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Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks

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A R T I C L E I N F O

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A B S T R A C T

Effective flood risk management requires updated information to ensure that the correct decisions can be made. This can be provided by Wireless Sensor Networks (WSN) which are a low-cost means of collecting updated information about rivers. Another valuable resource is Volunteered Geographic Information (VGI) which is a comparatively new means of improving the coverage of monitored areas because it is able to supply supplementary information to the WSN and thus support decision-making in flood risk management. However, there still remains the problem of how to combine WSN data with VGI. In this paper, an attempt is made to investigate AGORA-DS, which is a Spatial Decision Support System (SDSS) that is able to make flood risk management more effective by combining these data sources, i.e. WSN with VGI. This approach is built over a conceptual model that complies with the interoperable standards laid down by the Open Geospatial Consortium (OGC) – e.g. Sensor Observation Service (SOS) and Web Feature Service (WFS) – and seeks to combine and present unified information in a web-based decision support tool. This work was deployed in a real scenario of flood risk management in the town of São Carlos in Brazil. The evidence obtained from this deployment confirmed that interoperable standards can support the integration of data from distinct data sources. In addition, they also show that VGI is able to provide information about areas of the river basin which lack data since there is no appropriate station in the area. Hence it provides a valuable support for the WSN data. It can thus be concluded that AGORA-DS is able to combine information provided by WSN and VGI, and provide useful information for supporting flood risk management.

1. Introduction

Recent floods have shown that such disasters can cause damage to the economy and citizens of a country (Kaewkitipong et al., 2012; Merz et al., 2012). This is particularly the case in Brazil, where frequent serious flooding accounts for 54% of the disaster events for the past few years (IBGE, 2014). In view of this, flood risk management has become a critical issue. Timely and accurate information can greatly assist the emergency agencies involved in flood risk management. However, the continuous monitoring of the potential risks of flood hazards requires precise estimates of the risks incurred that are based on the observation of rainfall and water levels in local regions (Jha et al., 2012).

Wireless Sensor Networks (WSN) have emerged as an alternative approach which can provide updated information for water resource management at a relatively low deployment cost (Albuquerque et al., 2013). Although this approach has been successfully employed for different situations (Lee et al., 2008; Hughes et al., 2011; Seal et al., 2012; Shukla and Pandey, 2014), it requires a considerable effort to ensure it works effectively (Patel and Kaushik, 2009). In addition, WSNs often fail to provide data from several parts of the riverbed since there is a lack of an appropriate station in what are called "ungauged areas". Running parallel with this, another valuable source of information is Volunteered Geographic Information (VGI). This enables ordinary citizens who reside in high-risk areas, to provide information through various

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0098-3004/

devices (e.g. smartphones) (Goodchild, 2007; De Longueville et al., 2010; Roche et al., 2011).

The combination of WSN and VGI can act as a mutual support system for achieving effective flood risk management. However, it raises challenges which are threefold: (1) dealing with distinct formats (e.g. photos vs numeric values) at different levels of measurements (e.g. water level gauges vs citizen's perceptions), (2) ensuring interoperability among data providers, and (3) conveying the integrated information in a single and understandable way. This paper therefore aims to tackle these challenges by presenting AGORA-DS, a Spatial Decision Support System (SDSS) that integrates the information provided by WSN and VGI, and is an aid to decision-making in flood risk management. AGORA-DS was based on a conceptual framework comprising the following: (a) the acquisition layer responsible for defining available data sources, (b) the integration layer designed to integrate the data and make them available in compliance with interoperable standards, and (c) the decision-support layer, the purpose of which is to provide a web-based decision support tool for visualizing the integrated information to support decision-making.

This paper is based on our previous work: Horita and Albuquerque (2013) set out a conceptual architecture for supporting decision-making by using different types of data sources. Degrossi et al. (2013) show the early results of our attempts to monitor urban rivers. Horita et al. (2014) display a geodashboard that processes data streams of WSN and makes them available to support decision-making. Degrossi et al. (2014) adopt and evaluate a crowdsourcing-based approach to obtain VGI for flood risk management. Thus, this paper both consolidates the results of our previous work and supplements this with the following novel contributions:

1. *Conceptual framework*: a definition of a conceptual framework for collecting and integrating heterogeneous data sources (i.e. WSN and VGI), and the visualization of integrated information. It employs interoperable standards to ensure the integration of information, and thus makes the framework flexible enough to support the inclusion of different elements.
2. *Real scenario*: lessons learned from the deployment and analysis of AGORA-DS in a real scenario of flood risk management in São Carlos, Brazil. The data provided by both a group of installed in situ sensors and volunteers in the field were used rather than data from simulated scenarios.

This paper is structured as follows. Section 2 first outlines the conceptual basis of this work. Following this, Section 3 describes AGORA-DS and sets out its conceptual framework. On this basis, Section 4 describes the deployment used for analyzing AGORA-DS. Section 5 discusses the lessons learned from this deployment and the results obtained. The limitations of this work are also described in this section. Finally, Section 6 summarizes our conclusions and makes recommendations for future work.

2. Background

2.1. Flood risk management

Since floods are the most common type of disaster that affects communities around the world, flood risk management is a necessary measure to minimize their effect. This kind of management seeks to reduce the social, economic, and environmental consequences of floods by means of a set of activities grouped into three phases: pre-flood planning, emergency management and post-flood recovery (Ahmad and Simonovic, 2006). In view of the many variables involved, information about the current state of rivers thus plays an important role in defining the current situation and supporting decision-making.

Nevertheless, three key issues must be addressed to ensure the effectiveness of flood risk management and that the right decisions are made by the emergency agencies: (1) the response time of official and emergency agencies must be fast, integrated and reliable because a delayed response based on erroneous data can have serious consequences (Ostermann and Spinsanti, 2011); (2) there may be a lack of detailed and updated information concerning the different variables in the affected areas (Tu et al., 2009), and (3) since there is a wide range of existing systems, there is no single standard that can ensure their interoperability (Baharin et al., 2009).

In order to tackle the second issue, Wireless Sensor Networks (WSN) (Xu et al., 2004) have been proposed to provide updated information at a relatively low deployment cost (Lee et al., 2008; Hughes et al., 2011; Seal et al., 2012; Shukla and Pandey, 2014). Due to advances made in wireless computing, sensing devices and small batteries, a wireless sensor network can be defined in terms of its low-cost and low energy consumption, regardless of external services. This makes it possible to monitor distinct variables of interest like the level of pollution in the river. This network generally consists of a range of sensor nodes installed in different locations, which are designed to gather and transmit specific data through short-range wireless interfaces to a base station (Khedo, 2013). To carry this out, the architecture of the nodes is equipped with low-power wireless networking technologies (e.g. ZigBee device) and simple sensors (e.g. for measuring the volume of rainfall).

2.2. Volunteered geographic information

The increase of interactions made possible by Web 2.0, the widespread use of devices equipped with GPS and the availability of broadband access to the Internet, geographic information has being produced by relatively unqualified people. This type of information, called Volunteered Geographic Information, has been of great practical value to complement existing geospatial datasets (Goodchild, 2007), owing to the potentially large number of volunteers who act as "sensors" (Poser and Dransch, 2010). In recent natural disasters, VGI has been used to support the activities of emergency agencies and government departments (Poser and Dransch, 2010; Yates and Paquette, 2011; Roche et al., 2011; Kongthon et al., 2012; Kaewkitipong et al., 2012; Triglav-Čekada and Radovan, 2013; Chae et al., 2014).

The volunteered information can be obtained through different collaborative activities, such as information sharing through social media (e.g. Twitter), collaborative mapping (e.g. OpenStreetMap,[1] Wikimapia[2]), and participatory sensing (e.g. citizen observatories) (Resch, 2013; Degrossi et al., 2014). In this study, it was decided to employ participatory sensing by means of a citizen observatory. This is because this platform seeks to gather specific and structured data rather than providing free-text content (e.g. Twitter) (Miorandi et al., 2013). A good deal of work has been carried out on the use of a citizen observatory for supporting disaster management (McDougall, 2011; Gunawan et al., 2012; Valecha et al., 2013; Hirata et al., 2013; Degrossi et al., 2014). However, neither of these works considered the question of integrating volunteered observations with other data sources nor the sharing of data by complying with interoperability standards.

