# Chapter 12
# The Role of Information and Communication Technology in the Development of Early Warning Systems for Geological Disasters: The Tsunami Show Case

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**Abstract** Tsunami warning systems (TWS) are distributed software and hardware systems supporting the reliable detection of imminent tsunami hazards, the rapid situation assessment and the targeted dissemination of customised warning messages. The conceptual evolution of TWS within the last decades is stimulated by and depending on the development of Information and Communication Technology (ICT). The strong influence of ICT emerged in the 1980s when the availability of microcomputer systems and telecommunication facilities facilitated the development of global sensor networks. Since the 1990 s the growth of the Internet has driven standardisation processes for protocols, interfaces and data exchange, providing the foundations for today's TWS. The ongoing development of global warning infrastructures depends on the capability to integrate national and local TWS into system-of-systems. This requires structured software engineering methodologies guided by a reference architecture for TWS. Trends such as cloud computing, ubiquitous sensing and volunteered geographic information will strongly influence the future development of TWS.

## 12.1 Introduction

Early warning is a major element of disaster risk reduction. Its overall objective is the prevention of loss of life and the reduction of economic losses to a minimum. Following UN (2006) definitions a complete and effective early warning system comprises four interconnected elements:

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(1) Risk awareness: knowledge of the likely risks that communities face.
(2) Monitoring and warning service: monitoring of hazards as well as rapid and reliable decision-making processes for early warning.
(3) Dissemination and communication: transfer of understandable warnings and preparedness information to those at risk.
(4) Response capability: knowledge and preparedness of all partners of the information chain.

Early warning for geological disasters includes crises following volcano eruptions, landslides, earthquakes and tsunamis. In terms of Information and Communication Technology (ICT) geological early warning systems (EWS) are integrated software and hardware systems for data acquisition, decision making, and information dissemination thus supporting the detection and analysis of imminent hazards and the targeted dissemination of related warnings. Hence, EWS typically focus on the elements (2) and (3) of the list above.

The technological concepts and performance capabilities of EWS have significantly evolved over the last decades. On the one hand, this progress is resulting from the advancements in the scientific understanding of geological disasters and related phenomena as well as improved scientific modelling approaches. On the other hand, these advancements are directly linked with and enabled by the rapid development of ICT. The effect of ICT is not only reflected by the availability of high-performance tools for supporting near real-time modelling, decision support or visualisation. Both the upstream and the downstream information flow heavily rely upon and benefit from the capabilities of the underlying ICT infrastructures. ICT innovations have also boosted the performance of sensor systems resulting in an increased resolution and improved availability of time series data. Advances in telecommunication infrastructures in parallel with the growth of the Internet have enhanced the variety and performance of channels for warning purposes. More than that, the next generation of mobile computing systems support smart solutions, e.g. low-cost mobile sensor networks enabling new high-resolution monitoring strategies.

This paper investigates the dualism and mutual interdependence of ICT and EWS for geological disasters looking in particular at tsunami warning systems (TWS). TWS provide a representative show case due to their integrated architecture, distributed nature, and the complexity of decision processes. Additionally, requirements in terms of robustness and reliability are very challenging and result from the relative rarity of tsunami events in relation to the life cycle of ICT-based systems. In Sect. 12.2 we focus on the role of ICT in the past evolution of TWS over the last decades and the resulting architectural concepts. Based upon this historical outline Sect. 12.3 presents the main architectural elements of TWS. Section 12.4 proposes a first step towards a TWS reference architecture including tailored methodologies for the application of this reference architecture for the concrete engineering of individual yet interoperable TWS. Section 12.5 summarises the findings about the role of ICT in the evolution of TWS and concludes with a discussion of major ICT trends that will become important for the future development of TWS.

## 12.2 Evolution of Tsunami Warning Systems Over Time

### *12.2.1 ICT Development Phases*

In the last decades the rapid development of ICT has significantly transformed business processes in industry, government and science. The increasing potential of ICT revolutionised data and information management, in particular the acquisition, processing, analysis and visualisation of data as well as the integration of computer systems into infrastructures. Following Moore's (Schaller 1997) and Kryder's Law (Walter 2005), the ongoing change processes are driven by the continuous miniaturisation of integrated circuits and the increased performance of processing units, memory chips and graphic processing units but also the availability of large, affordable storage capacities. Other technological key drivers are the availability and performance of telecommunication facilities enabling local and wide area networks. The development of ICT in the last decades shows partly overlapping phases with specific characteristics (adapted from Mutsaers et al. 1998):

I. *Data Processing Era*: From the 1970s mainframes and minicomputers become more frequent. Their application is focused on specific, mostly centralised data processing tasks. The number of computer systems is still limited.

II. *Microcomputer Era*: From the early 1980s the appearance of microcomputers or Personal Computers (PC) extended the application of computers to more general information management but also data acquisition and processing tasks. The era is characterised by an increasing utilisation of Local Area Networks. Key concepts for the data transfer between different networks and the internetworking (Internet) have been developed. Microcomputer systems become widespread for distributed desktop applications in business and science.

III. *Internet Era*: In the 1990s, the Internet developed to a global platform for business processes, information provision, communication and entertainment. This process is enabled by the availability of both common protocols for system communication and data transfer combined with an ever increasing bandwidth available at low cost. Since the beginning of the pervasive development and enormous growth of the Internet a strong convergence process including media, applications, and data is obvious. This resulted in the merging of standardisation processes that were formerly restricted to specific communities. This includes not only communication protocols but also standards for data and metadata specifications as well as service interfaces.

IV. *Ubiquitous Computing Era*: As a result of the continuing miniaturisation of technology a new generation of mobile computer systems is available integrated into powerful mobile communication networks with high bandwidth. This development started with the availability of mobile telephones. Today, regular smartphone systems have a basic set of sensors on board (GPS, accelerometer, gyroscope) and, more than that, provide LAN protocols and routing functions thus supporting the implementation of low cost and volunteered sensor networks.

In the following the evolution of TWS will be considered from the viewpoint of these ICT Eras for three selected examples. The first example will look upon the development of seismic systems. Seismic monitoring is one of the core functions of today's tsunami warning systems. Standard software solutions include basis alerting functionality. The second example considers the TWS development in Japan. Permanently challenged by its specific geotectonical position with extremely high tsunami risks and reduced warning times the Japanese situation requires sophisticated technological solutions and conceptual leadership. The third example analyses the Indonesian TWS and its follow-on evolution. The overall concept and architecture of the system was designed from the scratch without limiting factors e.g. superimposition of legacy systems. These developments therefore deliver relevant contribution for a standards-oriented approach for the design of warning systems thus providing an important input for TWS reference architectures.

