertoni & Sarti, 2011; Ruocco *et al.*, 2014) and topographic surveys (e.g. Hesp, 2002; Armaroli *et al.*, 2013; Bertoni *et al.*, 2014) have been widely applied to characterize dune sedimentology and geomorphology. These conventional analyses have been recently backed by modern techniques characterized by high level of technology, such as video-monitoring (Delgado-Fernandez *et al.*, 2009), laser scanning (Nield *et al.*, 2011), and spectroscopy (Ciampalini *et al.*, 2015). Sediment transport on coastal dunes has been addressed using sediment traps (e.g. Jackson & Nordstrom, 2013), miniphones (Ellis *et al.*, 2009) and laser techniques (Bauer *et al.*, 2012; Davidson-Arnott *et al.*, 2012). Geophysical approaches has also been used to inspect the subsoil of dune systems (e.g. Jol *et al.*, 1996; Bakker *et al.*, 2012), in particular by means of ground penetrating radar (GPR) instruments (Bristow *et al.*, 2000; Jol *et al.*, 2002; Buynevich *et al.*, 2007). In addition, the evolution of beach dunes has been modeled in order to reproduce their development: XBeach is the process-based model most frequently used to predict erosion or accretion tendencies (Roelvink *et al.*, 2009; Splinter & Palmsten, 2012; Armaroli *et al.*, 2013). Since the vegetation is among the major factors driving the evolution of coastal dunes by trapping and stabilizing sand grains, a lot of works have been done to assess aspects on that regard (e.g. Martinez & Psuty, 2004; Maun, 2009; Ciccarelli *et al.*, 2012; Bitton & Hesp, 2013; Ciccarelli, 2014). Aerial photography is a reliable technique to investigate the evolution of beach dune morphology (Bini *et al.*, 2008), but it has also been used as a valuable tool to carry out vegetation assessment in remote, at least to recognize plant communities (Drius *et al.*, 2013; Malavasi *et al.*, 2013).

Most recent studies emphasized the notion that an all-round definition of this environment needs an approach that systematically involves several disciplines, merging every data collected from any individual analyses (Bertoni *et al.*, 2014; Ruocco *et al.*, 2014). Investigations addressing a physical or biological factor at once still are essential, but increasing the knowledge about how they interact is the basis for a better management of coastal dune systems. The best way to achieve this target is to collect as many data obtained from different disciplines as possible in the shortest span of time in order to minimize the negative effects of comparing datasets that are not simultaneous. Therefore, a new multidisciplinary approach to study coastal dunes has been conceived in order to integrate geology, biology, and modern wireless technologies. This method combines traditional analyses (topography, sedimentology, plant ecology) with state of the art survey techniques (unmanned aerial vehicles, ground-penetrating radar): the Wireless Sensor Network enables to gather discrete amounts of data at the same time by remote, without the need to directly go to the beach except for routine activities such as retrieving the stored data. Meanwhile topographic and geophysical surveys, along with vegetation sampling, can be carried out without affecting data collection of the remote network. Considering its activation and maintenance low cost and the ease to replicate elsewhere, this system might become a valid instrument to improve the understanding about coastal dunes, in particular the interactions between biotic and abiotic factors, which are instrumental for a successful evolution of this environment. It might also provide insights to optimize their management, which is imperative since several issues stem from lack of knowledge and awareness.

