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Original paper

A Water-Energy-Food Nexus-Based Conceptual Approach for Developing Smart Urban-Rural Linkages in Nagpur Metropolitan Area, India

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Abstract Urban and rural areas are dynamic systems, functionally interlinked through their social, economic, and environmental settings. While urban population heavily depends on the natural resources sourced from surrounding rural areas, the rural population is increasingly reliant on urban areas for employment, healthcare etc. In the recent years, the notion of urban-rural linkage has gained high prominence in the global policy outcomes, including the Sustainable Development Goals and The New Urban Agenda, particularly in response to the rapid urbanization trends and climate change. However, its application at local level development planning is still not apparent. In case of the Nagpur Metropolitan Area ‘NMA’ in India, a Smart City and Smart Rural ‘Rurban’ Cluster are being developed adjacently under two different missions of Government of India which are totally disconnected. While urban-rural systems in NMA are already stressed with the situations of resource conflict (like water supply), their relationships are expected to get further constrained under changing climate scenarios. Addressing this need, we present a knowledge-based conceptual framework that presents an overall picture of the water resource flow (specifically from a Water-Energy-Food nexus perspective) between urban and rural areas within NMA. Based on the developed framework, the study suggests feasible directions for smartly linking the upcoming developments in Nagpur Smart city and adjacent Rurban cluster.

Key words: Urban-Rural linkages, Smart City, Rurban Cluster, Water-Energy-Food nexus, Integrated Disaster Risk Management, Nagpur

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1. INTRODUCTION

Smart developments, be it in urban or rural areas, are today becoming a global reality. While the concept of smart development is still evolving, there is no established definition as to what makes an urban or rural area 'smart'. A few researchers refer to smart developments as the integration of Information and Communication Technology 'ICT' features into daily life activities and state functions (Komninos 2011; Randhawa and Kumar 2017), while others emphasize on knowledge management (Garcia 2007). The definitions, nomenclatures and the context of smart developments differ from place to place. However, it is acknowledged that they contribute to the regional vision of smart growth (Blais 2003). In the broadest sense, the concept of 'Smart' is related to different structuring aspects of a society like Smart Economy, Smart People, Smart Environment, Smart Living, Smart Governance and Smart Mobility, with the key objective of enhancing quality of life in terms of reduced energy consumption, inclusive growth, cleaner transport etc. (Chichernea 2015; Kumar and Dahiya 2017).

In the wake of growing urban population and increasing concentration of economic activities, cities around the world are increasingly embracing technologies like sensors, cameras, wireless devices, data centres etc. to enhance the provision of services to urban residents in a faster and efficient manner. Noticeably, the application of ICT features in cities has been debated for a long time under different labels including Knowledge cities, Intelligent cities, Digital Cities, Virtual Cities etc., which are often used interchangeably (Meijer and Bolívar 2013). However, the concept of 'Smart Cities' (recognized since late 1990's) has today overshadowed all other concepts in terms of academic research and is globally been recognized as an umbrella term for enhancing livability, sustainability and quality of life in urban areas. In recent years, there have been several policy initiatives around the world for implementing the 'Smart cities' concept, as well as private sector initiatives (like from IBM and CISCO) for enabling technology integration into cities (Mora *et al.* 2017). Likewise, there are also several pilot projects been implemented to develop 'Smart Villages' through technology integration, which is a relatively new concept (several initiatives highlighted by Zavratnik *et al.* 2018).

While smart developments are increasingly focused on securing investments, creating more jobs etc., it is important to understand that their resource demands will proportionately increase with the growing population and economic activities. As cities depend on surrounding rural areas for most of their resource demands in terms of water, energy, food, manpower etc. (Wilbanks and Fernandez 2013; Morton *et al.* 2014; Sukhwani *et al.* 2019), it is highly important to strengthen the urban-rural linkages to safeguard the flow of key resources, especially in the wake of changing climatic conditions and emerging disaster risks. The importance of urban-rural linkages has also been recognized at the global policy level, including the Sustainable Development Goals 'SDGs' (UNDP 2015) and The New Urban Agenda (UN-Habitat 2017). However, there is very limited progress in their application at policy and governance levels. The discrete governance of urban and rural areas has also become a major cause of concern amidst the ongoing COVID-19 'Coronavirus disease 2019' global pandemic (officially declared by the World Health Organization on 11th March 2020), as urban

and rural areas around the world have experienced increased isolation, with disrupted urban-rural supply chains (also discussed by Egal and Forster 2020).

In case of India, the development planning is moving forward with ‘Smart Cities’ under the Smart Cities Mission ‘SCM’ (SCM 2015) and ‘Smart Rural clusters’ (Rurban clusters) under the National Rurban Mission ‘NRuM’ (NRuM 2016). While SCM is focused on providing core infrastructure and improved quality of life to urban citizens, the NRuM is intended to complement the SCM by stimulating local economic development and enhancing basic services in rural areas with a cluster-based approach. Singh and Rahman (2018) explained that the definition of ‘Rurban’ cluster is not clearly defined under the NRuM, and it is often linked to peri-urban areas. However, in Indian context, the Rurban areas are increasingly been related to the rural areas that have urban amenities (Hui and Wescoat 2019). Moreover, both the development missions are been implemented separately in a disconnected manner. In case of Nagpur Metropolitan Area (NMA) in central India, Nagpur Smart city (Nagpur SCP 2016) and Wadoda Rurban cluster (Wadoda ICAP 2017) are being developed adjacently with no consideration to unintended mutual consequences. While Nagpur is being projected to be the fifth fastest growing city in the world from 2019-2035 (Holt 2018), it has recently experienced serious water stress concerns, across different sectors including urban domestic, industry, agriculture etc. (Deshkar 2019). Therefore, to ensure continued supply of water resources for sustainable development of Nagpur, it will be important to address the urban-rural linkages from a nexus perspective.

With that background, this study works towards identifying potential areas of shared concern in NMA where the upcoming smart developments can engage to foster urban-rural linkages. The three specific objectives of this research are as follows, (a) To study the action plans of ongoing Nagpur Smart City and Wadoda Rurban Cluster developments, and identify their key shortcomings; (b) To understand the flow of water resources between urban and rural areas in Nagpur Metropolitan Area (NMA), from a Water-Energy-Food (WEF) nexus perspective, (c) To suggest feasible directions for incorporating the component of ‘urban-rural linkage’ in the action plans of upcoming Smart City and Rurban Cluster in Nagpur region. It is important to note that this research will only focus on urban and rural areas as extreme ends of the continuum. To overcome the knowledge gaps on urban-rural linkages in NMA, this research builds on a knowledge-based conceptual framework of water resource flow between urban and rural areas, which is developed based on a literature review. For the context of this study, a ‘knowledge-based’ framework mainly refers to the notion of addressing the cross-sectoral linkages between different sectors (mainly WEF sectors) for achieving coordinated development planning.

The remaining paper is structured as follows. Section 2 provides a brief overview about the key concepts of urban-rural linkages, WEF nexus and knowledge-based approach. Section 3 introduces the case study area of NMA, and briefly explains the key characteristics and shortcomings in the upcoming smart urban-rural developments. The research methodology has been explained in Section 4. Section 5 elaborates on the independent flow of water, energy, and food resources between urban and rural areas in NMA, which are then interlinked to form a knowledge-based conceptual framework in Section 6. Building on the developed framework, Section 7 presents feasible measures to smartly link the upcoming smart urban-rural

developments. The last Section 8 summarizes the key conclusions and underlines the key research limitations.

2. LITERATURE REVIEW

This section is intended to provide a precise understanding of the existing scientific literature, related to the key concepts that form the basis of the conducted research. The section is divided into three sub-sections. The first sub-section discusses about the concept of urban-rural linkages and their growing importance in the present policy context. The second sub-section explains about the growing relevance of WEF nexus thinking for strengthening urban-rural linkages at transboundary scale. The last sub-section deliberates on the idea of knowledge-based approach for development planning. For the literature review, relevant publications from selected database of Scopus along with the online grey literature and academic research were referred.

2.1 Importance of Urban-Rural linkages

Urban and rural areas are geographically dispersed, but they are closely linked through a variety of spatial and sectoral linkages (Tacoli 1998). Urban-rural linkages basically refer to the two-way flow of a variety of resource elements like food, energy, water, goods, information, finances, people, culture etc. (Douglass 1998; Akkoyunlu 2015). Rural areas have traditionally served as the center of key natural resources and labor, which are crucial to urban regions. Likewise, their urban counterpart areas provide markets for agricultural products, specialized services like healthcare, education, employment etc. It has been found that the definitions of urban and rural areas, based on various factors like demographic and economic criteria, vary in different countries (van Leeuwen and Nijkamp 2006). However, with changing population dynamics, expanding urban areas and changing land use patterns, the nature of urban-rural linkages is also reported to be fast-changing even within the same country. More and more productive agricultural lands, wetlands, forests etc. are being acquired for urban development purposes (also discussed by Sukhwani *et al.* 2019). Particularly in fast developing countries like India, which have a predominant rural population (68.84% as per Census 2011), urban and rural areas within a regional space are increasingly interwoven. Over the years, a number of empirical studies have been conducted to study the changing dynamics of urban-rural linkages in India and globally (eg. Peeters and Marinho 2008; Bari and Munir 2014; Sivaramakrishnan and Sar 2014; Kim 2015). While majority of these studies have analysed the spatial level flow of resources, transportation connectivity has been identified as one of the key factors in shaping the urban-rural linkages.

At global policy level, the importance of urban-rural linkages has for long been recognized in development planning (UN-Habitat1976). However, the 2030 Agenda for Sustainable Development (UNDP 2015) and The New Urban Agenda (UN-Habitat 2017) have provided a

renewed attention to this concept. Against the conventionally discrete governance structures of urban and rural areas, regional level planning exercises in consideration to urban-rural linkages have today become critical to maintain the environmental balance. Researchers have also pointed out that enhancing the connectedness between urban and rural areas has potential to reduce poverty, economic inequality and at the same time maintain the ecological and cultural diversity that are crucial for sustainable development (Srivastava and Shaw 2013; Hussein and Suttie 2016).

2.2 Growing relevance of Water-Energy-Food (WEF) Nexus thinking

In the backdrop of expanding urban boundaries and growing population, the need for strengthening urban-rural linkages is increasingly being realized as urban areas largely meet their WEF resource demands from outside their physical boundaries (Heard *et al.* 2017; Romero-Lankao *et al.* 2017). Amidst the already existing shortfalls in meeting WEF resource demands (as detailed by Stephan *et al.* 2018), the World Economic Forum has for long underlined that food crisis, energy shocks and water scarcity are projected to be some of the major risks to contemporary world (WEF 2018). These concerns become even more serious as WEF sectors are closely linked in form of a nexus (eg. both water and energy essential for food production), and the demands for all of them are set to increase (Mohtar and Daher 2012). The notion of WEF nexus thinking has existed for a long time. However, it was officially recognized only after the Bonn 2011 Nexus Conference (Hoff 2011). WEF nexus has also gained increasing importance for policymakers in relation to the Post-2015 development agenda (Bizikova *et al.* 2013; Biggs *et al.* 2015; Jones *et al.* 2017). Today, it is widely recognized that failing to recognize the cross-sectoral interdependencies of WEF sectors will lead to unintended consequences to the overall system. As such, WEF nexus thinking has become a pre-requisite for enhancing resource efficiency and achieving sustainable development at transboundary scale (Schlör *et al.* 2018; Djehdian *et al.* 2019). Particularly for large developing countries like India with high population density, the WEF nexus thinking is increasingly important, as they are highly water stressed (Pandey 2019).

To date, considerable scientific advances have been made in WEF nexus research. Various research frameworks, models and multi-disciplinary approaches have been established for analyzing WEF systems (Bizikova *et al.* 2013; Mohtar and Lawford 2016). However, their applicability at policy and governance levels continues to be restrained as most of the existing frameworks do not incorporate spatial and temporal scales (Endo *et al.* 2015). The transboundary WEF resource linkages are seldom considered in development planning, as majority of the policy decisions concerning the WEF sectors are made by separate institutions, with a sectoral approach (Pittock *et al.* 2013; Leck *et al.* 2015). A genuine need for spatially visualizing the WEF linkages has been realized, in addition to producing grounded evidence for policy making at local level.

2.3 Knowledge-based approach for development planning

‘Knowledge’ has wide-ranging definitions, but it is commonly related to a fluid mix of framed experiences, values, contextual information (Liyanage *et al.* 2009). The importance of a knowledge-based approach for development planning has been recognized for a long time (Knight 1995). Emphasizing on using knowledge as a strategic resource, recent studies (eg. Yigitcanlar 2010a) have stressed for a knowledge-based development approach to cities and regions. The knowledge-based development approach mainly builds on knowledge (technical, financial, market etc.) as the central structuring element for developing urban areas and wider regions (Yigitcanlar 2010b; Lonnqvist *et al.* 2014). Although the key purpose of knowledge-based development are economic prosperity and human development (Laszlo and Laszlo 2007), it also focuses on environmental and social aspects for sustainable development of territories (Chang *et al.* 2018).

Recently, there have been several emerging perspectives for knowledge management ranging from knowledge-based economy to knowledge-based societies. Although these concepts are not firmly defined yet, the ‘knowledge-based’ attribute mainly aims to prioritize the intangible values or intellectual assets, rather than material and monetary (tangible) assets (Carrillo 2015). While information technology forms the basis of knowledge management, knowledge-based approach gives particular attention to local, historical, and ecological values, that affect the quality of life in cities and regions (Knight 1995). Various theoretical frameworks have recently been discussed for the application of knowledge-based approach to specific areas like disaster management (eg. Arain 2015) and urban development (eg. Yigitcanlar and Lönqvist 2013). Through these studies, the wide-ranging importance of knowledge-based frameworks in terms of facilitating well-informed decisions, risk assessment, swift disaster response, improved coordination etc. have been recognized. Building on the contextual strengths and values, researchers have emphasized on applying knowledge and information into all research and development activities at local level.

3. CASE STUDY AREA OF NAGPUR METROPOLITAN AREA (NMA), INDIA

Nagpur, often called the heart of India, is at the geographical center of the country (location map shown in Figure 1). The strategic central location and good connectivity from all parts of the country enables it to be the logistical hub of India. It lies on the Deccan plateau at an altitude of 310 meters above sea level. Spread over 217 square kilometers area (sq.km.), Nagpur is the third largest city and the winter capital of the Indian state of Maharashtra. It is also a major commercial and political center of the Vidarbha region of Maharashtra. Nagpur Metropolitan Area (NMA), that includes 721 villages and 24 Census towns, is spread across an area of 3,567 sq.km. (NMC 2011; NIT 2015). As per Census 2011, the population of Nagpur city is 2.405 million and the population of NMA is 1.037 million (predominantly rural). Within the boundary of NMA, Nagpur Smart City and Wadoda ‘Rurban’ Cluster are presently been

developed under two different missions of Government of India, as also explained in Section 1. The following sub-sections discuss about their actions plans, key strengths and shortcomings.

3.1 Nagpur Smart City

Nagpur is presently been developed as one of the 100 smart cities under the ‘Smart Cities Mission’ launched by Government of India in 2015 (SCM 2015). Under the SCM, Nagpur city aims to transform itself into a well-planned, Eco-friendly, Edu-city that Electronically connects governments, businesses, people and spaces seamlessly to co-create a clean, green, safe, prosperous, healthy and Inclusive ecosystem. As per its action plan (smart city proposal), ‘Area-based interventions’ are proposed in 951 acres (3.84 sq.km.) of land on the eastern border of Nagpur city wherein retrofitting will be undertaken through the town planning scheme to deliver smart physical and social infrastructure and introduce mixed-use allocations to increase commercial and economic activity. In addition to that, the ‘Pan-city initiatives’ under SCM include solid waste management and transportation monitoring through CCTV-monitored central command system (Nagpur SCP 2016).

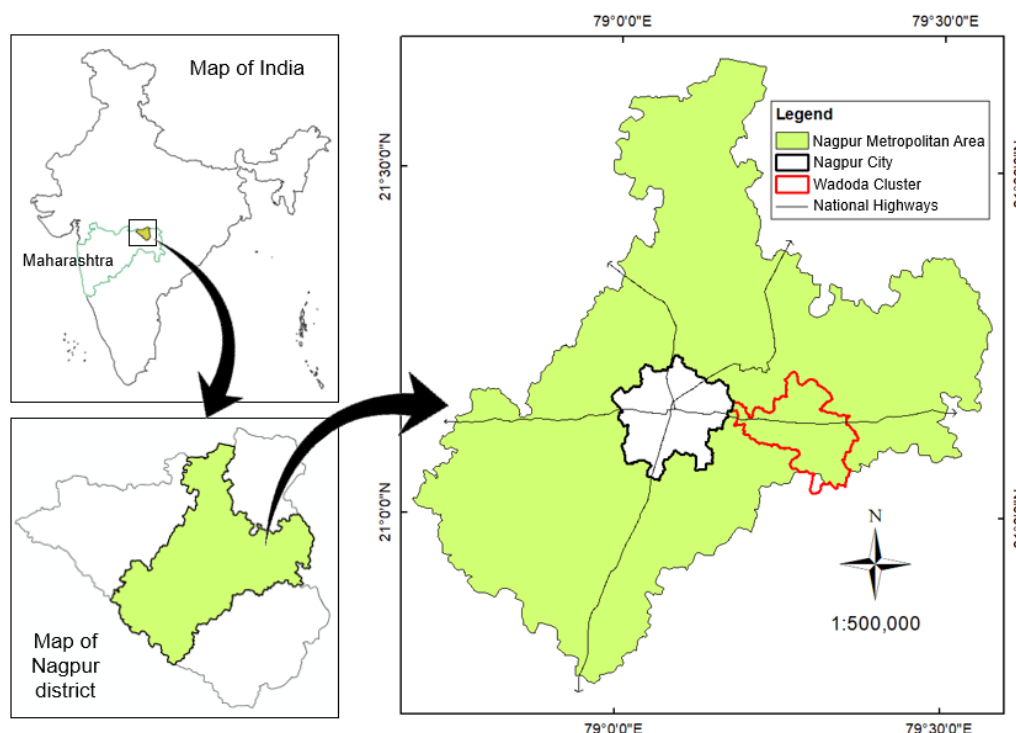


Figure 1. Location map of Nagpur Smart City and Wadoda Rurban Cluster in NMA (Author)

3.2 Wadoda Rurban Cluster

After a rigorous screening process, Wadoda Cluster from Nagpur district has been selected as one of the 300 Rurban Clusters being developed across India, under the ‘National Rurban

mission’ (NRuM) launched by Government of India in 2016 (NRuM 2016). Under this mission, a Rurban cluster is defined as a group of geographically contiguous villages. Based on 14 desirable components (shown in Table 1), NRUm aims to promote local economic development, enhance basic services and create well planned clusters.

Wadoda ‘Rurban’ cluster comprises of a total of 31 villages falling under 19 Gram Panchayats (village councils) and having a total population of 38,679. In lines to the objectives set by NRUm, the vision of Wadoda cluster is to retain the dominant agrarian culture besides borrowing urban features such as water supply, drainage, sanitation, and better road network. Accordingly, the cluster is being developed for agro-tourism, agro-service and processing, e-cluster and digital cluster, along with striving to fulfill 100 percent requirement of water supply, sanitation, road-drainage, and solid waste management (Wadoda ICAP 2017).