### *12.2.2 Seismic Monitoring Systems*

The development and performance of today's TWS is closely related to and depending on the evolution of seismology and earthquake monitoring. The first teleseismic earthquake event was registered 1889 in Potsdam by the scientist Rebeur-Paschwitz who initiated a global network of seismographs to monitor the seismicity of the Earth (Kind 2012). This teleseismic recording can be considered as the start to a systematic observation of seismic activities. The first seismometers were mechanical instruments followed by electrodynamic seismometers improving the accuracy of measurements. Before the 1970s analogue media (usually paper or film) were the sole means of recording seismic data.

Seismologists have used digital recording methods since about 1970. In the late 1970s very broadband digital instrumentation became available. At that time the concept of a global network of digital broadband stations, capable of recording large local earthquakes, became viable. One of the first projects to embrace the new digital technology was Global Seismographic Network (GSN) of the U.S. Geological Survey (USGS). Since the beginning the GSN has allied with other global operators (GEOSCOPE, GEOFON) and regional networks such as the Canadian Digital Seismic Network (CDSN), the China Seismic Network (CSN), and the Mediterranean Network (MEDNET) to enable wide distribution of high-quality stations around the world (IRIS Consortium 2003).

In the last two decades seismic sensor networks have been further developed and extended. In order to optimise the operation of seismic networks, observatories and research institutes integrated their networks to virtual networks. Virtual networks associate with recording stations and seismic networks either indefinitely or for a limited time period. The VSN concept supports large projects by integrating seismic stations from different networks to act as a single, newly formed entity. The virtual network naming system supports the provision of data under the auspices of one or more of these initiatives. For example, the GEOFON Extended Virtual Network (GEVN) is composed of more than 500 stations worldwide (Hanka et al. 2008).

Already in 2003 the IRIS Consortium envisioned an extension of the seismic network to multi-sensor platforms which, in addition to their primary purpose, is capable of monitoring a variety of environmental and tectonic parameters. Along with land and ocean seismic observatories, additional instruments may be included in global monitoring networks of the future. These instruments are laser strain meters, tilt meters, micro-gravimeters, differential GPS, micro-barographs, high-frequency geophones and temperature sensors in deep boreholes, meteorological and ionosphere monitors, monitors of gaseous emissions at volcanic sites, hydrophones, pressure sensors, ocean bottom temperature, salinity and current monitors.

The seismic community has developed and is maintaining a set of standards and tools for the acquisition of seismic data as well as the exchange and management of large seismic data archives. Digital recording methods used since 1970 have increased data quality but data exchange has been complicated by different data logger formats, by different computer systems and by incompatible exchange media.

In 1985, the International Association for Seismology and Physics of the Earth's Interior (IASPEI), Commission on Practice, formed a Working Group on Digital Data Exchange to propose a standard for international digital seismic data exchange. The Standard for the Exchange of Earthquake Data (SEED) was proposed as a new format by the USGS. After the review of a number of existing formats the Federation of Digital Seismographic Networks (FDSN) formally adopted SEED in 1987 (IRIS 2010). In 2004, the QuakeML schema for seismic data has been proposed by Schorlemmer et al. (2004).

### *12.2.3 Near- and Far-Field Tsunami Warning Systems*

Due to its geotectonical position close to a subduction zone Japan is frequently threatened by earthquakes and tsunami. A first systematic forecast/warning system for tsunami was established in September 1941 for the Sanriku Coastal Area, an area which was already devastated by the Sanriku Tsunami of 1933. It served as a blueprint of the Japanese TWS that started its services on April 1, 1952 (Imamura and Abe 2009). The specific challenge for a Japanese TWS results from the near-field situation with only short forecast times. However Japan is also threatened by far-field tsunamis which can be generated in the subduction zones around the Pacific Ocean. The Japanese Meteorological Agency (JMA) has the legal mandate for tsunami early warning.

In an early stage of TWS development, earthquake parameters were manually determined based on the emergency telegrams received from a geographically distributed network of local observatories. The telegram reported the observed earthquake parameters including magnitudes and observation time to the tsunami forecast centre. Within 15 min the centre estimated the earthquake epicentre. Forecasts were issued based on the distance to the epicentre. In the late 1950s Morse code was gradually replaced by tele-type machines for data communication purposes. Since the 1970s a new generation of seismographs was introduced providing important improvements concerning the time resolution of recording. After the 1995 Kobe earthquake the seismic observation system in Japan was improved considerably. A large number of strong-motion, high-sensitivity, and broadband seismographs were installed to construct dense and uniform networks covering Japan completely.

A core component of the Japanese warning infrastructure is a decision support system. In 1999 a simulation system for quantitative tsunami forecasting became operational (Imamura and Abe 2009). Forecasts include the expected height at the coastline. Tsunami forecast contains the expected maximum tsunami height and the arrival time of the tsunami. Warnings and/or advices are delivered to the national and local authorities for disaster prevention and the broadcasting media. Mayors of cities, towns or villages are responsible for giving evacuation directions to residents to leave tsunami-prone areas.

When a large earthquake occurs at a distant area from Japan, JMA determines the location and the magnitude using seismic data from global seismological observation network. In case of a possible tsunami occurrence, JMA immediately executes the tsunami forecast operation in the same manner as in the case of a near-field tsunami. JMA uses the database derived from numerical simulation to judge whether the tsunami affects the Japanese coast. Data of tsunami observations from foreign countries are also referred to in order to estimate the tsunami height.

Since 2006 forecasts can be issued within 2 or 3 min (Imamura and Abe 2009). When tsunamis are observed, the JMA issues information about observation points, tsunami heights and expected times of arrival (JMA 2009). The Japanese warning system includes a highly-efficient infrastructure for warning dissemination based on a multi-channel approach. Mobile communication and computer systems are increasingly integrated into warning strategies. For example, cell broadcasts were used in the Tohoku tsunami crisis. Additionally, Japanese warning systems are capable of triggering risk reduction measures. Already in the 1960s, an early warning system for stopping high-speed trains was developed (Nakamura 2004).

### *12.2.4 Standards-Based TWS Architectures*

After the Boxing Day tsunami 2004 and more than 200000 casualties, a series of activities have been started with the overall objective to establish an early warning system in the Indian Ocean. In close collaboration between Indonesia and Germany a TSW was designed and implemented (Lauterjung et al. 2010). The GITEWS project (German Indonesian Tsunami Early Warning System) addressed the specific challenges of early warning in a near-field environment with its limited reaction times. In parallel the DEWS project[1] focussed on both the multi-channel warning dissemination in a multi-lingual environment and the communication between warning centres.

