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Towards multi-agency sensor information integration for disaster management

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ABSTRACT

Having access to real-time spatial information is central to the functioning of disaster management, and in particular disaster response. Existing spatially-enabled solutions for managing urban disasters provide limited support for time-sensitivity and urgency underlying emergency situations. These approaches mainly suffer from low temporal resolution and inability to source a broad range of required disaster data, together with insufficient support for automated operations. However, disaster management procedures, integrated with in situ sensing, promise an extensive range of real-time data and automated processes to acquire and manage disaster information. In this research, we study the process of integrating multi-agency in situ sensors for supporting disaster management. For this purpose, the research was adopted in Australia as the case study area in disaster management of a flood by emphasizing on the response phase. This paper first identifies the issues and existing requirements in the process of multi-agency sensor information integration and then proposes a standard-based approach to overcoming these integration issues. Afterward, based on the presented approach and identified requirements, a GIS-based software IDDSS-Sensor is implemented to provide the functions of standard-based access, as well as on-the-fly harmonization, integration and usage of multi-agency sensor information. We evaluate the applicability of our developed approach by applying it to the use case of supporting flash flood evacuation response.

1. Introduction

Disaster is a major challenge in today's world that causes loss of lives and devastating impacts on infrastructures and economies. In 2014, natural disasters caused 7700 fatalities and losses of US$110 billion worldwide (Munich, 2014). Amongst all disasters, flood occurring is the most common (Leskens, Brugnach, Hoekstra, & Schuurmans, 2014). In Australia, flooding counts for an average $377 million in damages annually (Middelmann-Fernandes, 2009).

Currently, the role of spatial information and its exchange between public safety officials is part of the research agenda (Tran, Shaw, Chantry, & Norton, 2009; Zlatanova, Li, Fabbri, & Zlatanova, 2007; Mansourian, Rajabifard, Valadan Zoej, & Williamson, 2006) and is acknowledged in the current practices for multi-agency incident management (VINE, 2013). Recently, attention has been turning towards sourcing and exchanging dynamic disaster information between responding agencies for increased situational awareness (Chen, Wang, Xiao, & Gong, 2014; Farnaghi & Mansourian, 2013).

In line with this demand, in situ sensing has emerged as a spatial data sourcing technology that provides the automated collection of varied information in (near) real-time (Alamdar, Kalantari, & Rajabifard, 2014; Wang & Yuan, 2010). The complications surrounding urgency and time-sensitivity underlying emergency decision-making could be handled by enabling sensor-derived situational awareness to be shared across responder organizations. However, it poses threefold challenges: (1) ensuring interoperability between sensor data providers and disaster management authorities, (2) dealing with existing sources of inconsistencies in sensor data, and (3) derivation of actionable emergency information from raw sensor observations. The goal of this study, therefore, is to tackle these challenges by presenting an approach based on OGC Sensor Web Enablement (SWE) with the following novel contributions:

1. Empirical study: The paper is grounded on an empirical case study on current processes for sensor information integration in the emergency management of Victoria, Australia.
2. Conceptual development: Definition of components for standard-based sensor data access, harmonization, and connection to realize the real-time integration of multi-agency sensor resources across emergency operation centers.
3. System implementation: Development of a GIS-based software tool that enables the integration of sensor information, and aids decision-making in flood response.

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0198-9715/

This work builds on our earlier article: Alamdar et al., 2014 which set out a thorough survey of existing approaches to the state-of-the-art sensor monitoring research for disaster management.

The paper is structured as follows: Section 2 first provides a review of associated concepts, theories and related work. Next, section 3 outlines the results of the case study. Following this, section 4, presents the new approach for multi-agency sensor information integration and sets out its conceptual framework. On this basis, section 5 presents IDDSS-Sensor by describing the associated architecture, technologies and implementation results. Next, section 6 discusses the lessons learned from this deployment and future research considerations. Finally, the conclusion remarks are described in section 7.

2. Background and related work

The principle aim of this research is to improve the access, exchange and use of multi-agency in situ sensor data for supporting disaster decision making. In this section, we outline related work on sensor monitoring, with a special focus on SWE standards for sensor data exchange. Then, we discuss the related research on applying and integrating sensory information in emergency management. Finally, we provide an overview of the users of sensor-derived emergency information and their functional requirements.

2.1. From in situ sensors to real-time disaster information

At present, sensors turn into a very important source of spatial information (Liang & Huang, 2013; Liang & Huang, 2014). Significant live data on our environment (e.g., temperature, soil and water) and also its disasters (e.g., flood occurrence) and human activities during both normal and emergency situations (e.g., traffic and pedestrian behavior) can be observed by diverse types of sensors in the field. This method of data collection falls under the umbrella of in situ sensing, which is the collection of data either inside or in the proximity of a phenomenon (Teillet, Gauthier, & Chichagov, 2002). A series of computerized devices called in situ sensors, or simply sensors, gather this data. A sensor is an observing or measuring device which records environmental data such as rainfall, humidity, temperature, or even location (Duckham, 2013).

In the context of in situ sensing, integration of sensors and their observations for a common application (e.g., disaster management or environmental monitoring) has been targeted mainly through two broad research themes. As the first theme, research work in the (geo)sensor network domain emphasized on overcoming challenges related to constrained energy resources and bandwidth of the network of wirelessly communicating, spatially distributed in situ sensors (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002; Yick, Mukherjee, & Ghosal, 2008; Rawat, Singh, Chaouchi, & Bonnin, 2014). Thus, sensor network research largely deals with designing efficient and scalable protocols with the consideration of the network communication details, device layers, and heterogeneous sensor hardware. Unlike sensor network, sensor web (as the second research theme) hides the underlying sensor communication details and the heterogeneous sensor protocols (Bröring, Bache, Bartoschek, & van Elzakker, 2011a; Chen et al., 2014). Thus, sensor web can be considered as an inclusive and application-centered platform for connecting and integrating multisourced sensors to enable discovery, access, dissemination, and usage of sensor-sourcing information (Delin & Jackson, 2001; Wang & Yuan, 2010). As the major effort to realize the goals of sensor web, the Sensor Web Enablement initiative (SWE[1]) has been developed by Open Geospatial Consortium (OGC) and is designed as a suite of defined standards and web interfaces. The central objective of SWE standards is to enable interoperable web-based discovery, exchange and processing of sensor-derived data as well as task planning with hiding the heterogeneous sensor protocols (Jirka, Bröring, & Stasch, 2009b; Dìaz, Bröring, McInerney, Libert, & Foerster, 2013).

[1] http://www.opengeospatial.org/ogc/markets-technologies/swe.

Fig. 1, shows an overview of the architecture underpinning SWE standards and web interfaces. SensorML defines a schema for metadata description of sensors and sensor systems (e.g., description of identification, input and output of a pedestrian counting sensor). O&M specifies a schema for encoding sensor observations. For example, a pedestrian counting sensor has a result time (e.g., 2015–06-26 T14:30:00Z) and result (e.g., 500 counts) which is an estimated value of an observed property (e.g., number of people) for a feature of interest (e.g., Federation square). SWE Common defines encoding of low-level data building blocks that are used inside the elements of other SWE standards and web interfaces. TML, which is rarely used so far (Jirka et al., 2009b) also addresses encoding of senor observations and metadata, mainly for the application of data streaming. SOS, provides a standardized web service interface to enable web-based accessing and publishing of sensor data and metadata (e.g., SOS defines operations to register a new pedestrian counting sensor, insert or retrieve its observations based on spatiotemporal filters). SAS enables subscription to sensor alerts when certain criteria is met (e.g. receiving an alert if the total number of people observed by a pedestrian counting sensor goes beyond a threshold). SPS provides the ability to control sensors and change their measurement parameters (tasking a pedestrian counting sensor to collect data in finer resolution, if applicable). WNS supports the delivery of notifications between SWE web services and clients (e.g., notifying the generated SAS alert to the subscribed users).

2.2. Related work on integrating sensory information in disaster management

Applying and integrating sensory information in disaster management has gained attention in recent years as an efficient solution for providing live disaster information (Wang & Yuan, 2010; Bunker, Levine, & Woody, 2015). Multisourced sensor information integration concerns combining and processing sensor and spatial data sources to provide added-value information for a common application (Alamdar et al., 2014). Recent valuable research on multisourced sensor information integration applied to problems in disaster management and public safety has been made. Considering the metadata aspect of sensory information in flood monitoring, Chen et al., 2014 developed a sensor web node meta-model and a prototype system, called GeosensorNodeManager, that enables formal description of available node resources. This meta-model could facilitate the allocation of available nodes during flood monitoring tasks. Dìaz et al., 2013 emphasized on the registration and publication of sensor data into Geospatial Information Infrastructures (GIIs), and

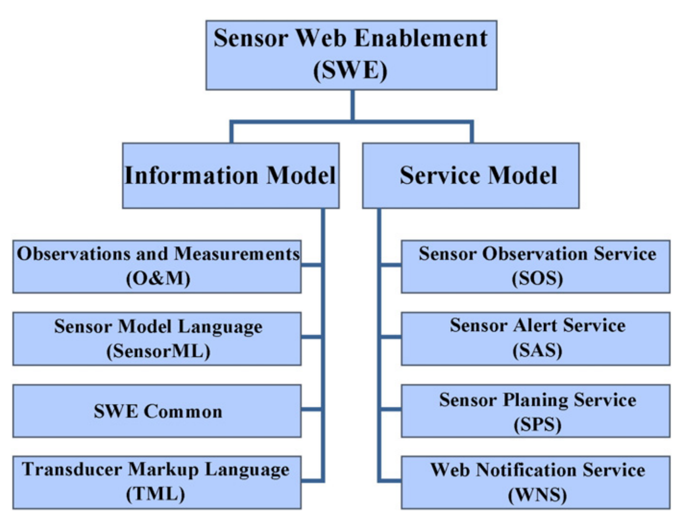

Fig. 1. Overview of Sensor Web Enablement architecture, adopted from Jirka et al. (2009b).

Table 1
Classification of the organizations involved in disaster management of Victoria and their activities with regards to operating in situ sensors.