Table 1. Key components in action plans of Nagpur Smart City and Wadoda Rurban Cluster
(Source: Nagpur SCP 2016; Wadoda ICAP 2017)

Nagpur Smart City	Wadoda Rurban Cluster
1. Carbon Neutral & Sustainable Habitat	1. Skill Development training
2. Swachh Nagpur	2. Agri-services and Processing
3. Urban Greens	3. Digital Literacy
4. Inclusive Living	4. 24x7 Piped Water Supply
5. Poly-centric City	5. Sanitation
6. Safe & Walkable Streets	6. Waste Management
7. Economic Vitality	7. Access to Village Streets
8. Transit Oriented Development	8. Village Street Lights
9. Connect Places & Move People	9. Health
10. Walk-to-Work principles	10. Up gradation of schools
11. Digital & Transparent Governance	11. Inter village Road connectivity
12. Boost job creation	12. Citizen Service Centres
	13. Public transport
	14. LPG Gas Connections

Table 1 highlights the key components specified in the action plans of Nagpur Smart City and Wadoda Rurban cluster. While Nagpur smart city is focusing on socio-economic wellbeing and good governance through components of ‘Smart Environment’, ‘Smart Living’, ‘Smart Mobility’ and ‘Smart Governance’, the Wadoda Rurban cluster is imprecisely building on similar components for stimulating local economic development and bettering public services. Notably, both the smart developments are focused on place-based goals and there is no

significant consideration to transboundary urban-rural linkages like water and food supply etc. It is also important to note that both the discrete developments are emphasizing on uninterrupted water and energy supply, however, their focus is more on localized infrastructure development rather than transboundary source conservation.

4. RESEARCH METHODOLOGY

Based on literature review, this study works towards developing a knowledge-based conceptual framework for understanding the flow of water resources within NMA from a WEF nexus perspective. To achieve that, the authors first establish a simplistic understanding of the complex flow of WEF resources between urban and rural areas in NMA. The key agencies managing the flow of WEF resources are also underlined to establish a thorough understanding of governance structures. The linear flow of these resources within NMA is understood based on existing literature, policy documents and media reports. Thereafter, for understanding the overall flow of water resources in NMA from a wider historical perspective, the authors studied the Performance Evaluation Study report of Pench Irrigation Project (key freshwater source of NMA) by Central Water Commission (CWC 2001). This report is an official document, which the authors collected from the office of Pench Irrigation Project at the State Irrigation Department in Nagpur. Based on this study, the authors discussed the key source areas for Nagpur city, key dependent sectors (including urban, industrial and agriculture), and the wastewater generated from the Nagpur city. With a precise understanding of the flow of water resources for WEF related sectors in NMA, the knowledge-based conceptual framework is developed in consideration to the cross-sectoral linkages between these sectors. Supported with relevant statistical information derived from the policy documents, the framework also explains the overall flow of water resources (both freshwater and wastewater) in NMA, in reference to Nagpur Smart City and Wadoda Rurban cluster. Based on the key findings derived from the developed framework, feasible measures are then suggested to link the upcoming smart urban-rural developments in NMA.

5. WATER-ENERGY-FOOD RESOURCE SUPPLY IN NMA

5.1 Water Supply

Water demands within NMA are met through surface and groundwater sources. While water for urban areas is mainly sourced from surface water sources like lakes, rivers and reservoirs, the rural areas are mainly dependent on groundwater sources. Pench reservoir located in Northern part of NMA (highlighted in Figure 2) is the main source of drinking water for Nagpur city as it caters to more than 70 percent of city's water demands. Through canal and pipeline network, water from Pench reservoir is brought to the treatment plants located at Gorewada and the treated water is then supplied to the residents of Nagpur city. The city's water supply is currently managed by Nagpur Municipal Corporation 'NMC' in collaboration with a private

agency named Orange City Water Pvt. Ltd. under a ‘Public Private Partnership’ (PPP) agreement. For the rural areas, the water supply is managed by multiple agencies including Zilla Parishad, the Maharashtra Jeevan Pradhikaran and the Groundwater Survey and Development Agency (NMC 2011; NIT 2015).

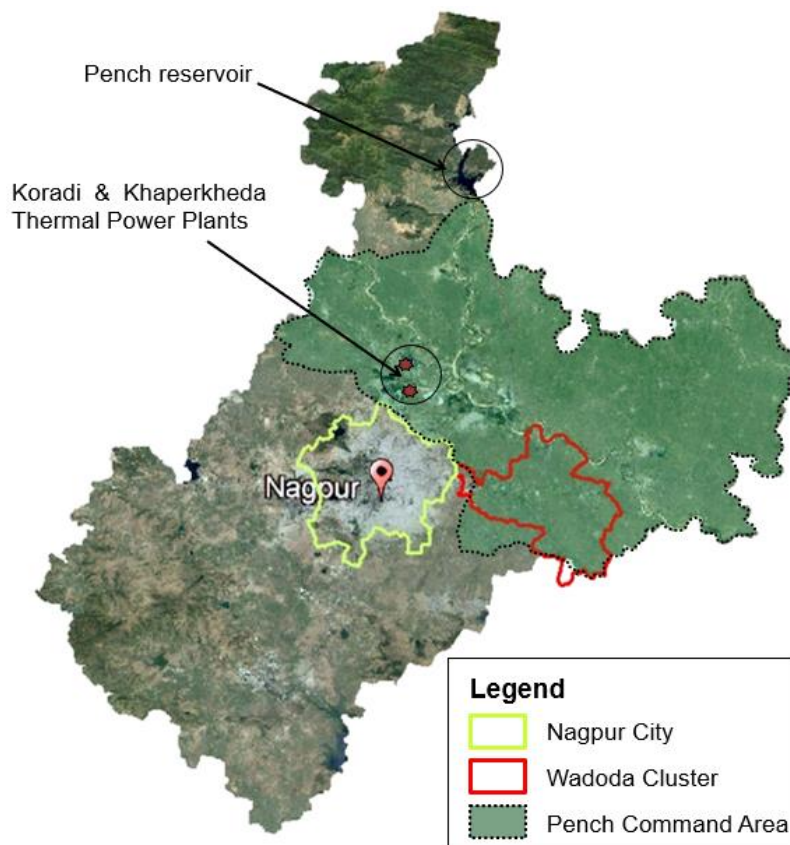


Figure 2. Google earth imagery of NMA (raster image sourced from USGS (2019)) Pench command area only within NMA boundary is shown, but it also extends outside NMA

As per MPCB (2019), the city presently generates around 505 Million Litres/Day ‘MLD’ wastewater, of which around 130 MLD is being treated at Bhandewadi sewage treatment plant (Roy 2018). In lines with the joint agreement between NMC and Maharashtra State Power Generation Co. Ltd. ‘MAHAGENCO’, the treated wastewater is supplied to the Koradi Thermal Power Station ‘TPS’ for reuse. The residual untreated wastewater is directly released in the natural drains which pollutes the streams and rivers (mainly Nag river) flowing through the city towards downstream areas through Wadoda Rurban Cluster.

5.2 Energy Supply

Nagpur region has a very prominent power sector as two important TPSs namely Koradi and Khaparkheda TPS (having total capacity of 3,740 Megawatt) are located near Nagpur city

(location highlighted in Figure 2) and operated by MAHAGENCO (Roy 2019). Although, the region is connected through the National Grid, it is important to note that Nagpur region contributes to around 47 percent of the Maharashtra state's power (UrbanEmissions.info 2019). Generation, transmission and distribution of electricity is divided between three agencies namely Maharashtra State Electricity Distribution Co. Ltd. 'MSEDCL' for power distribution, MAHAGENCO for power generation and Maharashtra State Electricity Transmission Co. Ltd. 'MAHATRANSCO', for power transmission (NIT 2015).

5.3 Food supply

NMA is predominantly an agricultural area. Around 71 percent of total geographical area of Nagpur is cultivable and crops are grown on 79 percent area of total cultivable area (NIT 2015). A bulk of these agricultural lands, as highlighted in Figure 2, fall under the command area of Pench Irrigation Project. Although there is no established database of the food source areas in NMA, much of Nagpur city's food demand is met through the food grown in surrounding villages including those in Wadoda Rurban cluster (Kulkarni 2019). The food produced in these villages is mainly brought to the Kalamna wholesale market in Nagpur city by farmers, traders, agents etc. wherein it is taxed before been sold to the retail traders. The food supply in Kalamna market yard is managed by the Agricultural Produce and Marketing Committee 'APMC', a marketing board established by the state government (APMC 2019).

6. KNOWLEDGE-BASED CONCEPTUAL FRAMEWORK

In reference to Yigitcanlar and Lönnqvist (2013), a knowledge-based conceptual framework has been developed for the case of NMA that recognizes the cross-sectoral interdependencies between urban and rural areas, particularly for the networks of freshwater and wastewater resource for WEF sectors (Figure 3). It has been developed with a precise understanding of the spatial settings related to the key water sources, human settlements, and the wastewater flow. Deriving information from key policy documents, the framework also highlights the relevant statistical information related to storage capacities of reservoirs and allocated quantities of water for different purposes.

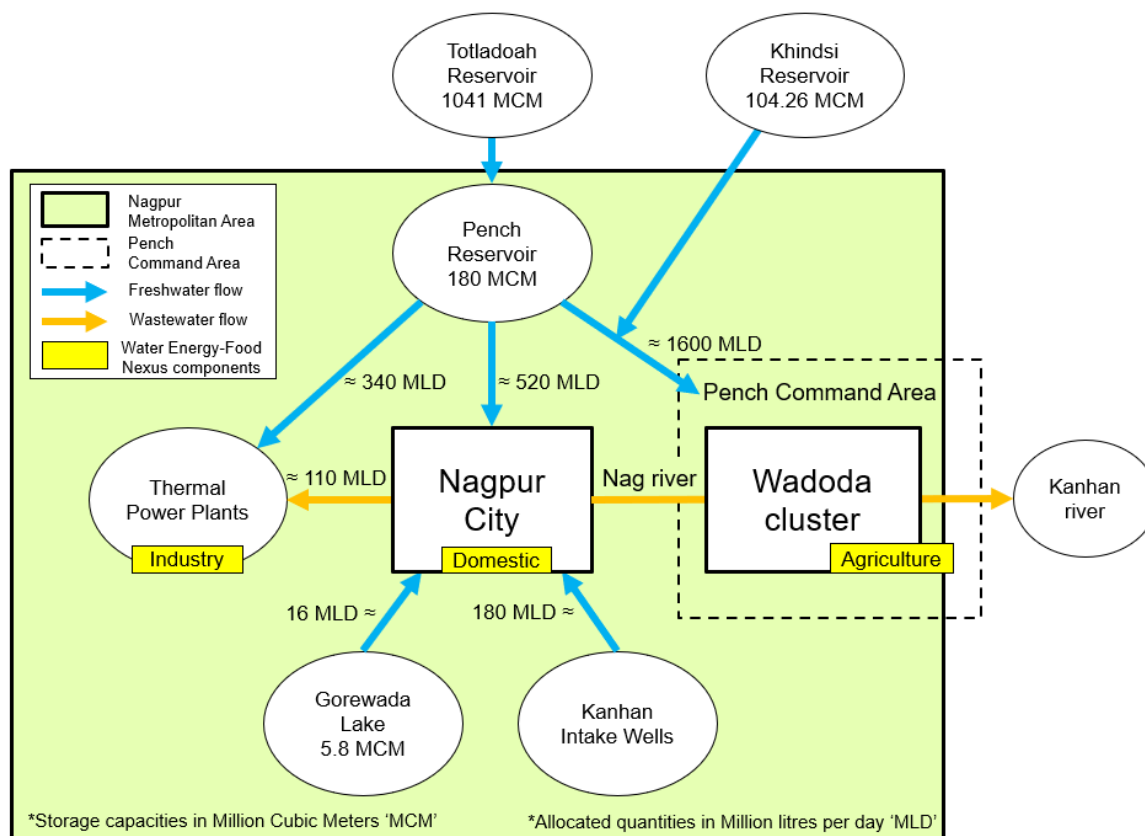


Figure 3. Knowledge-based Conceptual framework of water resource flow in NMA

As explained in Figure 3, Nagpur city presently receives bulk of its water supply from three key surface water resources namely Pench reservoir, Gorewada lake and Kanhan Intake wells (statistical data sourced from NIT 2015). Among these sources, the key freshwater source of 'Pench reservoir' is one of the three reservoirs under the Pench Irrigation Project 'PIP' (other two are Totladoah and Khindsi). As per the water allocation planning for the PIP (CWC 2001), it serves for several other purposes including energy production (for Koradi and Khaperkheda TPSs) and irrigation in around 104476 hectares of fertile land in North-Eastern part of NMA (MWRRA 2017), including all the villages in Wadoda Rurban cluster. In this manner, the PIP serves as a one key water source for urban domestic needs, agriculture and industries (TPSs) in NMA context.

Further to that, the treated wastewater from the city is also supplied to the TPSs for reuse in energy production. And, the untreated wastewater generated from the city flows through natural streams (Nag river) towards the downstream rural areas, where it serves for irrigation purposes (Mudholkar 2018). Since the supply of fresh food in Nagpur city considerably depends on the food grown in surrounding rural areas, the degrading water quality in these natural streams may also raise nexus-based concern for food quality in the city and the wider region. Moreover, the readers should note that this framework only provides a precise understanding of the water resource flow network. However, there are several other intermediary phases involved in the flow of these resources between urban and rural areas (like water treatment plants), that are discretely managed at various governance levels.

7. DISCUSSION

The developed knowledge-based conceptual framework, from the lens of water resource flow, helps in visualizing the nexus-based interdependencies between the WEF sectors in NMA. While PIP serves as a key water source for various purposes in NMA, it is important to understand that the project itself receives water from the upstream areas in the neighboring state of Madhya Pradesh. It is therefore highly important to address the WEF nexus issues in Nagpur at a transboundary scale. Specifically, because Nagpur has recently witnessed high climate variations in form of extreme cold, heatwaves and fluctuating rainfall patterns (Behl 2019). It has also experienced severe water stress situation due to the declining surface and groundwater availability (Dhyani *et al.* 2018; Deshkar 2019). As such, regional level planning exercises in reference to the developed knowledge-based framework will be critical to ensure sustainable development. While ‘SCM’ and ‘NRuM’ are meant to build ideal models that can be replicated widely for catalyzing the creation of similar smart urban-rural developments in various parts of India, the adjacent development of Smart city and Rurban cluster in NMA provides a genuine opportunity to infuse the idea of coordinated urban-rural development. Although, there is no single definition of smart developments, the study emphasizes that safeguarding the flow of key resources like water, energy, food etc. between urban and rural areas should be given due importance in the wake of emerging disaster risks like COVID-19. The cutting edge ICT features of smart developments in urban and rural areas should be duly utilized to develop smart urban-rural linkages in Nagpur region. To achieve that, the study suggests three specific focal points as follows.

7.1 Enhancing data collection at urban-rural interface

Smart developments build on ICT features and knowledge management. As such, data collection and management will play an important role in making any city or village smart. Based on the developed knowledge-based framework for resource flow in NMA (Figure 3), the upcoming smart developments should adopt strategies to enhance data collection at specific nodes of mutual concern. As explained through the knowledge-based framework, the flow of defined resources between urban and rural areas encompasses several intermediate phases. To ensure smart and effective flow of resources from source areas to consumers, there is need for improved data collection at different stages of flow across various scales. Table 2 presents few of the key focal points for data collection that could be taken into consideration for enhancing resource efficiency by the upcoming smart developments in NMA.

7.2 Enhancing sectoral and administrative coordination

Based on the developed framework (Figure 3), the resource elements of water, energy, and food are evident to be closely linked. Against the growing population, rapid urbanization trends and changing climate, there is a genuine need for integrated development planning at the urban-rural interface. While the stock of natural resources is limited, there is a need to find better

ways for collective resource management through transboundary cooperation. Presently, there are several departments and agencies at various territorial levels that discretely manage the flow of WEF resources between urban and rural areas in NMA (also explained in Section 5). However, there is a genuine need for enhancing the sectoral and administration coordination to ensure knowledge sharing for the success of smart developments. Partnerships and coordination between concerned departments can facilitate timely and informed decision making at the regional level.

Table 2. Potential areas of data collection to enhance coordinated urban-rural development

Sector	Exploratory research questions
Food	What are the key source areas of food (fruits, vegetables etc.) for Nagpur city?
	What are the consumer preferences for food products? What type of food products are grown in Wadoda Rurban cluster?
Energy	What is the overall energy demand for food production and water supply?
	What are the negative implications of energy waste (fly ash etc.) on groundwater resources and food production?
Water	What are the key water-related risks (floods, drought etc.) in Wadoda Cluster?
	What is the impact of Nagpur city’s untreated wastewater flowing through Nag river on food production in Wadoda cluster?

7.3 Need for urban-rural collaboration and partnerships

In contrast to the dichotomous development planning of upcoming smart developments, there is a need for holistic and territorial-based approaches to leverage their interlinkages and promote policy coherence. While the smart developments in NMA are currently being built with focus on specific dimensions like ‘Smart Mobility’, ‘Smart Environment’, ‘Smart People’ etc., it is also important to consider the other mutually important components like ‘Food Supply’, ‘Wastewater Management’ and ‘Integrated Governance’. The importance of continued food supply chains and integrated governance at regional level, has also been globally recognized under the ongoing COVID-19 pandemic outbreak (gFSC 2020). Focus on these aspects will also encourage urban-rural collaboration and partnerships between different stakeholders at various governance levels, in lines with the objectives of Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR 2015).

8. CONCLUSIONS

This study presents a knowledge-based conceptual framework that visualizes the flow of water resources in Nagpur region, from WEF nexus perspective. It has been highlighted that the resource flow between urban and rural areas encompasses a wide range of actors, across different sectors and administrative scales. While urban and rural areas in NMA are discretely governed, the study emphasizes on developing integrated platforms for natural resource management at regional level. This is in lines with the global policy frameworks of SDGs, The New Urban Agenda and SFDRR, that have emphasized on transboundary cooperation and multi-sectoral approaches to resource management. It is therefore hoped that this study will build the awareness of policy makers and assist for evidence-based policymaking in Nagpur region. It will also serve as an important basis for the integrated development planning of Smart Cities and Rurban clusters in India. While the concept of WEF nexus has recently gained increasing attention in policy making, this study would help to visualize the WEF linkages between urban and rural areas at regional scale. It will also provide a new perspective to researchers, academicians, policy makers etc. in context of urban-rural coordinated development. Moreover, the research contributes to linking the existing body of literature on urban-rural linkages, smart developments and WEF nexus.

The authors acknowledge three specific limitations to this research as follows, 1) The knowledge-based conceptual framework developed in this study only considered the linear flow of freshwater into Nagpur city and the wastewater outflows. However, further research needs to be conducted in consideration to groundwater utilization as well as other surface water sources (like lakes, ponds) within NMA; 2) The developed knowledge-based framework also poses limitations in precisely understanding the nexus-based linkages between the components of water, energy and food systems, which are mutually exclusive and yet interdependent. There is a need for further investigating and cross-validating these linkages by applying more scientific approaches, in consideration to other urban-rural linkage components like flow of goods, people etc.; 3) The developed framework is case specific and it may not be applicable in other contexts. The future scope of the study includes addressing these limitations as well as focusing on other ways of connecting smart urban and rural developments.

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Original paper

An Examination of the Self-Evaluations Over Time of 3.11 Tsunami Survivors Regarding Their Post-Disaster Recovery

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Abstract In this study, the factors that affected the sense of recovery of the victims of the Great East Japan Earthquake were analyzed from both short-term and long-term perspectives. We used the results of questionnaire surveys conducted in 2013 and 2017 amongst residents of Noda Village, Iwate Prefecture, to determine the factors that affected the sense of recovery of their personal lives as well as their sense of the recovery of the village itself. We also examined how differences in the choice of temporary housing affected their sense of recovery. Utilizing decision tree analysis, we clarified differences in the key factors that impacted their short-term and long-term perspectives as well as the sense of their own recovery and their sense of the village's recovery. Because the introduction of publicly-funded rental housing deviated from the temporary housing networks available in previous disasters, there remains the possibility that although the short-term sense of recovery of those in publicly-funded temporary housing was relatively low, it seemed to increase over the long-term.

Key words: Great East Japan Earthquake, Sense of recovery, Publicly funded rental housing, Location-specific capital, Human networks, Disaster-recovery policies

1. INTRODUCTION

This study analyzes the factors affecting the sense of recovery, from both short-term and long-term perspectives, of those who survived the Great East Japan Earthquake. Specifically, we use the results of questionnaire surveys, conducted in 2013 and 2017, of the residents of Noda Village, located on the coast of Iwate Prefecture, to examine and identify the factors that

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have affected their sense of personal recovery as well as their sense of the recovery of the village itself.