[1] DEWS = Distant Early Warning System, http://www.dews-online.org/.

These projects laid the foundation for the design of collaborative decision-support environment as investigated in the TRIDEC project[2].

These projects seized the opportunity to develop an overall generic architecture for TWS based on best practices and the results of international standardisation activities in the geospatial domain and the ICT community. This approach included service-oriented architectural design principles but also open geospatial and Sensor Web service and data specifications from the Open Geospatial Consortium (OGC) (Percivall 2010). Among others, the resulting system approach covers the following aspects:

- Sensor Integration Platform: Different sensor types are integrated via a sensor service bus based on a plug-in approach. Interfaces to seismic systems, buoys, GPS, and tide gauges have been implemented. Plug-in templates can easily be adapted to other types of sensor systems (Fleischer et al. 2010).
- Warning dissemination: Information logistics processes were implemented especially addressing the multi-channel dissemination of customised warning messages in a multilingual environment. Warning messages can be automatically adapted for different consumer groups using templates (Lendholt and Hammitzsch 2011).
- Decision support: Specific adaptable user interfaces were designed for tsunami detection, analysis of coastal hazards and tasking of warning dissemination. In this context the integration of the simulation system is of high relevance (Hammitzsch et al. 2012; Steinmetz et al. 2010).
- Centre-to-Centre: The DEWS prototype implemented centre-to-centre communication patterns. This approach is addressing the execution of complex collaborative emergency management tasks within loosely coupled system-of-systems (Lendholt et al. 2012).
- Workflow support: An open service-oriented architecture enables that transfer and adaption of the system approach to other regions, e.g. the Mediterranean Sea where the distances between potentially tsunamigenic sources and the coast are rather small. Here, decision makers need a customisable system which may be easily adapted to the individual regional situations. A workflow-based decision support system relying upon rule-based decision tables is proposed to deliver the required flexibility (Riedel and Chaves 2012).

## 12.3 Components of Tsunami Warning Systems

### *12.3.1 Main Architectural Elements*

The overall evolution of TWS as described in Sect. 12.2 reflects a rapid growth of the complexity resulting from an increase of the collaborating components and

[2] TRIDEC = Collaborative, Complex and Critical Decision Support in Evolving Crises, http://www.tridec-online.eu/.

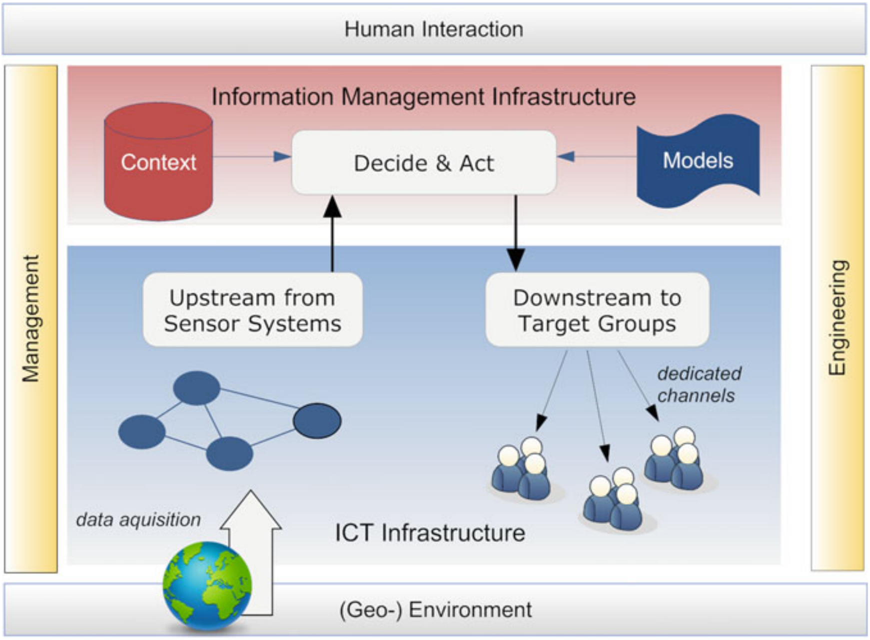


**Fig. 12.1** Typical components of tsunami warning systems

implemented functionality. As illustrated in Fig. 12.1 the mapping of TWS functions to main architectural elements reveals three building blocks (Wächter et al. 2012):

- *Data acquisition*: The upstream information flow into the TWS includes earthquake and sea-level monitoring data. In concrete operational warning systems the monitoring task are realised by sensor systems and sensor networks.
- *Decision support*: The decision support included two main tasks. Firstly, the system has to monitor earthquake activities and, once an earthquake has happened, it has to detect if a tsunami was initiated. Secondly, the hazard estimation for affected coastal areas has to be conducted as quickly as possible. As soon as these hazards have been analysed the TWS starts scheduled warning activities.
- *Information dissemination*: The downstream information flow out of the TWS is directed to dedicated customer groups including authorities and the public but also to other warning centres. Warning channels include sirens and radio broadcasting. Messages via E-mail or SMS are used to disseminate customised information.

### *12.3.2 Upstream Information Flow and Sensor Systems*

Sensor systems are responsible for the monitoring of environmental phenomena related to hazards. Sensor systems consist of one or more distributed sensors transforming real world observations into digital signals that are transmitted to or collected by a central processing and analysis component. Sensor systems process and filter incoming raw time series data into information about specific relevant events, e.g. an earthquake that can be used as a trigger or for validation purposes in decision processes. In addition to seismic monitoring, sea level observation is another important monitoring task of TWS. In this context tide gauges at coast lines play an important role complemented by an increasing number of buoys responsible for sea level monitoring in the open ocean.

The responsibility of seismic systems is the determination of earthquake parameters including location, depth, magnitude and rupture parameters as soon as possible after an earthquake. The data delivered by distributed seismometer network are time series (so called wave forms). In a first step the occurrence of the earthquake is automatically/manually detected ("picked") as a peak in the incoming time series. Based on incoming events from at least three sensors earthquake location and additional parameters like magnitude, depth, or moment tensor will be determined (Hanka et al. 2010). Especially for the assessment of the probability of a tsunami it is becoming increasingly important to identify the earthquake mechanics quite rapidly. Continuous GPS has gained an increasing importance (Falck et al. 2010).

There are two complementary approaches for sea level monitoring. Tide gauges document the effect of tsunami on the coast line. Supported by the WMO a global network of coastal tide gauges has been integrated using the Global Telecommunication System (GTS) operated by WMO for the collection and transfer of tide gauge data to a central facility. For tsunami monitoring in the open ocean the DART real-time tsunami monitoring systems plays a critical role in tsunami forecasting especially for near-field situations. The DART system consists of an ocean bottom unit with pressure sensors capable of detecting tsunami signals form water pressure data. The buoys have to be positioned at strategic locations throughout the ocean.