[1] http://openstreetmap.org
[2] http://wikimapia.org

2.3. Related work

The question of integrating heterogeneous data has been widely investigated in the literature. Some works employed a spatial data infrastructure as an alternative. Mansourian et al. (2006) devised an SDI conceptual model to allow an integrated infrastructure to be established for a different disaster management system. In a similar way, Molina and Bayarri (2011) design an SDI architecture and develop a web-based application that employs a cognitive approach to allow information sharing. Although the implementation of interoperable standards can be regarded as an important requirement, these works did not use them either for interoperability among the systems or for the integration of data sources.

This is addressed by another group of studies which seek to analyze the use of open standards of the Open Geospatial Consortium (OGC) to achieve interoperability among different systems. Zhang and Li (2005) stress the importance of OGC open standards – esp. Web Feature Service (WFS) and Web Map Service (WMS) – for sharing near real-time spatial data over the web. Moreover, Markovic et al. (2009) use OGC open standards, i.e. Sensor Observation Service (SOS), WFS and WMS, for encapsulating sensor and spatial data at the River water Monitoring and Alert System (RWMAS) with a view to detecting and preventing water pollution.

As for the integration between VGI with other data sources, Wan et al. (2014) and Schnebele et al. (2014) describe distinct approaches that integrate authoritative and non-authoritative data with the aim of providing location-based eventful visualization, statistical analysis and graphic capabilities for the authorities and the public. However, these studies are not concerned with interoperability, despite the aforementioned importance of using of open standards.

In summary, none of the studies mentioned above considered the architectural requirements for collecting and integrating heterogeneous data sources, and then carrying out the visualization of the integrated information. Moreover, there have not been any studies which have dealt with the complex question of achieving interoperability between VGI platforms and other information systems.

3. AGORA-DS: description and framework

The AGORA-DS was built on the conceptual framework shown in Fig. 1. This framework is based on the architecture proposed by Horita and Albuquerque (2013) and consists of the following layers: the acquisition layer, the integration layer, and the decision-support layer. The next sections will outline these layers in detail.

3.1. Acquisition layer

This layer seeks to encapsulate the idiosyncrasies of data sources, and provide the appropriate technological resources (e.g. interfaces or web services) to disclose their data to the integration layer. This encapsulation is beneficial in several ways such as improving scalability and maintainability, reducing the impact of a change in data sources, and allowing new data sources to be included in a flexible way.

In this manner, two adapters were employed owing to the difference in the data structure and external sources of communication. First, there is a sensor adapter which is responsible for defining a standardized and easy way to receive data from the WSN. Since it is an input interface, the sensor adapter also converts the received data to an Observation and Measurements (O&M) specification (the XML format used to describe an observation of interoperable standards) (OGC, 2011). This adapter conveys the data to the integration layer through the

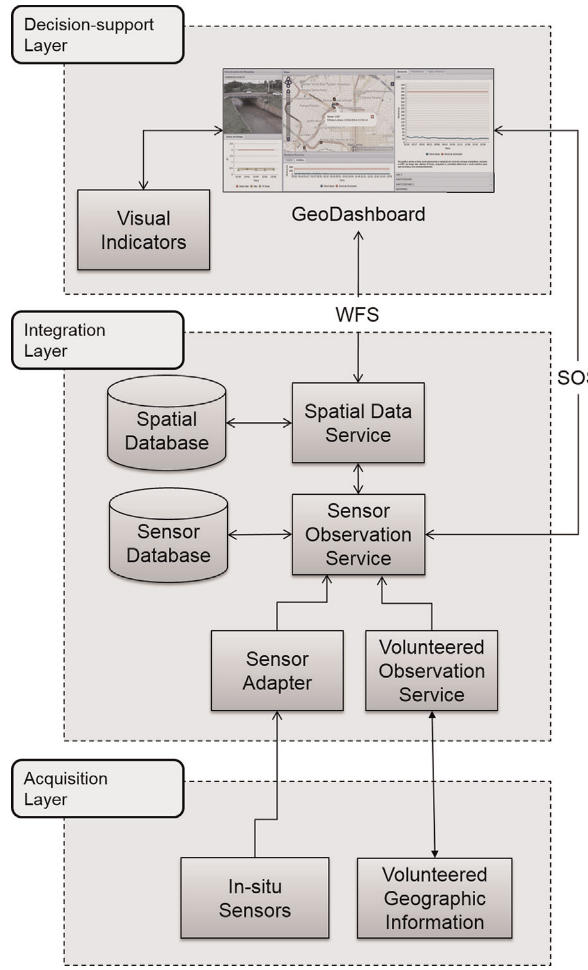

Fig. 1. Conceptual framework of AGORA-DS.

InsertObservation operation of the Sensor Observation Service (SOS) (OGC, 2012).

The second adapter called Volunteered Observation Service is based on our previous work (Degrossi et al., 2014) and handles the information provided by volunteers. This service interacts with the citizen observatory with the goal of collecting relevant information, e.g. the reports provided by volunteers. After this, it also executes the *InsertObservation* operation for conveying the data to the integration layer.

3.2. Integration layer

The purpose of this layer is to define mechanisms to receive, store, and share data provided by the acquisition layer. This is achieved by adopting the Sensor Observation Service (SOS), which defines interfaces both for receiving the data (via *InsertObservation* operation) and sharing them (via *GetObservation* operation). It also stores the received data in a sensor database (see data model in OGC, 2012). The SOS then supports the integration of distinct formats of data as well as the interoperability of data sources.

Furthermore, this layer sets up the Spatial Data Service which aims to convert data collected in SOS to the geospatial service standards, Web Feature Service (WFS). WFS provides resources which allow the creation, modification, and querying of geographical features[3] on the Internet rather than working with it on

[3] A geographical feature can be defined as an object that is an abstraction of a real phenomenon (OGC, 2014), e.g. in our case sensors data and volunteer information.

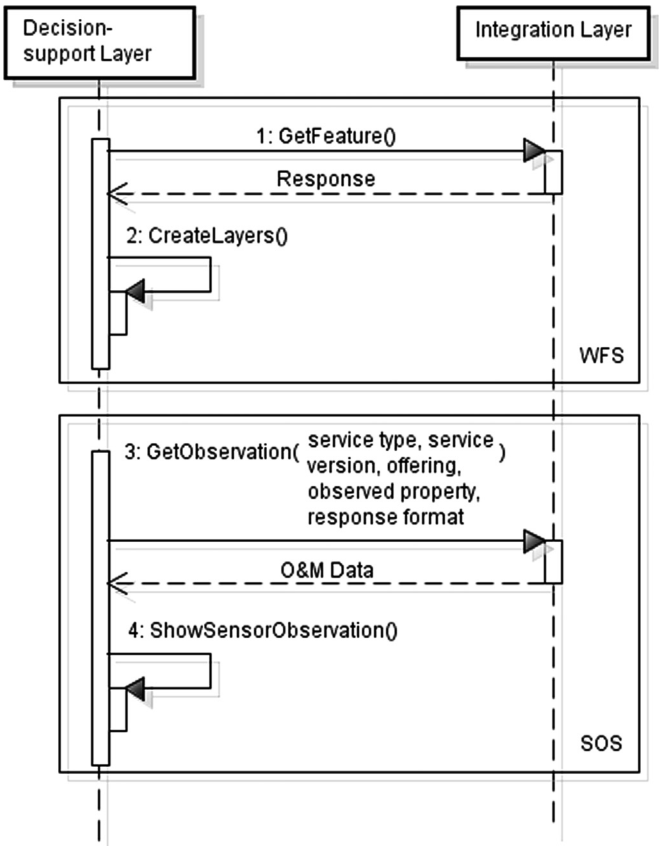

Fig. 2. The interaction with the decision-support layer.

the file level (e.g. raster or shapefile) using File Transfer Protocol (FTP) (OGC, 2014). We have considered WFS instead of Web Map Service (WMS) because it supports complex query operations regarding geographic features that result in low-time for data processing on the client-side (Zhang and Li, 2005). In addition, the Spatial Data Service also defines a simple database for storing all geographic information.