The Great East Japan Earthquake was a complex disaster that consisted of an earthquake, a tsunami, and a nuclear accident. The earthquake and tsunami were the largest catastrophes in recorded Japanese history, with the disaster extending 500 km from north to south. Recovery from such a calamitous combination of disasters has understandably taken a long time.

According to “Changes in evacuation shelters following the Great East Japan Earthquake, the Great Hanshin-Awaji Earthquake, and the Chūetsu Earthquake,” a report issued by the Reconstruction Agency and based on materials from the National Police Agency, Niigata Prefecture and Hyogo Prefecture, there were 307,022 evacuees recorded one week after the Great Hanshin-Awaji Earthquake, 76,615 after the Chūetsu Earthquake, and 386,739 after the Great East Japan Earthquake³. These numbers speak to the sheer magnitude of the damage in human terms inflicted by the Great Hanshin-Awaji Earthquake and the Great East Japan Earthquake.

Looking at the situation three months after the disasters, all evacuees from the Chūetsu Earthquake had been taken care of, whereas there were 50,466 evacuees remaining from the Great Hanshin-Awaji Earthquake and 88,361 from the Great East Japan Earthquake. One can clearly grasp the seriousness of the situation when this many people were forced to live in shelters or in other emergency living quarters three months following the disaster. Even after seven months, 21,899 people left homeless by the Great East Japan Earthquake were still living in evacuation centers, whereas 3,432 evacuees of the Great Hanshin-Awaji Earthquake remained in these centers. It can be seen that the restoration and reconstruction challenges left by the Great East Japan Earthquake were of a magnitude not seen in recent history.

The housing aspect of the recovery process in past disasters has followed a single path: initial emergency shelters, supplanted by the construction of temporary housing, followed by rebuilding. However, as pointed out by Kunitomo (2013), the Great East Japan Earthquake was a “rare disaster,” with the number of temporary housing units that were needed rising to 30,000, greatly exceeding the capacity to supply necessary emergency building materials. For this reason, the Ministry of Health, Labor and Welfare announced that it would recognize private temporary rental housing that victims could search for on their own, and that a post-disaster “publicly funded rental housing (minashi kasetsu jūtaku)” system would be introduced to provide rent subsidies. For this reason, it could be expected that the victims would have had a wider range of temporary housing options, and that there would have been a difference in their sense of recovery as a result of these expanded options.

Kuromiya *et al.* (2006) conducted a distinctive and notable study on how much time is required, what processes are involved and what social factors help bring about the recovery of the lives and livelihoods of people affected by natural disasters in Japan. Kuromiya *et al.* utilized Hyogo Prefecture panel data from 2001, 2003, and 2005 to grasp the extent to which

³ Reconstruction Agency, “Changes in evacuation shelters and shelters”
<http://www.reconstruction.go.jp/topics/000185.html>

the victims' sense of recovery had grown over these years following the Great Hanshin-Awaji Earthquake. Their analysis showed that lives rooted in a community could be improved without repeated post-disaster relocations, and that active connections with other people in the community are an important factor in building up a sense of having recovered.

Using the same data as that utilized in this paper, Nagata (2018) found that in 2017, six years after the Great East Japan Earthquake, the sense of recovery had generally improved over that which had been revealed in a 2013 survey, two years following the disaster. In addition, it was revealed that one of the most relevant factors for improving the sense of recovery was whether the victim's relationship with people outside the village had increased or decreased after the disaster. Another important factor was whether or not the individual had been able to meet someone or others with whom he or she could open up to and talk with.

In many previous studies, the meaning of a social network, which includes family members and other relatives, neighbors and co-workers has been researched and clarified. Members of one's social network provide vital disaster assistance including the communication of warning messages and recovery information, the provision of supplies, search and rescue assistance, shelter during evacuation and rebuilding, social, emotional, and financial support as well as help with debris removal, rebuilding and repairs. Thus, social networks contribute to the ability of a person to respond and cope with extreme events (Eric and Faas (2017), Elliott *et al.*(2010) and Hawkins and Maurer (2010)). Meyer (2017) found that family members play a central role in disaster support networks.

However, these earlier studies did not examine the effects of differences in temporary housing on post-disaster senses of recovery, because, as Kunitomo (2013) revealed, the publicly funded rental housing system was introduced after the Great East Japan Earthquake. Researchers on disaster recovery before the Great East Japan Earthquake had therefore not been able to take this system into consideration when looking at temporary housing. However, when taking into account the likelihood of future disasters, one would think that vacant houses in a disaster area could be fully utilized as publicly funded rental housing, which leads one to conclude that a diversity of temporary housing options should be taken into consideration by policy makers.

This paper therefore focuses on the following two points for analysis. The first point is whether or not the factors that affect the sense of recovery change over time. The second is the question of which type of temporary post-disaster housing is chosen by or made available to victims and how this affects their sense of recovery.

The structure of this paper is as follows. In the following section, the sense of recovery is defined using utility functions, and the determinants of the sense of recovery are described. In the next three sections, we conduct an empirical analysis using the results of two questionnaires carried out by the authors amongst the affected people. Finally, Section 4 summarizes the results of the paper and describes the implications for recovery policy that are suggested by these results.

2. THEORETICAL FRAMEWORK

Our analysis is based on the model of Lee, Nagata and Atsumi (2014). The reason we adopt their model is that it is a unique approach that uses location-specific capital to assess the human, social and economic impacts of a natural disaster. Our research, while referencing Lee, Nagata and Atsumi, focuses only on location-specific capital and the damage done to human networks. We assumed that the sense of recovery depends on the income and location specific capital before the disaster and the damage incurred as a result of the disaster.

Individuals' utility is assumed to be a function of their income (Y) and their stock of location-specific capital (C). Location-specific capital is defined as human networks. An individual's utility function before and after a disaster as follows,

$$\begin{aligned}
 U_{t=0} &= U_{t=0}(Y_{t=0}, C_{t=0}) \\
 U_{t=1} &= U_{t=1}((1 - \alpha)Y_{t=0}, (1 - \beta)C_{t=0})
 \end{aligned}
 \tag{1}$$

Where $U_{t=0}$ and $U_{t=1}$ denote the victim's satisfaction with life before the disaster and after the disaster, moreover, α and β indicate the extent of the damage to income and location-specific capital caused by the disaster.

The sense of recovery (R) is calculated by the difference of an individual's sense of utility in the period before ($U_{t=0}$) and after ($U_{t=1}$) the disaster. R is defined as follows.

$$R \equiv U_{t=1}/U_{t=0}, \quad 0 < R \leq 1
 \tag{2}$$

The sense of recovery was determined by how life satisfaction after the disaster drew closer to life satisfaction before the disaster. If a survivor's current life satisfaction approached that of his or her life before the earthquake, the sense of recovery was close to 1; if satisfaction after the disaster was lower than before, the sense of recovery approached 0.

From equations (1) and (2), the sense of recovery is determined as follows:

$$R = R(Y_{t=0}, C_{t=0}, \alpha, \beta)
 \tag{3}$$

That is to say, the sense of recovery depends on income and location-specific capital before the disaster and the damage incurred as a result of the disaster. In the questionnaire, it was not possible to obtain any information about the respondents' sense of satisfaction with their life before the disaster. We instead questioned them about their post-disaster sense of recovery. In

the paper, we used the sense of recovery score for the proxy variable of R, the comparison of the changes in the respondents' perceived sense of recovery before and after the disaster.

Several comparative statistical results emerge straightaway from the model. First, the sense of recovery decreases with the extent of damage to income caused by the disaster. Second, the sense of recovery also decreases when the damage done to location-specific capital increases. Third, the effects of income and the initial holdings of location-specific capital on the sense of recovery cannot be determined apart from one another.

3. EMPIRICAL ANALYSES

3.1 DATA

Our data were derived from the questionnaire surveys conducted by the authors in the village of Noda, located on the northern Sanriku Coast of Iwate Prefecture, in 2013 and 2017. Noda is a good example of a stricken coastal area. The population of Noda, according to the 2010 census, was 4,800 when the disaster occurred. A tsunami, 37.2 metres high, hit the centre of the village, killing 37 persons and obliterating or badly damaging 810 buildings and houses⁴. The most extensive damage was to the village centre and to basic industries such as fishing and agriculture.

The authors have been conducting disaster volunteer activities in Noda Village since the disaster struck in March 2011. Educational organizations, including Hirosaki University, Kyoto University, Osaka University, and the Hachinohe Institute of Technology, together with the Japan Disaster Relief Volunteer Network formed an organizational network called Team Kita-Rias and established an office in the affected area. The team engaged in immediate post-disaster activities such as sludge removal, food preparation, visits to and interviews at individual households. The team then moved on to help provide support for educational activities and to co-sponsor meetings related to reconstruction (Nagata (2012), Lee and Atsumi (2016)) As a result, Team Kita-Rias has been able to foster a relationship of trust with the villagers and obtain the cooperation of the Noda Village Office and other local bodies. This enabled the authors to conduct their "questionnaire survey on the lives and work of Noda villagers " in 2013 and again in 2017.

For the 2013 questionnaire survey, 2853 men and women between the ages of 18 and 69 who were listed in the village's Resident Registry as of February 2013 were included. On the other hand, the subjects of the 2017 survey were those who had graduated from Noda Junior High School, the only junior high school in the village. 1,276 individuals between the ages of 20 and 60 were surveyed. Of the 307 questionnaires that were received, 126 (41.0%) were from

⁴ For more information regarding the damage from the disaster, please refer to "Information on the Great East Japan Earthquake" on the Noda Village website. <http://www.vill.noda.iwate.jp/bosai/378.html>

respondents who lived in the village at the time of the survey, whereas the rest resided outside the village⁵.

3.2 Analytical Approach

In this paper, the results of the 2013 and 2017 surveys are compared and the factors that have had short-term impacts and long-term impacts on the disaster victims' sense of recovery are discussed. First, the determinants of their sense of recovery were analyzed using decision tree analysis. Next, we analyzed the effects of initial shelter selection on the sense of recovery utilizing an ordered logit model.

Decision tree analysis is a data mining method based on machine learning and is used to determine the independent variables that influence the classification of a set of independent variables and their order. This method is sometimes used to predict damage in the event of disaster (Haines (2012), Kim (2018), Luu (2017)). The boundary values of those independent variables that can be divided into two groups that form the greatest dependent variable differential are located and established as independent variables. Next, the boundary values of those independent variables that can be divided into two groups amongst the previously separated groups that form the greatest differential are located and established as independent variables. By repeating this until the difference falls within a certain range or until the difference reaches an established depth, it becomes possible to ascertain the influence of the independent variables on the dependent variables as well as their order.

In the case of this study, the sense of recovery is the dependent variable, and when the respondents are divided into two groups, the variable that maximizes the difference in the sense of recovery will be searched for. By analyzing common items in the 2013 and 2017 surveys as candidates for independent variables, it is possible to identify important factors in the sense of recovery, short-term important factors, and long-term important factors regardless of time. In this study, we use the CART (Classification and Regression Tree) Algorithm. This algorithm calculates the diversity of the dependent variable which was divided into two groups by the independent variables, and it chooses the level as well as the independent variable with the largest diversity. We use the Gini coefficient as the criteria for diversity, and stopped the algorithm when the number of observations in the group dropped to 20 or less.

There were two main reasons for using decision tree analysis in this study. First, since the sample size in the 2017 survey was particularly small, it would have been difficult to determine in advance those factors that would influence the sense of recovery. When doing regression analysis, it is necessary to establish in advance the independent variables that are to be used. However, the factors that affect the sense of recovery are not always obvious, so when the variables are selected it is possible that there may be a certain amount of arbitrariness involved.

⁵ Because of the survey method, the dataset in 2017 included residents who had moved out of the Village. Since Noda Village was severely damaged, some of the residents had moved out of area over these 6 years. We included these villagers in our dataset taking this into consideration. For survey details see Lee *et al.* (2013, 2018).

In addition, there were 34 items that were included in both the 2013 and 2017 surveys that were candidates to become independent variables. However, the sample size for 2017 was 111, making it difficult to do an analysis using all the variables⁶. Although decision tree analysis also requires a certain sample size, it is not as affected by the number of independent variables as is regression analysis because it seeks out the two boundaries that can most clearly be separated.

Second, there is the possibility that decision trees, drawn as an outcome of decision tree analysis can be applied to future disasters. One of the areas where decision tree analysis is most often used is in marketing and in the forecasting of consumer behavior. For example, By forming a decision tree from past sales results and the like, the purchase probability and the preferences of each customer type are predicted and are used for target selection and other sales or marketing strategies. This idea can be applied to disaster recovery as well. In other words, if you were to create a decision tree for the sense of recovery from past disasters, it should be possible to predict, to some extent, the sense of recovery, according to the type of victim in future disasters. By doing so, care and recovery programs and approaches can be adopted that vary depending upon the sense of recovery of the individual victim.

Because decision trees are set up as hierarchies they can be broadly classified without detailed information, and because they may need less information than the results of regression analysis results, they were utilized for our analysis⁷. Although this is not a major reason, there are already many researches on the sense of recovery using regression analysis, and we are trying to increase our understanding by analyzing it from a different perspective.

The order logit model is a method for analyzing the influence of discrete sequenced items on the selection probability of each individual item at each step. In ordinary regression analysis, explanatory variables are continuous, but in questionnaires that use the five-step method, they cannot be used because the answers are ordinal scales. The ordinal logit model is a method for performing regression analysis on a discrete ordinal scale. Since the sense of recovery, which is a dependent variable in this study, is an ordinal scale based on the 4-step method, the analysis was performed using an ordinal logit model. The interpretation of the analysis results is basically the same as in ordinary regression analysis⁸.

⁶ There was only one respondent residing in temporary housing in the 2017 survey, which could not be identified as a personal effect. In the 2017 survey, about 80% of the respondents answered that their recovery was 1, and there were few variations. This suggests that the recovery was progressing smoothly at the individual's life level, which is not a bad thing, but it still poses a problem for analysis.

⁷ Note that since decision tree analysis is a method of searching for a boundary to divide groups, it would be difficult for a variable having a small number of corresponding answers to become a boundary. For this reason, for those items where the number of affected persons in Great East Japan Earthquake or in Noda Village was small, it is difficult to evaluate that these items are important or not. In order to apply this to disasters in general, it will be necessary to conduct similar analyses of other disasters and to deepen our knowledge of possible post-disaster programs.

⁸ The coefficient calculated by the ordinal logit model is strictly an effect on the latent variable that affects the selection probability, and does not directly indicate the range that increases the selection probability. However, the interpretation of the sign and the comparison of the magnitude of the coefficients can be performed by the same interpretation as in ordinary regression analysis.

The reason for using the ordinal logit model to analyze the effects of housing is because it makes it possible to evaluate the impact of housing comparatively, while controlling other factors. In the case of decision tree analysis, in order to determine the boundaries at the time of the division into two groups, all of the variables are not necessarily used for the evaluations. Nor can comparable quantitative indicators be obtained. In regression analysis, after removing the influence of other established independent variables, the magnitude of the influence on the independent variables can be measured. At this time, if the scales of the independent variables are the same, the magnitude of the influence can be analyzed by directly comparing the magnitudes of the coefficients. In this study, we used the ordinal logit model because the occupied houses were used as dummy variables and therefore had the same scale, which allowed for a direct comparison of the estimated results.

Table 1-1. Descriptive statistics of survey results

Variables	2013	2017	note
Personal Recovery	1.97	1.38	4 steps (Almost full recovery (1) to Absolutely no recovery(4))
Village Recovery	2.97	2.30	4 steps (Almost full recovery (1) to Absolutely no recovery(4))
Evacuation housing			
Same house	74.5%	79.3%	
Different house	4.0%	9.9%	
Temporary housing	11.9%	0.9%	
Public-funded rental housing	4.0%	1.8%	
Others	5.6%	4.5%	
Damage to housing	2.14	1.68	5 steps (No damage (1) to Completely destroyed (5))
Increase/Decrease of personal relationships			3 steps (Increase (1) to Decrease (3))
Immidiata family and other relatives	1.98	1.92	
Local human network	2.08	2.03	
Friends in the workplace	2.05	1.90	
Person outside the village	2.01	1.84	
Within walking distance (before the disaster)			Number
Immidiata family and other relatives	8.89	6.60	SD 8.55, 0 to 50 (2013), SD 6.73, 0 to 40 (2017)
Local human network	9.33	4.51	SD 15.2, 0 to 200 (2013), SD 6.02, 0 to 30 (2017)
Friends in the workplace	4.60	4.46	SD 9.55, 0 to 100 (2013), SD 15.4, 0 to 150 (2017)
Within walking distance (after the disaster)			Number
Immidiata family and other relatives	8.98	6.55	SD 18.4, 0 to 300 (2013), SD 6.56, 0 to 40 (2017)
Local human network	9.17	4.69	SD 22.1, 0 to 300 (2013), SD 6.01, 0 to 30 (2017)
Friends in the workplace	4.24	5.18	SD 9.39, 0 to 100 (2013), SD 15.8, 0 to 150 (2017)
Change in numbers of persons before and after disaster			Subtracting number of persons before the disaster from after the disaster
Immidiata family and other relatives	0.09	-0.05	SD 14.9, -30 to 250 (2013), SD 3.63, -33 to 10 (2017)
Local human network	-0.17	0.18	SD 15.3, -35 to 250 (2013), SD 1.48, -5 to 3 (2017)
Friends in the workplace	-0.36	0.71	SD 3.07, -29 to 17 (2013), SD 3.57, -9 to 20 (2017)
Give advice			3 steps (Often (1) to Never (3))
Immidiata family and other relatives	1.91	2.13	
Other Villagers	2.25	2.56	
Gender	1.47	1.52	Male (1), Female (2)
Age	46.5	36.7	
Eldest child	1.37	1.47	Eldest (1), Not the eldest (2)
Educational level	3.33	3.05	Primary school (1) to University/Graduate school (6)
Marriage status	1.67	1.86	Married (1), Separated/Widowed (2), Single (3)
Children	1.57	1.47	Yes (1), No (2)
Household size			One person (1) to 5 person or more (5)
Before the disaster	3.49	3.50	
After the disaster	3.36	3.10	
Change	-0.13	-0.40	Subtracting number of persons before the disaster from after the disaster
Household income	4.73	5.41	9 steps (Zero (1) to \10,000,000 or more(9))
Change brought on by the disaster			3 steps (Increased (1) to Decreased (3))
Household income	2.31	1.90	
Household expenses	1.56	1.45	
Household savings	2.51	2.16	
Number of observations	302	111	

Table 1-2. Distributions of answers

Variables	Year	1	2	3	4	5	Obs.
Personal Recovery	2013	49%	13%	30%	8%	-	302
(Almost full recovery (1) to Absolutely no recovery(4))	2017	79%	8%	8%	5%	-	111
Village Recovery	2013	2%	8%	79%	10%	-	302
(Almost full recovery (1) to Absolutely no recovery(4))	2017	17%	41%	38%	5%	-	111
Damage to housing	2013	64%	6%	1%	9%	19%	302
(No damage (1) to Completely destroyed (5))	2017	78%	6%	3%	1%	12%	111
Increase/Decrease of personal relationships							
Immediate family and other relatives	2013	12%	78%	10%	-	-	302
(Increase (1) to Decrease (3))	2017	16%	76%	8%	-	-	111
Local human network	2013	11%	70%	19%	-	-	302
(Increase (1) to Decrease (3))	2017	11%	76%	14%	-	-	111
Friends in the workplace	2013	12%	72%	17%	-	-	302
(Increase (1) to Decrease (3))	2017	14%	81%	5%	-	-	111
Person outside the village	2013	15%	70%	16%	-	-	302
(Increase (1) to Decrease (3))	2017	21%	75%	5%	-	-	111

In this study, we analyzed only those items that appeared in both the 2013 and 2017 surveys. These are summarized in Table 1-1 and Table 1-2. In the decision tree analysis, if there was no answer provided for any of these items, they were excluded from the sample. As a result, the number of observations was 302 for the 2013 survey and 111 for the 2017 survey.