2. The multidisciplinary solution

The approach to the study of coastal dune systems here presented is based on the notion that a better definition of a multifaceted environment such as beach dunes is achieved by the integration of datasets provided by different analyses and collected within short spans of time. Such an accomplishment can be reached coupling the traditional surveys that need fieldwork activities (grain-size analysis, topographic and ground penetrating radar surveys) and the conventional remote sensing analyses to the implementation of a network of wireless sensors able to measure other physical parameters (dune height and volume variations, soil moisture, wind speed and direction) that would require frequent and time-consuming field operations. Systems involving remote sensing techniques applied to dune characterization have been already conceived. These solutions proved to be able to collect a wide range of different parameters, mainly dealing with sediment transport, wind speed and surface moisture detection. While these solutions are ideal for short-term monitoring (Delgado-Fernandez *et al.*, 2012), the system here presented could be much more useful in case of long term monitoring. The solution proposed by Delgado-Fernandez *et al.* (2012) is mainly based on the use of cameras: in this case no remote data collection is available. Moreover, being the data acquisition structure unique, its malfunctioning totally invalidates the data collection. The solution proposed in this paper allows the direct transfer of the data collected by the sensors through the use of a GPRS gateway: this means that datasets are received in real-time in laboratory, without the need to reach the sensors to collect them. At the same time this feature allows the real time detection of a possible sensor node malfunctioning when data transfer is interrupted. Furthermore, the proposed solution relies on the use of sensors: data are directly collected and made available, and not obtained as a result of image processing techniques. This means that data collection is straightforward and then notably easier. At last, the solution is totally modular: the addiction of new sensors and sensor nodes can be made without modifying the overall architecture of the system.

2.1. Topography

Topographic surveys will be carried out within the site that will be chosen for the implementation of the Wireless Sensor Network. Transects orthogonal to the coastline will be traced out on the beach, and every significant change in slope will be recorded with a DGPS-RTK instrument. The accuracy of the equipment is about 2 cm on regards to latitude and longitude, increasing to 5 cm on regards to the elevation. The surveys will be repeated after any relevant storm to monitor modifications on the beach profile. The spacing of the transects is strictly dependent on the width of the area where the Wireless Sensor Network will be set up: in this case the profiles will be traced out every 50 m. The topographic surveys will involve the backshore and the foreshore: in particular, the landward limit of the surveyed area is represented by the first steady dune ridge, whereas the seaward limit corresponds to the beach step crest. The resulting data will be processed with GIS-based software.

2.2. Grain-size analysis

A traditional sediment sampling will be completed to characterize the textural parameters of the sediments that constitute the beach where the Wireless Sensor Network will be realized. Samples will be collected from specific points along the transects traced out for the topographic surveys. These points will be selected taking into account the shape of the topographic profile and the plant communities, according to the protocol previously used by Ruocco et al. (2014): each relevant geomorphologic element will be sampled (step zone, swash zone, backshore, foredune front toe, foredune crest, foredune back toe, semi-mobile dune) along with the most significant vegetation features (annual vegetation of drift lines, embryonic shifting dune vegetation, vegetation of the shifting dunes, and vegetation of the fixed beach dunes). The samples, about 500 g each, will be heated to 100°C for 24 hours before being dry-sieved mechanically for 10 minutes. The sieves used for the analysis has a 0.5 phi mesh: the last sieve will be the 0.063 mm to discriminate the fine fraction from the sand. Further definition of the fine fraction is not functional to the sedimentological characterization of the beach sediments. The resulting data will be processed to obtain textural parameters such as Mean (Mz) and Sorting (σ) according to Folk & Ward (1957) formulae.

2.3. Aerophotogrammetry

The recent introduction of Unmanned Aerial Vehicles (UAV) greatly improved the traditional techniques of multi-temporal and high-resolution mapping of landforms (e.g. Bisson & Bini, 2012). Aerophotogrammetric surveys using a helicopter drone flying at 40 m of elevation above the surface will be implemented to analyze the topography of coastal dunes. Several ground control points (GCP) will be arranged on the beach and recorded with the RTK-DGPS instrument to enable the comparison of the results with those provided by the topographic surveys carried out by means of the RTK-DGPS instrument in order to prevent errors due to wrong calibration of the system mounted on the UAV. Nadir images will be collected by a Sony NEX5 camera (focal 16 mm) and eventually processed to obtain 3D visions and orthophotomaps.