Therefore, the information can be shared with the decision-support layer by means of two specific operations, as shown in Fig. 2. First, the *GetFeature* operation is processed at WFS and aims to return a document to the decision-support layer containing a set of available geographic features (OGC, 2014). Second, the *GetObservation* operation provides access to integrated information by means of the spatial, temporal, and thematic filtering which will be used by the visual indicators (Jirka et al., 2012). This operation needs a set of parameters (see details in OGC, 2012) and its response is based on O&M specifications (OGC, 2011). These operations allow them to the decision-support layer that receives independently geographic information and integrated information.

3.3. Decision-support layer

The decision-support layer defines elements for enabling decision-makers to interpret information in a more efficient and effective way. In the scope of this work, they are web-based decision support tool and visual indicators.

The web-based decision support tool displays the integrated information provided by the integration layer for supporting flood risk management. This "web-based decision support tool" is hereby called Geodashboard. The term "dashboard", well known in the field of business analytics, refers to an information system which aims at providing the most important information needed

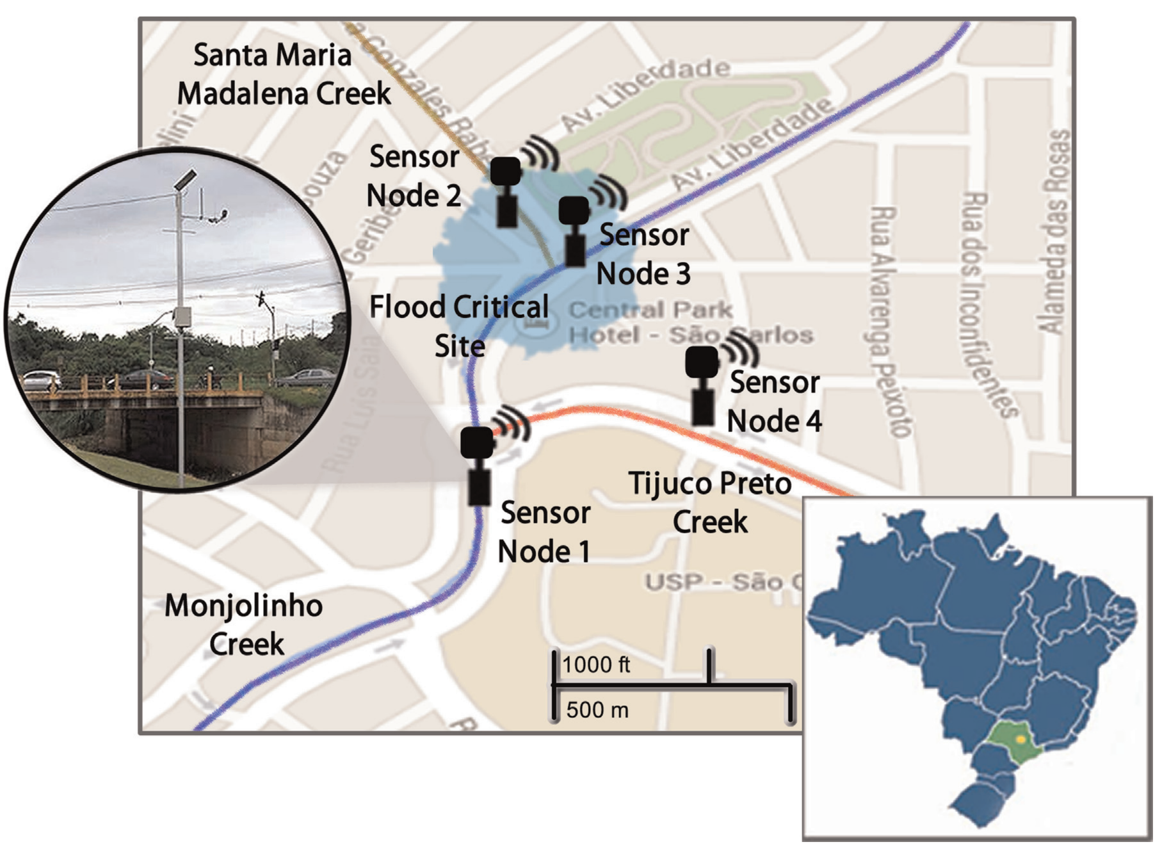

Fig. 3. The study area in São Carlos/SP, Brazil. Adapted from Horita et al. (2014). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

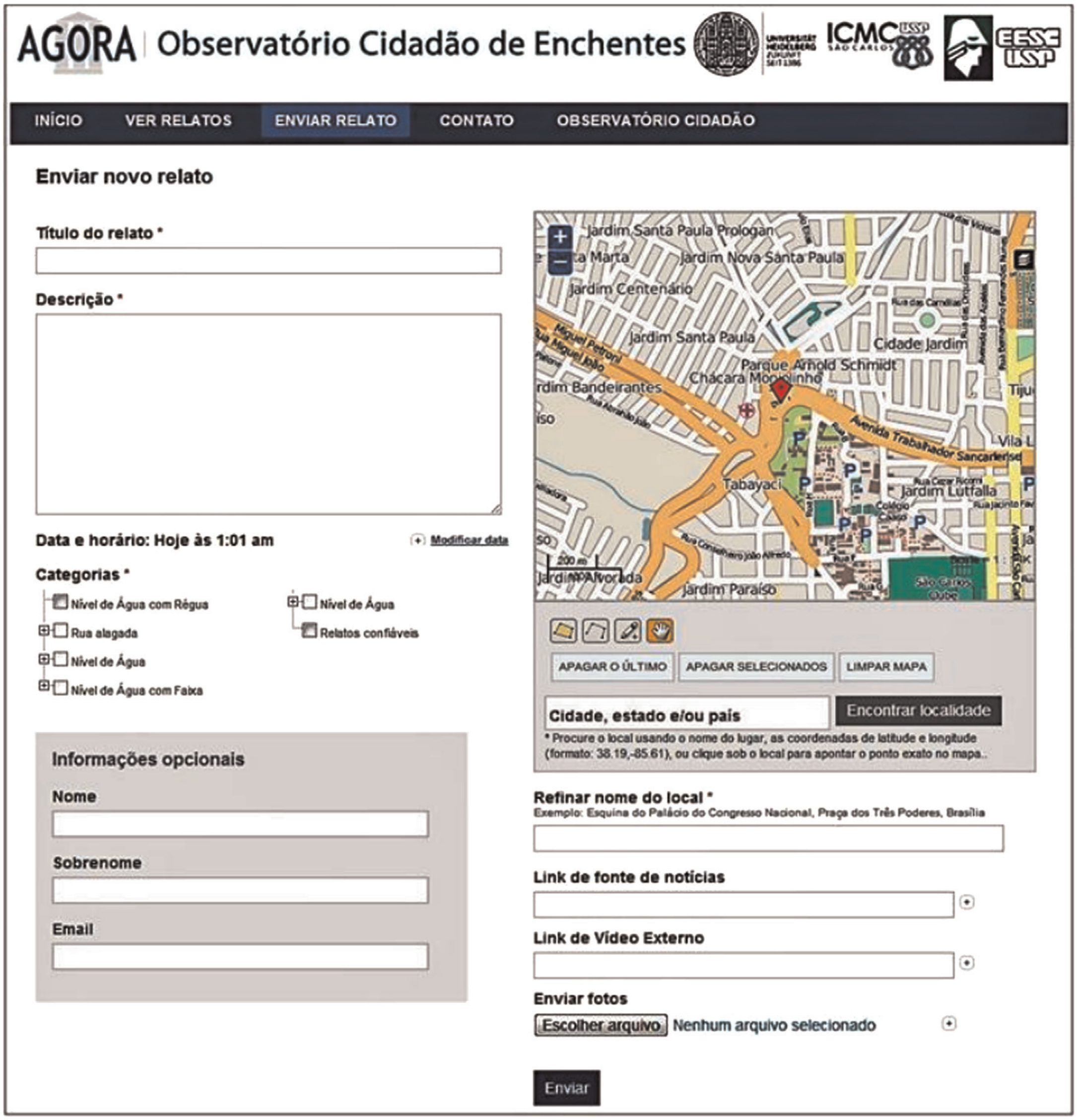

Fig. 4. Flood citizen observatory (Degrossi et al., 2014).

for supporting decision-making at different organizational levels (Few, 2006; Liang and Miranda, 2001). When geospatial factors are also important for supporting decision-making (e.g. location of customers and transport routes), it can be called “Geodashboard” (Horita et al., 2014).

