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Volunteered Geographic Information for Enhanced Marine Environment Monitoring

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Abstract: The ability to detect and monitor oil spills at sea is becoming increasingly important due to the high demand of oil-based products. Remote sensing frameworks have been proven to give accurate results in case of major events; nonetheless, also medium and micro oil spills have their own importance, especially in protected areas that deserve special attention. In this paper, we propose a monitoring framework based on the collection of in situ observations and on their integration with remote sensing in order to fill out existing observational gaps. In particular, besides the data collected by special monitoring devices, in situ observations include volunteered geographical information as an additional source of valuable data. Oil spill sights, notified by volunteers through a specially-designed app, are integrated in the monitoring system and therein processed together with remote sensing data in order to proactively detect anomalous events and produce alerts. Field operational tests in two areas demonstrate the technical validity of the approach, while users' reception testifies to its potential in raising people's awareness on marine pollution.

Keywords: marine environment monitoring; marine pollution; oil spills; marine traffic; volunteered geographic information; citizen science

1. Introduction

Since heavy maritime traffic and marine pollution impact the environment, the economy and the quality of life for coastal inhabitants, it is vital to prevent environmental disasters and to act immediately before pollutants are spread in a wide area. In the last few years, several technological advances were made in this sense, especially under the push of catastrophic events at a global scale. Nevertheless, most of the approaches have been focused on large-scale oil spills, while smaller ones and operational discharges have received less consideration, despite their importance in the routine work of local authorities, especially in protected areas of great environmental value. In particular, in Europe, short- and mid-range sea shipping is and will continue to be a central part of the logistics chain for transport; such an increment of marine traffic poses several concerns for coastal areas [1]. Indeed, risk does not only arise from major accidents with tankers, but also from illicit acts due to ship routine operations, like degassing and deballasting, that might end with an intentional and malicious discharge of pollutants [2]. Although each of these events seems to be negligible with respect to catastrophic accidents, it should be noted that operational discharges tend to be repetitive and may concentrate in ports and along shipping routes. Further, it has been estimated that cumulatively every year, they add up to eight-times accidental oil spills such as the Exxon Valdez. For the management of major oil spills and pollution events, today there exists a number of both prototypical and operational platforms. In Europe, for example, the European Maritime Safety Agency (EMSA) provides the CleanSeaNet service [3], covering all European sea areas, which are analyzed in order to detect and track possible oil spills on the sea surface. Besides operational services, the interest of the research community is witnessed by many projects and prototypical systems for marine pollution monitoring [4,5]. Recent works include cloud-based solutions [6], in which a cloud-based image processing facility for oil spill detection is integrated with a web-based geographical information system, and the framework introduced in [7], in which a fine-grained hydrodynamic model is used for accurately forecasting oil spill evolution and weathering.

The main contribution of this work is to propose an integrated and interoperable system based on advanced sensing capabilities yet suitable for local authorities and stakeholders in order to monitor, detect and provide adequate response also to medium and micro oil spills. To this end, we adopt the Marine Information System (MIS) presented in [8], which integrates Synthetic Aperture Radar (SAR) processed data, environmental data from in situ monitoring stations (e.g., sensorized buoys [9]) and dynamic data acquired from Autonomous Underwater Vehicles (AUVs). With respect to previous works—mainly pivoting on SAR images—the MIS introduced in [8] has shown that remote sensing can be effectively enriched by adding information collected in situ thanks to static and mobile sensors and leveraging innovative methods for data correlation and fusion. Besides the integration of the above information coming from authoritative sources, the contribution of this work is the integration of Volunteered Geographical Information (VGI), aiming at a more pervasive monitoring of the sea thanks to citizen science. Starting with the seminal work by Goodchild [10], VGI has been proven to provide useful information in the case of events like hurricanes, earthquakes and pandemics. The contribution of the public can be determinant in giving to authorities and stakeholders near real-time information and nowcasts for facing emergencies in a timely manner. This new way of producing geographic information brings up new potentials together with many issues as highlighted in [11]. Crowd-sourced information is extremely powerful, but at the same time, requires substantial changes to the conventional information chain by intertwining authoritative and non-authoritative data [12].