2.4. Subsurface stratigraphy

Ground-Penetrating Radar (GPR) is a fast and cost-effective electromagnetic (EM) method providing relevant information on the shallow subsurface stratigraphy. Aeolian dunes are frequently prospected using GPR because of the low conductivity of sandy sediments and high EM velocity, which limits the attenuation effects of GPR signals and increases the investigation depth. A GPR survey will be carried out on the pilot site using a Radar System device of IDS Company© (www.ids-spa.it), equipped with an antenna of 400 MHz of nominal peak frequency. The data will be captured in continuous mode, checking the step size by means of an odometer wheel. Topographic data will be acquired along the GPR survey line. After the fieldwork, a standard processing sequence will be applied to the raw data to filter out the noisy data, to gain attenuated GPR signals and to convert the time-to-depth data. Given the expected rapidly variable shape of the dune layering, an accurate sampling of EM signal returned to the receiver should be adopted to avoid the occurrence of spatial aliasing effects. Particular care will be paid to avoid to filter out sub-horizontal reflectors by the use of spatial median filter operators. The EM scattering by discrete object in the subsurface will allow to estimate EM velocity using the method of synthetic hyperbola fitting. The existence of shallow trenches in the dune profile with identifiable scattering points will consent a calibration of the velocity model. A static topographic correction is necessary at the end of the process to adapt the radar image to the dune profile. This last point needs particular care because, due to the stoss and lee topography of dunes, an additional correction for the tilting effect of the antenna will be required. Fences of vertical radargrams and 3D cubes of GPR data will be used to interpret the subsurface stratigraphic bedding.

2.5. Vegetation sampling

Coastal dune vegetation assessment will be carried out by the analysis of digital images collected by a helicopter drone (UAV), and validated as a confirmation by field campaigns during the spring and the autumn. The study site will be divided into sectors of an appropriate width. Each sector will be divided into three layers from the coastline to inland: upper beach with pioneer annual vegetation (BPV); herbaceous dune vegetation (HDV), which includes embryonic and mobile dunes; shrub and woody dune vegetation of fixed dunes (WDV). Distribution and coverage of the different plant communities will be detected in each sector.

2.6. Wireless Sensor Network

Wireless Sensor Networks (WSN) are becoming a key technology for low cost pervasive monitoring solutions (Mainwaring *et al.*, 2002; Werner-Allen *et al.*, 2006; Ramesh *et al.*, 2009; Grindvoll *et al.*, 2012). The term WSN encompasses all the monitoring systems composed by a set of autonomous sensing nodes provided with Short Range communication capabilities (Akyildiz *et al.*, 2002): WSN can be then composed by tens or even hundreds or thousands of nodes, they can be structured according to different network topologies and communication protocols and they can be employed virtually in a infinite array of different scenarios. Each sensor node is usually composed by at least the following items: *i*) a microprocessor managing data acquisition and transmission; *ii*) a communication module; *iii*) a set of sensors; *iv*) a battery or any other source of energy. A sensor node can be developed basing a simple microcontroller provided with low level data acquisition functions but also with more complex devices with data analysis and storage capabilities. At the same time it can be equipped with a single sensor monitoring ordinary parameters like temperature or humidity or it can be provided with a wide array of sensors monitoring complex parameters like for example water or air quality. It can be powered with common 9V batteries or even with photocells or other green power sources.
One of the key features of every WSN is the networking technology: the choice of the right communication protocols notably affects the performances of the monitoring system, both in terms of power consumptions and of reliability. In the last ten years several standard protocols have been proposed for WSNs: the most important are the IEEE 802.15.4 standard, specifying the physical layer and media access control for low-rate wireless personal area networks (LR-WPANs) and the ZigBee standard, a set of high level communication protocols for low-power wireless mesh networking. ZigBee standard has been thought for the definition of low cost, general purpose networks to be employed in several monitoring scenarios: ZigBee communication platforms are small, cheap and they can be easily integrated with microcontrollers and sensing devices. The most significant network typology proposed in the ZigBee standard is based on a multi-hop mesh network: it is a decentralized architecture where each node can act either as a receiver, a transmitter or a repeater (Fig. 1). Every node is able to transmit only to its neighbours: when a data packet has to be sent to a node that is too far to be reached in a single hop, the intermediate nodes act as repeaters. Such a kind