Moreover, the visual indicators were designed to show the information collected in the acquisition layer which has been processed by expert models or not, e.g. the water level at a particular period of time or the vulnerability of communities who live nearby the river. Additionally, the Geodashboard displays a simple chart for each in situ sensor with the aim of supporting the analysis of its water flow and the limit for flooding. Finally, in the context of this work, a photo taken by in situ sensor at the critical area of the flood site, also composes the current version of the Geodashboard.

4. AGORA-DS: deployment and analysis

4.1. Study area

The study area is located in São Carlos/SP, a city that is 230 km from São Paulo in Brazil; it has a high population density and is in a region that is frequently affected by floods. Because of this, a flood risk management of the river catchments of the city is carried out in this study area to analyze the deployment of AGORA-DS. Fig. 3 shows the creek of Monjolinho, Santa Maria Madalena, and Tijuco Preto, all located in the town center of São Carlos.

4.2. Deployment

A critical flood zone (the blue shaded area in Fig. 3) is also highlighted at the intersection of the Santa Maria Madalena and Monjolinho creeks, a region with a large number of inhabitants living in residential buildings and houses and often affected by floods (Mendes and Mendiondo, 2007; Barros et al., 2007; Perhovaz, 2010; Horita et al., 2014). Owing to these problems, the area is often monitored by a WSN installed along the riverbed (Hughes et al., 2011; Degrossi et al., 2013; Horita et al., 2014).

Furthermore, citizens had provided reports related to the water level in different parts of the study area, as a result of the crowdsourcing-based approach developed by Degrossi et al. (2014). This approach defines four interpretation mechanisms for helping volunteers to have a better understanding of environmental variables, i.e. water level ruler, multi-color band, puppet in the shape of a human figure, and general tags rather than the other strict mechanisms (e.g. the water level is low or

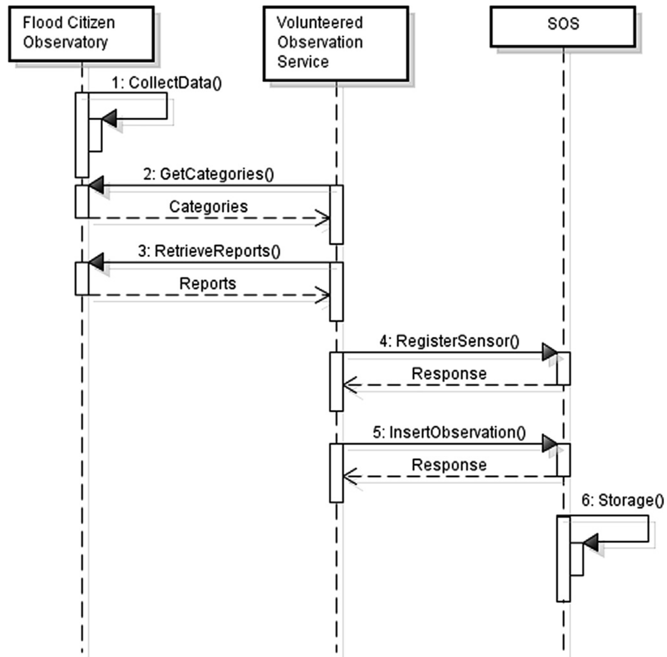

Fig. 5. Interaction with the flood citizen observatory.

	date text	observedValue text	observedValue numeric	procedure character varying(100)	observedProperty character varying(100)
1	05-16-2014 10:06:07		32.97	KARTODROMO 2	GAUGE HEIGHT
2	05-16-2014 10:07:00		0.00	USP 2	GAUGE HEIGHT
3	05-16-2014 10:07:00	A altura da água é de 0,30m.		FLOOD CITIZEN OBSERVATORY	níveldeáguacomrégua
4	05-16-2014 10:07:07		31.40	KARTODROMO 2	GAUGE HEIGHT
5	05-16-2014 10:08:00		0.00	USP 2	GAUGE HEIGHT
6	05-16-2014 10:08:07		32.97	KARTODROMO 2	GAUGE HEIGHT
7	05-16-2014 10:09:00		0.00	USP 2	GAUGE HEIGHT
8	05-16-2014 10:09:07		32.97	KARTODROMO 2	GAUGE HEIGHT
9	05-16-2014 10:09:41		21.04	USP	GAUGE HEIGHT
10	05-16-2014 10:10:00		0.00	USP 2	GAUGE HEIGHT
11	05-16-2014 10:10:00	KART 2 - 0.3m		FLOOD CITIZEN OBSERVATORY	níveldeáguacomrégua
12	05-16-2014 10:10:07		32.97	KARTODROMO 2	GAUGE HEIGHT
13	05-16-2014 10:10:44		0.00	KARTODROMO	GAUGE HEIGHT
14	05-16-2014 10:11:00		0.00	USP 2	GAUGE HEIGHT
15	05-16-2014 10:11:00	Kartódromo 1 : 25cm		FLOOD CITIZEN OBSERVATORY	níveldeáguabaixo
16	05-16-2014 10:11:00	0.2 m		FLOOD CITIZEN OBSERVATORY	níveldeáguacomrégua

Fig. 6. Observations stored in the observation table of the SOS database of AGORA-DS.

overflowing). They were also used to categorize the citizens' reports (e.g. “flooded area”). Following this, these mechanisms are employed in a web-based citizen observatory – also known as “Flood Citizen Observatory”, which is built as an instance of the Ushahidi crowdsourcing platform[4]. Fig. 4 displays the main interface of the Flood Citizen Observatory.

All reports provided by citizens are carried out manually by the Flood Citizen Observatory's administrator before making them visible on the Web or accessible through the Ushahidi REST API. This evaluation is important for improving credibility and quality of the shared volunteered information, although a more complex assessment is beyond the scope of this work. Finally, Fig. 5 shows that the Volunteered Observation Service obtains the categories and requests citizens' reports after the Flood Citizen Observation collected them from the volunteers. This communication is addressed by using the Ushahidi REST API. The *InsertObservation* operation is used afterwards for sharing the citizens' information with the integration layer.

The data provided by the data sources mentioned above are later shared with the integration layer. The sensor adapter was developed on this layer using Java Server Pages (JSP) while the volunteered observation service used Java language. The 52north framework[5] was used as an SOS implementation (Jirka et al., 2012). Both databases, sensor and spatial, used PostgreSQL as its database management system and had an extension to the geographic database (PostGIS). The Spatial Data Service was developed by means of Java language, together with the GeoServer.[6]

Finally, the GeoDashboard was implemented on the decision-support layer with the aid of ExtJS[7] with OpenLayers[8] which are used for structuring the geospatial data and displaying the visual indicators. This dashboard displays both the source of the information on the map, the volunteered information collected by the Flood Citizen Observatory and the in situ sensors. Furthermore, the expert model adopted in this work is called the “Hazard Index”

[4] http://www.ushahidi.com/

[5] http://52north.org/
[6] http://geoserver.org/
[7] http://www.sencha.com/products/extjs/
[8] http://openlayers.org/

(Rotava et al., 2013). This index represents vulnerability loss related to human stability in flood flows. It was defined based on the works proposed by Jonkman and Penning-Rowsell (2008) and HR-Wallingford (2006) that show how flood depth and flood velocity waters are combined for dynamical body equilibrium. This index is then related to human instability due to two physical mechanisms: moment instability (toppling) and friction instability (sliding).

4.3. Deployment analysis

The deployment analysis of AGORA-DS aims at gathering and classifying evidence of its efficiency in the real scenario of supporting flood risk management in São Carlos. This involves adopting two approaches: (1) drawing on evidence which shows the success of data integration and interoperability between WSN and VGI and (2) using evidence to show the usefulness of this kind of integrated information for supporting flood risk management.