Name of organization	Type of organization	Operating in situ sensor(s)
Emergency Management Victoria (EMV)	Disaster management	• N/A
Victoria State Emergency Service (VicSES)	Sensor data producer — Disaster management	• GPS-enabled tracking sensors for SES vehicles; GPS-enabled SES personnel devices
Bureau of Meteorology (BoM)	Sensor data producer — Flood management	• Rainfall gauges; River height gauges; Automatic Weather Stations (AWS); Weather watch radars; Deep Ocean Tsunami Detection Buoys; Lightening detection sensors; Coastal sea level stations
Department of Environment, Land, water and Planning (DELWP)	Sensor data producer — Disaster management	• Rainfall gauges; River height gauges
Emergency Services Telecommunications Authority (ESTA)	Disaster management	• N/A
Melbourne water	Flood Management	• N/A
Vicroads	Sensor data producer	• Inductive loop detectors; CCTV cameras on roads
Victoria Police	Sensor data producer — Disaster management	• GPS-enabled tracking sensors for police vehicles; GPS-enabled police personnel devices; CCTV cameras in urban areas
Public Transport Victoria (PTV)	Sensor data producer	• GPS-enabled tracking sensors for trains and buses
Yarratrams	Sensor data producer	• GPS-enabled tracking sensors for trams
City of Melbourne	Sensor data producer	• Pedestrian counting sensors; in-ground parking sensors; CCTV cameras in urban areas
Ambulance Victoria	Sensor data producer — Disaster management	• GPS-enabled tracking sensors for ambulance vehicles; GPS-enabled medical personnel devices
Country Fire Authority (CFA)	Sensor data producer — Disaster management	• GPS-enabled tracking sensors for CFA vehicles; GPS-enabled CFA personnel devices
Metropolitan Fire Brigade (MFB)	Sensor data producer — Disaster management	• GPS-enabled tracking sensors for MFB vehicles; GPS-enabled MFB personnel devices
Distribution companies	Sensor data producer	• Urban facility sensors

proposed an approach based on sensor web service interfaces to integrate in situ weather observations into fire danger models. Kussul, Skakun, Shelestov, Kussul, & Yailymov, 2014; Kussul et al., 2012; Kussul, Shelestov, & Skakun, 2009 developed a sensor web-based approach for flood monitoring in Namibia and Ukraine based on integration of data from satellite and ground stations. As another project, OSIRIS, is a disaster management framework based on sensor web technology for real-time notification and early warning of flooding risks (Jirka, Bröring, & Stasch, 2009a). These existing disaster monitoring sensor web systems address different levels of sensor integration through using open standards. However, none of these studies considered the question of integrating sensor data produced in a multi-agency environment.

A good deal of work on sensor integration for disaster management comes from volunteered geographic information domain (Fohringer, Dransch, Kreibich, & Schröter, 2015; Schnebele, 2014; Wan et al., 2014; Triglav-Čekada & Radovan, 2013; Resch, 2013). Rooted in SWE technology, Horita, Degrossi, Mendiondo, Ueyama, & de Albuquerque, 2015; Horita et al., 2014 developed a sensor web-based system called AGORA-DS for flood risk management in Brazil that combines volunteered geographic observations with in situ sensor observations.

A number of researchers focused on geospatial web service composition and proposed solutions based on OGC web service chaining (Amirian, Alesheikh, & Bassiri, 2010) to provide dynamic disaster information. From the work that considered sensor web services in the composition algorithm, Yulin et al., 2014 proposed a holistic framework based on aggregating and wrapping geospatial resources (including sensor observation services) to serve on-demand disaster information. Through semantic annotation, Babitski et al., 2009 proposed a more detailed procedure for automated composition of sensor observation services to enable sensor discovery and fusion in disaster management tasks. These approaches mainly focused on the problems associated with automated binding of web services, rather than integrating sensor data obtained from multiple sources.

In addition to the research studies in sensor web domain, some operational sensor-based disaster response platforms have been developed in recent years (NICS, 2015; ArcGIS-COP, 2014). The central function of these platforms is to enable shared situational awareness during response operations. Thus, they consider the necessity for sharing sensor-derived resources across responding agencies. However, they usually used proprietary formats for exchanging sensor observations. In addition, they provide limited support for analyzing and interpreting the sensor data in real time.

In summary, none of the above studies considered the architectural requirements for standard-based collecting and integrating multi-vendor sensor data for emergency management. Thus, what is needed is an effective method for making multi-vendor sensor data easily and immediately accessible and useful across emergency agencies.

2.3. Users of sensor-derived disaster information and their functional requirements

In addition to the review of scientific studies, a literature review was conducted based upon operational documentations, official governmental reports and road maps pertaining to sensor-derived emergency information requirements in Victoria, Australia.

Disaster management in Australia is conducted by inter-agency collaboration for various tasks concerning emergency command, control and coordination (EMA, 1998).

Organizations such as emergency services, local city councils, the Bureau of Meteorology and water authorities, public transport, traffic, medical and police departments, and utility companies are committed to collaborate in disaster management, particularly in the response phase. Table 1 provides a classification of the organizations involved in the disaster management of Victoria and their activities regarding operating in situ sensors.

In the context of sensor data provision and exchange for disaster management, the central agency is Emergency Management Victoria (EMV) (EMV, 2014). EMV is a leader in storing and providing real-time emergency information to stakeholders (VINE, 2013). Thus, an ideal workflow for EMV is to enable real-time multi-agency information to be gathered, combined and integrated, so that the value-added information reaches disaster decision-makers.

This literature review has also identified the main functional requirements of an integrated sensor network for agencies responsible for delivering emergency management services to the community. Two key variables were identified in the review, namely:

1. Who are the users?
2. What are their requirements for integrated sensor data?

In relation to the first variable, there are three key user groups which can be classified as the leading Emergency Management Organization (EMO), the emergency services and associated support agencies and the community or citizens. EMO is a term used to describe an organization which gathers and integrates multi-agency real-time information to both coordinate the activities of emergency services responding to an incident as well as provides the community with information and warnings in relation to that incident. Each of these discrete user groups has particular information requirements from the sensor network. Table 2 lists the functional requirements of the particular user groups and provides and overview of the current functionality that these users are able to access. To provide context regarding these requirements, an explanation is provided in the table to outline why the particular users need the information. This analysis is based on the current Victorian arrangements where Emergency Management Victoria (EMV) performs the role of the EMO.

3. Current approach for multi-agency sensor information integration in disaster management community of Australia

Using a case study approach (Yin, 2013), the real-time information flow across state-wide emergency management of Australia was assessed. The case study was conducted through exploring the activities throughout Victoria (a state in south-east Australia) from the viewpoint of incorporating in situ sensor datasets as a source of real-time information for supporting disaster decision-making.

Fig. 2 shows the result of the case study. As seen in the figure, each sensor data producer collects, stores and uses its sensor data for performing intra-agency operations. Data producers primarily use proprietary formats and standards for encoding and exchanging their sensor data. A number of sensor data producers share a part of their sensor data with Emergency Management Victoria(EMV). EMV then provides common access to raw sensor data feeds through visualizing the received data on a base map based on the location and timestamp of the data feeds. Hence, the multi-agency sensor data feeds are stored on separated data layers in EMV's database and the relation between data layers is not established.

The following interconnected issues and challenges which emerging from the current approach were identified:

- *Lack of access to multi-agency sensor data* — Currently, limited disaster-related sensor data is made accessible to EMV. At present, mainly emergency event data feeds (such as road closures) and in situ sensor data feeds (such as meteorological observations) are shared with EMV in near real-time. However, a large amount of disaster-response sensor data such as pedestrian counting data, traffic flow data, public transport data, the location of emergency vehicles and personnel is not yet accessible by EMV.
- *Lack of interoperability in multi-agency sensor data exchange* — For EMV, which needs to receive real-time sensor data from a large number of producers, an efficient exchange of sensor datasets is problematic. Currently, sensor data producers in Victoria use numerous types of sensor data formats (such as raw text data, binary, or different XML variants) and data access interfaces (such as proprietary web services or FTP servers). As a result, using proprietary sensor data formats and standards are causing significant work for integration. For this reason, to access new sensor data sources, the existing data brokering system of EMV needs to be manually changed.
- *Inconsistency in multi-agency sensor data* - Sensor data stakeholders involved in disaster management produce different types of sensor data. This multisourced real-time data shared with EMV may be accompanied by many inconsistencies (e.g., inconsistent or incomplete sensor data specifications).
- *Lack of automated usage of multi-agency sensor data* — Currently, the real-time data feeds shared with EMV are visualized on a base map based on their location and timestamp. More specifically, there is only common access to raw real-time data feeds. As a result, the multi-agency sensor data feeds cannot be used automatically, since the feeds are not machine-readable. In addition, the real-time data received at EMV is still stored on separated and detached data layers, so that concurrent manual or automated queries on multiple data layers cannot be performed.

Table 2
Users of integrated sensor data and their functional requirements.

Category of users	Required functionality	The current situation	Why do they need these functionalities?
Emergency Management Organization (EMO)	• Automated and on-the-fly access to multi-agency sensor data in the disaster area	• Common access to a few number of raw sensor data feeds is established	• To be regularly updated about the current emergency situation from the lenses of available sensors in the disaster area
	• Ability to manually interact with multi--agency sensor data (performing spatio-temporal queries on sensor data sourced from other organizations)	• There is no way for manual interaction with sensor data produced in other organizations	• To be able to perform queries in a higher level on the sensor data produced across other organizations
	• Automated interaction with multi-agency sensor data (automatic event detection and monitoring)	• There is no ability to automatically interact with multi-agency sensor data	• For automated event identification, emergency monitoring, and overcoming the dynamism underlying sensor data
Emergency services; medical service; local municipalities; and other sensor data producers (rather than emergency services)	• To have automated access to the relevant multi-agency sensor data that could assist them for performing their regular operations	• Only ESTA (000) has automated access to a part of sensor data sourced from other emergency services through its CAD system	• To make use of multi-agency sensor data in their intra-agency operations (e.g., emergency services use traffic flow data for improving their dispatching system)
	• To be automatically alerted about the emergency events that could affect their regular operations	• There is a manual and unstructured communication between emergency organizations and sensor data custodians	• To be able to take timely actions in emergency situations
	• To be automatically informed about the recommended actions issued at EMO	• The interaction between emergency organizations and sensor data custodians is manual and usually through phone calls	• To make use of decisions made in EMO based on its overall view of the emergency situation
Citizens	• Ability to view multi-agency emergency information in a unified map using web browsers and mobile devices	• Citizens can view emergency events and warnings in a unified map	• To be informed on the latest emergency situation and recommended actions
	• Ability to identify and perform basic spatiotemporal queries on multi-agency sensor data	• There is not an ability for citizens to perform queries on sensor data	• To be able to take timely actions in emergency situations

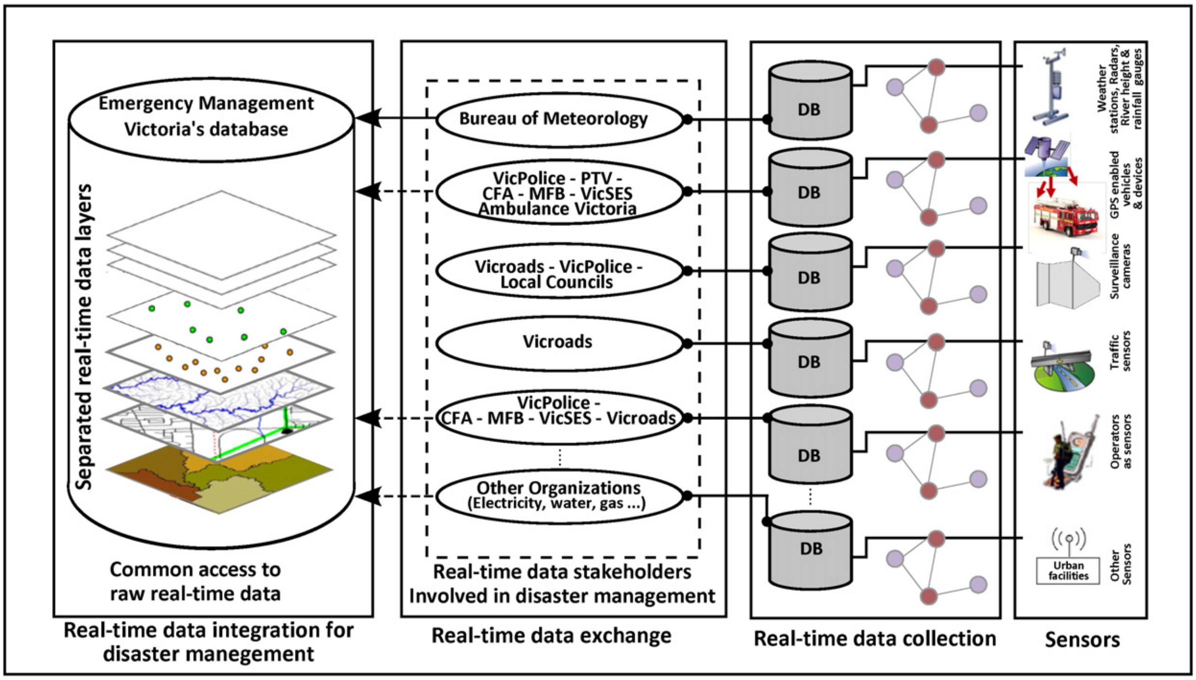

Fig. 2. Current approach for multi-agency sensor information integration in emergency management community of Victoria, Australia.