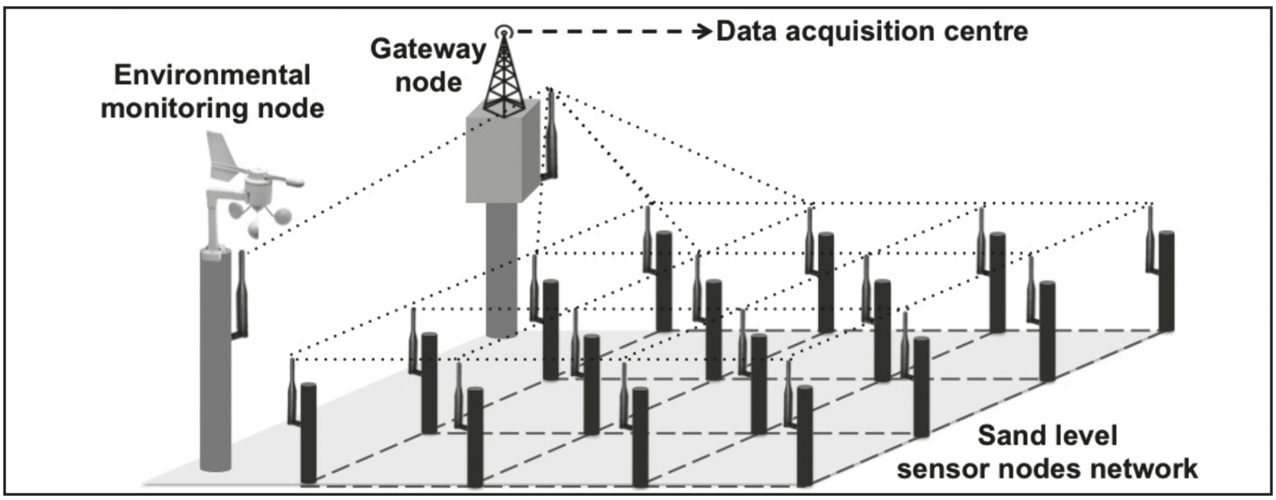

Fig. 1 - Architectural overview of the wireless sensor network.

of network is then able to cover long distances and it is extremely reliable in that the malfunctioning of a single node does not compromise the efficiency of the whole network.

The dynamics of sand dunes can be analysed in real-time by deploying an ad-hoc WSN based on a mesh topology and implementing the ZigBee protocol: this monitoring solution will be able to measure the variations of the sand dune height in several points and to collect data about wind speed, air and soil temperature and humidity. The proposed architecture integrates the following components: *i*) a set (15-20) of sensor nodes for the measurement of ground elevation; *ii*) a sensor node for the measurement of the other environmental parameters (wind speed and direction, soil moisture); *iii*) a gateway node for the remote data transmission.

The sand level sensor nodes are very simple devices, including only a sensor, a radio transmitter and a powering circuit. Two different solutions have been studied for the sensor designed for the measurement of the dune height. The first solution is based on the use of a Sharp GP2Y0A21YK0F analog distance sensor: this sensor is able to measure the distance of an object or a surface in the range of 10-80 cm. The return time of the infrared light is converted into a voltage and then interpreted as a distance measure. For the measurement of the dune height the sensor node will be tied to a wooden structure, with the surface where the sensor is positioned facing the dune surface: the sensor will then be able to measure its distance from the ground. The second solution is based on the use of a set of photoresistors. In these devices the resistance decreases with increasing incident light intensity: the value of this parameter allows to measure the light radiation. In the proposed solution a set of photoresistors (20) is positioned on a 1 cm wide and 1.5 m long plastic rod: the photoresistors are spaced 5 cm. This plastic rod is put inside a transparent rubber tube, and tied to a wooden pole that is stuck into the ground. The rubber tube is partially under and partially outside the dune surface. The buried photoresistors will not detect the presence of any source of light: instead, the number of photoresistors detecting the presence of light will give a measure of the length of the portion of the rod that is not buried, providing in turn a measure of the dune height. Both these solutions are able to provide an efficient measure of the variations in the dune height: while the first solution is easier to be developed in terms of sensor realization, the second one is notably easier to be deployed, with a lower impact in terms of equipment to be installed on site. The second solution will be chosen for the experimentation due to low environmental impact requirements (Fig. 1): however, the first solution has also been described in that it can be useful in other scenarios where wooden structures for the sensor node installation already exist on site.