4.3.1. Interoperability and data integration

As mentioned previously, the interoperability between the data sources was achieved through SOS. This service is based on commonly agreed standards and has been employed in different contexts to facilitate the integration of data. The provided data — hereby named “Observation” — is stored following an appropriate data model (see OGC, 2012). Within this data model, the table observation centers the all relevant information associated with a specific observation, i.e. its date, observed value, the procedure used, and *observedProperty*. The procedure refers to the source which provided the observation, and *observedProperty* could be water level or temperature. Therefore, an evidence of the interoperability between data sources and data integration might be giving when their respective data are stored into this table.

Fig. 6 evidenced the storage of some observations provided by WSN and VGI from the application of AGORA-DS in the table observation of SOS database. Due to the possibility of having distinct types of data, i.e. text or numeric, two different fields are used for observed value. This was especially useful for storing the complementary information provided by volunteers (e.g. “0.2 m”).

Moreover, the *observedProperty* considered for each observation provided by the Flood Citizen Observatory corresponds with the categories defined in the platform (see Fig. 5). While for the WSN, it depends on the measurement of the water level reported by the sensor, i.e. “GAUGE_HEIGHT”.

Additionally, other evidence which illustrates that there is interoperability between WSN and VGI is the result of the *GetObservation* operation of the SOS. This is because this operation retrieves observations stored in the SOS in accordance with the O&M specifications (OGC, 2012). One observation from the application of AGORA-DS can be seen in Listing 1. The structured XML provides the same information about the observation as what is stored in the observation table for each observation. The observation displayed in Listing 1 is thus linked to those on line 12 of Fig. 6. The information about the reports was conveyed by the comments on the XML, i.e. the date was May 16, the observed property was water level ruler (in which Portuguese is “níveldeáguacomrégua”), the procedure was “Flood Citizen Observation”, and the observed value reported was “the water level was 0.3 m”.

Listing 1. Return of *GetObservation* operation.

```
<om:ObservationCollection ... >
  <gml:boundedBy>...</gml:boundedBy>
    <om:member>
      <om:CategoryObservation ... >
        <om:samplingTime>
          <gml:TimeInstant>
            <!-- date -->
            <gml:timePosition>2014-05-16T10:10:00.000Z</gml:timePosition>
          </gml:TimeInstant>
        </om:samplingTime>
      <om:procedure xlink:href="urn:ogc:object:feature:
                        Sensor:Ushahidi:observatóriocidadão"/>

        <!-- observedProperty -->
        <om:observedProperty xlink:href="urn:ogc:
                        def:phenomenon:OGC:1.0.30:níveldeáguacomrégua"/>
          <om:featureOfInterest>
            <sa:SamplingPoint ... >
              <gml:description>NOT_SET</gml:description>
              <!-- procedure -->
              <gml:name>FLOOD CITIZEN OBSERVATORY</gml:name>
              <sa:sampledFeature ... />
              <sa:position ../>
            </sa:SamplingPoint>
          </om:featureOfInterest>
          <om:domainFeature ... />
            <!-- observedValue -->
            <om:result codeSpace="null">KART 2 - 0.3m</om:result>
      </om:CategoryObservation>
  </om:member>
</om:ObservationCollection>
```

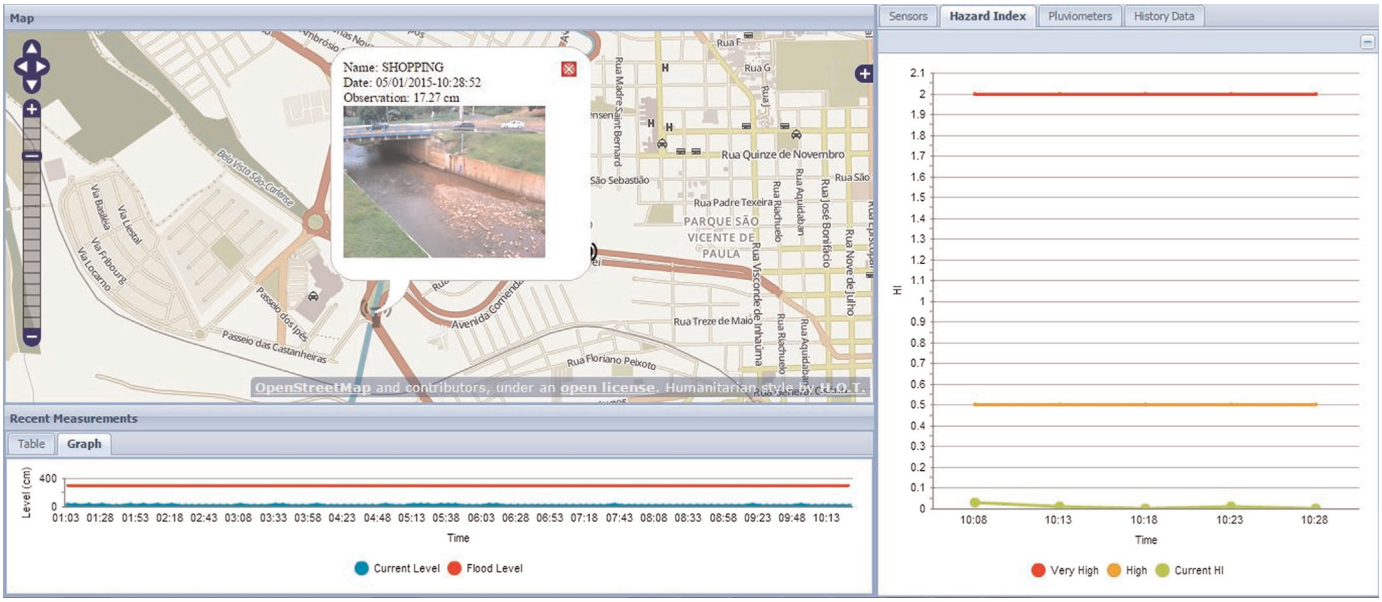

Fig. 7. Integrated visualization of heterogeneous data.

Thus, both sources of evidence outlined above – the observations stored in the SOS database and the response of the *GetObservation* operation – highlight the interoperability between WSN and VGI and the integration of data provided by these data sources. It should be noted that AGORA-DS is fully compliant with the interoperable standards. These ensure the reuse of available data by other information systems, allow the inclusion of new data sources and provide easier access to data for the next layer (or potential data consumers).

Finally, Fig. 7 also presents an evidence of the integration of heterogeneous data given by the Geodashboard. In the same view, the Geodashboard displays the numeric values about water flow (esp. the raw data and calculated hazard index) and a photo provided by the in situ sensor, called "SHOPPING". Thus, this integrated visualization may give more information about the overall situation with the aim of supporting the analysis of decision-makers.

4.3.2. Supporting flood risk management: lessons learned

The use of integrated information gathered via WSN and VGI makes it possible to assess the data collected by the in situ sensors and to provide data about poorly gauged or ungauged areas. In the case of data assessment, VGI supports the decision-makers' analysis to provide data from the same location as the in situ sensors, e.g. the citizens reports that the water level at a specific location of riverbed is 50 cm on the Water Level Ruler while the sensors state that it is 10 cm. This might be because the sensor is broken, needs recalibration or requires a change of battery.

On May 16 2014, this fact was witnessed in the study area. At 09:28 by using the Flood Citizen Observatory, a citizen reported that the water level at the specific location monitored by sensor node 4 called USP 2 measured 30 cm on the water level ruler mechanism, although the visual indicator of the respective sensor was measuring 0 cm, as shown in Fig. 8. After this was checked manually, we found that the sensor had become clogged with mud from the river.

On the same day, citizens had reported the current situation of the riverbed by resorting to the Flood Citizen Observatory. Fig. 9 illustrates an example of these reports on the Geodashboard that was provided by a volunteer. The general tag mechanism of the Flood Citizen Observatory was used by the volunteer to estimate the water level as "Normal". As can be seen from the chart on the right-hand side of Fig. 9, this volunteered information is coherent with the data collected by the in situ sensor called "Kartdromo 2", which lies closer to the area observed by the volunteer. This situation therefore shows that VGI might expand effectively the coverage of monitored areas.

5. Discussion

The deployment described in the previous section provides evidence of the effective use of AGORA-DS for combining heterogeneous data sources, and for supporting decision-making in flood risk management.