We tested the differences in demographics from before the disaster and between the two samples⁹. Because “Age” was significantly lower in 2017 there were more respondents with “Single” marriage status in 2017. We included respondents outside of the village in 2017, so the ratio of “Not the eldest child” increased in 2017. Other demographics showed no not significant difference.

3.3 Analysis results

Before going into a detailed analysis, we will first take a look at the changes in the 2013 and 2017 responses. First of all, the numerical values for the two entries related to the sense of recovery were smaller in 2017 than in 2013, indicating that recovery was progressing. Taking into consideration that recovery and reconstruction progress over time, this is a natural outcome (Nagata (2018)).

As for evacuation housing, around 16% of respondents in the 2013 survey were living in temporary or publicly funded rental housing. But that figure had fallen to about 3% by the time of the 2017 survey. A possible reason for this change is that the proportion of persons residing in Noda who responded to the 2017 survey was high. It can also to be assumed that the homes of those who were moved into temporary or publicly funded rental housing had been severely damaged by the earthquake or the tsunami. The 2013 survey was conducted around 2 years after the disaster, so it is possible that the residents continued to live in temporary housing.

⁹ Some demographics were indicated after the disaster. We did not test these variables because they possibly included the impact of the passage of time.

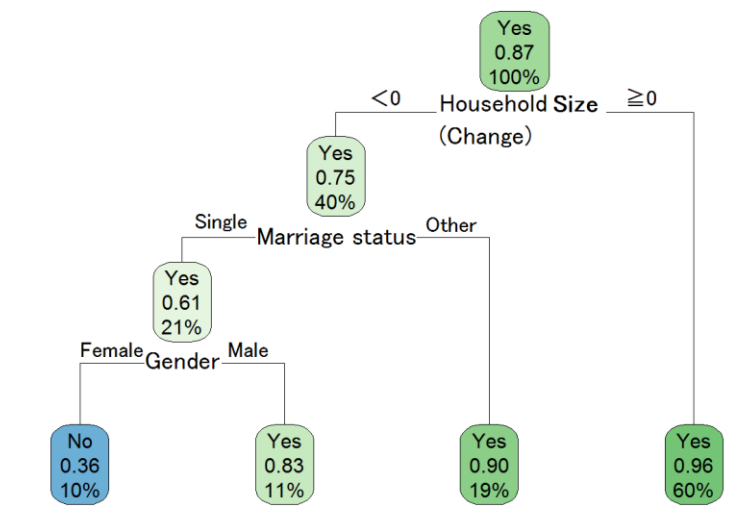
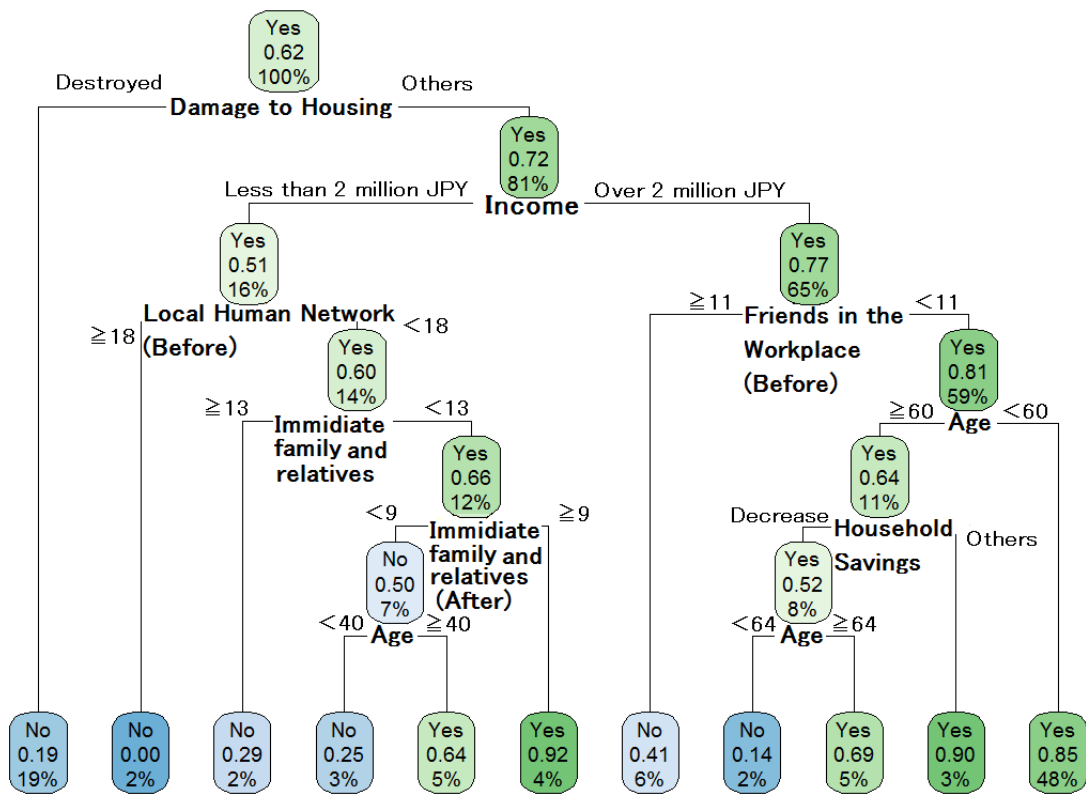


Figure 1. Decision tree for the personal sense of recovery¹⁰

¹⁰ The top of each nodal square indicates the dominant response for that group. The middle numbers indicate the percentage of those expressing “non-recovery” within the group. The numbers at the bottom indicate the ratio of the group to the entire sample. Below the node are the variables and their values that serve as boundaries; on the left are the groups that meet the conditions for a boundary; on the right are those that do not.

However, by the time of the 2017 survey, more than 5 years after the disaster, it is possible that most of the victims had moved on from their temporary living quarters.

Regarding the number of family members and others who resided within walking distance, in the 2017 survey the number of immediate family members or other relatives as well as the number of acquaintances had decreased, whereas the number of workplace friends had increased. This may indicate that post-disaster recovery and reconstruction was progressing and that a return to one's place of work had occurred.

In addition, the 2017 survey showed improved results for income, expenditures and savings when compared with their pre- and short-term post-disaster circumstances. This may be an indication that lives had improved due to the progress of reconstruction and recovery.

3.3.1 Decision tree analysis results

First, we analyzed how victims viewed their own sense of recovery. The dependent variable was a 4-step configuration and it was possible for analysis to be carried out employing a continuous variable or broken down into two divisions based on a certain reference points. Although analysis was carried out utilizing both approaches, no significant differences emerged. Therefore, this paper describes only the results of the two-division approach¹¹. As for the two divisions, answers 1 and 2 were categorized as "recovered" and 3 and 4 "not-yet recovered".

The left side of Fig. 1 shows the results for 2013 and the right side for those of 2017. Looking at the 2013 results, the sense of recovery was low if the victim's home had been completely destroyed. If household income was low and the number of the victim's acquaintances before the disaster had been large, the sense of recovery was also low. If household income was above a certain level and the number of workplace friends in which the victim was in contact after the disaster was large, the sense of recovery was high. Furthermore, if household income was low and the number of pre-disaster friends was high the sense of recovery was low. Next, looking at the 2017 results, the sense of recovery was high if the number of household members had not decreased. When the number of household members had dropped, the sense of recovery was high if they were married. Women who were not married tended to have a low sense of recovery.

Comparing the results of the 2013 and 2017 surveys, the impact of the damage to one's home, which was a significant factor in 2013, had lost its significance in 2017. On the other hand, being married or not, which had little effect in 2013 was of consequence in 2017. In both 2013 and 2017, changes in the number of households, changes in household income and savings, as well as changes in family composition and the changing economic environment were factors that showed an impact.

¹¹ Some of the conclusions reflect the results of analysis using continuous variables.

Next, we analyzed the sense of recovery of Noda itself using a decision tree. The left side of Figure 2 shows the 2013 results; on the right are those for 2017. Only 10% of the responses had answer at or below option 2, so it was not possible to establish a group with a high sense of recovery. When comparing these results to the personal sense of recovery, changes in the entries for the number of family members and relatives, the number of local acquaintances, the number of friends in the workplace, and the number of households in the area showed common outcomes for both. On the other hand, entries such as changes in relationships with persons outside of the village, the number of children, and changes in income did not affect one's personal sense of recovery, but did affect their sense of the village's recovery.

The results of the 2017 survey indicated that post-disaster household size had an impact; if the number of members of a household was above a certain number, the sense of recovery tended to be high. If the number of household members after the disaster was small, but the number of post-disaster workplace friends was large, the sense of recovery was also high. In addition, even if the number of workplace friends was small, the sense of recovery was high if damage to one's house was minimal. If the damage to the home was above a certain level, the sense of recovery diminished as household size increased.

3.3.2 Changes over time in factors affecting the sense of recovery

Table 2 summarizes the results of the above analysis. The underlined elements are those that affect both the individual's sense of his or her own sense of recovery as well as that of the village. Also, (before) and (after) indicate the number of people before and after the disaster, respectively¹².

First, in both the 2013 and 2017 surveys, the number of local workplace friends before the disaster and the number after the disaster as well as changes in household size affected both their own sense of recovery and their sense of village recovery. In 2013, both the sense of personal recovery and the sense of the village's recovery were affected by damage to homes, the number of immediate family members and other relatives who were in the area before and after the disaster, the number of friends who were nearby after the disaster and subsequent changes in the number of these friends, changes in family membership, consultations with villagers, and changes in household income due to the disaster. In 2017, none of these factors affected the sense of individual recovery or village recovery.

¹² It should be noted that decision tree analysis has a feature where, due to the nature of grouping, variables having a small number of relevant respondents are difficult to be adopted as boundaries. The results show the importance of variables for which a certain number of responses were received.

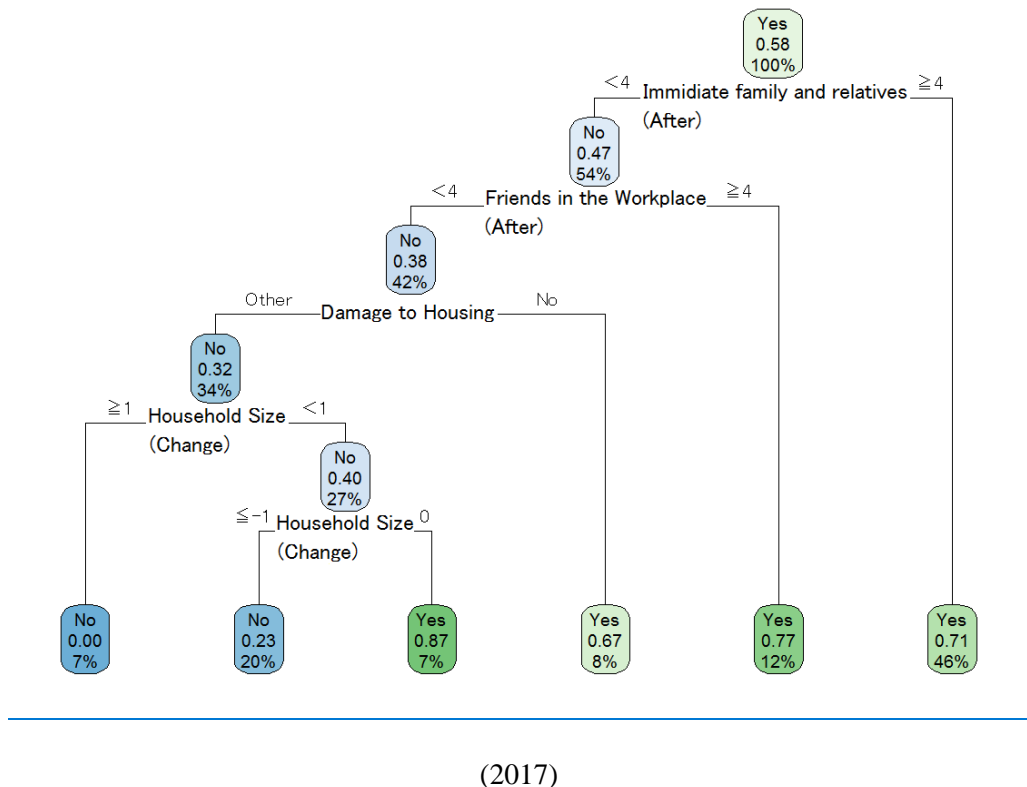
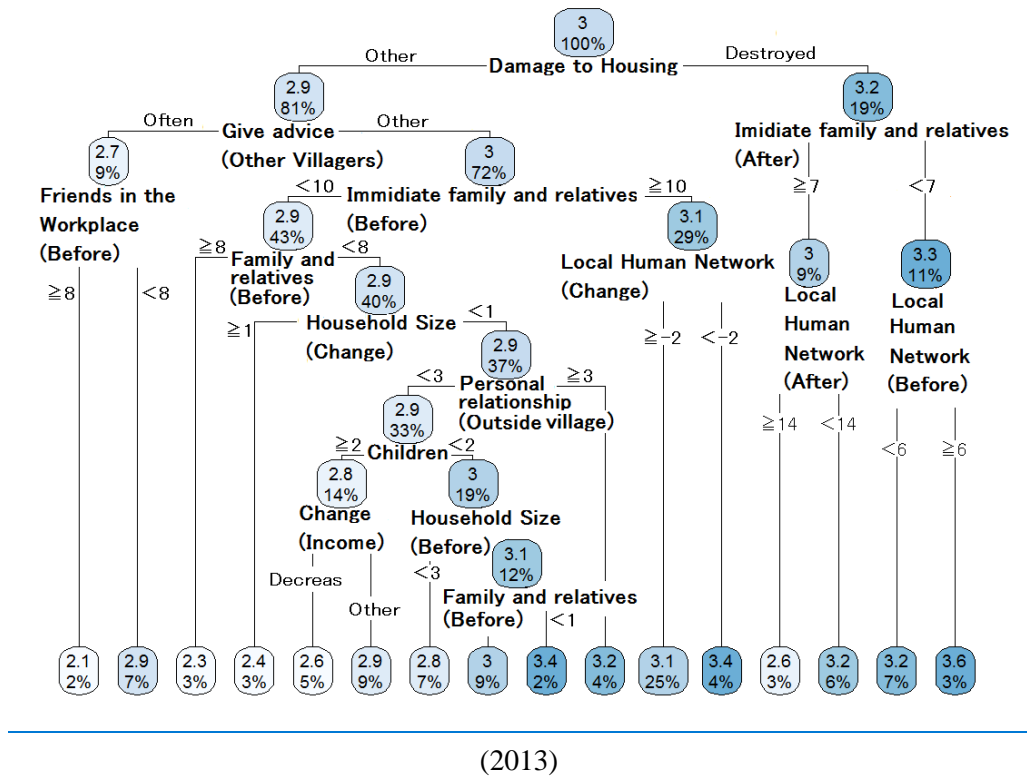


Figure 2. Decision tree for the sense of recovery of the village

Table 2 Key factors for sense of recovery¹³.

	Influence on personal recovery	Influence on village recovery
2013 only	Damage to housing, number of family members and other relatives (before) (after), number of local friends (after), change in the number of local friends, advice & counsel (villagers), age, changes due to the disaster (household income)	Changes in relationships with persons outside the village, number of family members and other relatives (before) (after), changes in the number of friends in the community, advice & counsel (villagers), children, number of households (before)
Both years	Number of local friends (before), number of friends at work (before) (after), gender, changes in the number of households, household income, changes due to the disaster (household savings)	Damage to housing, number of local friends (before) (after), number of friends at work (after), changes in the number of households, changes due to the disaster (household income)
2017 only	Marriage status	Advice and counsel (immediate family / relatives), age, firstborn child, educational background, number of households (after)

As for the sense of personal recovery, pre-disaster factors such as the number of workplace friends, gender and household income were factors in both the 2013 and 2017 surveys. In the 2013 survey, factors such as damage to homes, the number of friends in the area after the disaster, age and changes in income due to the disaster affected their sense of recovery, whereas in the 2017 survey they did not. On the other hand, in the 2017 survey, whether or not they were married influenced their sense of recovery.

Regarding the sense of recovery of the village, damage to homes, the number of friends in the area after the disaster, and changes in household income due to the disaster affected the sense of recovery in both the 2013 and 2017 surveys. On the other hand, factors such as changes in social relations outside the village, the number of children, and the number of households before the disaster affected the sense of village recovery in the 2013 survey, but did not in the 2017 survey. In the 2017 survey, having family members or other relatives available to offer

¹³ In the section 3.3.1, we describes only the results of the two-division approach. We describe the decision tree which uses dependent variables as continuous. Because Table 2 reflects the results of both, some dependent variables are added.

advice and counsel, age, being the firstborn or not, educational background, and the number of household members after the disaster had emerged as factors.

3.3.3 Results of ordinal logit analysis

Next, we analyzed the impact of the type of housing into which victims moved after the disaster and their sense of recovery using the ordered logit model. The dependent variables were the sense of personal recovery and the sense of village recovery. The independent variables were based on the results of the decision tree analysis described above. We used changes in the number of workplace friends, gender, household size, household income, and post-disaster changes (household savings).

For the sense of village recovery, we used the number of local friends and acquaintances before and after the disaster, the number of friends in the post-disaster workplace, changes in household size, the extent of damage to one's home, and other post-disaster changes (household income). In both analyses, the types of housing into which displaced persons lived or were placed after the disaster were divided into 9 categories and included as independent variables: one's own home (resided in before the disaster), one's own home (different from that resided in before the disaster), temporary housing, publicly-funded rental housing, plus five other categories.

The sense of personal recovery is set forth in Table 3¹⁴. The sense of recovery is the dependent variable; the smaller the number the higher the sense of recovery. This indicates that the variable with a negative estimated coefficient has the effect of increasing the sense of recovery, while a positive one has the effect of reducing the sense of recovery. In addition, the value assigned to the first living quarters in which the disaster victim lived was based on the victim's pre-disaster home. First, the coefficient of household income was negative and significant in both 2013 and 2017, indicating that the higher the household income, the higher the sense of recovery. In addition, the coefficient of change (household savings) after the disaster was positive and significant, indicating that an increase in savings increased the sense of recovery. Other variables were not statistically significant.

As for the type of housing into which the victim moved after the disaster, there was no significant difference between living in the home that one lived in prior to the disaster and other housing. However, in 2013, the coefficients were all positive, indicating that having a home in the same location led to the highest sense of recovery. In 2017 the coefficients were all positive, indicating that remaining in one's own pre-disaster home brought on a high sense of recovery, whereas in 2017 the coefficients were negative, suggesting the possibility that this choice had not enhanced their sense of recovery.

Moving on to a comparison of the size of the coefficients, in 2013, living in one's pre-disaster home > one's own home in a different location > temporary housing > publicly funded

¹⁴ Only those independent variables that showed significant results, other than those relating to the home, were shown. In the calculations, all of the independent variables listed above were used.

rental housing. In 2017, living in one's own home in a different location>publicly funded rental housing>one's pre-disaster home>temporary housing. In the short term, living in the house in which one was familiar seemed to have increased the sense of recovery, but in the long term this was not necessarily the case. In the short-term, publicly funded rental housing correlated with a low sense of recovery, although the results suggest that this was not necessarily so for the long-term sense of recovery. In the long-term this did not necessarily diminish the sense of recovery.