The dune height sensor will be then integrated in hardware platform including an XBee radio transmitter based on the ZigBee protocol and a power management circuit, required to control the power consumption, allowing thus to extend as much as possible the lifetime of the battery used to power the node.

The node intended for the environmental parameters monitoring is a more complex platform based on an Arduino Uno board: this platform integrates an ATmega328 microcontroller, it provides 6 analog input pins and 14 digital input/output pins and it can be equipped with an XBee radio transmitter. Three sensors will be connected to the node: *i*) a soil moisture/temperature sensor; *ii*) an anemometer for the wind speed measurement; *iii*) an air humidity/temperature sensor. The Arduino board will allow not only the data collection, but also their analysis and encapsulation in a single data packet to be transmitted to the gateway. The data collected by the sensor network will be acquired and transmitted to a remote data acquisition centre by a Gateway node, also based on an Arduino Uno board: this device will be equipped both with an XBee transmitter acting as the Coordinator for the ZigBee network, and a GPRS transmitter that will be in charge of transmitting the received data to a remote data collection centre.

The array of sensor nodes will be positioned according to a grid subdivision of the chosen site, which will depend on the characteristics of the dunes. This will allow the acquisition of the real-time data concerning the elevation of the single points of the dune, in order to depict the dynamic variation of the elevation of the whole surface along a span of time up to three months, in agreement with the battery lifetime.

3. Pilot site

This multidisciplinary approach has been implemented on a pilot site within the Migliarino – San Rossore – Massaciuccoli Regional Park (herein referred to as San Rossore Park). This site was chosen because of a variety of physical features that made it an appropriate place to test the system. The San Rossore Park is located along the Ligurian Sea, in the northern part of Tuscany, Italy (Fig. 2), in an area characterized by sectors subjected to erosion and accretion processes (Pranzini, 2001; Bini *et al.*, 2008). This aspect is crucial because the system can monitor the evolution of both sectors, gathering information about the behavior of eroding and accreting beaches. Dunes are well established where erosion processes do not affect the coast, reaching a maximum height of about 7 m on the crest (Bertoni *et al.*, 2014). Elsewhere they are generally lower, at times almost completely eroded. On the back of the frontal dunes there is an area of variable width (about 30 to 100 m) characterized by semi-mobile dunes, backed by several ancient dune ridges referred to as steady dunes (Bertoni and Sarti, 2011).

Fig. 2 - Map of the site where the Wireless Sensor Networks have been set up: the red dots point out the area where the sensors have been deployed (the background satellite image has been taken from the Google Earth database, 2014).

The Wireless Sensor Network has been installed north of the mouth of River Arno (Fig. 2), the most important source of sediment of the area (Cipriani *et al*., 2001), where the littoral drift is univocally northward-trending (Gandolfi & Paganelli, 1975). The beach is prevalently composed of medium sand, the mean diameter of the sediments that constitute the backshore is about 0.3 mm (Bertoni & Sarti, 2011). Wave climate on this sector of the Ligurian Sea is characterized by dominant southwesterly wave direction, with wave heights usually about 1 m (Fig. 3); most powerful storms come from the southwest as well (Bertoni *et al*., 2013). Being a natural reserve, the whole area is not subjected to any anthropogenic activity, which is essential to get undisturbed data.

The study site is characterized by the prevalence of shifting dunes with *Ammophila arenaria* and plant communities of fixed beach dunes; while annual vegetation of sand beach and plant communities of embryonic shifting dunes are less present, because coastal erosion has cancelled in several sites the first vegetation towards the sea (Ciccarelli *et al*., 2012).