### *12.3.3 Decision Support for Tsunami Detection and Hazard Estimation*

Within the upstream information flow sensor data streams are processed in a way that only relevant information for decision making is extracted. The resulting high-level event data are the basic input for the decision support in the TWS. The interfaces of individual sensor systems with domain specific protocols and encoding are subject to ongoing standardisation processes.

One key objective of a TWS is the detection of a tsunami as early as possible so that the time available for preparation and response activities is maximised. Frequently, seismic systems delivering earthquake information are the unique input for decision making. In this case warning activities are determined by exceeding predefined thresholds based on the strength of earthquake. However not all earthquakes trigger a tsunami. In regions with strong earthquake activities the verification of the possible generation of a tsunami is a key issue. Currently sea level observation can provide the necessary input to validate the tsunami generation. Buoys linked with ocean bottom sensors implemented offshore threatened coasts offer reliable option keeping at least a minimum warning time frame for near-field tsunami.

A second key objective of TWS concerns the proper preparation and targeted execution of warning activities. Two aspects are important. Firstly, once a tsunami has been generated the location of the epicentre, the bathymetry and the geometry of the coastline will determine the local tsunami hazard. Tsunami propagation models deliver the input for this process (Babeyko et al. 2010; Behrens et al. 2010). In the Indian Ocean region and also proposed for the Mediterranean a segmentation of the coastal zone in geographically similar units is a way to describe the concrete tsunami threat for defined coastal areas (Lendholt et al. 2012).

Decision support components have to support the continuous interaction of the responsible key personal with the system so that the human/system interface is of particular importance. For instance, there may be very early information provided by the system that point to a major disaster, but information is very unsure. For these reasons decisions about the scheduling and execution of warning activities have to be substantiated based on data resulting from the analyses of comparable events in the past. Based on this input a set of probable earthquake locations is selected. For each of these points, the tsunami propagation is calculated for a defined range of magnitudes. The resulting data sets are stored in a database.

In case of a real alert situation the best fitting simulations are retrieved from the database once the earthquake parameters have been determined thus providing the basis for high resolution coastal hazard determination. The selection of best fitting propagation models is one of the key decision processes of warning centres (Hammitzsch et al. 2012).

TSWs can be linked with other warning centres in regional networks, e.g. in the Indian or the Pacific Ocean region. In this case TWS alerts can not only be initiated by sensor systems but also by other warning centres. The alerts will initiate similar warning dissemination activities to those as described above.

### *12.3.4 Warning Dissemination and Downstream Information Flow*

The management of downstream information flows follows the challenging objective to deliver "the right information, to the right people, in the right time" (GDIN 1997). The situation awareness and warning information dissemination has two addressees, decision makers in crisis management organisations and the public. Decision makers have to be informed about imminent threats and start evacuation procedures. Rescue organisations have to be prepared for the immediate start of rescue activities after the tsunami reached the coast. Warning dissemination to the public helps to reduce the concrete number of potential casualties.

The resulting downstream information flow includes processes that transform alerts into customised warning messages satisfying the information needs of addressed target groups. Effective targeted warning dissemination depends on a detailed description of the information needs of potential target groups. Finally, this prepared information is disseminated via dedicated channels. A standardised approach for warning dissemination has been proposed by Lendholt (2011).

Tsunami crises do not affect single countries but are a threat to many countries in a specific geographic setting, e.g. the Indian Ocean, the Pacific or the Mediterranean. This specific situation makes coordinated activities of national warning centres necessary based on the effective information exchange between warning centres. The organised reaction of independent systems on common threats is a key challenge for new system-of-system architectures.

## 12.4 Towards a TWS Reference Architecture

### *12.4.1 TWS Domain Requirements*

In the Pacific Ocean a central tsunami warning centre and core elements of a warning infrastructure have been continuously developed since 1949 when the Pacific Tsunami Warning System (PTWS) was founded (UNESCO 2009). In other regions, e.g. the Indian Ocean and the Mediterranean, no such systems were in place. The Boxing Day Tsunami 2004 triggered various international efforts focused on the establishment of a tsunami early warning infrastructure. These activities were organised under the auspices of the UNESCO/IOC. Despite of significant progress the specification process of warning systems and their general architecture is still on-going (ICG/NEAMTWS 2009, 2011; TOWSWG 2011; UNESCO 2011).

Currently, the main high-level structural elements and components of the tsunami warning infrastructure have been identified including their basic functionality and standard operational procedures. Accordingly, tsunami warning infrastructures consist of national and regional warning centres (NTWC: National Tsunami Warning Centre; RTWC: Regional Tsunami Watch Centre). RTWCs operate as a hub for several NTWCs and coordinate the exchange of regional tsunami related information. NTWCs are responsible on the national level according to respective national legal frameworks and provide warnings, watches, and advisories to their citizens, public and private agencies.

The importance and the need for an adequate and tailored provision of information systems and resource management systems for risk and emergency management is widely recognized (Turoff et al. 2010; Henricksen and Iannella 2010). Starting from stand-alone systems with dedicated tasks there is a trend towards warning systems consisting of loosely-coupled systems. These systems typically have to span organizational, national and/or technological barriers. The distribution of a system-of-systems over a large geographic extent results in an "even greater emphasis on interface design that in traditional system architecting and engineering" (Maier 1998).

### 12.4.2 Reference Model for TWS

Warning infrastructures have to meet very high domain-specific requirements concerning resilience, robustness, performance and security. Especially in a system-of-systems consisting of independently developed warning systems all interfaces and communication protocols of all participating warning centres have to fulfil these requirements. In order to safeguard a proper and reliable behaviour of the infrastructure the detailed specification of reference architecture for the overall TWS domain is required. On a high level of abstraction this reference model for tsunami warning system (RM-TWS) provides a reference architecture including basis structural elements and relations for the construction of concrete TWS. The specifications typically have to satisfy expectations of readers with different competences and technical backgrounds. The key elements are structured according existing patterns that have been observed in a number of implementations. A sound documentation of its architecture is essential not only in order to guarantee the proper development of TWS that should become elements of a tsunami warning infrastructure but also to support the maintenance and the evolution of an EWS.

The design of a RM-TWS should be based on the existing capabilities of underlying ICT which nowadays encompasses geospatial service platforms. Additionally, the RM-TWS should follow the design principles of service-oriented architectures (SOA) as defined by Erl (2008) in his encyclopedia. These principles include:

- Loose Coupling: “Service contracts impose low consumer coupling requirements and are themselves decoupled from their surrounding environment”.
- Service Abstraction: “Service contracts only contain essential information and information about services is limited to what is published in service contracts”.
- Service Reusability: “Services contain and express agnostic logic and can be positioned as reusable enterprise resources”.