Table 3 —Results of the ordered logit analysis

	Personal Recovery		Village Recovery	
	2013	2017	2013	2017
Household Income	-0.24 (0.07)*** [-0.37, -0.11]	-0.45 (0.15)*** [-0.74, -0.15]		
Change by the disaster (Household savings)	0.33 (0.19)* [-0.05, 0.70]	0.93 (0.44)** [0.07, 1.78]		
Damage to housing			0.23 (0.09)** [0.05, 0.41]	0.07 (0.16) [-0.24, 0.38]
Household size (Change)			-0.58 (0.20)*** [-0.97, -0.19]	-0.26 (0.12)** [-0.46, -0.02]
Temporary housing	0.05 (0.34) [-0.61, 0.71]	2.42 (1.58) [-0.69, 5.52]	-0.39 (0.44) [-1.25, 0.47]	1.58 (1.93) [-2.20, 5.36]
Public funded rental housing	0.66 (0.57) [-0.45, 1.78]	-0.33 (1.27) [-2.81, 2.15]	-0.18 (0.76) [-1.67, 1.31]	-2.05 (1.06)* [-4.13, 0.03]
Different house	0.03 (0.58) [-1.10, 1.17]	-0.88 (1.16) [-3.15, 1.39]	0.04 (0.74) [-1.41, 1.49]	-0.01 (0.06) [-0.13, 0.11]
Others	-0.13 (0.49) [-1.09, 0.82]	0.68 (0.99) [-1.26, 2.62]	-0.38 (0.64) [-1.63, 0.87]	-1.48 (0.98) [-3.40, 0.44]
Log likelihood	-341	-67	-201	-121
Number of Observations	302	111	302	111

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Next, looking at the results of the sense of village revival, the housing damage coefficient was positive and significant in 2013, indicating that the greater the damage to the house, the lower the sense of recovery. In 2017, however, this coefficient had lost its significance. Changes in household size were negative and significant in both years, indicating that a reduction in the size of a household contributed to a diminished sense of recovery of the village. Other coefficients were not significant.

Looking at the housing occupied after the disaster, in 2013, temporary housing>publicly funded rental housing>one's pre-disaster home>a home in another location. For 2017, publicly funded rental housing>a home in another location>one's pre-disaster home>temporary housing.

In 2013 and 2017, the order of the pre-disaster home and a home in a different location were reversed, with publicly funded rental housing having the highest ranking in 2017.

The above results show that publicly funded rental housing tended to reduce the personal sense of recovery in the short-term compared to living in one's pre-disaster home, but over the long run tended to increase the personal sense of recovery. In both the short-term and the long-term, living in one's own home tended to increase the sense of the village's recovery. On the other hand, being housed in publicly funded rental housing, which showed a low sense of recovery in 2013, in the long-run was not necessarily low as compared to living in one's pre-disaster home and it contributed more to a sense of the village's recovery in both 2013 and 2017. In addition, when a comparison was made of living in one's pre-disaster own home versus living in a home owned in a different location, it showed that the personal sense of recovery and that of the village tended to drop over the short-term, whereas it tended to increase for both over the long-term. It should be noted, however, it is possible that these results may have resulted from a change in the base case, which was the home in the same area.

In other words, if the impact of living in one's home in the disaster area lowered the sense of recovery over the long-term, this result may have been obtained even if the influence of other housing did not change much. In addition, regarding temporary housing, there was only one respondent in the 2017 survey, so we cannot judge the results for that year. In 2013, this accounted for more than 10% of the total, indicating that the sense of personal recovery tended to be low, while the sense of village recovery tended to increase.

4. CONCLUSION

This study has analyzed the factors affecting the sense of recovery of the victims of the Great East Japan Earthquake from both a short-term and a long-term perspective. We used the results of questionnaire surveys conducted in 2013 and 2017 of residents of Noda Village, Iwate Prefecture, to determine the factors that affected the sense of recovery of their personal lives as well as their sense of the recovery of the village itself. We also examined how differences in the choice of temporary housing affected their sense of recovery.

Decision tree analysis revealed that the severing of ties with workplace friends and changes in household size should be avoided. In order to do so, evacuations should to some extent be undertaken within a specific defined region. It was also shown that in the short term, it is important for their sense of recovery that victims maintain a personal network of immediate family members, other relatives and local workplace friends as well as assurances that their income would not diminish. However, in the long run, the sense of one's own recovery as well as that of the community in which one lives will be influenced by a number of other factors, and that a person's sense of his or her own recovery will be influenced by personal and economic factors such as changes in marriage circumstances and household income and savings that were brought on by the disaster.

On the other hand, the sense of recovery of the village seems to have been influenced by family factors that included whether or not one was the firstborn, being able to consult with relatives as well as social status factors such as educational background. In this regard, for those whose relocation to another area proved to be difficult due their being the firstborn or their educational background, interest in the village tended to increase and it is possible that this was linked to their sense that the village was not recovering. In the short term, the sense of the recovery of the village seems to have been affected by changes in relationships with persons outside the village, the presence of children and the comparisons they make with other regions and exchanges within the region through their children. In the long run, factors that affect the sense of recovery will change, so it will be necessary to implement flexible policy and post-disaster management approaches.

As for temporary post-disaster housing, living in the same home as one did before the disaster increased the short-term sense of recovery, but it appears that this was not the case for the long-term. Although living in the home to which one is accustomed has the effect of helping that person rebuild his or her life in the short-term, due to the correlation between village-wide reconstruction plans and the location of one's home as well the differences in government subsidies, it is possible that in the long term it does not lead to a sense of recovery. Therefore, given the limited availability of temporary housing and publicly funded rental housing units, it will likely be necessary to have some or many of the disaster victims, depending upon the circumstances, live in their own home. However, from a long-term perspective, this may not be the best solution.

On the other hand, with regard to temporary housing, the sense of recovery was low in the short-term, but tended to increase over the long-term. Because the introduction of publicly funded rental housing deviated from the previous network of temporary housing, there is a possibility that the sense of rebuilding one's life will be reduced in the short-term. However, in the long-term, we think that the flexibility of movement has helped to raise the personal sense of recovery along with the sense of the recovery of the village itself.

According to Yamada (2020), the availability of publicly-funded temporary housing was 0.3% at the time of the 1995 Great Hanshin Awaji Earthquake, 56.6% at the time of Great East Japan Earthquake in 2011 and 74.6% at the time of 2016 Kumamoto Earthquake, which shows that the availability of this type of temporary housing increased year by year in Japan. However, as Yamada pointed out, in the short term, the degree of the satisfaction with life held by disaster victims dropped significantly, and the introduction of short-term support mechanisms, as taken up in this paper, and the correlation with how victims viewed their lives emerge as important issues that must be taken into consideration.

From the perspective of the effective utilization of unoccupied housing units and other housing resources as well as the prevention of the spread of infectious diseases like Covid-19, the promotion of the use of unoccupied housing banks to provide publicly-funded temporary facilities can offer up important policy options for future post-disaster countermeasures. In addition, as pointed out in our paper, the building of short-term support systems for publicly-funded temporary housing is also a matter of urgency.

There are some issues than remain regarding this study, the biggest of which is the sample size of the 2017 survey. For this survey, we included only the respondents who had answered all the items that were found in both the 2013 and 2017 surveys. As a result, the sample size of the 2017 survey was significantly reduced to 111. Because the sample size was small, the responses were biased and an adequate analysis could not be carried out.

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Original paper

Incorporating Public Participation into Landslide Risk Information and Response: Disaster Response Switch in the Taisho District of Shimantocho, Kochi, Japan

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Abstract A disaster response switch is a tool for incorporating public participation into disaster risk information and response and is considered by communities in determining the timing of disaster response actions through a combination of local information in the community and public information from local government and professional organizations. In this study, a trial for a disaster response switch for landslide risk was conducted in the Taisho District, Shimantocho, Kochi, Japan. The study verified a method for implementing the switch and the effects of this public participation. The results showed that the communities largely considered switches based mostly on local information. In addition, they improved their understanding of the relationships between subjective local information and objective public disaster risk information through bosai (disaster prevention) recording, where communities take pictures of places around the disaster response switches as community records. This trial showed the importance of considering communities' participation when they evacuate. The public participation of the disaster response switch moved the focus of risk information from the contents or accuracy of the information to the social system of evacuation action in the community, based on the acceptance of uncertainty in the information.

Keywords: Public participation, Disaster response switch, Disaster information, Community disaster prevention, Landslide

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1. INTRODUCTION

Recently, various extreme meteorological phenomena have increasingly occurred worldwide (Hoeppe 2015). This situation affects Japan, where torrential rainfall events exceeding estimated scales have caused damage to cities every year (Japan Meteorological Agency 2020). To address this, governments have adopted policies based primarily on disaster information (meteorological warnings, evacuation information, etc.) to improve pre-evacuation behavior before meteorological disasters occur. For example, they have introduced emergency warning systems to announce the highest-risk situations when meteorological warnings are issued. Such systems categorize disaster information into five levels to communicate the risk level clearly. However, the low evacuation rate during meteorological disasters in Japan is a major issue (Okamoto *et al.* 2012); although this situation has yet to be fully resolved, disaster information has improved.

Takenouchi *et al.* (2020) proposed the “Disaster Response Switch (DRSwitch)” to create an evacuation system based on passive public disaster information from outside sources— meteorological warnings or evacuation information— and local information produced through community participation—precursory phenomena or past experiences in a community. The DRSwitch is based on community participation related to disaster risk information and response. Communities make the disaster response rules within themselves, switching their behavior and consciousness from normal mode to disaster mode. They make DRSwitches through the combination of local information and public disaster information. The DRSwitch helps establish judgment standards for disaster responses in a community and clarifies the relationship between local and public disaster risk information so that various disaster information can be used in a disaster effectively.

If public disaster risk information is sufficient, communities can easily establish the proper DRSwitch. For example, the water levels of some rivers can be used to judge flood risk visually. Landslides, however, are both highly local and unpredictable, making them comparatively more difficult to predict. These characteristics make it difficult for communities to judge disaster responses against landslides based on disaster risk information. Furthermore, evacuation becomes complicated during landslides, making pre-evacuation by communities extremely important. However, Japan has faced multiple challenges to smooth evacuation. Three-quarters of the country is mountainous, and there are over 660,000 risk-prone locations, such as those designated as landslide disaster warning areas or landslide disaster special warning areas (Ministry of Land, Infrastructure, Transport and Tourism 2019). The landslide risk of each city and town should be assessed. Most deaths and missing persons due to meteorological disasters are due to landslides. A survey by Ushiyama (2015) showed that from 2004 to 2013, landslides accounted for 43.5% of fatalities during meteorological disasters.

Takenouchi *et al.* (2020) considered DRSwitches for flood disasters, whose risk can be easily judged from the water level, and classified the DRSwitches by the sufficiency of relevant public disaster risk information. This study refers to their method and considers a method for constructing DRSwitches for landslides together with various members in a research field. Landslide risk cannot be judged easily because of high locality and uncertain occurrence;

therefore, communities take pictures near spots flagged by DRSwitches to grasp the relationships between local situations and public disaster risk information (bosai recording). This study does not focus on the contents of the DRSwitches but on the cooperation between local and public disaster risk information. Based on the results, this study verifies action research of public participation that incorporates local and public disaster risk information and discusses the importance of such cooperation through DRSwitches.

2. RELATED STUDIES

2.1 Disaster information on landslides and evacuation

Recently, various methods to evaluate landslide risk have been developed, although the nature of disaster information for landslides varies by country and region. In the case of Japan, there are four basic pieces of disaster risk information for landslides: heavy rainfall advisories, warnings, emergency warnings, and sediment disaster alerts. This information is based not on the preceding amount of rainfall but soil water content calculated by a physical model of groundwater movement (Okada *et al.* 2001). For analysis of landslide risk, most countries other than Japan use methods based on the laws of natural science, such as rainfall, or results from physical models.

Segoni *et al.* (2018) reviewed 107 recent studies on rainfall thresholds for landslide occurrence (115 thresholds). The literature collected on rainfall thresholds fell into four categories: publication details, geographical distribution and uses, dataset features, and threshold definition. These results showed that rain gauges made up 79.5% of the rainfall source. Further, 48.6% listed intensity duration as a threshold parameter, and most thresholds were based on basic observation on rainfall. The studies had some issues concerning validation. For example, about 40.0% lacked any analysis of predictive capability. Nevertheless, many discussions of the rainfall threshold for landslide occurrence show that the general risk information on landslides is defined by the laws of natural science; their accuracies have improved in recent years.

When checking actual landslide evacuation cases in communities, there are cases of safe evacuations based on factors other than those based on natural science. Chiba *et al.* (2008) reported a case of huge rainfall in July 2006. This disaster caused landslides in Okaya and Suwa cities in Nagano prefecture. However, there were differences in the cities' evacuation. The Suwa community noticed precursory phenomena and took pre-evacuation measures. This was derived from the usual cooperation between the community and the local government. The local government rapidly issued evacuation information based on local information from a leader's inspection. Irasawa and Endo (2010) conducted a questionnaire survey for communities in Kamaishi City, Iwate Prefecture, which were damaged by landslides during Typhoon Chataan in 2002. The results showed that 40% of the people in the communities who noticed some precursory phenomena tended to consider whether to evacuate. Huang *et al.* (2015) reported a case of stakeholders' judgment based on such precursory land changes as a

successful case of emergency landslide response. Members of the public reported timely clues in slope deformation, and landslide specialists and governmental officials made prompt collaborative decisions that contributed to a successful emergency evacuation. Chen and Fujita (2013) noted that “Inhabitants take evacuation actions based on environmental conditions or the aforementioned government-issued warning information, including evacuation preparedness, voluntary evacuation, and mandatory evacuation.” However, the results of an analytic hierarchy process (AHP) method from some questionnaires on decision-making factors for government officers and people in Taiwan showed most people were more influenced by “circumstances” than if they “receive alerts.” In addition to such situations, some cases involved evacuations based on warning information, such as evacuation orders.

Conversely, the number of pre-evacuation cases for landslides is small. Surveys in 206 locations where human or residential damage occurred due to huge rainfall in July 2006 and during the 13th typhoon of the same year showed pre-evacuations by community judgment were found in only 5% of cases (10 locations) (Japan Erosion and Sediment Control Department 2009).

From Kikui and Sano’s (2008) questionnaire survey to communities affected by the Niigata heavy rainfall in 2004, most communities evacuated just when they noticed some phenomena on landslides, and some communities only evacuated after landslides happened. Similarly, Takahashi *et al.* (2005) surveyed the details of communities’ actions in Minamata city, Kumamoto prefecture, which was affected by a debris flow in July 2003. The communities took actions to prepare for the disaster based on the realization that “This situation isn’t usual”; however, they did not understand the precursory phenomena that might have given them an early warning. Consequently, most communities evacuated after the debris flow. There are cases of safe pre-evacuation in some areas, but other communities failed to evacuate safely.

2.2 Public participation in disaster information

Experts on landslides have advanced landslide disaster risk information. In addition, the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations 2015) noted the importance of local communities’ participation in disaster mitigation and the need to consider each community’s characteristics. Researchers discussed some public participation in disaster risk information, but these cases have used various methods as below cases show.

Chen *et al.* (2014) reported on non-structural preventive strategies developed by the government in Taiwan. One strategy is “debris flow professional volunteers.” Residents in communities near debris flow torrents have been recruited since 2005 by the Soil and Water Conservation Bureau as debris flow professional volunteers to assist with real-time rainfall monitoring, disaster notification, and local evacuation tasks. During routine days, debris flow professional volunteers inform communities about the local environment, areas vulnerable to debris flows, and relevant disaster prevention information. When typhoons or torrential rains occur, these professional volunteers cooperate for monitoring the local real-time rainfall using simple rain gauges and report their readings using available communication equipment. In

addition to providing rainfall data in areas lacking formal rainfall stations, they assist with disaster notification and advise their communities to evacuate. Chen and Huang (2010) reported actual cases where this system worked efficiently. This system in Taiwan characteristically creates cooperation between communities and government officers and encourages public participation in disaster risk information through rain gauges. Such a community-based rain gauge system has spread in various countries (Oi *et al.* 2016; Smith *et al.* 2017; Gautam *et al.* 2013; Catherine *et al.* 2012).

In Japan, what some communities tried to share was not rain gauge information but reference information around their districts. In Minamiawaji, volunteers from a fire department help the local government issue evacuation information. Volunteer members of the fire department check local situations and inform the local government officers. Subsequently, the local government considers the issuance of evacuation information. Such cooperation conventionally occurs in various districts, but in this case, the local government constructively promotes and controls this collaboration (Japan Fire and Disaster Management 2016). A similar practice of community monitoring occurred in Sayo town, Hyogo prefecture, where major human losses occurred when they evacuated in a torrential rainfall by Typhoon Etou in 2009 (Tamura 2016).

Weathernews Inc. (2016), as a local government service, serves as a community participatory “Disaster Reduction Project.” Weathernews Inc. has operated a “Weather Reporter” service for consumers. The Weather Reporter service is used by approximately 130,000 users per day. A user registers weather photos and messages through a smartphone application, which explains each local situation. The registered information is shown on a map, and all users can access each other’s information and gain more detailed information about situations in which general weather information cannot be expressed. Weathernews Inc. applied the features of the “Weather Reporter” to the “Disaster reduction project.” Local governments use this service to share the detailed conditions of each district. Communities register various information for each district, such as river water level, local inundation, traffic conditions, and lifeline availability, and they understand situations and act in reference to others’ information. Based on community information, local governments grasp local situations on maps and consider appropriate responses.

The United States Geological Survey (USGS) started “Did You Feel It?” (DYFI)—a system to collect information from people who experienced an earthquake—in 1999. This system collects data through an internet website regarding what people experienced, the extent of any damage, and information on the location of responders, such as postal codes. The collected data can be used to make automatic maps, such as “Community Internet Intensity Maps” (CIIMs), which contribute to the quick assessment and analysis of earthquakes. DYFI data were used by Atkinson and Wald (2007) to calculate the modified Mercalli intensity (MMI) from DYFI data and then compared the two to observed ground motions. The results indicated the usefulness of the DYFI data because it showed differences in earthquakes’ intensity with distance of earthquakes between California and the central and eastern United States. Cremen *et al.* (2017) pointed out the issue that DYFI tends to evaluate stronger intensities compared to actual observations. However, Wald *et al.* (2011) clarified the advantage of widespread use of

the DYFI system that has been used worldwide, including in the USA (1,603,100 of individual entries in the USA and 140,623 outside of the USA on July 2011). With summaries of response situations of entries and the accuracies, Wald *et al.* (2011) said that a major advantage of the DYFI system was that its contributors do not need to be trained for the task and its participants are not “citizen scientists”; rather, DYFI is “citizen-based” science.

Similar to the public participation of mass users, in recent years, we have also seen some efforts to utilize Big Data to clarify disaster sites and other information. In this manner, we note the development of many systems that utilize user-collected data. Aulov and Halem (2012) analyzed the Deepwater Horizon oil spill disaster using social media data as a human sensor network. In this analysis, the researchers gathered social media data that mention oil sightings from the Flickr social media community, geolocated them, and used them as boundary forcings in the General NOAA Oil Modeling Environment (GNOME) software for oil spill predictions. Thus, they showed how social media data could be incorporated into the GNOME model to obtain improved estimates of the model parameters. In this case, public participation through social media data was used to improve information quality through predictive modeling. For the useful application of these users’ information, technological methods and improvements in certainties have been developed rapidly. For example, Asakura *et al.* (2016) proposed a new task for classifying a flood disaster with information from social media, in addition to predicting the geolocation of events from the user-generated text, reported the annotation of the flood disaster corpus, and developed a classifier to demonstrate the use of this corpus for disaster analysis. Further, Ma *et al.* (2014) evaluated the relationship between mass tweets and disasters in the spatial heterogeneity of the data.

Public participation in disaster risk information is also discussed in early warning systems (EWS). Baudoin *et al.* (2016) explored various pathways to involve local communities in EWS from top-down to more participatory approaches based on a literature review. Three case studies in Kenya, Hawaii, and Sri Lanka were outlined at various participatory levels. Each of their participatory cases have different characteristic as community-centric approaches and depend on conditions such as location, access to risk information, use of communication devices, and level of response capability. Based on their findings, Baudoin *et al.* (2016) suggested a need to review the way EWS are designed and applied, promoting a shift from the traditional expert-driven approach to one that is embedded at the grassroots level and driven by vulnerable communities. Through educational projects in São Luiz and Cunha in Brazil, Marchezini *et al.* (2017) suggested a valuable means of drawing on guiding principles of education to work out a participatory EWS in four interrelated areas (risk knowledge, monitoring, communication of warnings, and response capability). They showed that networking for the protection of local communities is a suitable way to address the aims of a “first mile” approach as a participatory EWS. The project was able to interconnect several spheres through a dialogue-oriented learning process that included the municipal civil defense systems, high school students and teachers, local communities, universities, and researchers from the federal government).