In this context, our contribution aims at properly integrating VGI for improved monitoring of oil spills. Notice that the use of VGI for water monitoring and security is rather new and is experiencing a period of increased interest. Pioneering works such as [13,14] have shown the capability of VGI in connection with the monitoring of streams and with the preservation of their biological richness. The fitness for use and the limits of VGI are analytically discussed in [15] for flood damage estimation; it is shown that VGI can be a great opportunity for water monitoring and disaster management, although quality control methods are envisaged to be essential for fully deploying this potential. More recently, [16] proposed a crowd-sourced information system devoted to vessel tracking for interpreting maritime traffic in an ecological context; the system is capable of providing a spatially-resolved dataset, which put in relation individual ships with their mobility patterns and vessel attributes by incorporating quality checking methods with volunteered geographic information. In [17], a Geographic Information System (GIS) solution is developed using a VGI approach to reduce the burden associated with collecting and managing marine mammal observations. Suitable web and mobile applications are made available for the general public to submit marine mammal observations and visualize the results. In [18], the utility of citizen science in cetacean research and marine spatial management has been assessed. A new data source on whale locations, observation data collected voluntarily by whale-watching vessels, is procured, compiled and digitized. Globally, it has been shown that VGI is an opportunity for marine research [19], having good potential to contribute to the marine policy evidence-base alongside traditional monitoring, remote sensing and modeling; however, according to [20], this can happen only if outputs from citizen science projects are judged individually on quality. As regards oil spills and, especially, small-scale events, in [21], important considerations and guidelines for setting up a citizen science approach to sea monitoring were presented. It is argued that combining citizen and traditional science may increase the quality of monitoring of small-scale pollution events, but in that paper, no actual implementation was tested and experimented.

By converse, in our work, VGI is actually collected thanks to a specially-designed mobile application. The proposed app allows people to notify the MIS about the sighting of oil spills; in turn, the MIS is capable of integrating and filtering the received data so as to produce alerts in a timely manner to be issued to the authorities. To the best of our knowledge, this is an important contribution of the paper: indeed, it is shown that VGI can be integrated in a monitoring system and therein deployed by automatic reasoning systems in order to obtain a more accurate control of the sea. Users' acceptance, surveyed through statistical data, shows that the approach is suitable for large-scale uptake.

The paper is organized as follows. We first recall in Section 2 the architecture of the designed MIS, describing its components and features. In Section 3, we describe the motivation and the issues in integrating such a kind of information into the MIS. Methods for real-time assessment of risk based on the heterogeneous data collected into the MIS are discussed in Section 4, while automatic reasoning and alert generation services are described in Section 5. Such services are capable of exploiting the computed risk maps and data gathered from volunteers for issuing alerts to local authorities. Finally, we discuss the field tests performed for the validation of the proposed model (Section 6) and users' reception (Section 7). Section 8 concludes the paper with ideas for further work.

2. The Marine Information System

In this section, we briefly recall the Marine Information System (MIS) [8], which is used in this paper as a baseline platform for the integration of Volunteered Geographical Information (VGI). The MIS has been designed to provide an effective and feasible detection and management of marine pollution events, by integrating and analyzing data acquired by disparate monitoring resources, exploited to get useful and relevant information about the sites under surveillance. The main task of the MIS is to serve as a catalyst for integrating data, information and knowledge from various sources pertained to the marine areas of interest, by means of adequate Information Technology (IT) tools. More precisely, following the Infrastructure for Spatial Information in the European Community (INSPIRE) and Global Monitoring for Environment and Security (GMES) recommendations [22], the MIS has been conceived as an interconnected group of subsystems for performing data storage, decision-support, data mining and analysis over data warehouses, as well as a web portal with GIS functionalities for the access and usage of products and services released to end-users.

As an output of designing, a list of general subsystems has been identified, having the following roles:

(i) SAR image acquisition, devoted to the management of all the information workflow related to SAR image acquisition and processing.
(ii) Hyperspectral-thermal image analysis, devoted to the management of the information workflow related to the analysis of the hyperspectral images acquired by airborne sensors.
(iii) Mathematical simulation, devoted to the provision of simulation results on the basis of models for 3D hydrodynamics, waves, oil-spill transport and weathering.
(iv) Integrated communication system for the management of geographically-located devices, to provide an information infrastructure, able to transfer data between the actors located in the geographic area to be monitored and the MIS.
(v) AUVs management and data analysis. AUVs are able to carry on board special sensors (e.g., including an E-nose for assessing the quality of water in the area under monitoring).
(vi) Marine traffic monitoring, devoted to the collection of Automatic Identification System (AIS) data and to the provision of services for accessing, retrieving and visualizing them. AIS technology offers an efficient and practical way to track vessels [23,24].
(vii) Data mining and warehousing, devoted to the collection and analysis of historical data by means of advanced statistical tools for discovering and understanding relationship among the data (e.g., between traffic density and the probability of occurrence of pollution events) and supporting strategic decision-making.
(viii) Environmental Decision Support System (EDSS), committed to the identification and monitoring of possible oil slick events by analyzing and combining the multi-source data coming from the different data acquisition and processing subsystems of the MIS.