It can be seen that the integration of heterogeneous data sources provides more complete, accurate and updated information about the situation in the affected areas. Although official data has provided useful information, they still need to be supplemented by other information to estimate the overall situation, e.g. it is difficult to determine the situation outside the area covered by in situ sensors. These findings about the advantages of using of distinct data sources are in line with those of previous studies (Schnebele et al., 2014; Wan et al., 2014). However, the approaches adopted by these studies only address the question of integration without complying with any interoperable standards. As a result, this might restrict the possibility of including additional data sources. In contrast, in our study we employed these standards so that the data sources could be included in a more flexible way.

In our approach, the integration of distinct data sources is facilitated by adapters responsible for gathering heterogeneous data and converting them to uniform data formats and interoperable standards, as defined by the integration layer. This is because most of the data sources have their own data structures and employ distinct formats (e.g. photo and numeric values) for the same observed property (e.g. the water level), and a different periodicity of data provision. Regarding the data structure, they can be well structured (e.g. water level provided by in situ sensors), semi-structured when some complementary information is needed (e.g. categories of the citizen observatory), or unstructured when inference techniques are necessary (e.g. social media). Thereby, this paper builds upon and extends previous works that use adapters

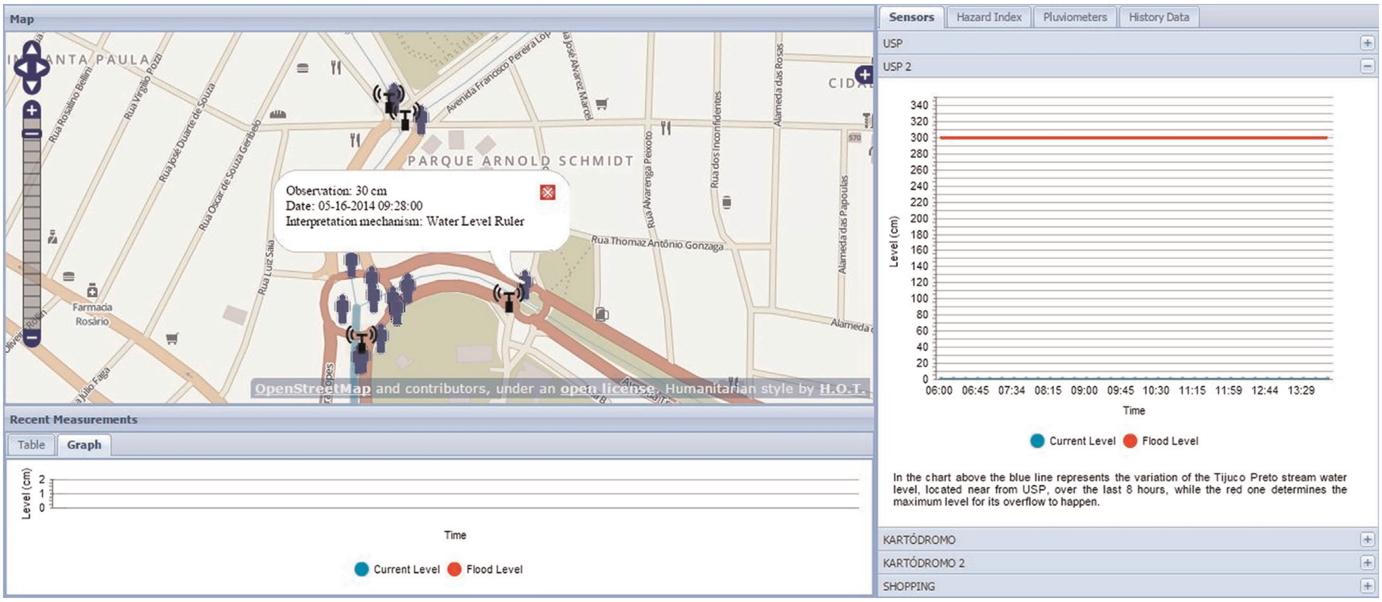

Fig. 8. Citizen's report used for assessing the sensor data.

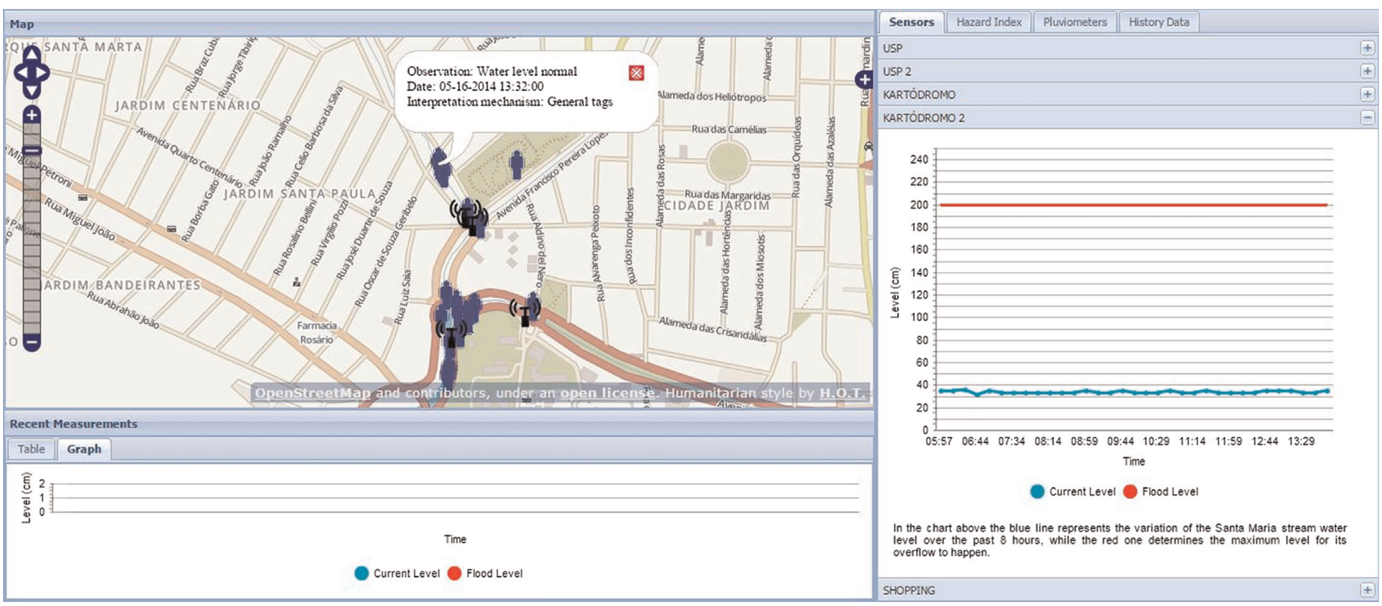

Fig. 9. Citizen's report from the ungauged area.

for integrating geosensor data (Broering et al., 2010a, 2010b; Koga et al., 2012). This is performed by using adapters for encapsulating the different data sources, converting the available data to standardized specifications (i.e. the O&M scheme), and then sending them to the appropriate web service (e.g. SOS). In this way, we were able to handle the discrepancies and idiosyncratic features in the data.

Additionally, the advantages of employing a dashboard to convey the integrated information to the decision-makers, should also be considered within this work. Unlike information systems with various functions that may produce information overload, dashboards concentrate all the information needed on a single screen by means of understandable visual indicators. This can thus be regarded as an extension of previous studies (Zhang and Li, 2005; Markovic et al., 2009; Molina and Bayarri, 2011) in so far as it enables the information to be analyzed and makes clear the amount of integrated information that is available.

Finally, the lessons learned from the deployment in a real scenario have confirmed that AGORA-DS brings relevant contributions to flood risk management. This was made evident by the analysis of the integrated data provided by in situ sensors and citizens' reports. This adds to existing experimental studies which indicate that citizen observations of river levels can be considered statistically equivalent to data acquired from in situ sensors (Degrossi et al., 2014; Moreira et al., 2015). However, to the best of our knowledge, this paper is the first study to evaluate the integration, visualization, and usefulness of heterogeneous data sources (esp. WSN and VGI) using a real-world deployment rather than simulated scenarios. Thus, the findings indicate that the approach described herein can effectively leverage volunteered information to complement data from sensors. The result is then the expansion of the coverage of monitored areas which might extend the perception of decision-makers about the overall situation.