As the above cases show, we need to promote the development of methods for public participation in disaster risk information in addition to the extensive development of

forecasting and observation technologies. The DRSwitch can apply the concept of public participation to disaster risk information. Therefore, it can be regarded as a bottom-up approach for communities. However, the DRSwitch is a collaborative approach that creates cooperation between bottom-up local information and top-down public disaster risk information. It changes the social system on disaster risk information. A DRSwitch's objective is that communities, specialists, and government officials participate in consideration of communities' disaster responses together, sharing not only public disaster risk information but also local knowledge and observations.

3. METHODS

This study verifies a method to construct DRSwitches for landslides (here and below, "landslide" refers to various types of events, such as the failure of steep slopes, debris flows, and other landslides) and bosai recording to understand the relationships between the constructed DRSwitches and public disaster risk information. Through this trial, the researcher checks how communities consider participation in disaster risk information on landslides and what roles the DRSwitch's approach can take in the cooperation of stakeholders. The results should expand and deepen our understanding of what types of DRSwitches are appropriate for advancing communities' evacuation.

The Taisho District in Shimanto-cho, Kochi, Japan, was set as the research field (516 households, 1,160 persons according to the 2015 National Population Census), where a practical trial of a DRSwitch for landslides was conducted. As Figure 1 shows, the Taisho District is located in a mountainous area surrounded by 300–400 m high mountains. Most residential areas are designated as landslide disaster warning areas or landslide disaster special warning areas, where have some landslide risks. Mountainous areas in Japan are formed by orogeny and river erosion; the Taisho District is representative of areas at risk of landslides. The Taisho District is divided into three community areas: north, central, and south.

The trial was conducted cooperatively between representatives of voluntary disaster prevention organizations, the general communities, the local government, and the researcher. Workshops were conducted with the cooperation of voluntary disaster prevention organizations and local government. The period of the trial was from March 2019 to February 2020, but the communities considered DRSwitches and tried using them in this period and are expected to continue using them.

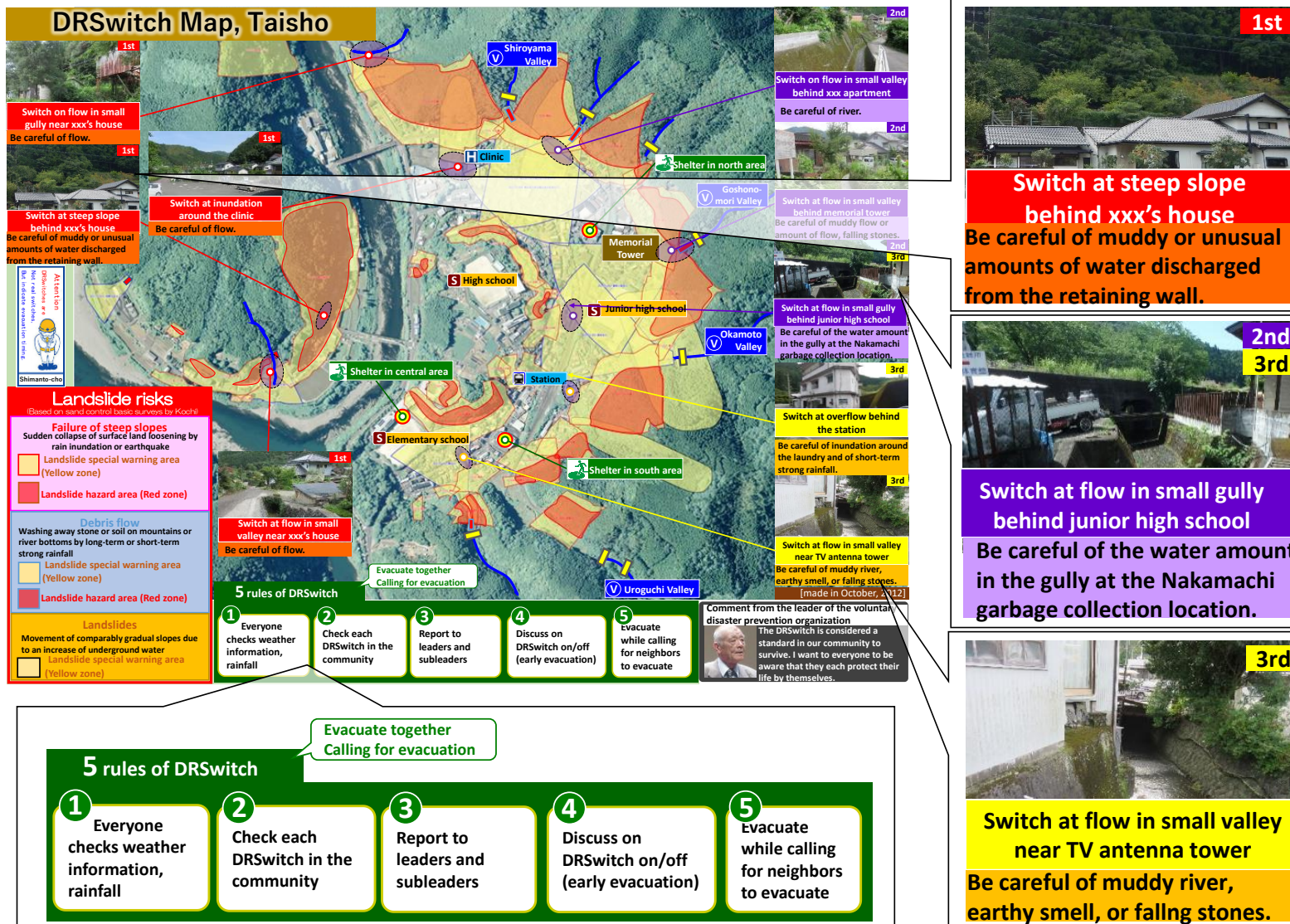


Figure 1. Research Field (Taisho) and examples of constructed DRSwitches (WS1, WS2)

As shown by Takenouchi *et al.* (2020), a DRSwitch needs at least three items: i) content, ii) relevant disaster risk information, and iii) disaster responses appropriate to the DRSwitch. Therefore, Takenouchi *et al.* (2020) held five workshops to construct DRSwitches on flood risk, comprising WS1 (understanding DRSwitches), WS2 (selection of DRSwitches), WS3 (checking disaster risk information), WS4 (consideration of disaster responses), and WS5 (summary), with “WS” signifying “workshop.”

Appropriate methods to construct DRSwitches vary depending on the disaster risks, social situations, and activities in communities. Stakeholders discussed procedures for constructing DRSwitches. Communities consider disaster prevention lecture meetings and evacuation drills as important events, which are conducted annually with comparatively more community participation. Therefore, we decided that these events should be used for the trial. Public disaster risk information is lacking and unclear regarding landslide risk. Therefore, we decided to use local disaster risk information first and consider the use of related public disaster risk information gradually. Finally, we constructed a DRSwitch Consideration Committee in Taisho, which consisted of the three communities, two members of the volunteer fire department of each area, and representatives from a local kindergarten, elementary school, junior high school, and high school. The total number of committee members was 48: 23 in the northern area, 13 in the central area, and 12 in the southern area. A DRSwitch can have various types of evacuation warnings, such as staying home or returning home; however, we decided to make DRSwitches for the evacuation of the general residents of the communities because most districts have landslide risks that may necessitate evacuation.

There were six workshops, including two events attended by the general residents of the communities (WS1, WS4): WS1, consideration of content by general residents of the communities; WS2, selection of DRSwitches; WS3, discussion of DRSwitch evacuation drills to check disaster responses; WS4, DRSwitch evacuation drill by general residents of the communities; WS5, connection between local and public disaster risk information; and WS6, summary.

A summary of each workshop appears below. Figure 2 shows scenes from the workshops.

WS1: Consideration of content by general residents of the communities (9:00–11:45 March 17, 2019; about 100 persons)

Landslide risk depends on location, and individual can focus on different areas to apply caution; therefore, we used a disaster prevention lecture meeting to gather various opinions. First, the local government showed the trial in the Taisho District, and the author explained DRSwitches through actual cases. The participants discussed candidate DRSwitches using a district hazard map. The participants were separated into nine groups, and they checked both the hazard map and the various candidate DRSwitches to express representative landslide risks based on their past experiences and observations from their everyday lives.

WS2: Selection of DRSSwitches (18:00–19:45 May 30, 2019; 33 persons)

As mentioned, this trial focused on local disaster risk information as a reference for DRSSwitches because of insufficient information expressing local landslide risk. The committee summarized the candidates' discussion from WS1 to risk information based on characteristics such as landslide risk around the area or inundation risk in a gully. Next, they evaluated each risk and discussed the proper situation for pre-evacuation.

WS3: Discussion of DRSSwitch evacuation drills to check disaster responses (18:00–20:00 July 30, 2019; 25 persons)

The committee discussed their responses when a local situation might reflect a DRSSwitch. However, they also performed the DRSSwitch evacuation drill for the first time so that the representatives of the committee and local government could set the flow of the evacuation drill before WS4, as Figure 3 shows. The members of the committee then finalized the content of WS4.



Figure 2. Workshops in the Taisho District

	Time	Content	Northern area	Central area	Southern area
Before	9:00	i) Information collection of meteorological information or rainfall (use of smartphone or PC)	All collect information		
		ii) Check DRSwitch	(Person checking DRSwitches)		
		iii) Report to share DRSwitch information	Checker reports to each leader (Communication method:)		
	9:30	iv) Discussion on calling for evacuation	Discussion among leaders		
Disaster Response Switch is ON					
After		v) Start of calls to evacuate	Each leader contacts each subleader (Communication method:)		
		vi) Calls for evacuation to neighbors by everyone	All residents inform each other (Transfer method to resident)		
	-10:00	vii) Start of evacuation <u>*Without a call to evacuate, all start to evacuate at 09:45</u>	(Shelter)	(Shelter)	(Shelter)
	-10:30	viii) Check results of evacuation drill, hazard map, and DRSwitches <u>*Check DRSwitch locations on the way home</u>	All discuss results of evacuation drill at each shelter		

Figure 3. Flowchart of DRSwitch evacuation drill (WS3, WS4)

WS4: DRSwitch evacuation drill by general residents of the communities (9:00–11:00 September 1, 2019; northern area: 70 persons; central area: 95 persons; southern area: 93 persons)

The district has held an annual evacuation drill, but the method has been simple. The local government broadcasts an evacuation information test through the administrative radio system, and the residents of the communities gather at shelters. The number of participants was low, sometimes just a few dozen. Therefore, we planned an evacuation drill using the DRSwitches selected in WS2. First, the leaders in the community communicated with the checker of each DRSwitch to learn the local situation. Next, if any situations applied to a DRSwitch (meaning the DRSwitch was activated), the communities switched their behavior and consciousness from normal mode to disaster mode. The leaders began to call for evacuation using various methods, such as telephone or e-mail. Finally, the residents of the communities evacuated to shelters while calling for the evacuation of others located around their houses. After gathering at the shelters, they rechecked the DRSwitches and landslide risk for the areas around their homes.

WS5: Connection between local and public disaster risk information (18:00–20:00 October 25, 2019; 15 persons)

In the period of this trial, some members of the committee attempted bosai (disaster prevention) recording, taking pictures of the situation of each DRSwitch when they noticed certain phenomena or dangerous situations. Some selected checkers tried this recording not by

going to each spot when there was heavy rainfall but by observing from safe places such as from their home's windows, which would be done in a disaster, depending on the situation.

This bosai recording by the communities was conducted for DRSwitches on flood risk in Takenouchi *et al.* (2020). However, we clearly cannot judge the relationships between the rainfall situation and landslide risk; therefore, this bosai recording takes the role of uncovering local risks. Some members tried bosai recording after WS2. In WS5, they brought photos related to the DRSwitches and compared them with the public disaster risk information to better understand their DRSwitches.

WS6: Summary (18:00–19:30 February 25, 2020; 30 persons)

The committee discussed three points: i) good points, ii) issues, and iii) future plans. The constructed DRSwitches were regarded as somewhat subjective; therefore, the committee thought it necessary to make them more accurate and easier to understand using objective data. Thus, the committee discussed community observation systems using IoT devices (IoT-COS), such as soil water content or spring water levels, in a later trial (as IoT-COS is outside the scope of this study, the details are omitted from this paper).

These workshops were conducted as fieldwork, including questionnaire surveys, to confirm participants' opinions.

The next section assesses the results of the trial from three viewpoints: i) Results of DRSwitches for landslides and bosai recording, ii) Results of the DRSwitch evacuation drill, and iii) Communities' opinions on the DRSwitch trial. This includes an examination of the effects of, issues with, and community opinions of public participation in disaster risk information for uncertain landslide risks.

4. RESULTS

Here, we first confirm the constructed DRSwitches, view the results of the DRSwitch evacuation drill, and then finally confirm the results on the communities in this trial.

4.1 Results of DRSwitches for landslides and bosai recording

Figure 1 shows the results of the DRSwitches selected in WS1 and WS2. These DRSwitches have two characteristics. One is that some landslides can occur near residential areas. In these cases, the DRSwitches indicate the general precursory phenomena of landslides such as "Be careful of earthy smells or falling stones." The other is that some landslides can occur far from residential areas, such as around the tops of mountains. In these cases, the DRSwitches indicate

the indirect phenomena of landslides that change with risk level in lower areas, such as “Be careful of muddy or unusual amounts of water discharged from the retaining wall” or “Mind the amount of water in the gully at the Nakamachi garbage collection location.” In Takenouchi *et al.* (2020), most of the DRSwitches on flood risk clearly indicated changes in the observable values related to flooding, such as “when the water level reaches two-thirds of the height of the dike.” In this trial, indirect evaluations were the main checkpoints, such as unusual situations, precursory phenomena, or the amount of water in a gully. Once a landslide occurs, certain options become impossible but evaluating the risk is very difficult. Therefore, we can consider DRSwitches for landslides likely to contain indirect information.

Northern group “switch on flow in small gully near xxx’s house”

Situation	Date & Time	Radar data	Landslide risk	DRSwitch	Check items
Normal	2019. 10.01 08:58		 No risk color		Switch Standard
A little rainfall	2019. 10.02 12:42		 No risk color		Rainfall mm Landslide risk color
Heavy rainfall	2019. 10.03 06:55	 18th Typhoon approached 06:09 Heavy rainfall warning issued 09:10 Sediment disaster alert information 09:30 Set Town Disaster Management Headquarters 11:07 Remove heavy rainfall warning	 Other area is yellow		Rainfall mm Landslide risk color

Figure 4. Example of checking bosai recordings (WS5)

After WS2, some members attempted bosai recording to record the situations of the selected DRSwitches. Figure 4 shows an example of a comparison between bosai recording and public disaster risk information in WS5. Here, communities can check the relationships between the DRSwitches and the meteorological situations, such as the amount of rainfall, based on the bosai recordings. Thus, the communities share a common recognition of the DRSwitches in their communities. Although the DRSwitches tend to be subjective and indirect, the situations can be considered more fully using the DRSwitches with public disaster risk information through bosai recordings.

4.2 Results of DRSwitch evacuation drill

This section presents the results of the DRSwitch evacuation drill in WS4.

The actual methods for activities after DRSwitches can be considered adjustments in each case. In this trial, the communities had an evacuation drill using the constructed DRSwitches. We checked the effects or issues with this evacuation drill. As Figure 3 shows, the communities checked each DRSwitch and followed the action of calling to neighbors for evacuation. Figure 5 shows the timing of the call to evacuate in this drill. The results show that 74% of the participants heard the call to evacuate within 10 minutes, and almost all participants heard the call to evacuate within 20 minutes. This result confirms that the call to evacuate in neighborhoods with a DRSwitch can be effective for evacuation in a mountainous area. The method for the call to evacuate was oral in 65% of cases and by telephone in 24%. Although 11% of the community residents could not hear the calls for evacuation, they evacuated under their own judgment because they knew that the evacuation drill started from 9:00 a.m. The average number of persons called by a single participant was 2.9; most people were called by neighbors or community leaders. This was the first trial with calls to evacuate in this community, and some dependency on leaders was found; therefore, the promotion of calls to evacuate neighborhoods was an issue.

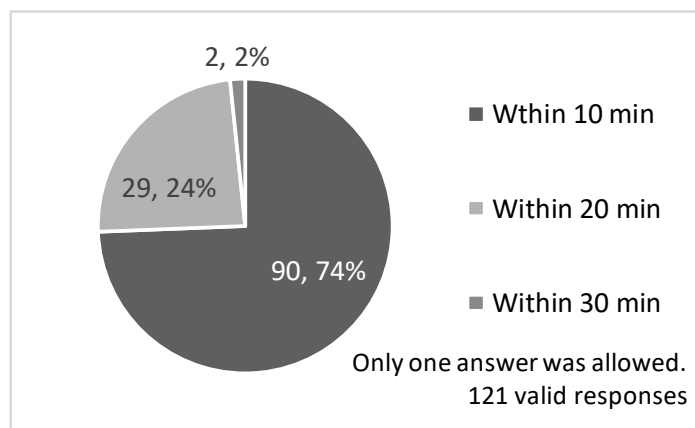


Figure 5. Timing of received calls to evacuate during the DRSwitch evacuation drill (WS4)

Figure 6 shows the possibility of calls to evacuate during actual disasters. As 87% of the participants answered “Possible” or “Somewhat possible,” to the question of evacuation, most communities expressed no hesitation to call for an evacuation. However, 7% answered “Impossible,” indicating that the surrounding communities need to support them.

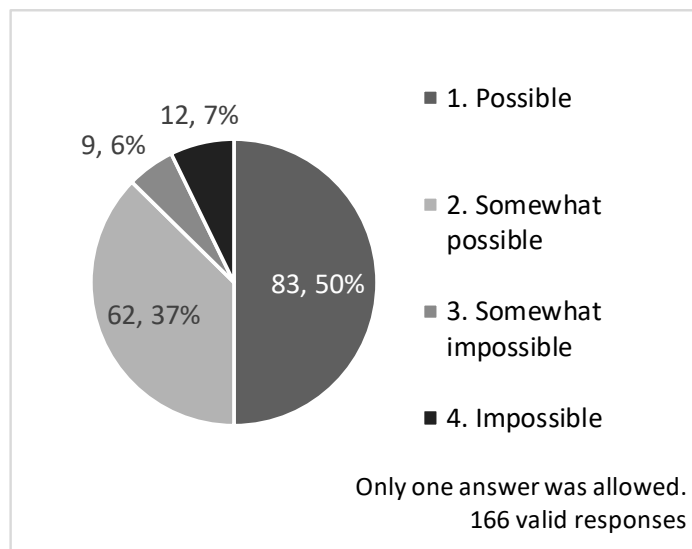


Figure 6. Possibility of calls to evacuate in a real disaster situation (WS4)

Figure 7 shows the advantages of this evacuation drill compared to a conventional one. The most advantageous point was that participants stated that the drill was “more relevant to me.” This may be because we used DRSwitches made by the communities and because the communities themselves called for the evacuation. Moreover, 45 persons tried “with more seriousness,” indicating that they approached the evacuation drill with more practical intent.

The constructed DRSwitches worked effectively as the origin of this evacuation drill.

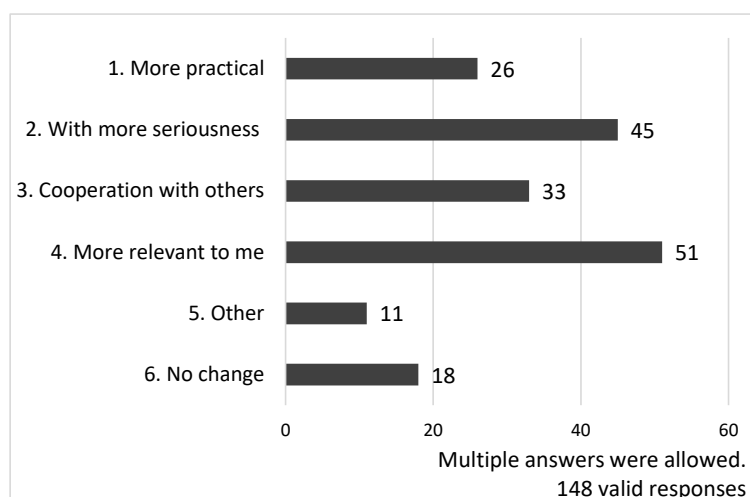


Figure 7. Advantages of the DRSwitch evacuation drill (WS4)

4.3 Communities’ opinions on DRSwitch trial

This section examines communities’ opinions about the DRSwitch trial based on the results of questionnaire surveys from some of the workshops.