To address the above issues and challenges, the following sections introduce a new approach to improve the current status of access and dissemination as well as the manual and automated usage of multi-agency sensor datasets for disaster response.

4. Multi-agency sensor information integration approach

As outlined above, the current approach for multi-agency sensor information integration is to provide EMO with common access to raw sensor data. This approach for real-time emergency information provision inhibits EMO and emergency services from taking full advantage of sensor information for supporting disaster decision-making (Alamdar et al., 2014). In consideration of this shortcoming, we developed an approach based on OGC SWE standards (Fig. 3), which contains four main functional components, including:

- Sensor data standardization;
- sensor data harmonization;
- integration data model; and
- sensor web service-based operations.

Sensor data standardization concerns transforming organizational non-interoperable formats and standards to the elements of SWE standards. Sensor data harmonization performs the required steps for identifying and resolving the inconsistencies in sensor data flows that reach EMO. The integration data model connects the multi-agency sensor datasets to enable actual usage of the data for supporting disaster decision-making. Sensor web service-based operations consume the standardized, harmonized and connected sensor data and send back the value-added emergency information. The remainder of this section will be devoted to the description of standardization, harmonization and integration data model components. Section 5, will then illustrate how the actionable sensor information resulted from these components is used by sensor-web service based operations to provide live disaster information.

4.1. Sensor data standardization

The first step to enable multi-agency sensor information integration across the disaster management community is to establish interoperability in the context of sensor data exchange. Until now, various standardization efforts (such as ANZLIC initiatives in Australia (ANZLIC, 2004)) have been set out to address interoperability issues in the context of static spatial data and metadata exchange (Mohammadi, Rajabifard, & Williamson, 2010). However, concerning real-time data management and sharing in Australia, sensor data producers mainly use their proprietary data formats (e.g., binary, text-based, or different JSON and XML formats) and standards. As a result, a common language is required so that homogeneous exchange of sensor data between EMO and sensor data producers could be established. For this purpose, this research makes use of the OGC SWE framework of standards as they enable i) domain independency, ii) producer independency, iii) openness, and iv) inter-organizational interoperability (Bröring et al., 2011b). To achieve this goal, three parts of the SWE standards are considered in this research:

- Observations and Measurements (O&M) that is an information model for encoding sensor observations;
- SensorML that is an information model for sensor metadata specification; and
- Sensor Observation Service (SOS) that provides a standardized web service interface to access and publish sensor metadata and sensor observations.

Given the aim to adopt OGC SWE in large-scale sensor use for disaster management, a agreement on how to apply these standards is needed. Meaning that amongst the generic framework of SWE, only relevant and necessary elements (i.e., those elements that provide added-value for EMO and emergency services) have to be extracted and applied. The challenge here is to develop a profile to restrict the SWE standards to a minimum set of elements that have to be applied by data producers to share their sensor data with EMO. Some SWE profiles were developed in the previous studies for the application scenarios such as environmental monitoring and sensor discovery (Jirka & Bröring, 2009; Jirka, Bröring, Kjeld, Maidens, & Wytzisk, 2012). However, development of a profile for disaster management goes beyond the scope of the previous work and lies in the consideration of this research. Thereby, the sensor data standardization part of this research builds upon and extends previous studies based on the special requirements of EMO for access to the multi-agency sensor data. Two constraints needed to be considered during profile development. The profile has to be minimal in terms of the number of mandatory elements for sensor data exchange since a multitude of elements would result in more complexity, and consequently less acceptability by contributing organizations to share their sensor data. On the other hand, the profile has to be comprehensive in terms of fulfilling EMO's various sensor data requirements. Actionable observations, analysis and alerts need to be derivable from the exchanged sensor data to provide a dynamic and shared view of changing emergency conditions. In this light, the profile development was conducted with close cooperation of industry experts involved in both sensor data provision and emergency management of Victoria.

Table 3 provides an overview of the developed profile. The table consists of three main sections including, SensorML, Observations and Measurements (O&M) and SOS. Each table row at these sections represents a profile element as well as its description. To begin with, SensorML elements specify the required sensor metadata to make sensors identifiable, discoverable and recognizable for EMO. The identification and keywords elements in the SensorML section help emergency decision-makers to rapidly identify and discover the available sensors in the field. The classification element specifies the type of the sensor, which distinguishes whether the sensor continuously delivers observations, or it produces observations only if an event has happened. Relying on sensor type clarification, EMO will be able to distinguish between procedures for monitoring erroneous sensor observations (e.g., detecting packet delivery delay or loss due to sensor failure or communication breakdown). For example, in the case of receiving observations from a continuously monitoring sensor, EMO expects to receive a continuous flow of observations. Thus, the sensor is to be regularly monitored to ensure successful delivery of its observations. The featureOfinterest element includes a reference to the geographic feature that the sensor is collecting observations. The featureOfInterest in SensorML section enables the connection between stationary sensor data sources with the spatial data available at EMO's database through harmonization process (see Section 4.2). The outputs element specifies which observable properties can be sensed by the sensor. This element makes sensors recognizable for EMO in terms of their supported observation types and units of measurement. The capabilities element comprises of a number of sub-elements that define the data-capturing configuration of the sensor as well as its current status. The existence of these sub-elements is important for EMO to automatically identify the measurement range of the sensor, the temporal resolution of its observation, the current status of the sensor for data collection, and, if applicable, the area that is monitored by the sensor. The position element defines the geographic location of the sensor and an attribute that indicates whether the sensor is stationary or mobile.

The O&M section in the table specifies the required elements for exchanging organizational sensor observations. The phenomenonTime, resultTime and validTime are included to handle sensor observations with respect to time. Having a combination of elements for observation time is of particular importance for sensors with even-responded monitoring type. The reason is that phenomenonTime might significantly differ from resultTime for event observations due to the post-processing step(s). Besides, in contrast to the continuously monitoring observations, the validTime for event observations may be varied from time to time. Herein, since auto-generating validTime based on sensor frequency may not apply to all types of observations, the validTime element is included in the O&M section of the profile. The procedure element establishes the connection between observation and sensor metadata through providing a reference to the sensor that delivered the observation. The featureOfInterest element in the O&M section is required for mobile sensors, particularly because the featureOfInterest associated with the sensor observations might change during the course of time. The observableProperty and result elements define the data content of the observation through the specification of the observed phenomenon, the type of observation, and if applicable, its unit of measurement.

The SOS section in the table lists the required operations to provide EMO with web-based access to multi-agency sensor data. The GetCapabilities operation gives high-level information about the SOS server, including a description of its content as well as its supported operation parameters. The DescribeSensor enables EMO to get access to the SensorML files of the sensors. The GetObservation operation is used to access sensor observations. The GetFeatureOFInterest operation allows retrieval of geometric descriptions of features assigned to the observations. A more detailed description of all profile elements can be found in Table 3.

4.2. Sensor data harmonization

As mentioned above, sensor data standardization is the first step to enable interoperable flows of multi-agency sensor data by providing a common agreement on how to share the produced sensor data with EMO. Thus, standardization filters a number of existing sources of inconsistency in multi-agency sensor data. However, standardization cannot guarantee the full integratability of the exchanged multisourced

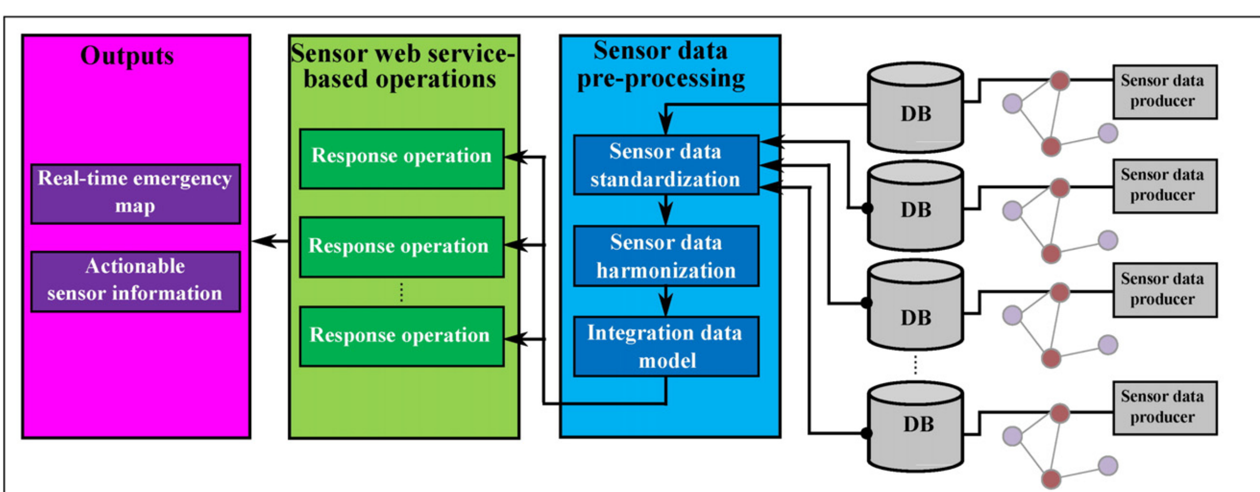

Fig. 3. The new approach proposed for multi-agency sensor information integration to facilitate disaster response.

Table 3
The proposed profile of SWE standards for exchanging multi-agency sensor data with EMO.

Element	Description	
identification	An element comprising the names of the sensor (i.e., short name and long name) as well as one unique identifier for the sensor.	SensorML 2.0
keywords	A list of human readable terms that describe the sensor. The keywords help emergency responders in the discovery of sensors.	
classification	Classifiers characterizing the type of the sensor. There shall be a classifier describing the sensor type that takes a value from “Continuously Monitoring” or “Event Responded Monitoring”.	
contacts	The contact information of the sensor's administrator.	
featureOfInterest	A list of references to the geographic features(s) that the sensor is delivering observations (e.g., the feature of interest of a deployed traffic sensor shall include a reference to the road segment that the sensor is delivering traffic flow observations).	
outputs	A list of observed properties as the outputs of the sensor. Each observed property includes the name, definition, supported data type and if applicable the unit of measurement.	
position	The geographic location of the sensor including the reference frame and a Boolean attribute that describes whether the sensor position is fixed (true) or not (false).	
validTime	The time period in which the sensor description is valid.	
capabilities	lists up the attributes that describe the configuration of the sensor including the following sub-elements:	
	Sub-element — *Description*	
	measurementRange — Specified range(s) that the sensor is capable of delivering observations (mandatory for sensors with numeric or count observations).	
	frequency — The precision of sensor measurement with respect to time (mandatory for sensors with continuously monitoring type).	
	status — Indicates whether the sensor is collecting data at the moment (active) or not (inactive).	
	observedBBOX — The area that is observed by the sensor (e.g. observedBBOX for a pedestrian counting sensor is the counting zone that the sensor is capable for observing the number of pedestrian).	