This paper proposes core services and a related information model of a TWS reference architecture based on well-established standards for reference model specifications, e.g. the ISO Reference Model for Open Distributed Processing (ISO/IEC 10746-1). The use of viewpoints is derived from the principle of abstraction as the central idea of architectural specifications. The RM-TWS proposes five viewpoints following the OGC best-practices reference model for environmental risk management applications (Usländer 2007). The main high-level structural elements and components of the tsunami warning infrastructures, as defined in the UNESCO/IOC process, are part of the RM including their basic functionality and standard operational procedures:

- The **Enterprise Viewpoint**: Reflects the analysis phase in terms of the system and the user requirements as well as the technology assessment. Includes rules that govern actors and groups of actors, and their roles.
- The **Information Viewpoint**: Specifies the modelling approach of all categories of information including their thematic, spatial, temporal characteristics as well as their meta-data.

- The Computational Viewpoint: Specifies the interface and service types in a service-oriented TWS, thereby referred to as the **Service Viewpoint**.
- The **Technology Viewpoint**: Specifies the technological choices of the (geospatial) service platform, its characteristics and its operational issues.
- The **Engineering Viewpoint**: Specifies the mapping of the service specifications and information models to the chosen platform obeying its specific characteristics and principles.

The following section describes the current status of the RM-TWS encompassing the information and the service viewpoint. Its mapping to a technological platform such as a Web service environment, i.e. the contents of the Technology and Engineering Viewpoint, is out of scope of this paper and shall be performed by implementation projects, respectively, based on the methodology detailed below.

### *12.4.3 Service and Information Viewpoint to Foster Interoperability*

The interoperability between components in one TWS as well as the interaction between different TWS in a system-of-systems environment is determined by the degree of the standardisation of interfaces, data exchange formats and protocols. TWS shall enable an efficient and flexible exchange of information as well as the remote call and eventually reuse of their embedded functional components across system boundaries. Thus, there must be an agreement on information models and service interfaces—in the best case based on international standards.

An essential element of such an ICT support is an "open geospatial service platform" (see fig. 12.2) which provides seamless access to resources (sensor data, information, services and applications) across organizational, technical, cultural and political borders. "Open" hereby means that service specifications are published and made freely available to interested vendors and users with a view to widespread adoption. Furthermore, an open service platform makes use of existing standards (e.g. International Standardization Organization ISO and the Open Geospatial Consortium OGC) where appropriate and otherwise contributes to the evolution of relevant new standards.

Based on a systematic analysis of user and system requirements, the ORCHESTRA project[3] has specified and implemented a reference model and a series of abstract services that provide the generic and technology-neutral functional grounding of such a platform (Usländer 2007). The SANY project[4] (Havlik et al. 2007) extended it into a Sensor Service Architecture (SensorSA) by the inclusion of sensors and sensor networks (Usländer 2009). This extension is based upon the services and information models of the OGC Sensor Web Enablement (SWE) architecture

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[3] ORCHESTRA = Open Architecture and Spatial Data Infrastructure for Risk management, http://www.eu-orchestra.org/.

[4] SANY = Sensors Anywhere, http://www.sany-ip.eu.

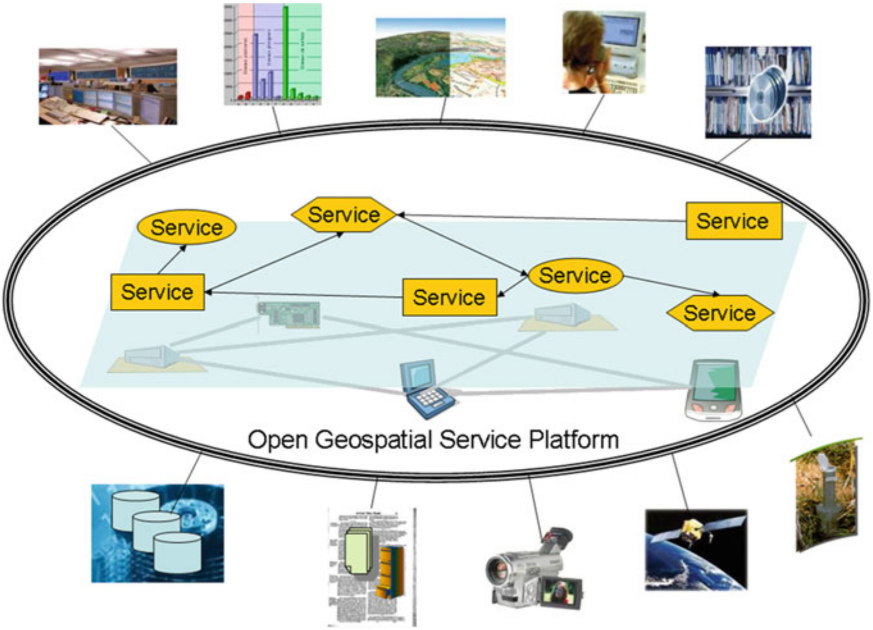


**Fig. 12.2** Open geospatial service platform

(Simonis 2008a). The SWE services provide the input data for environmental monitoring as well as for risk management of geo-hazards, whether natural or man-made. They support the upstream part from sensor system according to Fig. 12.1. For the downstream part to target groups standards of OASIS are of high relevance as elaborated and implemented by the European research project DEWS (Distant Early Warning System) (Lendholt et al. 2012).

As a result, a high percentage of the required functionality of the major TWS components as illustrated in Fig. 12.1 is already covered by mapping these proposed abstract services to the given geospatial service platform and tailoring them to the needs, respectively. This design activity results in service profiles that encompass both the Service and the Information Viewpoint of the RM-TWS. Hence, the resulting service profile specifications define the service operations to be supported as well as the models of the data communicated across the network.

The ***Upstream*** from Sensor Systems may use the following services:

- Sensor Observation Service: Provides access to observations from sensors and sensor systems in a standard way that is consistent for all sensor systems including remote, in-situ, fixed and mobile sensors.
- Sensor Alert Service: Provides a means to register for and to receive sensor alert messages.
- Sensor Planning Service: Provides an interface to task any kind of sensor to retrieve collection assets.

- Web Notification Service: Supports asynchronous dialogues (message interchanges) with one or more other services.