In particular, by integrating specific analysis models that are strictly connected to all the devices and subsystems, the EDSS processes the environmental data acquired by the various monitoring resources by applying simulation and optimization models for site characterization and observation and detects possible marine pollution events by applying risk analysis models. The high level MIS architectural design is shown in Figure 1. The core components are interconnected thanks to a middleware layer that achieves communication and cooperation among the various units. All data gathering service (including AUV, AIS, image analysis and mathematical simulation) are implemented using a set of reconfigurable service units that are in charge of fetching data from the providers and transforming them into a suitable format to achieve interoperability with the other MIS components.

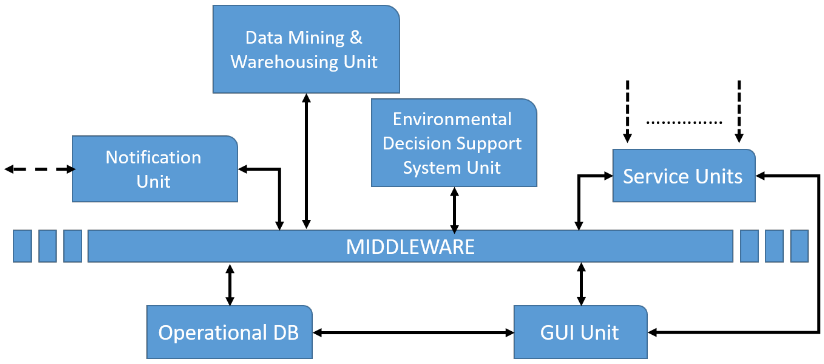

Figure 1. Architectural design of the Marine Information System (MIS).

3. Integration of Volunteered Geographic Information

In this section, the proposed methods for the collection of Volunteered Geographical Information (VGI) for oil spill monitoring are introduced by describing the developed app and an ad-hoc device. Then, the back-end for the management of the collected data and integration within the Marine Information System (MIS) is presented.

3.1. Methods and Tools for VGI Data Collection

In this section, we introduce the main methods and tools that are used to acquire real-time information collected directly on-site in order to overcome the limits of conventional monitoring frameworks and to improve their timeliness and accuracy.

A major requirement is to include data with precise geographic information, originating from reliable sources, yet from the widest community, so as to guarantee good coverage of critical areas. For these reasons, it has been decided to use nomadic devices (e.g., smartphones and tablets), which have now a ubiquitous diffusion around the globe; since most of them are equipped with a Global Navigation Satellite System (GNSS) receiver, they can register the exact location of sighting and, then, share these data using the cellular network interacting with the MIS. With the aim of having an easy and intuitive interface and of fostering the submission of precise data, a dedicated app, codenamed ARGO Sentinel, has been designed and developed. The app makes transparent to the users the retrieval of their location and the interaction with the MIS. By tapping one of the alert buttons (see Figure 2) according to the severity of the sighted spill, the app gathers the current position and codifies a text message that is sent via Short Message Service (SMS) to a receiving station managed by a service unit of the MIS. The use of SMS is a convenient solution since it suffices for sending the required information (consisting only of a few bytes) and because 2G/3G/LTE networks are not commonly available at sea, even in coastal areas.

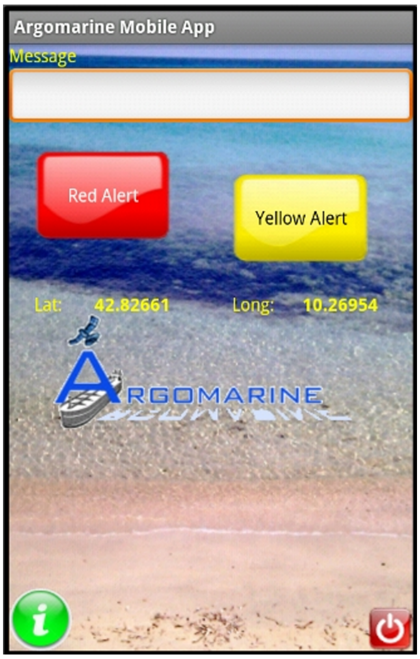

Figure 2. The main screen of the ARGO Sentinel, available at Google Play.