WS1 assessed seven activities for local disaster prevention (A-G) before the trial. Figure 8 shows the resulting activities that the communities considered important and notes which were actually conducted. A low rate of actual practice was found for “C. We should decide which responses to take,” (30%) “D. We should decide when to respond,” (29%) and “F. We should prepare to communicate with family members and neighbors” (31%). The DRSwitch especially focuses on item D, but the resident did not consider specific actions as in item C or item F.

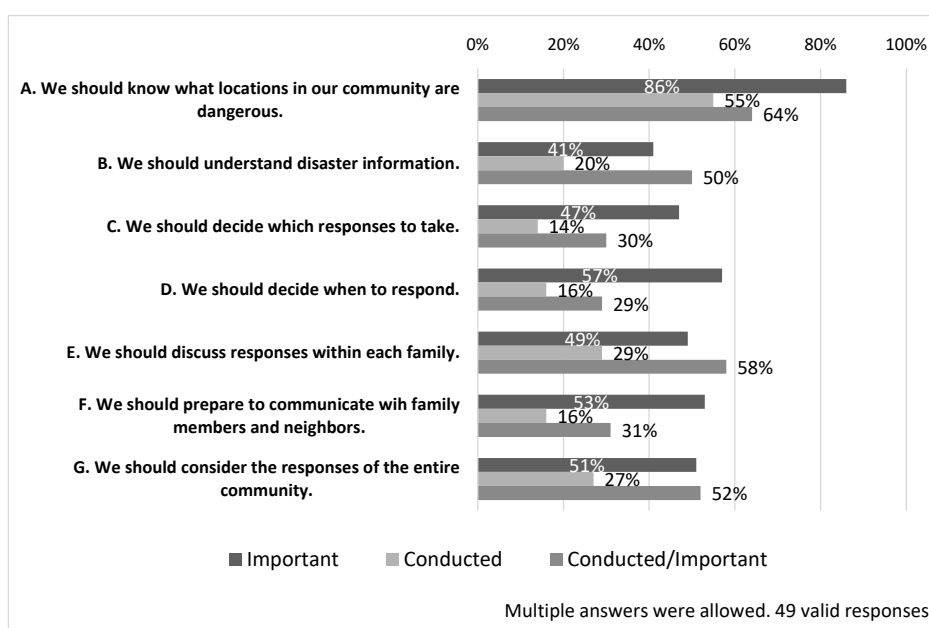


Figure 8. Disaster prevention activities for meteorological disasters in the Taisho District (WS1)

The questionnaire in WS3 checked whether participants judged the evaluation of evacuation from landslides to be difficult. Overall, 83% answered “Difficult,” and all others answered “Somewhat difficult.” Figure 9 shows the rank order of the reasons for this difficulty. “I don’t know when a landslide happens,” and “I don’t know how dangerous the current situation is” were the primary reasons. These reasons are derived from the locality and uncertainty of landslides. Discussion of when communities should take action regarding landslides was insufficient, and the communities did not have a method to judge the risk.

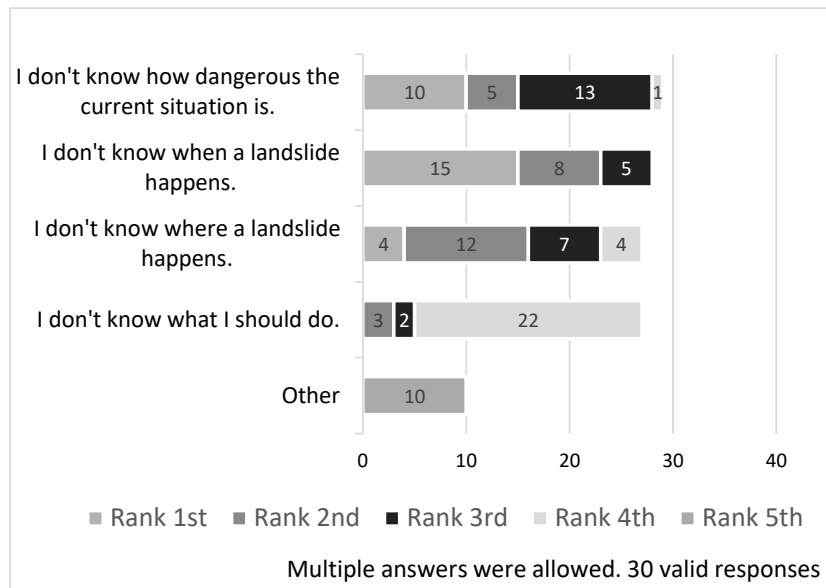


Figure 9. Rank order of reasons for difficulty in judging evacuation from landslides (WS3)

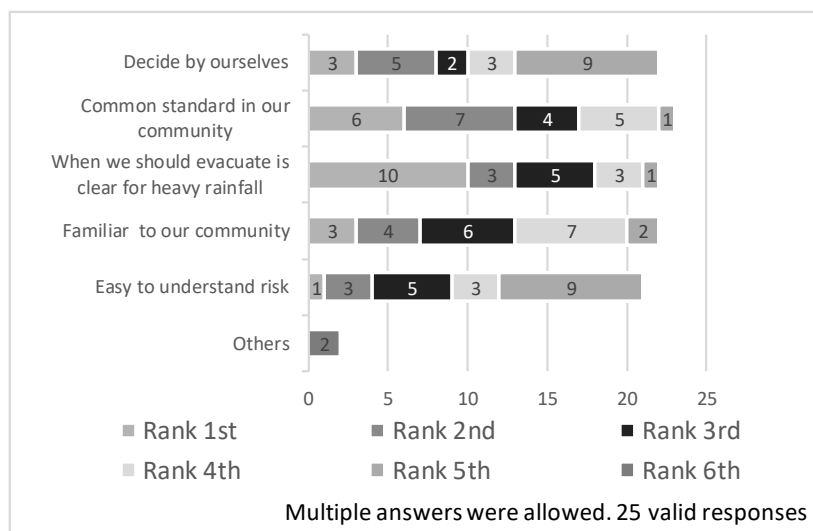


Figure 10. Rank order of reasons why DRSwitches can lead to evacuation (WS2)

In a landslide situation, how could the DRSwitch work?

WS2 checked whether the constructed DRSwitches were useful for the timing of the evacuation. Given a statement asserting DRSwitch usefulness, 48% of participants answered, “I agree totally,” and the remaining 52% answered, “I agree somewhat.” Figure 10 displays the rank order of the reasons for their agreement. “When we should evacuate is clear for heavy rainfall” was the most frequently cited reason, indicating that the DRSwitches are a solution to the problem of evacuating from a landslide. The second most frequent reason was that DRSwitches could become a “common standard in our community”; therefore, the communities may regard evacuation as an action for the entire community and may favor

cooperative evacuation in the community over individual action. Other general residents of the communities (158 participants in WS4) answered similarly positively: 66% answered, “I agree totally,” and 32% answered, “I agree somewhat” to the question “Do you think the DRSwitches can be used for the timing of evacuation?”

Next, we investigated the opinions about public participation in disaster risk information by communities, as in the case of DRSwitches, to assess what communities think about not depending on the local government and, instead, joining in to consider evacuation timing based on local disaster risk information. Figure 11 shows the results of the questionnaire from WS4. Before this trial, the communities only received evacuation information from the local government, and often they did not take evacuation actions. However, the DRSwitch trial changed this concept. Figure 11 shows that 91% of participants answered, “We need to discuss evacuation timing together.” Figure 12 shows points considered important for public participation in evacuation judgments. A high percentage of respondents noted the following: “It produces an opportunity to consider evacuation in the community” and “It increases evacuation awareness in the community”, both of which likely derive from effects of the public participation. In addition, about a third of the participants selected “We can prepare for local situations not known to local government” and “We can identify points that we don’t understand enough,” indicating that the communities consider cooperation between themselves and the local government as important.

While it is difficult to judge the need to evacuate in response to landslide risk, public participation using DRSwitches gave communities an answer to the question “When should we evacuate?” and promoted an understanding of the importance of public participation in disaster risk information.

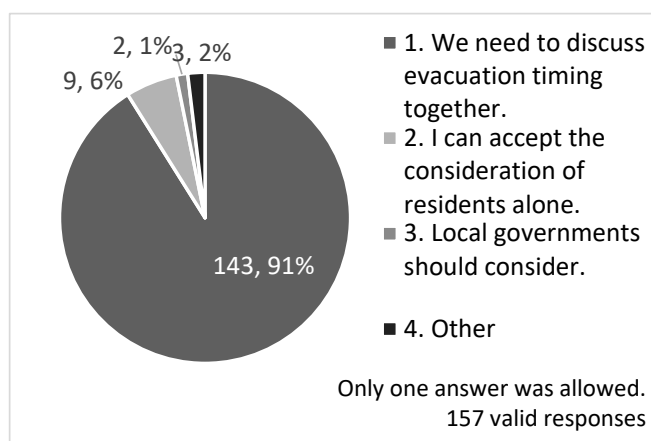


Figure 11. Opinions on public participation in evacuation judgments (WS4)

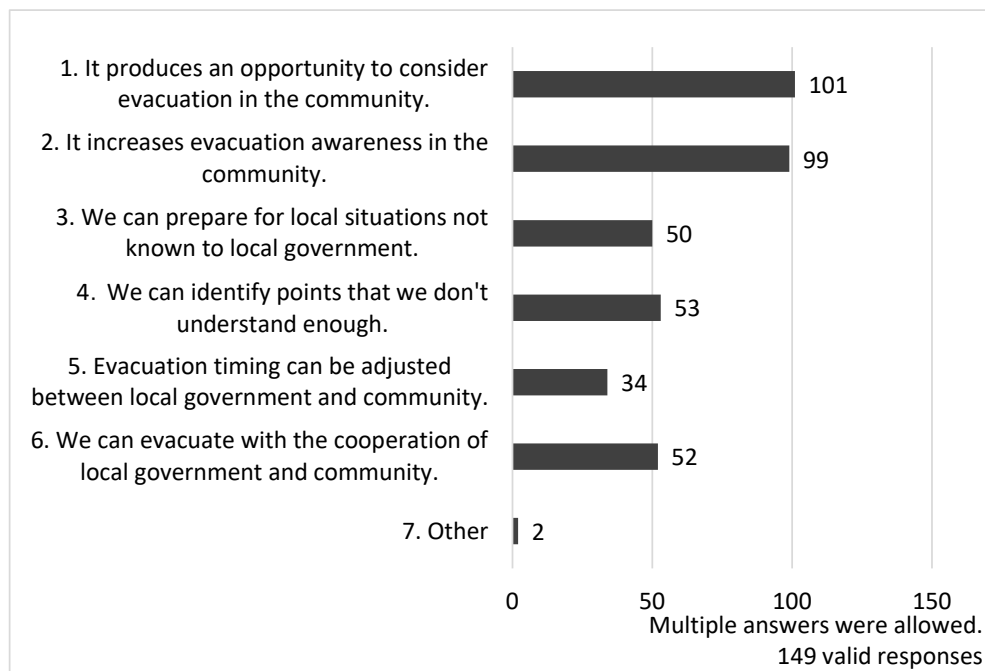


Figure 12. Reasons for the importance of public participation in evacuation judgments (WS4)

At the last workshop, the WS6 committee discussed the following: i) good points, ii) issues, and iii) future plans. Table 1 summarizes their resulting opinions, and Figure 13 shows their opinions on the following: i) the whole trial, ii) the constructed DRSwitches, iii) the Evacuation drill using DRSwitches, iv) bosai recording, and v) the continuous desire to keep the DRSwitches.

Regarding good points, the committee members showed highly improved disaster awareness. In addition, some members emphasized that the constructed DRSwitches are concrete and effective for real disasters. Additionally, this trial created better communication among the participating communities. However, not all aspects were positive. Participants regarded the operation system as an issue; communications sometimes took a long time among leaders, DRSwitch checkers, and the persons designated to call for evacuation in an evacuation drill. This means that, when considering disaster situations, some members thought this system should be changed so that the checkers judge and inform the communities. They discussed improvements, including a contact list, in WS6. In addition, the members discussed the necessity of understanding the DRSwitches and the greater participation of other communities. As future plans, continuity and more trials were common topics. The members considered DRSwitches to be one disaster prevention culture in their community.

Figure 13 displays the participants' opinions of the DRSwitch trial. Most of the members answered positively about each point.

Table 1. Opinions of summary on DRSwitch trial (WS6)

i) good points	<ul style="list-style-type: none"> Improved disaster awareness. Created more concrete actions in the community. Constructed DRSwitches that can work efficiently in real disasters. Communities communicate better than before. Checked risky areas and evacuation routes.
ii) issues	<ul style="list-style-type: none"> Leaders must improve the operation system. Other residents need to understand the DRSwitches and join much more. DRSwitch standards need to be more accurate.
iii) future plan	<ul style="list-style-type: none"> Promote sharing the DRSwitches. Continue this trial and more drills. Improve communities' disaster awareness. Improve the DRSwitch evacuation drill.

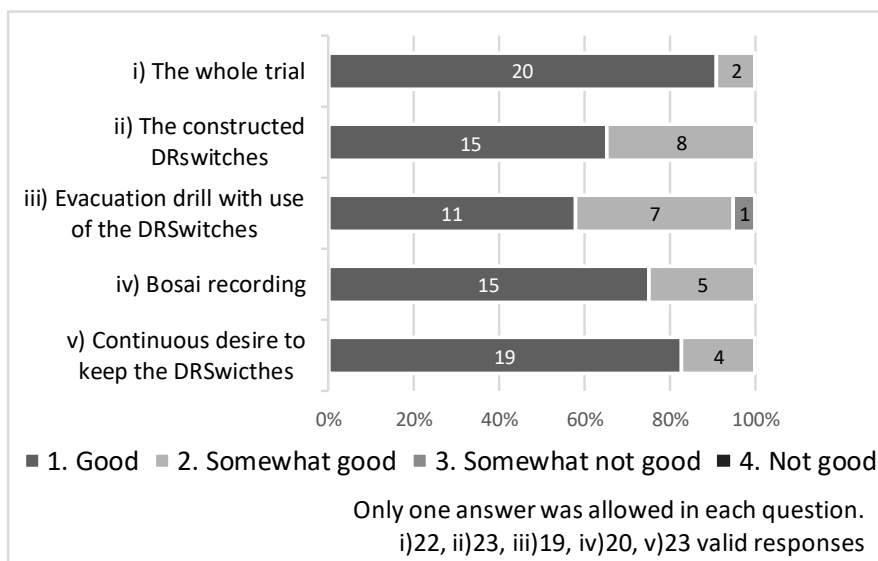


Figure 13. Overall opinions and those for each activity in this trial (WS6)

5. DISCUSSION

Landslides occur locally and are not easily predicted. However, the trial of DRSwitches for landslides created an opportunity for communities to consider the timing of evacuation using community participation in disaster risk information. In addition, the communities could connect their DRSwitches and public disaster risk information using bosai recordings.

From the previous section's results, we consider the ideal state of public participation in disaster risk information for landslides.

5.1 Construction of relationships between the local situation and objective information

This trial of DRSwitches for landslide risk identified some local disaster risk information to reference evacuation timing; however, the trial included slightly subjective content that was different from that applicable to flood risk. Therefore, there was some uncertainty regarding the risk information for disasters. Some communities tried bosai recording, which could link uncertain information with objective and quantifiable public disaster risk information. In other cases, such as debris flow, professional volunteers in a Taiwanese community, and weather reporters in Weathernews Inc., systems have taken steps to evaluate local disaster risk. The method in this study led to the construction of another system. First, the communities gained an understanding of local risk information in the community, and subsequently, they evaluated these relationships with quantifiable public disaster risk information.

In general, observation of rainfall amounts is a representative example of public participation in disaster risk information; however, as observation systems have increased in society, it has become more difficult for lay members of the public to participate in these systems. This tendency can lead to a weak relationship between disaster risk information and communities and an over-dependence on public disaster risk information from professionals. In fact, the latter case applies to most Japanese communities, including the Taisho District. DRSwitches can change these relationships. DRSwitches promote public participation by considering local disaster risk information. Participants rebuild the relationship between communities and public disaster risk information by recording local situations. Against this background of weakening public independence supplemented with more additional information, bosai recording can increase the independence of risk-assessment information and connect subjective local disaster risk information and objective public disaster risk information.

Separately from communities, some technological developments can determine local landslide risk information based on observations by inexpensive IoT devices (Ueyama *et al.* 2018). As some communities in the Taisho District expressed that they wanted to clarify the conditions of the local mountains, we discussed the possibility of installing some of these devices during WS6. Caution is important when constructing such a local observation system; even if we can easily obtain objective and quantifiable local risk information on landslides, the relationship between disaster risk information and communities will not change without a system of public participation. The most local and accurate information does not necessarily equate to a change in the position of information in the social system but rather equates to differences in the observed items or accuracy. Similarly, such an approach cannot promote the change in information awareness we found in this trial. Public participation using DRSwitches provides an approach to addressing some issues that an improvement in locality or accuracy cannot resolve.

5.2 Desire to participate in disaster risk information

Some questionnaire survey results showed the effect of the public participation method. DRSwitches can resolve the difficulty in making evacuation judgments, which derive from the highly local and uncertain nature of landslide risk. Generally, we focus on the content or accuracy of information when we discuss the improvement of disaster risk information. However, as we cannot forecast landslide occurrence with 100% accuracy, some uncertainty remains.

In this discussion, the DRSwitch moves the focus from the content or accuracy of disaster risk information to a community system of disaster evacuation (“How do communities cooperatively evacuate?”) through community participation in disaster risk information. The results here showed that residents could accept uncertainty in disaster risk information, or, if they have no awareness of disaster risk information, that they can consider their own evacuation timing. This can be seen in that most communities thought that DRSwitches could be used for evacuation timing.

As Figure 10 shows, positive opinions on public participation in disaster risk information are important. Figure 14 shows a conceptual model of communities’ disaster responses based on disaster risk information. The Figure 14a is for a conventional approach in which the local government issues evacuation information, and communities receive it and consider disaster responses. This is quite typical today. However, the low rate of evacuation in Japan shows that this style cannot work sufficiently there. Effectiveness depends on the various aspects of nations, communities, cultures, and disaster characteristics. Public participation can change this conceptual model into the Figure 14b. If evacuation information on landslide risk is issued by local governments based on scientific standards, the communities sometimes do not feel that the information is realistic and often wonder whether they actually need to evacuate. The DRSwitch approach departs from this conventional approach; in this approach, communities not only receive disaster risk information but also evaluate landslide risk for themselves and take actions based on the DRSwitches. Their roles expand to include checking local risks by adding local items to the evacuation-judgment process. The DRSwitch changes communities’ perspectives from considering evacuation (which may not produce action) to judging them (which can lead to action). The results in Figure 13 support this type of approach.

DRSwitches can create an opportunity to discuss action standards or risk information through the lens of cooperation between local government and communities. Such cooperative construction is important for promoting landslide evacuation.