Element	Description	
identifier	Indicates a unique identifier for the observation.	O&M 2.0
phenomenonTime	The time instant when the observation was made (e.g., the time instant when a Traffic Management Point (TMP) was issued by the operator on the scene).	
resultTime	The time instant when the observation became available (e.g. the time instant after the issued TMP was processed at Traffic Management Center, and it became available). If there is no postprocessing step, the resultTime is the same as phenomenonTime.	
validTime	The time period during which the result is valid (mandatory for sensors with event responded monitoring type).	
procedure	The identifier of the sensor that has performed the observation.	
observedProperty	The observed phenomenon underlying the observation.	
featureOfInterest	The identifier of the geographic feature in which the observation is assigned to (e.g., identifier of the road that the TMP is issued). This element is mandatory for observations with geometry type.	
result	The value of the observation specified based on one of the following supported data types:	
	Type of observation — *Result type*	
	CountObservation — Observations that take an integer value.	
	NumericObservation — Observations that take a scalar value including the unit of measurement.	
	CategoryObservation — Observations that take a value from a predefined enumeration.	
	TruthObservation — Observations that take a Boolean value (i.e., true or false).	
	GeometryObservation — Observations that take a position value (e.g., (x,y)), including the reference frame.	
	TextObservation — Observations that take a text value.	

Operation	Supported parameters	Description	
GetCapabilities	N/A	Requesting a description of the content and allowed operation parameters of a SOS server.	SOS 2.0
DescribeSensor	procedure	Requesting SensorML file of a sensor based on the sensor identifier	
GetObservation	offering	Requesting observations based on offering identifier (optional)	
	temporalFilter	Requesting observations restricted to a time period or time instant (optional)	
	procedure	Requesting observations based on sensor identifier (optional)	
	observed Property	Requesting observations based on phenomenon identifier (optional)	
	featureOfInterest	Requesting observations based on geographic feature identifier (optional)	
	spatial Filter	Requesting observations restricted to a bounding box (optional)	
GetFeatureOfInterest	featureOfInterest	Requesting geographic features restricted to a time period or a time instant (optional)	
	spatialFilter	Requesting geographic features restricted to a bounding box (optional)	
	observedProperty	Requesting geographic features based on phenomenon identifier (optional)	

sensor data. Some of the frequent issues while the organizational sensor data flows reaches EMO are:

- Inconsistency in sensors' metadata, such as noncompliant observed properties and units of measurement; and
- inconsistency in sensors' observations, such as missing and faulty sensor data particularly as the consequence of disaster occurrence.

Therefore, once the standardized sensor data reaches EMO, there is a need to automatically identify and resolve the remaining inconsistencies in the received data. The sensor data harmonization component of our approach addresses this necessity with on-the-fly validation and harmonization of the sensor datasets before they can be used by the integration data model and sensor web services.

Fig. 4, shows the workflow for sensor data harmonization developed as part of our work. Our approach to harmonization involves two main steps, one for consistency checking and harmonizing the received SensorML files and one for validity checking of the O&M files. The workflow begins upon receipt of the user's request for retrieval of sensor data. The user's request includes the URL of an SOS instance, a temporal as well as a spatial filter specifying the time range and the bounding box of the area of interest for retrieving sensor data. Based on the SOS URL, harmonization service first generates a GetCapabilities request to be notified about the content of the SOS server. The received GetCapabilities document is then parsed and analyzed, and consequently an array of relevant procedure identifiers are retrieved. For each procedure identifier, a DescribeSensor request is generated and submitted to the SOS server. Thereby, the SensorML file associated with the procedure is retrieved and parsed. The result of the parsing process is the SensorML elements and their associated building blocks, including attributes, attribute values, and element values. The following two basic levels of consistency checks are then performed to ensure that the content and structure of the received elements are compatible with the profile:

- Element existence check, to ensure that the profile elements and building blocks are existing in the received SensorML file; and
- element null value check, to detect SensorML building blocks with empty value.

According to the necessity for automatic harvesting of sensor metadata during its usage, the SensorML elements can be classified as either critical or non-critical. Critical elements are to be harvested automatically by web processing services, whereas noncritical elements are to be manually used by a human user. As the result, inconsistency in the critical elements would impair the performance of the developed services for on-the-fly analysis of the incoming sensor data. Therefore, after performing the above two levels of validity checking, in case the element is critical, harmonization service proceeds with performing consistency checks based on the content of the element. For this work, we considered five elements and their sub-elements as critical (including position, featureOfInterest, outputs, classification, and capabilities) since they are harvested automatically and used as input for our developed services.

Harmonization for the position element includes identification of sensor mobility, as well as recognition of geo-coordinate format and spatial reference system (SRS), and if required converting the coordinates and SRS to a common format. As a key harmonization step, featureOfInterest is assessed to establish the relationship between the sensor and spatial data at EMO's database. In this process, harmonization service first extracts the relationship between the sensor type and feature classes from the schema of the integration data model (see Section 4.3 for data model description). In case a relationship is found, the consistency of the feautureOfInterest is validated through executing an existence check against EMO's data dictionary. Once the featureOfInterest is recognized as a compliant feature, the sensor relationship is constructed and saved in the database. In consideration of the outputs element, harmonization involves recognition of the sensor's observed properties as well as underlying data types and units of measurement. For this purpose, the content of the outputs element is compared with EMO's phenomenon dictionary to ensure the availability of the observed properties in the dictionary. If required, a conversion is performed to transform different representation of the properties and units of measurement to a common format. Consistency checking for the classification element includes sensor type recognition with distinguishing the sensor as continuously monitoring or event-responded monitoring. Finally, consistency checking for the capabilities element includes its analysis to harvest the data capturing configuration of the sensor. The results of the harmonization operation for each element are determined as status flags, through assigning a state amongst the possible outputs of the operation. The generated flags are added as extra attributes to the original data and saved in the EMO's database.

Once the consistency checking of all SensorML files served by the SOS server is completed, a report based on the stored flags is generated. In this reporting process, the noncompliant critical elements are classified and provided to the user for taking action in resolving the identified inconsistencies. Depending on the source of inconsistency, the possible actions vary and include selecting an item from a drop-down list of suggested values (e.g., for noncompliant observed properties), selecting a feature from the map (e.g., for noncompliant feature of interests), or manually completing the value of the inconsistent items.

After completion of the harmonization process for sensor metadata, the process continues in case the user requested sensors' observations. Harmonization for sensors' observations mainly consists of getting and parsing O&M files as well as on-the-fly detecting of unusual events that may happen during GetObservation process. The input parameters for this process are supplied by the initial user-defined parameters (i.e., SOS URL, spatial and temporal filter), as well as some of the harmonized SensorML elements (comprising procedures' identifier, outputs, frequency, measurement range, type, and mobility). In this iterative process, harmonization service continuously generates a URL of the GetObservation request and submits it to the SOS server. Once the O&M files are received, they are individually parsed, and their contents are retrieved. Since each observation is served independently by the SOS server, the retrieved observations for the sensors with multiple outputs are grouped and analyzed together. Next, if the observation is belonging to a mobile sensor, steps for relationship construction and consistency checking of its featureOfInterest are performed (using similar methods described above for dealing with featureOfInterest in SensorML files).

Based on the type of the sensor associated with the observations, the remainder processes are sub-divided into two streams. In case the sensor that delivers observations is of event responding type, methods for event validity check, as well as data duplication and faultiness detection are called. Otherwise, for a sensor with continuously monitoring type, methods for detecting packet loss and delivery latency, along with observation duplication and faultiness are invoked. In this regards, event validity check function regularly monitors the events using the validTime and result values to keep track when they expire, or their status changes. Functions for packet loss and delivery latency detection work based on the resultTime in combination with the procedure's frequency and outputs. These methods monitor the delivery of observations with respect to time and trigger in case observations are missing, or there is a substantial delay in their delivery. Method for faulty data detection checks the validity of the observation's result to ensure that it falls within a range of allowed values. For this operation, procedure's measurementRange is applied for numeric and count observations, whereas the code-list included in the procedure's outputs is used for validity checking of category observations.

Upon completion of the analysis for GetObervation request, the times for sending subsequent requests are defined based on either the procedure's frequency (for continuously monitoring observation), or validTime (for event observations). The harmonization result for each GetObservation response is determined as a status flag (e.g., valid or faulty observation, etc.), stored as an extra attribute to the original data and saved in the EMO's database. The user is also notified if an important issue (e.g., sensor failure) is detected during GetObservation operation.

4.3. Integration data model

As mentioned previously, one of the major issues inhibiting actual usage of multi-agency sensor data for disaster management is storage of the exchanged real-time data on separate and detached data layers. As a result, derivation of actionable information from the isolated layers of sensor data remains problematic. To address this shortcoming, a data model needs to be in place to establish the relations between organizational sensor data that reach EMO with static spatial data stored in EMO's database.

This paper therefore tackles this challenge by developing integration data model, a database model that provides linkage between the sensor and spatial data sources. The process of data model development was guided by a systematic and continuous requirement analysis which in turn included extensive documentary review, data audit from the operational sensor-based disaster response frameworks in Victoria, as well as discussions with experts involved in the emergency management of Victoria.

Fig. 5, shows the conceptual design of the integration data model illustrating the required features and their relationships. This data model is based on the sensor data requirements of EMO for flood disaster management. The UML class diagram was used for the presentation of the data model. Because of limited space here, the class attributes are not included in the class diagram.