These services rely upon data and meta-data specification of the OGC Sensor Web Enablement initiative (Simonis 2008b) such as the Sensor Model Language (SensorML) for the description of sensor characteristics and the Observation and Measurements Model (O&M) for the description of observations of all kinds ranging from sea-level time-series retrieved from buoys up to text entries in social networks (Zielinski et al. 2012).

***Decision support*** processes may benefit from the following information management services:

- Catalogue Service: Ability to publish, query and retrieve descriptive information (meta-information) for resources of any type.
- Coordinate Operation Service: Changes coordinates on features from one coordinate reference system to another.
- Document Access Service: Access to documents of any type (e.g. text and images).
- Feature Access Service: Selection, creation, update and deletion of features available in a service network.
- Map and Diagram Service: Enables geographic clients to interactively visualise geographic and statistical data in maps or diagrams.

These services mainly rely upon the OGC general feature model and catalogue data specifications (Percivall 2010). This Infrastructure may be enhanced by semantic services and interfaces in order to overcome semantic heterogeneity:

- Annotation Service: Relates textual terms to elements of an ontology (e.g. concepts, properties, instances).
- Ontology Access Interface: Supports the storage, retrieval, and deletion of ontologies as well as providing a high-level view on ontologies.

The ***Management*** covers user management and service monitoring as follows:

- Authentication Service: Proves the genuineness of principals (i.e. the identity of a subject) using a set of given credentials.
- Authorisation Service: Provides an authorisation decision for a given interaction context.
- User Management Service: Creates and maintains subjects (users or software components) including groups (of principals) as a special kind of subjects.
- Service Monitoring Service: Provides an overview about service instances currently registered within service network incl. status and load.

These services mainly rely upon data and meta-data specification of the OASIS security information models, in particular the Security Assertion Markup Language (OASIS SAML 2006) and the eXtensible Access Control Markup Language (OASIS XACML 2010).

The ***Downstream*** to target groups may benefit from the series of XML-based messaging standards called Emergency Data Exchange Language (EDXL) provided by the OASIS Emergency Management Technical Committee (EM-TC):

- Common Alert Protocol (CAP): CAP is an XML-based data format for exchanging public warnings and emergencies between alerting technologies. Originally developed by OASIS, the ITU adopted the Common Alerting Protocol as Recommendation X.1303 in 2007 (ITU 2007; Botterell 2006).
- The EDXL Distribution Element (EDXL-DE): An envelope standard for message-distribution among emergency information systems. It serves as container message providing addressing information to route the payload which can be any XML fragment, such as a CAP message (Lendholt et al. 2012).

These two data models may be used in emergency systems in general. In the case of TWS, a dedicated language is required. One candidate is the Tsunami Warning Markup Language (TWML) that is tailored to the communication of tsunami warnings and the edition of tsunami bulletins (Iannella and Robinson 2006). It comprises language elements to describe bulletin contents such as bulletin metadata (issuer, time, frequency of future bulletins, geospatial scope), observations about the seismic activity that triggered the tsunami, observations and predictions about wave activity and expected impacts. TWML may be used in conjunction with EDXL-DE and CAP to represent intended recipients and the category of alerts, respectively.

### *12.4.4 Engineering of Tsunami Warning Systems*

The engineering of TWS requires a sound analysis of user requirements that is fundamental for a successful design and development. Additionally, the engineering methodology should enable a seamless application of the general RM-TWS specifications for the engineering phases of concrete TWS. A combination of the following basic principles is recommended to foster the application of the RM-TWS:

- Step-wise refinement of the design artifacts: It shall be distinguished between an analysis, abstract design, concrete design and engineering step.
- Co-development of requirements and capabilities: An agile analysis and design methodology is recommended following the basic ideas of agility and lean software such as "fix quality—deliver a small increment in a timebox—repeat" (Leffingwell 2011).
- Incremental architecture documentation: It is recommended to incrementally document the resulting TWS architecture according to an established reference model.

These principles require a step-wise refinement of design artefacts. In the ***Analysis*** step the user analyses the problem and expresses the outcome in the form of user requirements, e.g. as use cases. For example, a use case that requests to "get a diagram containing the average sea water gauge values of the last 10 years in the Gulf of Naples, Italy". In the ***Abstract Design*** step the user requirements are transformed by the system designer into system requirements which then have to be matched with the capabilities of an abstract service platform. Example: Provide a service that enables to "get observation values with a sampling time in the interval [2000-01-01,

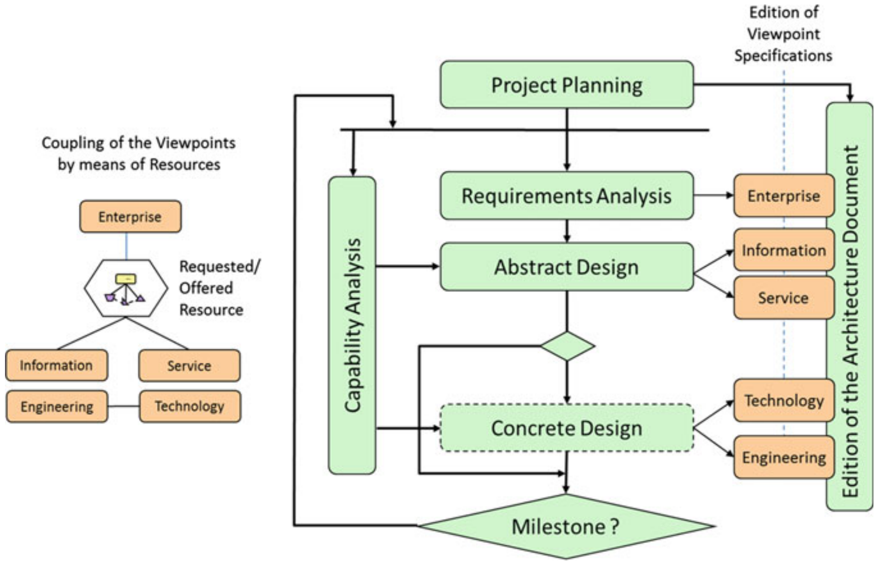


**Fig. 12.3** Mapping of design steps to RM-TWS viewpoints

2009-12-31] for the parameter "sea water level" for all water gauge stations located in the Gulf of Naples, Italy". Such services may also be formally specified in the platform-independent modelling language UML (Unified Modeling Language) or its service profile SoaML (OMG 2008).

In the ***Concrete Design*** step the capabilities of the abstract service platform turn into requirements for the design of the concrete service platform and finally result in a specification of its capabilities. Example: The getObservation operation request of the OGC Sensor Observation Service (Na and Priest 2007). In the ***Engineering*** step the specified capabilities of the concrete service platform are implemented as service components and deployed in the context of a service network. Figure 12.3 illustrates the mapping of these design steps to the documentation of a TWS architecture according to the RM-TWS viewpoints. The recommendation for agility is expressed by iteration loops.