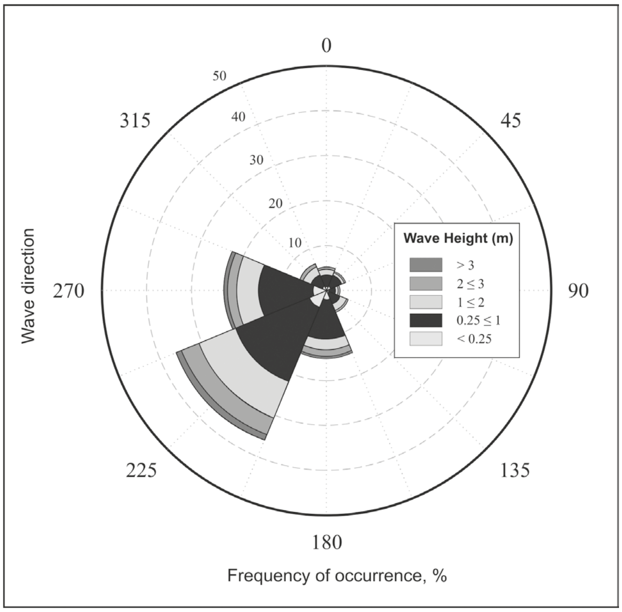

Fig. 3 - Historical wave climate (height and direction) of northern Tuscany coast collected during the years 1989-2007 by the ISPRA buoy located offshore La Spezia.

4. Future perspectives

The solution here presented represents a significant change in the way costal dune systems are studied. This all-around approach provides datasets as full as any, embracing different disciplines that are all instrumental to improve the understanding of this environment. Geologic and biologic data are linked together (Bertoni *et al*., 2014; Ruocco *et al*., 2014) and as such they cannot be analyzed separately: the Wireless Sensor Network enables to measure considerable amount of parameters with minimal in situ human effort, thus allowing the chance to collect data about sediment grain-size, topography, and subsurface stratigraphy simultaneously. Besides, UAV flights provide for a high-definition photographic coverage of the site, which makes possible to identify the vegetation up to the species remotely: this level of accuracy could not be reached with techniques such as traditional aerial coverage or even LiDAR surveys. Any measurement and analysis result will be stored: such a database is unique and it will be useful to set up a fitter management of the dune system. In particular, the outcomes this approach yields will be valuable to improve the efficiency of protection schemes involving artificial dune reconstruction, which is frequently used *i*) where erosion processes already struck the coast, in order to prevent further retreat, and *ii*) to prevent the onset of the erosion processes where they have not hit the coast yet.

A significant advantage of this solution is constituted by the fact it is not tied to a specific site with peculiar characteristics: it can be implemented elsewhere and properly customized to fit in the place where it is installed to maximize the results. Since the sensors are relatively inexpensive, the wireless network system can be set up also on large dune fields, not only on narrow beaches characterized by a small dune ridge. Hence, the approach here proposed will be soon realized on a second site, totally different relative to the MSM Park: the Acarai State Park (southern Brazil). Acarai State Park beaches are characterized by frontal dunes about 5-10 m high, backed by parabolic dunes, which can reach a crest height of about 20 m, or by irregularly shaped dunes, followed by ridge alignments classified as fixed dunes (Possamai *et al*., 2010). Blowouts punctuate non-vegetated areas, whereas they are almost completely vegetated. This will be paramount to test the efficiency of the system on a different setting, and to check the consistency of the collected data. In addition, the results from both sites regarding geologic, biologic and physical parameters will be compared and integrated in order to conceive an index of coastal dune vulnerability that can be applied to any dune field and not only on a given setting. On that regard, the integration of such different datasets will require severe attention in order to avoid inconsistency of the results the system might produce. Therefore, the collected data will be processed through Canonical Correspondence Analysis (CCA) to find correlations between every physical parameter that will be measured and plant community coverage (Ter Braak, 1986; Ter Braak, 1987).

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