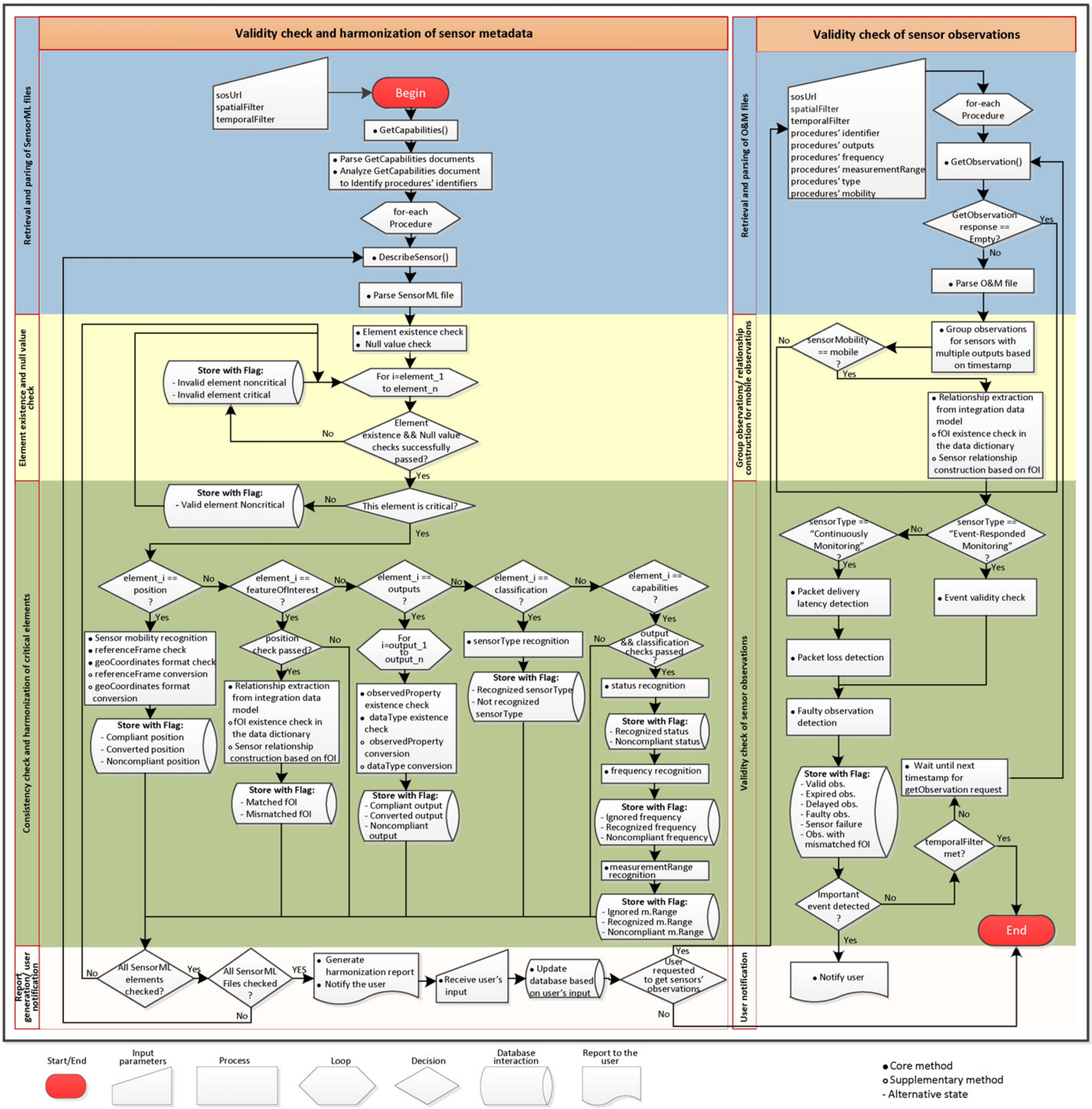

Fig 4. The process chain of sensor data harmonization component for on-the-fly validation and harmonization of the exchanged sensor data.

A high-level classification of the classes is provided and color-themed in the figure, including Flood, Water Features, Transportation, Ground Observations, Emergency Events and Important Infrastructures. The flood comprised of the required classes to represent the historical (e.g., flood risk scenario maps) and real-time flood information (e.g., flood forecasts, warnings and observations). The water features register the important hydrologic features in which EMO needs to use during the management of a flood calamity. These features include static spatial data such as river network and water storages and also sensor data like river height and rainfall observations. The transportation contains classes required for monitoring traffic and people movement during disaster management. These classes include spatial data about transportation infrastructures such as road and railway network, but also the live sensor datasets that are linked to them (e.g., pedestrian counting, traffic flow and public transport data). The ground observations hold the multi-agency sensor data that is collected by the operators in the field (e.g., water level observations). The emergency events pertain to the event observations that are published by emergency services (e.g., tree down). Finally, the important infrastructures contain the features of interest that their status needs to be regularly monitored during a disaster. Examples are elements at risk such as underground car parks and emergency service stations, in which data about their occupancy or capacity needs to be shared with EMO in real-time.

According to the updating rate of information, the classes are classified into four types and distinguished in the figure, including static feature classes, static tables, dynamic feature classes and dynamic tables. Static feature classes maintain information describing spatial locations with slow and steady rate of collection and keeping up-to-date (e.g., spatial data in EMO's database and metadata of stationary sensors). Static tables keep invariant non-spatial data (e.g., transportation network connectivity). Dynamic feature classes consist of information describing spatial locations with a rapid rate of acquisition and keeping up-to-date (e.g., sensor observations of mobile sensors). Dynamic tables maintain non-spatial highly variant data (e.g., sensor observations of stationary sensors).

In terms of the relation between data sources, the featureOfInterst identifier (encoded in the sensorML and O&M files) is used for binding sensor data to spatial data. This process is undertaken as part of harmonization process and discussed in Section 4.2.

5. System implementation and flood monitoring experiment

On the basis of the presented approach, a GIS-based software IDDSS-Sensor is implemented to provide the functions for standard-based accessing, integrating and visualizing real-time sensor data. For the application scenario of flood monitoring, flash flood evacuation use case is selected as an example to evaluate the applicability of IDDSS-Sensor. Section 5.1 outlines the overall picture of the architecture underlying the system. Section 5.2 introduces the employed technologies for developing the architectural approach, and finally Section 5.3 presents the implementation results.

5.1. Architecture

Fig. 6 illustrates the system architecture and outlines an overall picture of the involved communities, the core components of the system and the linkage between these components. Based on the architecture, each organization is responsible for managing its sensor-derived datasets for everyday businesses as well as intra-agency emergency management. For enabling the flow of sensor data between sensor data producers and EMO, two possible solutions were considered and illustrated in Fig. 7.

As the first solution, sensor data producers share raw sensor data feeds with EMO. Thereby EMO performs all the steps for sensor data standardization, harmonization and usage. This approach reduces the amount of work that needs to be done on the sensor data producers' side for transforming their produced data into SWE profile. However, this approach incurs more integration efforts for EMO since to access a new data source, EMO requires a new adapter for converting data to standardized specification.

As the second solution, sensor data producers rely on a Sensor Observation Service (SOS) server provided by EMO that offers standardized interface for publishing sensor data into the system of EMO. The advantage of this approach is that standardized sensor data can be directly pushed to EMO, so that it frees EMO from standardizing the sensor data. Also, this approach provides the capability for two-way exchange of data between data producers and EMO. Due to these advantages, the second one was preferred in this paper.

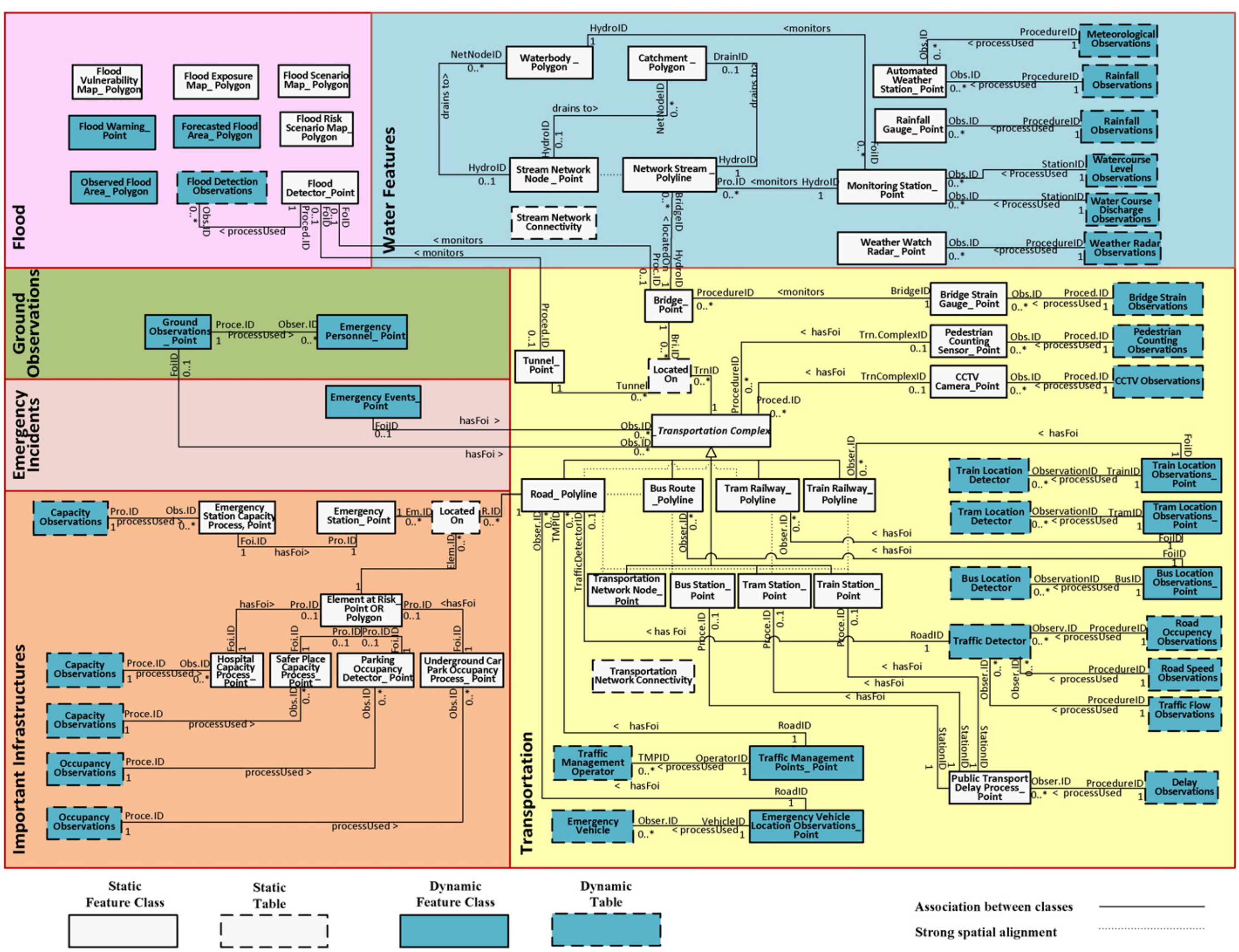

Fig. 5. Integration data model class diagram representation.

In addition to the workflow for sensor data exchange, the supporting methods for publishing sensor data to EMO needed to be defined in the architecture. In this regard, two methods for publishing sensor data are supported through the system. In the first case, data producers actively push (i.e. transmit) their sensor data into SOS server, so that these data feeds are regularly reached and stored in EMO's database. In the second case, sensor data are pulled from SOS servers to EMO's database upon EMO's request. The reason underlying push-based and pull-based sensor data exchange is that a portion of the sensor data feeds (e.g., he location of emergency vehicles and personnel) needs to be regularly shared with EMO for supporting its emergency management decision-making. As a result, organizations such as emergency services, medical service and police department should regularly provide EMO with their produced sensor data. On the other hand, other parts of the organizational sensor data (e.g., pedestrian counting data) are considered as on-demand emergency information and should be transmitted to EMO during emergency situations and upon EMO's request.