Besides the app, that can be used on common smartphones and tablets and is suited for the general public, it has also been decided to develop a device dedicated to special communities of enrolled users (e.g., nautical clubs, fishermen networks). This device, codenamed WhiteBox, is an embedded system equipped with a GNSS receiver and a Global System for Mobile Communications (GSM) modem. Its user interface consists of three physical buttons that, besides controlling device powering, allow one to communicate the sighting of pollution events with two different severity grades. This minimal interface makes it possible to use the WhiteBox with just one hand, thus not compromising any sailing activities.

3.2. Management of Volunteered Data

For integration into the Marine Information System (MIS), the app and the WhiteBox device are complemented by a suitable back-end, whose main features and components are described in this section. Namely, a dedicated service unit in the MIS manages the volunteered data by controlling the information sent by volunteers through text messages (SMS) and received by means of a mobile extension of the MIS, i.e., a specific hardware component dealing with communication through the cellular network. The data-flow is shown in Figure 3.

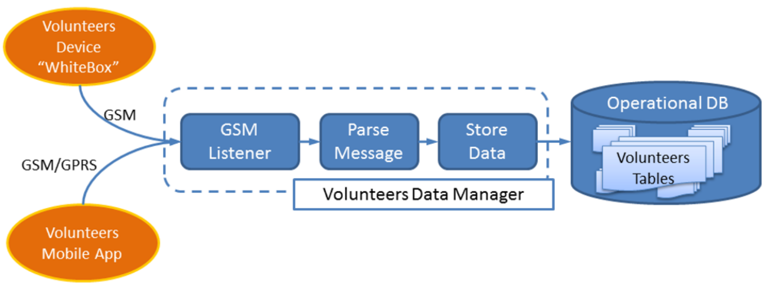

Figure 3. The service unit in the Marine Information System (MIS) dedicated to the management of Volunteered Geographical Information. The service unit takes care of storing received data in the operational database of the MIS.

In particular, a GSM listener has been set up for managing the communication with an external GSM modem connected via a Universal Serial Bus (USB) interface to the mobile extension of the MIS. The GSM listener is constituted by the open source Gammu SMS Daemon [25], a program that periodically scans the GSM modem for received messages and stores them in a predefined storage. The Gammu SMS has been configured for storing the received messages in the inbox table of a local Database (DB). For parsing and processing volunteered data, a Java scheduler procedure checks every thirty seconds if a new message has been stored by Gammu in its local DB. When a new message is found, this is processed by a Java class, which stores the information into the MIS. Two kinds of messages are currently managed, namely the messages issued via the ARGO Sentinel app and via the WhiteBox device. For each of them, the payload of the SMS, the sending phone number and the timestamp are passed to a parser, which decodes the message, extracting the location where the message has been issued. Finally, the parsed data are stored in a suitable table in the operational geo-enabled DB of the MIS and associated with a particular volunteer as identified by the phone number. Figure 4 shows how an alert reported by a volunteer using ARGO Sentinel appears through the web interface of the MIS.

Figure 4. A report displayed through the Marine Information System (MIS) web interface of an alert produced by a volunteer: data, identifier of the volunteer (if registered), severity, wind speed, remarks, latitude and longitude are displayed.