6. Conclusion

This paper has outlined AGORA-DS, a spatial decision support system designed to support the decision-making of emergency agencies by combining WSN and VGI. It was implemented based on a conceptual framework which employs interoperability standards. The results of our deployment in a real scenario showed that AGORA-DS is able to combine the information provided by WSN and VGI and then display it in a way that can be useful for flood risk management. This integration can support the decision-making of emergency agencies by improving the maintainability and assessment of WSN, as well as providing data from poorly gauged or ungauged area through VGI. They also show that well-known interoperable standards are appropriate for handling both this integration and the interoperability of heterogeneous data sources. These standards ensure that the available data can be used again; they also make it easier to include new data sources and obtain access to integrated data for potential data consumers.

Although it has been applied to flood risk management, we believe that the results of this study can be extended to support decision-making in other types of disasters (e.g. landslides). It is recommended that future studies should address the question of the limitations of VGI in composing visual indicators. This will involve adopting an approach that can make use of the data that are based at their location (i.e. the volunteers' reports will provide the historical information of a specific critical flood site). The hydrological time series service could also be used to improve the interoperability and implementation of information supplied by our prototype (OGC, 2014).

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References

Ahmad, S., Simonovic, S.P., 2006. An intelligent decision support system for management of floods. Water Resour. Manag. 20, 391–410. http://dx.doi.org/10.1007/s11269-006-0326-3.

Albuquerque, J.P., Ueyama, J., Mendiondo, E., Caramori, V., 2013. Using wireless sensor networks for urban flood risk adaptation in Brazil. In: Proceedings of the Geoinformatik, Heidelberg, Germany, pp. 1–3.

Baharin, S., Shibghatullah, A., Othman, Z., 2009. Disaster management in Malaysia: an application framework of integrated routing application for emergency response management system. In: Proceedings of the 2009 International Conference of Soft Computing and Pattern Recognition (SOCPAR). Washington, USA, pp. 716–719. doi:http://dx.doi.org/10.1109/SoCPaR.2009.144.

Barros, R.M., Mendiondo, E.M., Wendland, E., 2007. Cálculo de áreas inundáveis devido a enchentes para o plano diretor de drenagem urbana de Sao Carlos (PDDUSC) na bacia escola do córrego do Gregório. Rev. Bras. Recur. Hídr. 12, 5–17.

Broering, A., Foerster, T., Jirka, S., Priess, C., 2010a. Sensor bus: an intermediary layer for linking geosensors and the sensor web. In: Proceedings of the 1st International Conference and Exhibition on Computing for Geospatial Research Application, pp. 1–8. doi:http://dx.doi.org/10.1145/1823854.1823870.

Broering, A., Jirka, S., Foerster, T., 2010b. The sensor bus—integrating geosensors and the sensor web. In: Proceedings of the 2nd Open Source GIS UK Conference (OSGIS), pp. 1–4.

Chae, J., Thom, D., Jang, Y., Kim, S., Ertl, T., Ebert, D.S., 2014. Public behavior response analysis in disaster events utilizing visual analytics of microblog data. Comput. Graph. 38, 51–60. http://dx.doi.org/10.1016/j.cag.2013.10.008.

De Longueville, B., Annoni, A., Schade, S., Ostlaender, N., Whitmore, C., 2010. Digital earth's nervous system for crisis events: real-time sensor web enablement of volunteered geographic information. Int. J. Dig. Earth 3, 242–259. http://dx.doi.org/10.1080/17538947.2010.484869.

Degrossi, L.C., Albuquerque, J.P., Fava, M.C., Mendiondo, E.M., 2014. Flood citizen observatory: a crowdsourcing-based approach for flood risk management in Brazil. In: Proceedings of 26th International Conference on Software Engineering and Knowledge Engineering (SEKE), Vancouver, Canada, pp. 1–6.

Degrossi, L.C., Amaral, G.G., Vasconcelos, E.S.M., Albuquerque, J.P., Ueyama, J., 2013. Using wireless sensor networks in the sensor web for flood monitoring in Brazil. In: Proceedings of the 10th International Conference on Information Systems for Crisis Response and Management (ISCRAM), pp. 458–462. URL: ⟨www.iscramlive.org/ISCRAM2013/files/165.pdf⟩.

Few, S., 2006. Information Dashboard Design: The Effective Visual Communication of Data. O'Reilly Media, Sebastopol, CA, USA.

Goodchild, M.F., 2007. Citizens as sensors: the world of volunteered geography. GeoJournal 69, 211–221. http://dx.doi.org/10.1007/s10708-007-9111-y.

Gunawan, L.T., Fitrianie, S., Yang, Z., Brinkman, W.P., Neerincx, M., 2012. Travelthrough: a participatory-based guidance system for traveling through disaster areas. In: Proceedings of the 2012 ACM SIGCHI Conference on Human Factors in Computing Systems. Austin, Texas, USA, pp. 241–250. doi:http://dx.doi.org/10.1145/2212776.2212802.

Hirata, E., Giannotti, M.A., Larocca, A.P.C., Quintanilha, J.A., 2013. Dynamic and collaborative mapping of flooding in the city of s ao paulo. Bol. Ciênc. Geod. 19, 602–623.

Horita, F.E.A., Albuquerque, J.P., 2013. An approach to support decision-making in disaster management based on volunteer geographic information (VGI) and spatial decision support systems (SDSS). In: Proceedings of the 10th International Conference on Information Systems for Crisis Response & Management (ISCRAM). Baden-Baden, Germany, pp. 301–306. URL: ⟨http://www.iscramlive.org/ISCRAM2013/files/221.pdf⟩.

Horita, F.E.A., Fava, M.C., Mendiondo, E.M., Rotava, J., Souza, V.C., Ueyama, J., Albuquerque, J.P., 2014. AGORA-GeoDash: a geosensor dashboard for real-time flood risk monitoring. In: Proceedings of the 11th International Conference on Information Systems for Crisis Response and Management (ISCRAM). University Park, USA, pp. 304–313.

HR-Wallingford, 2006. R&D Outputs: flood risks to people: phase 2 project record. Technical Report, HR Wallingford, FD2321/PR.

Hughes, D., Ueyama, J., Mendiondo, E., Matthys, N., Horra, W., Michiels, S., Huygens, C., Joosen, W., Man, K., Guan, S.U., 2011. A middleware platform to support river monitoring using wireless sensor networks. J. Braz. Comput. Soc. 17, 85–102. http://dx.doi.org/10.1007/s13173-011-0029-3.

IBGE, 2014. Perfil dos Municípios Brasileiros 2013. Technical Report, Instituto Brasileiro de Geografia e Estatística (IBGE).

Jha, A.K., Bloch, R., Lamond, J., 2012. Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century. The World Bank, Washington, DC, USA.

Jirka, S., Boring, A., Kjeld, P., Maidens, J., Wytzisk, A., 2012. A lightweight approach for the sensor observation service to share environmental data across Europe. Trans. GIS 16, 293–312. http://dx.doi.org/10.1111/j.1467-9671.2012.01324.x.

Jonkman, S., Penning-Rowsell, E., 2008. Human instability in flood flows. J. Am. Water Resour. Assoc. 44, 1–11. http://dx.doi.org/10.1111/J.1752-1688.2008.00217.X.

Kaewkitipong, L., Chen, C., Ractham, P., 2012. Lessons learned from the use of social media in combating a crisis: a case study of 2011 Thailand flooding disaster. In: Proceedings of the 33th International Conference on Information Systems (ICIS), Orlando, USA, pp. 1–17. URL: ⟨http://aisel.aisnet.org/icis2012/proceedings/ProjectManagement/8/⟩.

Khedo, K.K., 2013. Real-time flood monitoring using wireless sensor network. J. Inst. Eng. Maurit., pp. 59–69.

Koga, I., Medeiros, C.B., 2012. Integrating and processing events from heterogeneous data sources. In: Proceedings of the 32th Brazilian Computer Society Conference (CSBC).