5.2. Implementation technologies

To develop the architectural approach, certain open-source technologies are combined to interactively work together. As shown in Fig. 6 (earlier), the architecture of IDDSS-Sensor has three layers, namely, the storage, service, and presentation layer. The characteristics of each layer and the open-source technologies used to implement the layer components are as follows:

5.2.1. Storage layer

This layer provides the databases that store the sensor and spatial data for the prototype system. PostgreSQL, an open-source object-relational database system (PostgreSQL, 2015), was selected for the storage layer of the IDDSS-Sensor. PostGIS (PostGIS, 2015) which adds spatial capabilities to PostgreSQL was used for spatial enablement of the databases. The following databases are then generated:

- Integration data model's database: this database was created to implement the integration data model, in which plays the role for EMO's database. It provides the storage place for the spatial data, the spatial relations defined in the data model, and the harmonized sensor data feeds.
- Sensor data producers' databases: these databases were created and deployed on the cloud to couple the SOS servers of sensor data producers.

5.2.2. Service layer

This layer aims to provide the required SWE compliant services for the following tasks:

1. Publishing interoperable sensor data flows by sensor data producers and receiving the data at EMO;
2. validating and harmonizing the standardized sensor data flows reached at EMO;
3. identifying events through retrieving sensors' observations and processing against stored event queries;
4. monitoring the flood area through concurrent aggregation of the result value of sensors' observations.

In order to address the first task, the existing open source 52^0North SOS (52North, 2015) was employed as SOS implementation and for the last three tasks three new sensor web services were developed. For the development of these web services Java language was used. This process was facilitated by hiring geodata manipulation features from an open source platform called Intelligent Decision Support System (IDDSS) (Rajabifard, Thompson, & Chen, 2015). IDDSS is a framework of disaster management information infrastructure facilitating the integration and interpretation of multi-sourced spatial data and services.

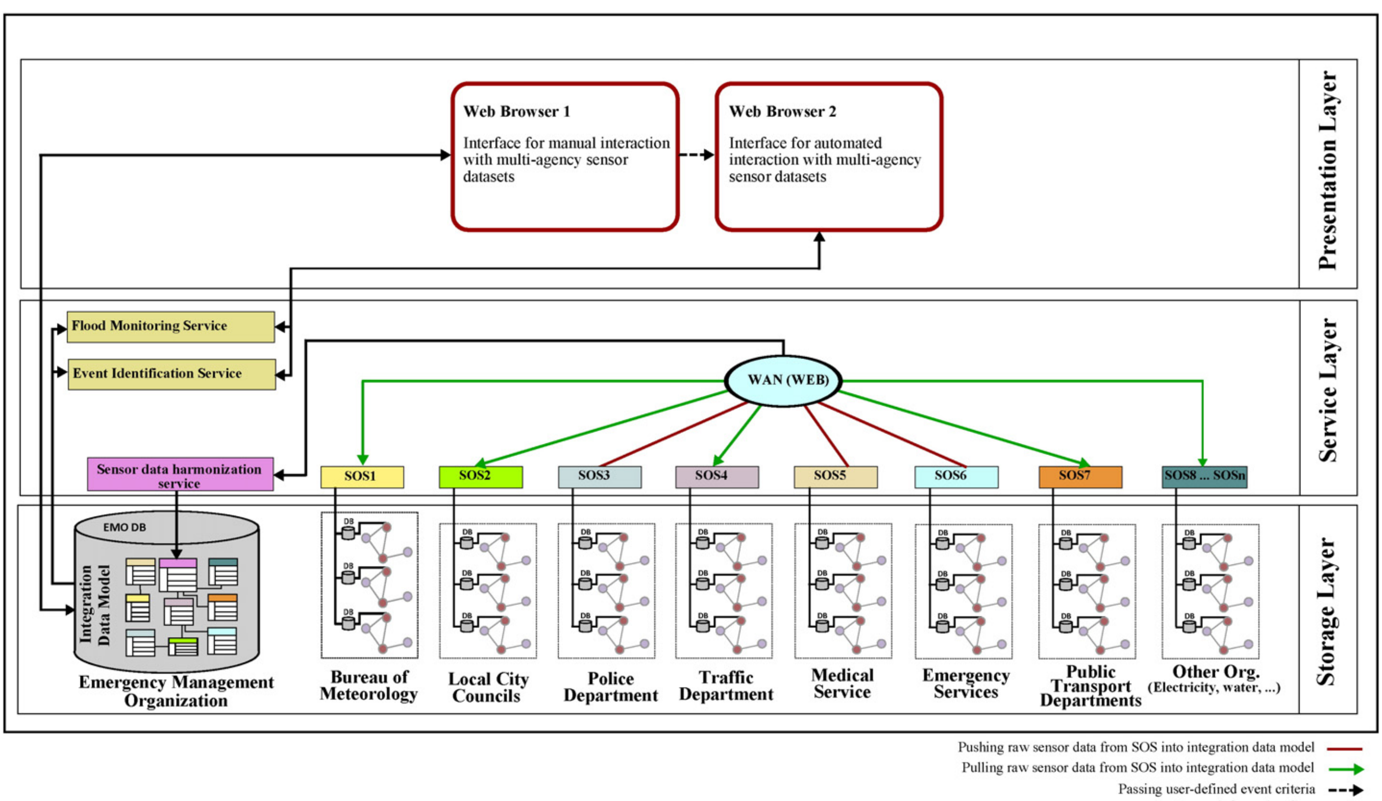

Fig. 6. Technical architecture of IDDSS-Sensor.

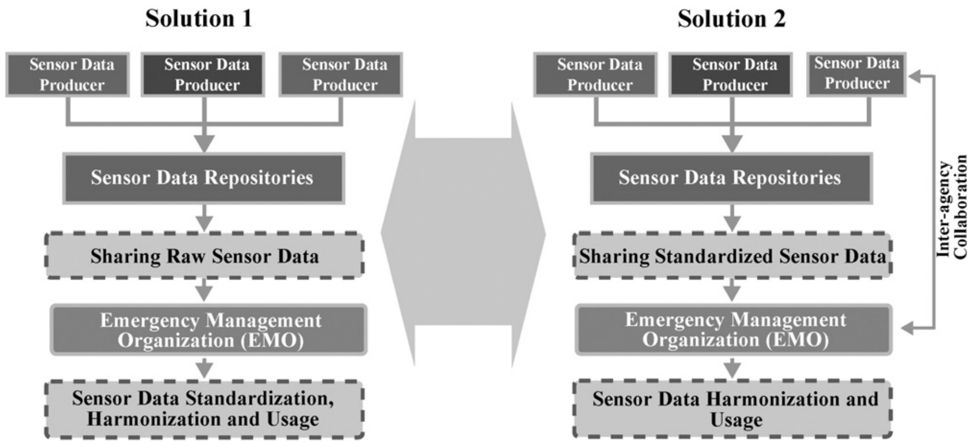

Fig. 7. Two possible workflows for multi-agency sensor data standardization, harmonization and usage.

IDDSS-Sensor is developed as a module of IDDSS. This module adds functionality related to sensor data integration and interpretation into IDDSS.

In addition, wherever needed GeoServer (GeoServer, 2015), which is supported by IDDSS, was used as spatial data service for serving static spatial data.

5.2.3. Presentation layer

This layer provides the GUI of the system. For GUI implementation JavaScript was used as development language with the aid of CESIUM,[2] ExtJS[3] and IDDSS which are used for displaying the sensor data and visual indicators.

The above three layers work interactively to provide the functionality highlighted throughout this paper. In addition, the layers as well as the components in each layer are loosely coupled and module-based. This separation gives the flexibility to choose later between different arrangements of deploying the software application on a set of servers thus providing more performance and scalability for working with highly dynamic sensor data. Fig. 8 outlines the overall view of IDDSS-Sensor client application. The reminder of the paper presents how IDDSS-Sensor works in consideration of supporting flash flood evacuation task through providing simulation results.

5.3. Implementation results

In order to evaluate whether the proposed approach is suitable for supporting disaster response operations, flash flood evacuation monitoring is selected as a use case scenario to test its applicability and effectiveness. For this purpose, the general timeline of flood evacuation operations is first briefly described, allowing us to examine the application of the presented approach during this timeline. The pilot project area and data sources are then described, and the simulation results obtained with IDDSS-Sensor are presented and discussed.

5.3.1. Flash flood evacuation timeline

To deal with understanding of the timing and dynamics of large-scale flood evacuation operations, Opper & Wales, 2004 and Lindell, 2002 developed methods to distinguish the key elements of flood evacuation. Based on these methods, flood evacuation response operations can be subdivided into five overlapping phases, including flood prediction, decision making and mobilization, warning delivery, evacuation operation, and rescue phase (ESM, OAM, & Davies, 2010). Flood evacuation monitoring is an application scenario that involves most of the multi-agency sensor resources, so that integrated management of sensor data could serve an important function during this process. Effective monitoring and supporting the progress of this highly dynamic process at EMO depends on the availability of homogeneous sensor information feeds, and consequently the possibility for deriving actionable information from the raw sensor feeds. This experiment is accordingly conducted to demonstrate the application of our work during flood evacuation timeline through simulating and then processing sensor data in a pilot study area.

5.3.2. Pilot study area

City of Melbourne, a municipality within the capital city of Melbourne in Victoria, is selected as the pilot project area and shown in Fig. 8 (earlier). This municipality is in a region that has existing vulnerability to frequent sever flash and river in floods (Comrie, 2011). City of Melbourne is consistently one of the fastest growing municipalities in terms of deploying and incorporating state-of-the-art of sensor monitoring technologies. Because of flood proneness and feasibility of applying the proposed approach in the City of Melbourne, this region is selected as a pilot study area to run the experiment.

5.3.3. Data sources

Given the aim to test the effectiveness of the developed models and implemented prototype system, a pragmatic approach towards data sources was needed, meaning that relevant spatial and sensor data sources were required to be collected, prepared, standardized and loaded into the system. The main limitation inhibiting data collection phase was scarcity of the accessible sources for organizational sensor observations. As the result, to run the experiment, metadata of sensors was obtained from official sources, whereas the observations of the sensors were simulated for a period of six hours in every ten minutes time interval. The sensor types were selected in a way that they included both continuously monitoring and event-responded types and covered all the supported observation types. Table 4, provides the sources of gathered data for running the experiment. Afterward, the standardized sensor metadata and simulated observations were loaded to the SOS servers deployed on the cloud. The process for sensor data loading into SOSs was aided by 52^{0}North SOS Importer.[4] Also, the static spatial data was prepared and loaded into the integration data model's database.

5.3.4. Simulation results

Within the pilot study area, we used the above data sources to test the system.

[2] http://cesiumjs.org/.

[3] http://www.sencha.com/products/extjs/.

[4] 52north.org/bin/view/SensorWeb/SosImporter.