4. Real-Time Risk Estimation

Integration is not limited to mere data collection, but the semantics of the data is analyzed to offer decision support services, as explained in this section. Indeed, the Marine Information System (MIS) has been endowed with methods for the provision of real-time risk assessment, in order to produce a snapshot of risk in the region of interest, which, in turn, can either be (i) automatically exploited by proactive services (as explained in the next section) or (ii) directly analyzed by stakeholders helping them to keep the threat to safe navigation and the natural environment as low as reasonably practicable. Conventionally, risk assessment regards (i) estimation of hazard potential and (ii) vulnerability analysis [26], which do not have a single universally-accepted definition, but that are usually considered to rely on a number of static and time-varying features, including the presence of harbors, the density of marine traffic and weather and hydrodynamic conditions. In addition, proximity to the coast or the presence of endangered biological species favor the increase of hazard potential. In the past few decades, several frameworks for hazard potential have been described in the literature [7,27,28]. Vulnerability analysis addresses instead the impact of the actual hazard or the set of conditions/processes resulting from biophysical, environmental and socio-economic factors that decrease resilience of an area [29]. In particular, in the context of marine pollution, the presence of a pervasive monitoring system and of an effective risk management chain increases resilience to hazardous events. Extending these ideas, we aimed at devising a method for the computation of a local risk estimate for each point in a geographical region of interest. The computed pointwise estimates can then be visualized in a thematic map of risk for the given region, similarly to Environmental Sensitivity Index (ESI) maps [30]. In our framework, global hazard potential is derived by multiplying the likelihood of occurrence of adverse consequences by the magnitude of each consequence. In addition, the monitoring efficiency and coverage are quantitatively translated into numerical features representing the vulnerability of the monitoring system. To this end, among the data integrated into the MIS, a selection has been made to extract those parts of information that might be relevant in risk analysis for oil spills and other pollution events. In particular, it has been decided to encompass: (i) maritime traffic data; (ii) the oil spill reports produced by remote sensing; (iii) all the in situ observations including volunteer reports; and (iv) an index expressing the goodness of local monitoring coverage. A dynamic risk map is automatically recalculated at regular time intervals and whenever new information coming from a connected data source deserves an update. This is the case when the MIS receives a report from a volunteer. Figure 5 shows an example of the risk map modification upon the reception of an oil spill report from a WhiteBox device.

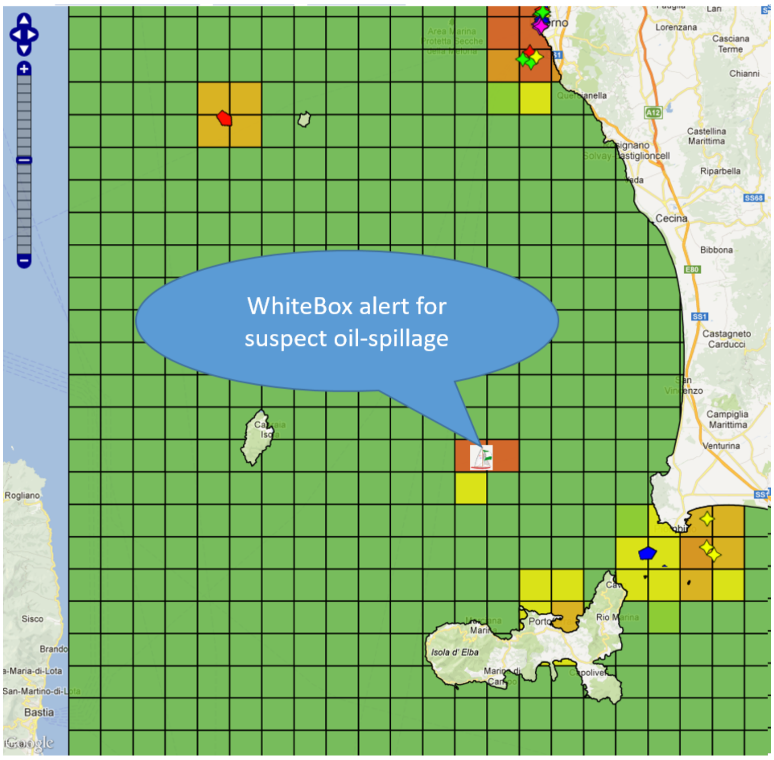

Figure 5. Marine Information System (MIS) interface showing dynamic risk map modification produced after reception of an alert from a volunteer.

Having the general risk computational framework being described in [8,31], we briefly describe here how the contribution of volunteered data is incorporated. The available reports generated by volunteers contribute to the risk in location qat time t by the following amount:

$$R_{\text{volunteer}}(q,t) = \sum_r w_r(\Gamma * \chi_r)(q)\exp(-\lambda|t - T_r|) \quad (1)$$

where the sum runs overs all the available reports r generated at location P_r and time T_r, χ_r is the characteristic function of the point P_r, Γ is a convolution kernel determining the size of the region affected by the report, λ is a parameter controlling the time decay of the report and, finally, w_r is the weight assigned to the volunteer report. In particular, an adaptive weighting scheme might be adopted. Volunteers, which have been proven to give reliable information (because their reports have been confirmed either by other volunteers or by the authorities), deserve an increase in the weights associated with their reports; on the contrary, reports that have been proven to be irrelevant produce a decrease in the weight of future reports by the same volunteers. In the performed test, users registered in the system or enrolled for the use of the WhiteBox device were given a greater weight, with respect to the unregistered general public using the app.