In the project planning step the architecture document is being set-up and structured. The Enterprise Viewpoint is being described in the requirements analysis step, mostly in terms of semi-structured use case descriptions (Cockburn 2001; Usländer and Batz 2011), whereas the information and service viewpoint specifications result from the abstract design step. The results of the Concrete Design step, i.e. the platform-specific specifications, are documented in the Technology and Engineering Viewpoint sections. This step may be omitted in a given iteration loop if the focus is first on reaching a milestone by agreeing on the platform-independent level. In parallel to these steps the analysis of the platform capabilities is carried out in order to judge if requirements may be matched with existing capabilities, or how big the gap (and hence the design and development effort) is.

By applying the prescribed structure of the RM-TWS all relevant architectural aspects are covered. However, readability is a problem as the viewpoints are not enough interrelated. For instance, it is not visible which information model is required by a given service, or vice-versa, which service uses a given information model.

Furthermore, there is a huge gap to the use case descriptions of the Enterprise Viewpoint as these are, by their very nature, independent of the service and information models. In order to better overcome these gaps, a resource-oriented methodology may be used following the resource-oriented architectural style of Fielding (2000). An example is the SERVUS design methodology that is tailored to geospatial service-oriented architectures and relies upon the modeling of both use cases and platform capabilities as resources (Usländer 2010). On the left-hand side of Fig. 12.3 it is illustrated how viewpoints may be better coupled by expressing requirements and capabilities in terms of requested and offered resources.

SERVUS relies upon a resource model as a common modelling language to which both use cases and capabilities may be mapped. Hereby, a resource is an information object that is uniquely identified, may be represented in one or more representational forms (e.g. as a diagram, text document or a map layer) and support resource methods that are taken from a limited set of operations whose semantics are well-known (uniform interface). A resource has own characteristics (attributes) and is linked to other resources forming a resource network. Applying this idea, the abstract design step is then understood to be an iterative discovery and matching activity: requested resources derived from user requirements have to be mapped to fitting offered resources that represent the information objects being accessed and manipulated by geospatial services.

## 12.5 Conclusions and Perspectives

### *12.5.1 ICT and Tsunami Warning Systems*

The evolution of TWS reflects the development of ICT as motivated in Sect. 12.2.1. In Phase I (Mainframe Era) computer systems were only used for very dedicated TWS functions (Table. 12.1). A first strong influence of ICT on TWS architectures became visible in Phase II (Microcomputer Era) with the availability of microcomputer systems and the digitalisation of sensor data. The architectural foundations for today's sensor networks have been established. Phase III (Internet Era) created the concepts and foundation for the architecture of modern TWS and their basic components which include sensor systems, decision support components, and warning components. The standardisation processes of component interfaces and the encoding of data were fostered by the development and success of the Internet promoted by the work of standardisation organisations such as W3C, OASIS, OGC, and ISO.

**Table 12.1** Development phases of tsunami warning systems

| Phase/Era<br><before | I-Data processing<br>1980 | II-Microcomputer<br>1990 | III-Internet<br>2000 | IV-Ubiquitous computing<br>today> |
|---|---|---|---|---|
| TWS | | | | |
| Architecture | Limited application of computers | Far-field TWS | Near-field TWS | Networks of TWS, system-of-systems |
| Upstream sensor systems | Analogue registration,first digital seismic recording | Start broadband digital seismic recording | Sea level observation, virtual seismic sensor networks | Multi-sensor platforms, mobile sensors networks |
| Decision support | Manual evaluation of seismic events | Automatic earthquake detection | Decision tables, tsunami propagation models | Enhanced user interfaces, quantitative tsunami forecasting |
| Downstream dissemination | Sirens, radio broadcasting | FAX, telephone, TV broadcasting | Mail, web portals, TV narrow casting | Multi-channel warning dissemination, cell broadcasts |
| ICT | | | | |
| Computing | Mainframe | Client-server | Internet, Service platforms | Internet of services, cloud computing, internet of things |
| Communication | Morse telegraphy, teletype, telephone | Proprietary LAN protocols, WAN with limited bandwidth | Internet protocols broadband WAN, satellite links | Broadband mobile communication; ZigBee, PAN, IPv6 |
| Standards | Programming languages | Domain specific protocols: e.g. SEED, RINEX | Global IT standards: OASIS, W3C, open geospatial consortium | Mobile networks, future internet |

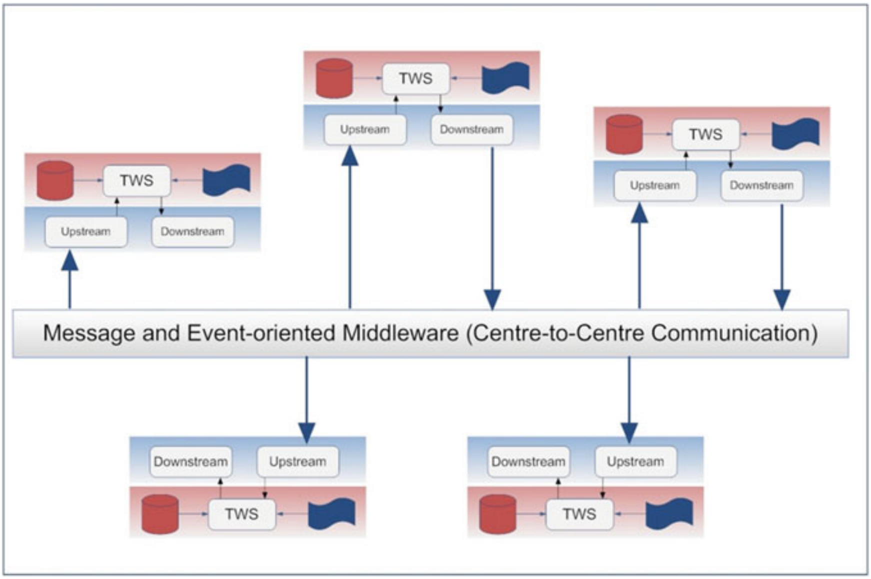


**Fig. 12.4** Tsunami warning system of systems

In Phase IV (Ubiquitous Computing Era) the development of ocean-wide warning infrastructures, as discussed in responsible UNESCO/IOC bodies, will become technologically viable. TWS in such environments are systems that are developed and operated independently. In a system-of-systems context of a basin-wide TWS these individual TWS have to collaborate to fulfil common and complex task in crisis management. Core component in such loosely-coupled system-of-systems are message- and event-oriented brokers (fig. 12.4). The RM-TWS outlined above is currently being further developed by the TRIDEC project for such basin-wide warning infrastructures (Moßgraber et al. 2012).