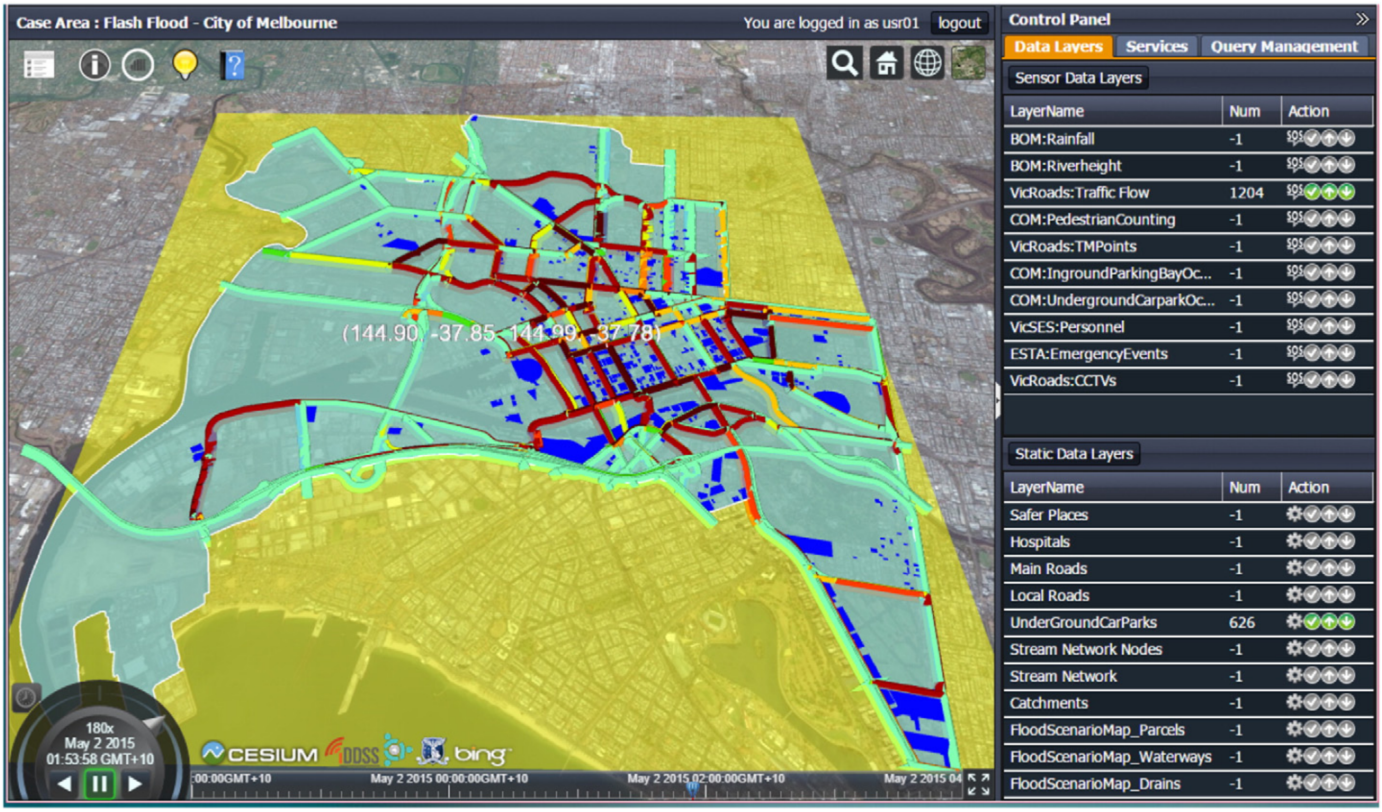

Fig. 8. The GUI of IDDSS-Sensor client application.

Three panels are deployed in IDDSS-sensor, one panel for loading and harmonizing sensor data (i.e., Sensor Data Layers panel), and two panels for integration of sensor information (i.e., Query Management and Services panels). The interaction between user and the system starts with defining a use case area (in our case, City of Melbourne) as well as selecting the requested data source (SOS URL for sensor data and WFS URL for static features). To enhance this, the application provides interactive tools and commands for obtaining user inputs (e.g., temporal filter for retrieval of sensor observations). In case of requesting sensor data source, the harmonization service is called through passing it the defined SOS URL as well as the spatial and temporal filter. Sensor harmonization service then performs the workflow that is specified in Section 4.2 to check the consistency, and to harmonize the data served by the SOS instance. AJAX technology is used to handle the interaction between client-side and server-side of the application together but also with GeoServer and SOS servers. Having completed the server-side harmonization operations, a report is generated and provided to the user showing the identified sources of inconsistency in the retrieved SensorML files. Fig. 9, illustrates the harmonization results for the SOS server that serves pedestrian counting data.

As can be seen in the figure, the noncompliant critical metadata elements for each sensor are provided to the user to take action. In case the sources of inconsistencies are resolved by the user, sensors' observations can be collated and displayed. For visualizing time-series sensor observations and query results in IDDSS-Sensor, CZML format was used. CZML is an open JSON schema for describing properties that change value over time in a web browser running Cesium (Cesium, 2015). During get observation process, harmonization service is still in place to identify and alert events that may happen during access to sensor observations (e.g., observation loss or delivery latency).

In addition to on-the-fly harmonization, a key functionality of IDDSS-Sensor is to enable performing spatial-temporal queries on sensor data from multiple sources. Fig. 10, shows the deployed user interface for query management, in which the user can define a time-dependent query across multiple sensor observation layers. The query management panel contains three sections to do the followings:

1. Define query condition for the first observation layer;
2. Define query relation; and
3. Define query condition for the second observation layer.

1) Define query condition for the first observation layer: To define a query, the user is first prompted to select an observation layer or alternatively an observedProperty. Once an observation layer or observed property is selected the associated metadata such as supported observation types are retrieved from the database and populated in the panel. Next, the desired condition on sensor observations has to be defined. The displayed condition differs depending on the observation type. For instance, in case of numeric or count observation type (which is ratio variables), the eligible conditions include greater than, smaller than, equal to, and percentage of measurement range. Whereas, in case of category or boolean observation type (which is categorical variables), merely equal to condition is displayed. Finally, the user has to provide the condition value. For count and numeric observation type, the allowed value is integer and double numbers, respectively. For category observations, the condition value is the observed property's code list. At this point, the user has the option to either submit the defined query on a single sensor data source or proceed to include sensor observations from another source to the query.

2) Define query relation: In case the user intends to perform query across two observation layers, first a relationship needs to be defined. Two types of relationship are currently supported by the system namely, located on (i.e., relational query based on the relations defined in the integration data model) and in proximity

Table 4
Multi-agency sensor and spatial data sources used for simulation.

	Data	Sensor data source		Observation type
		Metadata source	Observation source	
Sensor data	- Rainfall data	Bureau of Meteorology	Simulated	Numeric
	- River height data	Bureau of Meteorology	Simulated	Numeric
	- Traffic flow data	VicRoads	Simulated (Aimsun)	Numeric
	- Ground observations	Simulated	Simulated	Category & Geometry
	- Emergency event data	Emergency Management Victoria	Simulated	Category
	- Pedestrian counting data	City of Melbourne	City of Melbourne	Count
	- Underground car park occupancy	City of Melbourne	Simulated	Count
	- In-ground parking bay occupancy	City of Melbourne	City of Melbourne	Truth
	- CCTV data	VicRoads	VicRoads	Text

	Data	Spatial data source	Geometry Type
Static spatial data	- Elements at risk	Department of Environment, Land, Water and Planning (Vicmap Feature of Interest data)	Point; polygon
	- Water bodies	Bureau of Meteorology (Geofabric data)	Polyline; polygon
	- Road network	OpenStreetMap	Polyline; point
	- Underground car parks	City of Melbourne	Polygon
	- Rail network	Department of Environment, Land, Water and Planning (Vicmap Transport data)	Polyline; point
	- Flood scenario maps	Department of Environment, Land, Water and Planning	Polygon
	- Demographic data	Australian Bureau of Statistics	Polygon; table

(i.e., spatial query that considers distance around the input features).

3) Define query condition for the second observation layer: Selection of the second observation source is similar to the above-described process (i.e. selecting an observation layer or observed property, thereby defining the condition on sensor observations).

Once the query is generated and submitted, the results based on the latest SOS observations are retrieved from the database and displayed on the map. In addition, the query rules can be passed and stored as event criteria into the event identification service. The event identification service then regularly retrieves the latest SOS observations, processes against stored event criteria to identify events, and generates alerts on-screen. Fig. 11, illustrates the results of query management and event identification service for six different queries that are obtained using the system. All these queries are the typical examples of analysis that the user at EMO might wish the system to handle during a flash flood evacuation scenario.

6. Discussion

Disaster management and specially response operations depend on the availability of a wide range of data with high spatio-temporal resolution, which can consequently enable better support for emergency decision making. In particular, organizational datasets provided by in situ sensors are an essential input for disaster decision support systems. Hence, this multisourced sensor data needs to be readily available, accessible and actionable by emergency management organization and disaster decision makers. We face a number of interconnected challenges to incorporate multi-agency sensor data in disaster management. First, sensor data providers, which are not necessarily established organizations for disaster management, mainly produce and then consume sensor data for their intra-agency operations. Since these organizations mostly rely on proprietary formats and standards for encoding and managing their produced data, utilization of such data for the purpose of disaster management turns into a manual and labor-intensive task. In addition, sensor data sources are primarily produced for different purposes rather than disaster management. Thus, providing access to raw sensor data might not be readily usable for emergency management tasks. Instead, the raw sensor datasets need to be integrated in a higher level based on the requirements of emergency decision makers.

In this work, we tackled these issues by presenting a new approach and prototype capabilities that provides interoperability and more automation for incorporating multi-vendor sensor data in disaster management. To evaluate the level of enhancement that can be achieved by our presented approach, we compared IDDSS-Sensor with three of the existing sensor-based disaster response frameworks (Table 5). Amongst the existing ones, these frameworks were selected systematically based on their purpose (i.e., providing shared sensor-derived situational awareness), scope (i.e., large scale sensor use for disaster management), disaster type (i.e. supporting flood monitoring), software platform (i.e., web application), and domain of awareness (i.e., supporting

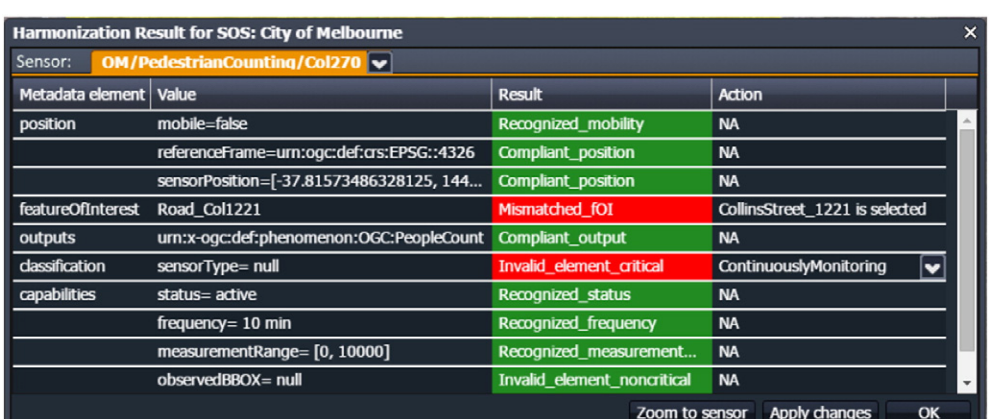

Fig. 9. Harmonization results.