5. Proactive Services and Alert Generation

Exploiting the dynamic risk map described in the section above, it is possible to configure a collection of proactive services for 24/7 monitoring of the areas of interest in order to automatically issue alerts in case anomalies are detected.

The main goal has been to infer from the heterogeneous collected data, which are a mixture of authoritative and non-authoritative information, events and trends of interest. From an architectural point of view, we decided to use a collection of services, each of them being implemented by an intelligent software agent. Agents work in autonomy and are independently reconfigurable to a large extent. Each of them has a number of probes for fetching data from the MIS and a set of preconfigured actions. Each one is endowed with an inner logic, which represents the workflow that it is committed to carry out. Each step in the workflow is represented as a condition-action rule. The workflow might include the acquisition of further data or the triggering of external computational methods (e.g., for running simulation or assessing risk again). Agents activate their probes at regular interval of times (e.g., they poll data from a repository) or they are triggered on demand (e.g., by other agents or upon reception of special requests or new data). A number of agents, each one, implementing alerting services were designed and developed. As described in the previous section, the real-time risk estimation offers a synthetic parameter blending all the available information in a certain area. It is therefore natural to configure an agent dedicated to the observation of estimated risk and to the generation of alerts in case unexpected increases occur. Another agent that has been configured is based solely on the analysis of the collected VGI. In particular, this agent applies spatial and temporal aggregation on the set of received volunteers' alerts and detects the presence of significant clusters. In case one is found, an alert is generated with variable grades of severity. Besides the mere generation of an alert message, agents take care of contacting the most suitable authority selected automatically on the basis of a proximity criterion. A message is composed including all the information that might be useful for understanding and evaluating the alert. In particular, the location the alert refers to, the observations that triggered the event and a link to an ad hoc resource of the MIS web interface are provided. Finally, the service connects through specific Application Programming Interfaces (APIs) with the actual dispatching interfaces (e.g., either email server or the mobile extension of the MIS for SMS).

6. Data Collection Methods and Field Tests

The proposed system has been tested in three different field operational tests performed in the framework of the EU FP7 Argomarine Project (FP7-SST-2008-RTD-1-234096) at different times, one in Zakynthos, Greece (hosted by the National Marine Park of Zakynthos), and two in Elba Island, Italy (hosted by National Park of Tuscany Archipelago). Selected sites are of great environmental relevance. Indeed, the National Marine Park of Zakynthos, established in 1999, is home to the endangered Loggerhead Sea Turtle (*Caretta caretta*), which is considered one of the oldest forms of life on the planet [32]. The National Park of Tuscany Archipelago is one of the areas with the highest oil spill densities according to the work [33] and is located in the Mediterranean Sea, between the Ligurian

Sea and the Tyrrhenian Sea. The Archipelago is also included in the area of the Pelagos Sanctuary for Mediterranean Marine Mammals [34].

Field tests were oriented to global assessment of the MIS platform and involved the acquisition and processing of data coming from heterogeneous sources including volunteers, as well as to the provision of decision support services. Tests included the acquisition of true data for verifying storage capabilities and near-real time functionalities. With a small amount of work for fixing interoperability issues, no problems were found for data integration. Stress tests using dummy data have also been performed for understanding the limits of the platform. On this basis, it can be judged that the system is adequate for managing regional data; in any case, the system might be scaled to an arbitrarily wide areas. Support for multiple areas is already included and operational. Besides true data, simulated data were also injected into the MIS to produce artificial perturbations and thus creating interesting anomalies to be managed by the implemented proactive services. The methods for real-time risk assessment were run automatically at regular time intervals to produce risk maps. The maps were visualized by experienced users belonging either to the Italian National Coast Guard and to the two marine parks (an example of the appearance of the map at the coarse scale is given in Figure 5). By visual inspection, the users found the map to convey meaningful and significant information and regarded it as a useful tool to better focus the attention on the areas that deserve a more accurate monitoring. The proactive services were asked to poll data from the databases including the computed risk maps. On the basis of polled data and of the logic used by the services, alert notifications were issued. A group of volunteers (also enrolled from the Pisa Naval League) has been asked to report a simulated oil spill either by using the WhiteBox device or the ARGO Sentinel app on their GNSS-equipped smartphones. The computed risk map changed consistently after receiving the volunteer reports. In particular, thanks to the inner logic of the agent in charge, such an event triggers a list of actions, including the updating of the risk map and the issuing of a notification to the authorities in charge of the area by SMS and emails.