Looking at the domains driving the development of TWS there is a clear shift from domain to ICT experts. In Phase I and II the progress of TWS is mainly driven by development activities within specific scientific communities, e.g. geophysicists, geodesists and geologists. Within Phase III these developments become more and more integrated in and depending on mainstream ICT evolution resulting from both the increasing system complexity and the progress in standardisation. Especially for Phase IV it becomes clearly visible that the potential and strength of ICT is increasingly challenging and pushes the architectural and functional evolution of TWS. Some highly important trends for TWS are cloud computing, ubiquitous sensing, integration of Earth Observation (EO) systems and volunteered geographic information that will be briefly addressed in the following sections.

### 12.5.2 Cloud Computing

TWS-supporting ICT infrastructures are embedded into the mega-trends of the Internet and the economic domain. **Cloud Computing** provides a new way of thinking about underlying ICT infrastructures for applications. It is not only that data may be "virtually" hosted in a reliable, performing and scalable way on a pay-per-use basis by a cloud provider. For TWS, and for early warning systems in general, it is the even more demanding factor that functions bundled as services will be offered by "the cloud". One of the objectives of the European **Future Internet** Public Private Partnership (FI-PPP) program is to increase the effectiveness of business processes and of the operation of infrastructures supporting applications in application domains such as transport, health, environment or energy (Havlik et al. 2011). The resulting core platform will be defined in terms of so-called "generic enablers" that support the following functions:

- creation, publishing, managing and consuming the Future Internet services;
- deploying the Future Internet services on the cloud, i.e. using cloud computing technologies;
- accessing, processing and analyzing massive data streams, as well as semantically classifying them into valuable knowledge;
- leveraging the ubiquity of heterogeneous, resource-constrained devices in the Internet of Things; and
- accessing the networks and devices through consistent service interfaces.

Using an agile design methodology this core platform will be enhanced and tailored to the application domains by FI-PPP usage area projects running in parallel. There are two usage area projects dealing with geospatial aspects: the ENVIROFI project[5] for environmental applications and the SafeCity project[6] that focuses on public security in cities. These projects are currently developing "specific enablers" that will be highly relevant for TWS-supporting ICT infrastructures of the future. Referring to generic TWS (Fig. 12.1), it is envisioned that in the future both the upstream and the downstream part of the overall TWS architecture may be provided by "cloud services" based upon international standards assuming that the non-functional aspects of trust and dependability of such cloud environments will be solved.

### 12.5.3 Ubiquitous Sensing

Sensors of various types are indispensable tools in order to feed TWS with data about environmental phenomena and the features of interest that are relevant to assess given geo-hazards. The progress in micro-electronics and the continuing downsizing trend fosters the development and the wide-spread availability of new types of **sensors**.

[5] http://www.envirofi.eu/

[6] http://www.safecity-project.eu

They are getting **ubiquitous** in the sense that sensing capabilities are increasingly embedded in various types of objects, ranging from mobile phones, objects of daily use up to dedicated sensor platforms such as buoys or unmanned aircraft vehicles. They are getting **smart** in the sense that more and more data processing and communication capabilities are embedded in the sensors themselves. These trends have an impact upon the information and communication architecture of TWS. In addition or instead of unprocessed raw data such sensors may deliver already pre-processed information to the higher-level TWS component, accompanied by context information (meta-data) about the conditions at the time of measurement and the associated uncertainty of the transmitted information (e.g. mean water gauge value of the last hour).

The communication capabilities of the sensors may be exploited in two ways:

(1) Sensors with wireless communication and self-description capabilities may connect on local level with other sensors to form **ad-hoc sensor networks** (comprising in-situ and mobile sensors). By exchanging and fusioning their individually observed data, local monitoring results with higher resolution and lower uncertainty may be achieved.
(2) Sensor tasking may be used to request the execution of a "monitoring task" on the sensor level with configurable notification policies towards interested consumers, e.g. notification only when thresholds have been exceeded.

A combination of (1) and (2) enables flexible monitoring strategies with a higher level of dependability. A group of sensors may be requested to execute a "monitoring task" relying upon the self-organization capabilities on the sensor level. The task results may then be linked with the results of process monitoring on a higher level.

### *12.5.4 Improving Damage Estimation and Situation Awareness*

In order to improve the situation picture, two other data sources are getting increasingly important for TWS and for early warning systems in general: remote sensing information and volunteered geographic information. **Remote sensing information** continuously gathered by various EO missions under the auspices of national or cross-national (e.g. European) space agencies is made accessible by means of EO product catalogues and service-oriented infrastructures. Typically, these tasks are provided by ground segment software services which may be called through corresponding interfaces by client applications, e.g. Web portal applications, or other software components such as GIS applications. However, without a coordinated strategy and harmonized development, these ground segment services all have different interfaces following the needs and the business requirements of the individual stakeholders.

While this may not be a problem when accessing EO products just from one mission, it gets difficult and tedious when EO products are required from multiple missions, or even worse, when the EO products from multiple missions shall be combined or processed together in order to provide higher-level services or to deliver fused EO datasets. In order to solve this problem, service-oriented architectures, also heavily relying upon OGC SWE standard but tailored (profiled) to EO product search and delivery are being defined. Examples are the Heterogeneous Mission Accessibility (HMA) initiative of the European/Canadian Ground Segment Coordination Body (Usländer et al. 2012) and the world-wide initiative to create GEOSS—a Global Earth Observation System of Systems.

The second source of data with an increasing importance is **Volunteered Geographic Information (VGI)** which draws on the concept of citizens as sensors for a next generation digital earth (Craglia et al. 2008). Social media platforms change the way people create and use information during crisis eventsm. It is assumed that the rich information made available by members of the public can contribute to a more effective response to natural disasters (Ostermann and Spinsanti 2011).

### *12.5.5 ICT and the Human Factor*

However, a powerful ICT infrastructure can only solve part of the problem of early warning. The human factor still remains important, too. Coppola (2011) stresses that “Early warning mechanisms must include public education, accurate risk perception, a communications system to relay the message, and an emergency management system to adequately coordinate the response”. Public safety from environmental dangers is one of the five key elements in Environmental Security that has to be considered “within and across national borders” (Landholm 1998). According to Coppola (2011) there is a need for further action and the inclusion, training and education of end-users of various disciplines (e.g., geo-scientists, citizens, emergency organizations, environmental and security agencies) including their cultural context and risk perception in order to really exploit the potential of TWS and their underlying ICT capabilities.

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