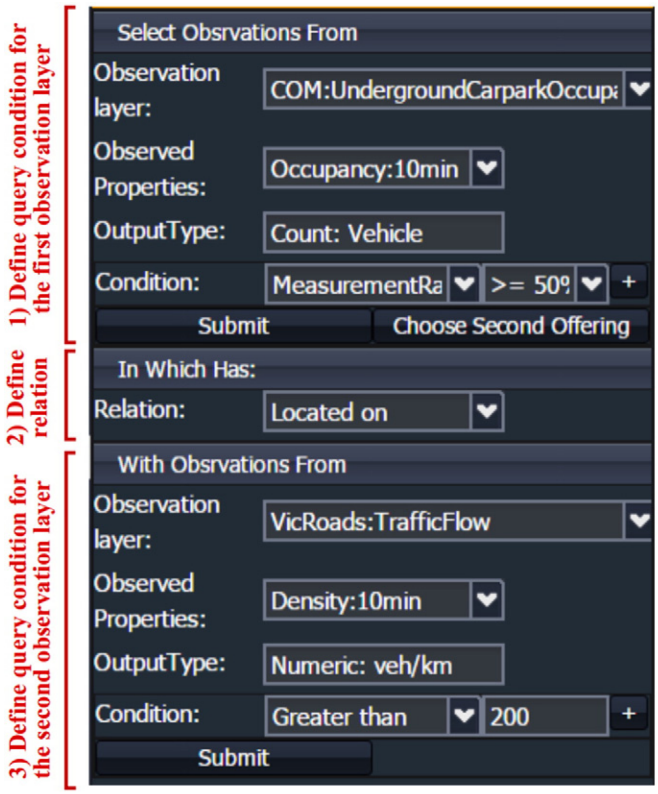

Fig. 10. Query management interface.

operations at emergency control centers). The features column in the table lists the measures used for comparison of the approaches. These measures pertain to the functional requirements for sensor information integration, discussed throughout the paper. As can be summarized from the table, all approaches support capabilities for access to sensor data. NICS supports the greatest variety of standards and formats for providing access to sensor data. However, only IDDSS-Sensor and AGORA-DS support OGC SWE for encoding sensor observations. Also, amongst the existing approaches IDDSS-Sensor provides more functionality for usage of sensor data in terms of on-the-fly analysis and integration of data sources.

The presented approach is rooted in the OGC Sensor Web Enablement standards and web service interfaces.

Overcoming the technical and non-technical issues (including institutional issues, policy issues, legal issues and social issues) regarding interagency sensor data standardization remains a challenge in some jurisdictions. These issues might hinder sensor data producers from sharing standardized sensor data with emergency management organization. During development of the research, a number of technological challenges and limitations were encountered. The most important challenge is as follows:

- Lack of maturity of the tools for working with sensor data: During the recent years, a number of industry-specific, commercial and open source toolkits and applications are developed to support SWE. Despite of these advancements, it is still too difficult and time-consuming to work with the current tools to integrate multisourced sensor data, and particularly mobile sensor data into an interoperable sensor web-based solution.

Also, disruption of communication and sensor infrastructure, as a typical consequence of disasters, poses another challenge for incorporating

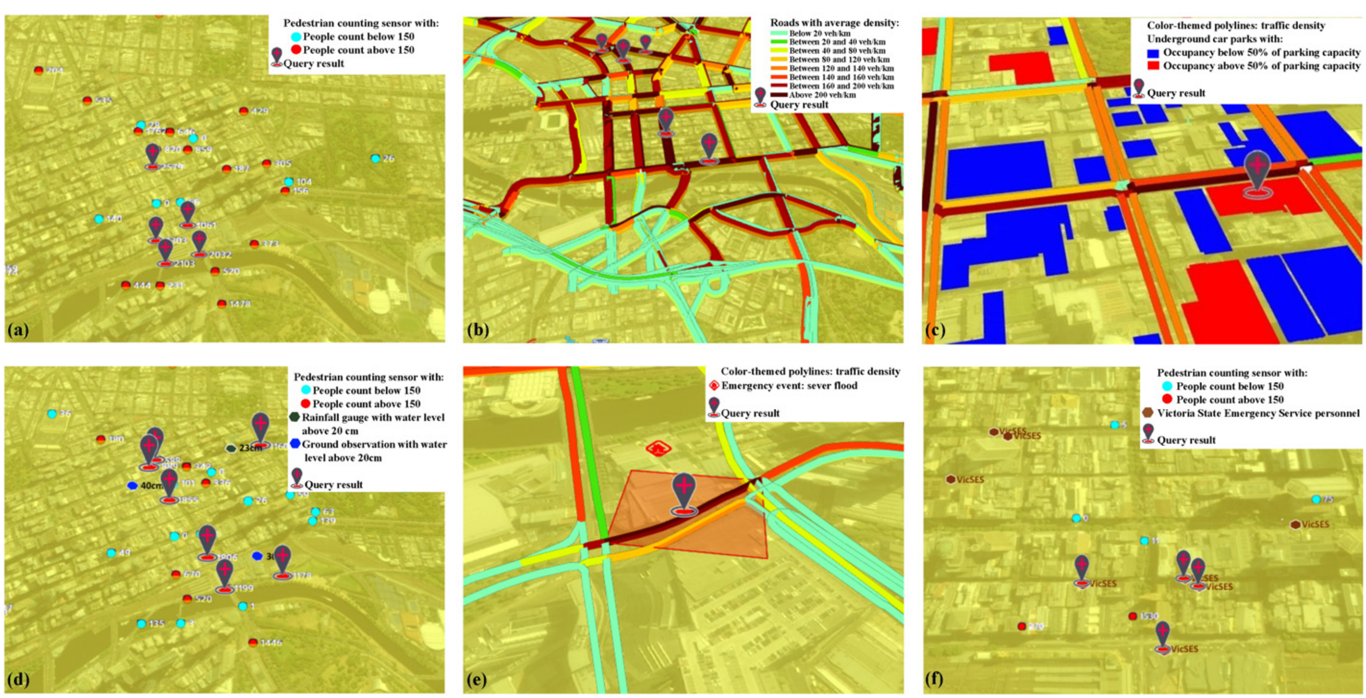

Fig. 11. Results for six different queries: (a) Alert for pedestrian counting observations when the result of people count observedProperty reaches greater than 2000 counts; (b) show traffic flow observations where the result of density observedProperty is greater than 200 veh/km and the result of flow observedProperty is smaller than 10 veh/h; (c) alert when for underground car park observations the result of occupancy observedProperty is greater than 90% of procedure's measurementRange and has located on relation with trafficFlow observations where the result of density observedProperty is greater than 200 veh/km; (d) show pedestrian counting observations where the result of people count observedProperty is greater than 500 counts and has in proximity:1 km relation with observations where the result for water level observedProperty is greater than 20 cm; (e) show traffic flow observations where the result of density observedProperty is greater than 200 veh/km and has in proximity:1 km relation with emergency event observations where the result of flood severity observedProperty is sever flood; and (f) show VicSES personnel observations where the result of location observedProperty has in proximity:1 km relation with pedestrian counting observations where the result of people count observedProperty is greater than 150 counts.

Table 5
Comparison of IDDSS-Sensor with existing sensor-based disaster response frameworks.

Features			IDDSS-Sensor	Next-Generation Incident Command System (NICS) (NICS, 2015)	ArcGIS COMMON OPERATIONAL PICTure (ArcGIS-COP, 2014)	AGORA-DS (Horita et al., 2015)
System components	Software platform		Web-based	Web-based	Web-based	Web-based
	System architecture		Client–server	Client–server	Client–server	Client–server
	Client-side component (web mapping API)		CESIUM, ExtJS, JavaScript	Open Layers	ArcGIS Viewer for Flex	ExtJS, OpenLayers
	Server-side component (spatial application server)		52^{0}North SOS, GeoServer, Java	GeoServer	ArcGIS for Server	52^{0}North SOS, GeoServer
	Database		Postgres/PostGIS	Postgres/PostGIS	Geodatabase	Postgres/PostGIS
Data access and exchange	Supported data layers	Basemaps	Yes	Yes	Yes	Yes
		Static spatial data	Yes	Yes	Yes	Yes
		Emergency events	Yes	Yes	Yes	No
		Stationary sensor data	Yes	Yes	No	Yes
		Mobile sensor data	Yes	Yes	No	No
		Volunteered observations	No	No	No	Yes
	Supported OGC standards/services		O&M, SensorML, SOS, WFS, WMS	WFS, WMS, KML	WFS, WMS, KML	O&M, SOS, WFS
	Supported formats for encoding sensor data		XML	CAP, Cursor On Target (CoT), EDXL, KML and JSON	Unknown[1]	XML
	Support multi-agency sensor data exchange		Yes	Yes	Yes	No
Multi-agency sensor data usage for emergency management	Sensor data evaluation	On-the-fly sensor metadata consistency checking	Yes, harmonization service	No	No	No
		On-the-fly sensor metadata harmonization	Yes, harmonization service	No	No	No
		On-the-fly sensor observations validity checking	Yes, harmonization service	No	No	Yes, validating sensor observations based on volunteered observations
	Sensor data integration	Sensor metadata + sensor observations	Yes, integration data model	No	No	No
		Sensors + sensors	Yes, integration data model	No	No	Yes, sensor observations + volunteered observations
		Sensors + spatial data	Yes, integration data model	No, separated data layers	Yes, limited support for spatial queries	No
	Manual usage of sensor data	Spatio-temporal queries on sensor data from a single source	Yes, query management interface and event identification service	No	Yes, limited support for anomaly detection in sensor data feeds	No
		Spatio-temporal queries on sensor data from multiple sources	Yes, query management interface and event identification service	No	No	No
	Automated usage of sensor data	Continuous analysis of incoming sensor data	Yes, event identification service	No	No	No
		Concurrent aggregation of incoming sensor observations	Yes, flood monitoring service	No	No	Yes, aggregation of sensor and volunteered observations

Note:
[1] Unknown means the project documentation does not describe the supported formats.

the existing sensor another challenge for incorporating the existing sensor assets in the disaster area. This research emphasizes on the role of sensor information integration for flood management, since it is more likely that communication and sensor infrastructures stay operational before (e.g., during warning time) and somehow in the aftermath of flood occurrence.

Consideration of the issues, challenges and limitations discussed above could turn sensor data sourcing into a reliable technology for providing real-time disaster information. As future work, we aim to expand the functionality of the query management tool and event identification service to handle a time range for analyzing observations (e.g., alert when a road remains gridlocked for 30 min). The current system considers the latest SOS observations for analyzing the event queries. Also, we plan to evaluate the whole system based on a questionnaire-based survey. The survey will be participated by industry experts who are involved in emergency management organizations and sensor data custodians.

We have presented an approach that lowers the barrier to provide real-time disaster information based on sensor data sourcing. The proposed approach and the presented technology, can be reused to manage other large scale natural hazards such as bush-fires or storms, or at smaller scale events such as monitoring festivals in an urban area.

7. Conclusion

This paper studied the process of utilizing multi-agency sensor data as a potential source for providing real-time spatial information for disaster management. Based on a case study, the issues and functional requirements regarding access, dissemination and usage of multi-agency sensor data for disaster management were identified. In order to address the explored issues and requirements, a new approach based on OGC Sensor Web Enablement was developed which constitutes functional components for standardization, as well as on-the-fly harmonization and connection of sensor data. On the basis of the presented approach, a GIS-based software IDDSS-Sensor is implemented to support the decision-making of emergency agencies by integrating multi-agency sensor information in real-time.

In conclusion, having the multi-agency sensor information integration approach in place would give more efficiency and effectiveness for employing multi-vendor sensor resources in an urban area before, after and in particular during emergency events. The presented approach would also provide improvement in inter-agency collaboration through providing more automation in the interaction between organizations involved in disaster management.

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