7. Users' Reception

Besides the performed field tests, the framework for collecting VGI regarding oil spills was evaluated by analyzing the users' acceptance and the actual use of the ARGO Sentinel app. A high number of users sent information using ARGO Sentinel: specifically, from 7 September 2012–31 August 2013, we received 186 reports. Even if our test sites were very narrow, we received reports from many areas in the world. For the most part, these were only tests; however, by integrating received reports with other information on the MIS, we deducted that 19 could not be false positives, and thus, we forwarded them to the Italian Coast Guard. The media and social impact has been unexpectedly high; indeed, after ten days from the publication of the app, 7–17 September 2012 from, there were more than 25 million results by searching ARGO Sentinel on Google with comments positive or neutral, and more than 500,000 Twitter accounts were informed about the initiative. In Figure 6, the dissemination of media after the first ten days is shown. Besides web sites, blogs, social channels and news aggregators, also local and international newspapers, radio and televisions provided information about ARGO Sentinel, reaching a very high number of people all over the world.

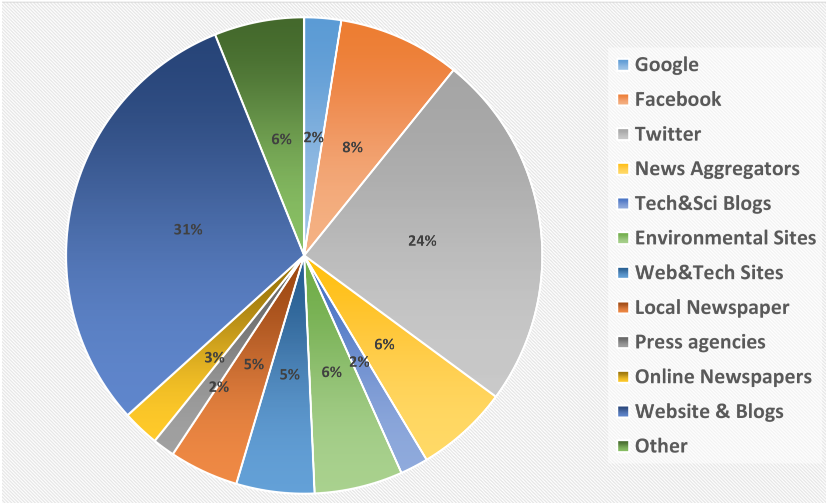

Figure 6. Media impact of ARGO Sentinel in ten days after its publications.

8. Conclusions

In this paper, we have demonstrated that the fight against pollution towards more sustainable marine traffic may have a large number of new avenues: volunteers. Moreover, the work done suggests that this kind of technology can be applied in many other contexts. In order to appreciate the full potentiality that is possible to gain thanks to the contribution of volunteered data, we have integrated the ARGO Sentinel app into the Marine Information System (MIS) that has been presented in [8]. In this way, the contribution of people is fused with authoritative information coming from remote sensing, airborne sensors and other in situ devices in order to produce a neat picture of the status of the sea and resolving the ambiguities that each single data source might suffer.

For example, possible lookalikes detected by SAR images may be either filtered or confirmed by volunteer reports. In the MIS, all the gathered information, including volunteered data, is processed by innovative services in order to produce proactive and timely suggestions to assist authorities and stakeholders facing emergencies. Moreover, it is noteworthy to observe that fraudulent actions can be dissuaded by a prompt report of on-site observers. Improvements and developments could offer new facilities to authorities for more efficient and responsive mitigations and law enforcement.

In the future, we will investigate the use of a two-way connection between the users and the MIS. In this way, we will be able to provide information to the public and, at the same time, encourage their contribution to support the monitoring of sea for improved environmental protection. In addition, it is planned to add the possibility to send images of the pollution events. By means of computer vision and artificial intelligence methods, it will be possible to accumulate a knowledge base of possible pollution events and perform their automatic classification. Finally, direct integration with social networks will be evaluated in order to reach an even greater penetration of the ARGO Sentinel app and raise public awareness on the theme of marine pollution.

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