Kongthon, A., Haruechaiyasak, C., Pailai, J., Kongyoung, S., 2012. The role of Twitter during a natural disaster: case study of 2011 Thai flood. In: Proceedings of the 2012 Technology Management for Emerging Technologies (PICMET), Vancouver, Canada, pp. 2227–2232.

Lee, J., Kim, J., Kim, D., Chong, P.K., Kim, J., Jang, P., 2008. RFMS: real-time flood monitoring system with wireless sensor networks. In: Proceedings of the 5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS), Atlanta, USA, pp. 527–528. doi:http://dx.doi.org/10.1109/MAHSS.2008.4660069.

Liang, L.Y., Miranda, R., 2001. Dashboards and scorecards: executive information systems for the public sector. Govern. Finance Rev., pp. 14–19.

Mansourian, A., Rajabifard, A., Zoej, M.V., Williamson, I., 2006. Using SDI and web-based system to facilitate disaster management. Comput. Geosci. 32, 303–315 http://dx.doi.org/10.1016/j.cageo.2005.06.017.

Markovic, N., Stanimirovic, A., Stoimenov, L., 2009. Sensor web for river water pollution monitoring and alert system. In: Proceedings of the 12th International Conference on Geographic Information Science (AGILE), Hannover,

Germany, pp. 1–9. URL: ⟨http://www.agile-online.org/Conference_Paper/CDs/agile_2009/AGILE_CD/pdfs/120.pdf⟩.
McDougall, K., 2011. Using volunteered information to map the Queensland floods. In: Proceedings of the 2011 Surveying & Spatial Sciences Biennial Conference, Wellington, New Zealand, pp. 13–23.
Mendes, H.C., Mendiondo, E.M., 2007. Histórico da expans ao urbana e incidência de inundaç oes: O caso da bacia do Gregório, São Carlos-SP. Rev. Bras. Recur. Hídr. 12, 17–27.
Merz, B., Elmer, F., Kunz, M., Mühr, B., Schröter, K., Uhlemann-Elmer, S., 2012. The extreme flood in June 2013 in Germany. La Houille Blanche 1, 5–10 http://dx.doi.org/10.1051/lhb/2014001.
Miorandi, D., Carreras, I., Gregori, E., Graham, I., Stewart, J., 2013. Measuring net neutrality in mobile internet: towards a crowdsensing-based citizen observatory. In: Proceedings of the 2013 IEEE International Conference on Communications (ICC), Budapest, Hungary, pp. 199–203. doi:http://dx.doi.org/10.1109/ICCW.2013.6649228.
Molina, M., Bayarri, S., 2011. A multinational SDI-based system to facilitate disaster risk management in the andean community. Comput. Geosci. 37, 1501–1510. http://dx.doi.org/10.1016/j.cageo.2011.01.015.
Moreira, R.B., Degrossi, L.C., Albuquerque, J.P., 2015. An experimental evaluation of a crowdsourcing-based approach for flood risk management. In: Proceedings of the 12th Workshop on Experimental Software Engineering (ESELAW), Lima, Peru, pp. 1–11.
OGC, 2011. Observations & Measurements - XML Implementation. Open Geospatial Consortium. URL: ⟨http://www.opengeospatial.org/standards/om⟩.
OGC, 2012. Sensor Observation Service Interface Standard. Open Geospatial Consortium. URL: ⟨http://www.opengeospatial.org/standards/sos⟩.
OGC, 2014. OGC Sensor Observation Service 2.0 Hydrology Profile. Open Geospatial Consortium. URL: ⟨https://portal.opengeospatial.org/files/?artifact_id=57327⟩.
Ostermann, F.O., Spinsanti, L., 2011. A conceptual workflow for automatically assessing the quality of volunteered geographic information for crisis management. In: Proceedings of the 14th International Conference on Geographic Information Science (AGILE), Utrecht, Netherlands, pp. 1–6. URL: ⟨http://www.agile-online.org/Conference_Paper/CDs/agile_2011/contents/pdf/shortpapers/sp_122.pdf⟩.
Patel, R., Kaushik, B., 2009. RIFMAS: river flow management system using wireless sensing agents. In: Proceedings of the 2009 IEEE International Advance Computing Conference (IACC), Patiala, Punjab, India, pp. 853–857. doi:http://dx.doi.org/10.1109/IADCC.2009.4809126.
Perhovaz, R.P., 2010. Estudo experimental e teórico da qualidade de água da drenagem urbana com base ecohidrológica (Master's thesis). Engineering School of São Carlos, University of São Paulo.
Poser, K., Dransch, D., 2010. Volunteered geographic information for disaster management with application to rapid flood damage estimation. Geomatica 64, 89–98.
Resch, B., 2013. People as sensors and collective sensing-contextual observations complementing geo-sensor network measurements. In: Progress in Location-Based Services. Lecture Notes in Geoinformation and Cartography, Springer, Berlin, Heidelberg, pp. 391–406. doi:http://dx.doi.org/10.1007/978-3-642-34203-5_22.
Roche, S., Propeck-Zimmermann, E., Mericskay, B., 2011. Geoweb and crisis management: issues and perspectives of volunteered geographic information. GeoJournal 78, 21–40. http://dx.doi.org/10.1007/s10708-011-9423-9.
Rotava, J., Mendiondo, E.M., Souza, V.C.B., 2013. Simulação de instabilidade humana em inundações: primeiras considerações. In: Proceedings of the 20th Simpósio Brasileiro de Recursos Hídricos, Bento Gonçalves, Brazil, pp. 1–8.
Schnebele, E., Cervone, G., Waters, N., 2014. Road assessment after flood events using non-authoritative data. Nat. Hazards Earth Syst. Sci. 14, 1007–1015. http://dx.doi.org/10.5194/nhess-14-1007-2014.
Seal, V., Raha, A., Maity, S., Mitra, S.K., Mukherjee, A., Naskar, M.K., 2012. A simple flood forecasting scheme using wireless sensor networks. Int. J. Ad hoc Sens. Ubiquitous Comput. 3, 45–60. http://dx.doi.org/10.5121/ijasuc.2012.3105.
Shukla, S., Pandey, G., 2014. To design an architectural model for flood monitoring using wireless sensor network system. Int. J. Comput. Sci. Inf. Technol. 5, 502–507.
Triglav-Čekada, M., Radovan, D., 2013. Using volunteered geographical information to map the November 2012 floods in Slovenia. Nat. Hazards Earth Syst. Sci. 13, 2753–2762. http://dx.doi.org/10.5194/nhess-13-2753-2013.
Tu, Y., Li, Q., Liu, R., 2009. A geospatial information portal for emergency management of natural disasters. In: Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Cape Town, South Africa, pp. 404–407. doi:http://dx.doi.org/10.1109/IGARSS.2009.5418100.
Valecha, R., Oh, O., Rao, R., 2013. An exploration of collaboration over time in collective crisis response during the Haiti 2010 earthquake. In: Proceedings of the 34th International Conference on Information Systems (ICIS), Milan, Italy, pp. 1–10. URL: http://aisel.aisnet.org/icis2013/proceedings/ResearchInProgress/96/⟩.
Wan, Z., Hong, Y., Khan, S., Gourley, J., Flamig, Z., Kirschbaum, D., Tang, G., 2014. A cloud-based global flood disaster community cyber-infrastructure: development and demonstration. Environ. Model. Softw. 58, 86–94 http://dx.doi.org/10.1016/j.envsoft.2014.04.007.
Xu, N., Rangwala, S., Chintalapudi, K.K., Ganesan, D., Broad, A., Govindan, R., Estrin, D., 2004. A wireless sensor network for structural monitoring. In: Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems (SenSys), pp. 13–24. doi:http://dx.doi.org/10.1145/1031495.1031498.
Yates, D., Paquette, S., 2011. Emergency knowledge management and social media technologies: a case study of the 2010 Haitian earthquake. Int. J. Inf. Manag. 31, 6–13. http://dx.doi.org/10.1016/j.ijinfomgt.2010.10.001.
Zhang, C., Li, W., 2005. The roles of web feature and web map services in real-time geospatial data sharing for time-critical applications. Cartogr. Geogr. Inf. Sci. 32, 269–283. http://dx.doi.org/10.1559/152304005775194728.