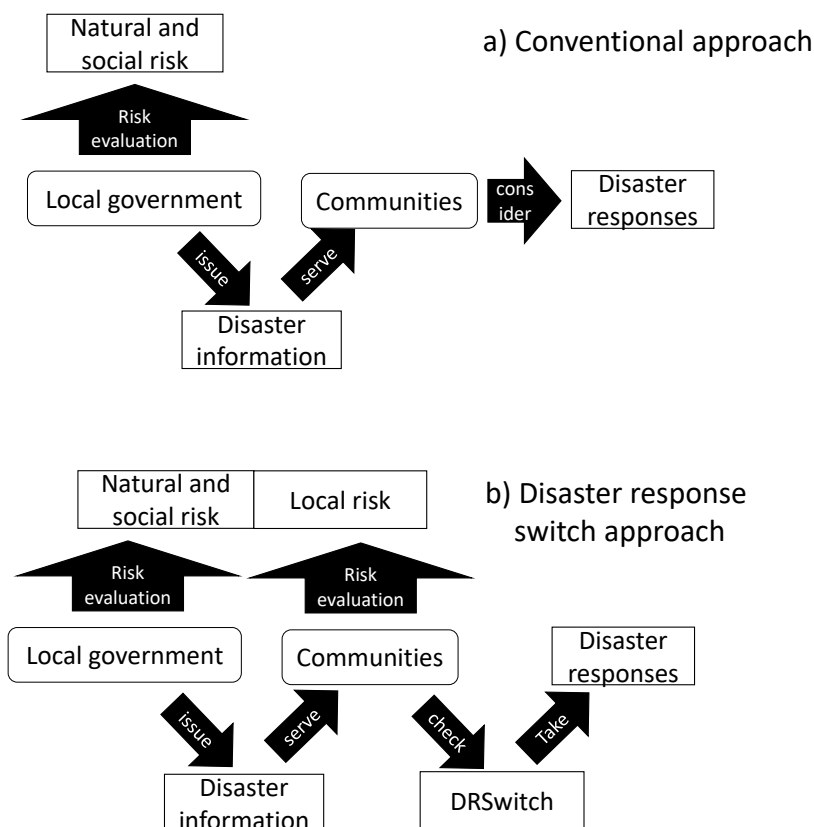


Figure 14. Conceptual model of communities' disaster responses based on disaster risk information
a) conventional approach; b) DRSwitch approach

6. SUMMARY

Through practical research in a mountainous area of Japan, this study verified the effects and issues of public participation via DRSwitches with respect to highly local and uncertain landslide risk.

Communities participated in this trial and constructed DRSwitches based on local disaster risk information. Thus, the communities accepted the uncertainty in disaster risk information on landslide risk and simultaneously connected their subjective local disaster risk information to objective public disaster risk information through bosai recording. This trial thus resolved the over-dependency on local government information and allowed the communities to reconstruct their concepts of evacuation. Consequently, the DRSwitch promoted an independent attitude toward evacuation from landslides.

This trial was conducted in a mountainous area, and therefore, it was easy for the community to accept the concept of common evacuation. However, some locations, such as urban areas with landslide risk, make it more difficult to forge cooperation within communities. If community communication is difficult, some communities, such as representatives of voluntary disaster prevention organizations, should first attempt DRSwitch construction. It is

not known whether this will lead to the same effects as seen in this study; additional verification is required for urban areas.

The issue of technology is also a challenge for the future. Smartphones, AI, Big Data, and technological developments have become increasingly widespread in social systems, causing community systems for local disaster prevention to change. As the methods of public participation in disaster risk information continue to change, we must attempt additional and ongoing research on the proper methods to adjust to these technological changes.

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Original paper

VigiFlood: Evaluating the Impact of a Change of Perspective on Flood Vigilance

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Abstract Emergency managers receive communication training about the importance of being 'first, right and credible', and taking into account the psychology of their audience and their particular reasoning under stress and risk. But we believe that citizens should be similarly trained about how to deal with risk communication. In particular, such messages necessarily carry a part of uncertainty since most natural risks are difficult to accurately forecast ahead of time. Yet, citizens should keep trusting the emergency communicators even after they made forecasting errors in the past.

We have designed and implemented a serious game called VigiFlood, based on a real case study of flash floods hitting the South West of France in October 2018. In this game, the user changes perspective by taking the role of an emergency communicator, having to set the level of vigilance to alert the population, based on uncertain clues. Our hypothesis is that this change of perspective can improve the player's awareness of flood risk, and response to future flood vigilance announcements.

We evaluated this game through an online survey where people were asked to answer a questionnaire about flood risk awareness and behavioural intentions before and after playing the game, in order to assess its impact. The results are encouraging, showing improved risk awareness, protective intentions, vigilance, and trust after playing. However, it also suggests that the current "game design" is still poor and unable to engage the general public, in particular school students. Future research will therefore address this issue.

Key words: crisis communication, trust, subjective risk, agent-based model, serious game

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1. INTRODUCTION

1.1 Context

Nowadays, our societies are exposed to increasingly frequent natural disasters (CRED Center for Research on the Epidemiology of Disasters n.d.) that cause more and more victims and economical losses as the density of population increases (Svetlana *et al.* 2015; Duan *et al.* 2016). Floods in particular are expected to happen more and more often in some parts of the world due to the global warming (Roudier *et al.* 2016; Kerr 2007; Schiermeier 2011). (Attansey 2012) found that individuals might get desensitized after multiple occurrences of floods, and that communication has a key role to play to maintain vigilance. Unfortunately, meteorological events such as flash floods are hard to predict, highly undeterministic, depending on many factors (Duan, He, Takara, *et al.* 2014). For instance, thunderstorms can be predicted but it is hard to know in advance their exact trajectory and the area that will be affected by intense rain or subsequent floods. As a result, the weather information and alerts communicated to the population by meteorological services are inherently probabilistic and uncertain. Forecasts are usually accompanied by a trust index indicating how certain they are, but people have trouble interpreting probabilistic or statistical messages (Eiser 1998), and they underestimate rare or extreme events (Burningham *et al.* 2008). Yet it is crucial to warn people so they can take protective actions soon enough (Grothmann and Reusswig 2006), even though these precautions might end up unnecessary.

Consequently, weather forecasters are faced with a dilemma about when to raise an early warning (Pearson 2012; Geleta 2013): either wait to have more certainty before announcing a weather event, at the risk of missing it or announcing it too late, possibly causing victims; or announce a probable event before being sure, based on insufficient or unreliable clues, at the risk of over-alerting the population. This second option is generally considered as more acceptable, as it does not cause immediate victims. For instance, Météo France communicates a ratio of about 15% of over-alerting, but only 2-3% of under-alerting (Le Monde 2018). However, alerts should be used with precaution to avoid panic (Arru *et al.* 2019). Besides, the population might lose trust after several over-alerts, that they might consider as “false alerts”. This would result in not trusting subsequent alerts even when justified. This is for example what happened in recent floods in the South West of France in October 2018 (Libération-AFP 2018; Gominet 2018).

1.2 Problematic

Efficient crisis communication is very challenging, and the population’s actual reaction does not always match what is recommended and expected by the authorities (Rhodes 2014), with potentially disastrous consequences (refusal to evacuate, lack of preparation, *etc.*). This gap can have many explanations (Parker, Priest, and Tapsell 2009): a lack of understanding of instructions, mistrust in the authority and their messages, or not knowing which actions to take exactly; social attachment (making gathering with one’s family more important than saving

one's life (Bañgate *et al.* 2017)); cognitive biases (Murata *et al.* 2015; Arnaud *et al.* 2017); or a lack of personalization of communication (Adam and Gaudou 2016).

There is clearly a misunderstanding here, where the population and media believe that the weather forecasters do a poor job (Libération-AFP 2018), without realizing the underlying difficulties (Gominet 2018); and the weather forecasters do not understand why the population will not listen to the warnings (Rhodes 2014). In such a situation, role-playing games have shown their interest for changing people's perspective and letting them understand other points of view and gain "enhanced awareness of other perspectives" (Bowman 2014). As also suggested by Shubik (1971), "in many of the uses of gaming seeing the other individual's point of view by role playing his position appears to be of value" (p. 6).

1.3 Proposition / approach

Our goal here is therefore to propose such a role-playing experience to improve communication between weather forecasters and the population of flood-prone areas. Concretely, we propose **VigiFlood**, a serious game where the player has to take on the role of an emergency communicator setting the level of vigilance based on uncertain weather forecast; they get feedback about the effect of their actions on the simulated population (trust, evacuation decision). We have implemented a first prototype of this serious game (Adam and Andonoff 2019), but improvements are still ongoing. The game is based on a multi-agent model grounded on psychological and sociological theories, and on real hydrological and meteorological data from a flood-prone area in the South West of France.

In this paper, we want to verify if the change of perspective induced by Vigiflood does let the players gain awareness about the difficulty of flood risk prediction and communication, and leads to a subsequent change in their behaviour. We have therefore designed an online questionnaire to measure the objective impact of this change of perspective on the players' awareness of the challenges of flood risk communication. Concretely, we measured several indicators, both before and after playing the role of a weather forecaster: the players' risk awareness, trust, vigilance, consciousness of their own responsibility for action, and protective actions intentions. The first results described here show an improvement in these values, suggesting that such a serious game has an interest in raising awareness in the population and improving communication and prevention in case of floods.

In order for the final serious game to have an actual impact, it needs to be played by the population. In line with participatory research (Becu 2020), this is easier to achieve by involving the target users early on. This is why our survey also integrates subjective questions about the responders' opinion on the subjective interest and playability of the serious game, and their will to see it implemented in their town or in schools. With no surprise, our first prototype is not engaging enough, but people find it really interesting and are willing to see such a tool implemented on the field. This is encouraging us to pursue research on this path, and ongoing work is now directed towards improving the game design and immersion of our first prototype.

1.4 Outline

This paper is structured as follows. Section 2 discusses the use of agent-based simulation and serious games for crisis management. Section 3 then provides the reader with an overview of useful research in the social sciences about crisis communication, trust, or risk evaluation, that will serve as the basis for our model. Section 4 presents some context about flash floods, the French vigilance system, and our case study. Section 5 describes our serious game, Vigiflood, and its underlying agent-based model. Section 6 is the core contribution and presents our evaluation of Vigiflood, the questionnaire design, its ethical validation, and the results obtained from an analysis of 80 answers gathered during the month of June 2019. Finally, Section 7 concludes and discusses future prospects of this research.

2. SIMULATIONS AND SERIOUS GAMES

In this paper we want to provide a solution to improve communication, vigilance and trust around flash flood risk in flood-prone areas. Our approach is to provide a computerized serious game offering a change of perspective to players from the population. This serious game is based on an agent-based simulation of the reaction of the population to the flood vigilance messages received. This section defines the concepts and reviews existing research in this field.

2.1 Agent-based simulations

Agent-based social simulations (Bonabeau 2002) are a computer science approach modelling the behaviour and interactions of autonomous entities called agents, each representing a human individual, in order to study the resulting behaviour of the global society. It is a very useful tool to understand the behaviour of a complex system as emerging from the individual behaviours of its members, for instance how a crowd evacuates from a building, or how traffic jams appear on a busy road.

Axelrod (1997) defines seven purposes of simulations, including **prediction** (simulate a system very realistically to predict its future behaviour, e.g. meteorology), **training** (provide a believable interactive environment to rehearse actions, e.g. flight simulator), or **education** (let the user learn by trial-and-error in a virtual world). Predictive simulations require a high degree of realism to lay valid predictions, while training and education simulations can be simpler and less realistic (they “need not be rich enough to suggest a complete real or imaginary world”). Besides, Axelrod also claims that “the simpler the model, the easier it may be to discover and understand the subtle effects of its hypothesized mechanisms”; educational simulations are therefore often quite simple.

Computer simulations allow to explore completely controlled scenarios, to repeat them as many times as necessary, at no cost and with no stakes, in order to gain simulated experience. As a result of such advantages, computer simulations have often been used in crisis

management (Murakami *et al.* 2002) for various purposes. For instance (Yang *et al.* 2018) provide a very realistic model based on field data, to **predict** the impact of early warnings on population behaviour in terms of reducing material losses from floods. Others focus on realistically modelling the physical flood phenomenon in order to **support decisions** regarding early warnings for tsunamis (Friedemann *et al.* 2011), based on data from multiple sensors (Behrens *et al.* 2008).

Other simulations focus on communication, but not necessarily during floods. (Arru *et al.* 2019) study if the population should be alerted or not of an ongoing crisis (e.g. terrorist attack), depending on the anticipation of their potential reaction (e.g. crowd panic), which is based on a psychological model. Since events considered are ongoing, they do not deal with false alarms and their potential impact on long-term trust. (Adam and Dugdale 2018) study the propagation of awareness in the Australian population after a bushfires warning, depending on its channel and (familiar vs unfamiliar) source. Since they consider a single event, they do not deal with long-term dynamics of trust over multiple (right and wrong) alerts. (Haer *et al.* 2016) use an agent-based model to study the effectiveness of flood risk communication strategies, showing that it is important to communicate not only about the risk but also about how to cope with it; they also find that this impact propagates through social networks.

Computer simulations are often designed and implemented by computer scientists, and then used on the field. Participatory simulation (Becu 2020) is an approach where the stakeholders or users are invited to participate in the entire process of designing, modelling and simulating a given problem. This co-construction lets participants share knowledge and points of view. This approach is very adapted to environmental stakes or urban planning, to accompany discussion between scientists, deciders and citizens.

2.2 Serious games

Clark Abt coined the term of “serious games” in 1970 (Abt 1970; Djaouti *et al.* 2011). This American researcher worked on computer simulation games for military training during the cold war, and supported the potential of games for serious applications, in particular for education. He defines serious games as games that “have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement” but insists that this does not and should not prevent serious games from being entertaining. He reviewed many examples of such serious games on various formats: board games, card games, outdoor games, or computer games, which we focus on here.

An important advantage of serious games compared to more traditional educative approaches is to favour the learners’ engagement (Garris *et al.* 2002; Boyle *et al.* 2016). For instance (Burke *et al.* 2009) have obtained encouraging results when using video games to solve disengagement problems and motivate patients to stick with intensive and repetitive rehabilitation exercises. Many serious games are specifically targeted at children. It is argued that children are often more enthusiastic, motivated to learn, and receptive to new ideas (Izadkhah and Hosseini 2005) (p. 142). Besides, they are a good channel to reach (and

convince) their parents, and spread the ideas to the wider society (Barreto 2014) (p. 19). (Fitzgerald *et al.* 2000) (p. 1) confirm that it is better to develop an active (rather than fatalistic) mind-set about disaster risks at an “early age”, and a culture of prevention takes time to form. However, engaging children requires engaging their teachers first.

In crisis management and disaster prevention, serious games are often used to teach appropriate behaviours or to train deciders (see (Di Loreto *et al.* 2012) for a review). Indeed, they are a good way to make the population aware of their responsibilities, and to promote their active participation, compared to more traditional or vertical approaches of imposing knowledge (Yamori 2012). For instance, these authors have developed Crossroad, a card game for tsunami prevention in Japan where the players have to find their own viable solutions to social dilemmas, rather than accepting externally prescribed solutions. (Horita *et al.* 2014) also study the use of gamification to improve community knowledge, awareness and resilience in case of disasters; they have developed an online platform to foster collaboration.

Some serious games focus on communication. For instance (Adam and Bailly 2019) proposed a serious game for trying various communication strategies to alert the population (focused vs wide targeting, information vs recommendations) before and during bushfires in Australia, but they do not deal with the timing of alerts nor the impact on trust. Indeed, they report no habituation phenomenon to fire alerts, which could be due to the easier predictability of fires compared to flash floods, or to normative and cultural differences.

Several serious games exist that address floods, with different targets and different formats. Anycare is a table-top role-playing game to involve stakeholders (Terti *et al.* 2019), and requires some organization, a lot of time and an animator. LittoSIM (Becu *et al.* 2017) is very realistic and aimed at emergency managers; SPRITE (Taillandier and Adam 2018) teaches risk management to engineering students; however, both games focus on longer-term management and protection against coastal submersion (e.g. building dykes) rather than communication.

2.3 Role playing

In serious games, the player can take their own normal role, an imaginary role (invented for the game), or another existing role. This change of perspective is a powerful tool to get people to understand the specific point of view and challenges of a different role, and can make it easier to accept decisions made by that role. (Shubik 1971) supports the usefulness of role playing a different position in order to understand another individual’s point of view. Also of benefit in his view is the ability for participants to watch how stakeholders make their decisions in the game. This suggests that observing people playing can also be of interest, and that not only the players themselves learn from the game. This is also in line with Bowman’s findings, that a “shift in perspective provides players with the opportunity to understand the motivations of others more clearly” (Bowman 2010), and that “the adoption of a role contributes to a greater awareness of one’s own perspective, but also leads to an increased understanding of the perspectives of others” (Bowman 2014).

Existing simulators are often aimed at training or supporting decisions of emergency managers. Here we adopt a different approach where we propose a serious game aimed at changing the population's perspective by letting them play the role of an emergency manager confronted with difficult decisions. Our game will provide the players with feedback about the reaction of the simulated population. In order to make this simulated population representative of reality, the underlying model is grounded on literature from psychology and sociology, as discussed in the next section.

3. RELATED RESEARCH

In order to simulate people accurately, it is essential to understand how they interpret crisis communications, what determines their trust, how they evaluate risks, and what motivates them to be vigilant and to take protective actions before a possible natural disaster. Below we define the concepts used in our study, and review related literature studying how people react to official crisis communication. This will provide the theoretical basis for modelling how the artificial population in Vigiflood reacts to the player's decisions in terms of communicating vigilance.

3.1 Crisis communication

(Samaddar *et al.* 2012) show the importance of integrated flood risk management, including both structural physical measures, and appropriate communication. Indeed, individual protective actions by the population could drastically reduce costs induced by flash floods (up to 80% according to (Grothmann and Reusswig 2006)). But crisis communication is complex, and emergency managers are trained about it (Reynolds 2010; Reynolds and Seeger 2014). It fills several functions. First, it informs people about risks, raising their risk awareness (Maidl and Buchecker 2015; Terpstra *et al.* 2009). It also keeps people vigilant despite repeated crises which could induce desensitization (Attansey 2012). Finally, it should motivate protective behaviours (Neuwirth *et al.* 2002).

3.2 Subjective risk evaluation

However, there is no similar training for citizens about receiving and interpreting crisis warnings. Studies show that people cannot predict the negative emotional impact of floods, which they greatly underestimate as long as they have not experienced floods (Siegrist and Gutscher 2008). They also have trouble interpreting probabilistic or statistical messages (Eiser 1998), they underestimate rare or extreme events (Burningham *et al.* 2008), and often rely on heuristics and cognitive biases (Murata *et al.* 2015; Arnaud *et al.* 2017).

Risk perception and evaluation is therefore highly subjective and emotional, depending on socio-cultural, environmental and linguistic factors (Infanti *et al.* 2013). Several authors study

the role of culture (Douglas and Wildavsky 1983; Johnson and Covello 1987). Various cognitive and affective factors are also identified such as mental noise, stress, a focus on negative content, and lack of trust in the authorities (Covello and Sandman 2001; Covello 2003). For instance (Samaddar *et al.* 2012) study in Mumbai, India shows the importance of the population's trust in the information source on the resulting risk awareness and preparedness.

3.3 Protection motivations

But being aware of the risks is not sufficient to trigger protective actions (Grothmann and Reusswig 2006). For instance, an analysis of the behaviour of people during the Black Saturday bushfires in Victoria, Australia in 2009 (Fire Services Commissioner 2013) listed several profiles; this list includes a 'wait-and-see' behaviour where residents, although asked to leave early, would wait to see if the fire really came their way before evacuating, often too late, putting their lives at risk. A subsequent report focused on why people did not do what the authorities thought they should do (Rhodes 2014); they concluded that communication was not personalized enough, and did not target individual residents' motivations. (Boer *et al.* 2014) also find that communication should address the motivations of people to trigger preventive actions.

An important factor for motivation is the feeling of agency (Covello 2003) or locus of control (Hurnen and McClure 1997): if people believe they have no control (external locus of control) they will feel helpless, and be less likely to take preventative action or react to warnings. Similarly, (Khan *et al.* 2012) discuss the lack of response of the population when the perceived risk is either too high (fatalism) or too low ("blasé effect"): in both cases, people feel powerless.

(Floyd *et al.* 2000) review research about protection motivation theory (PMT), a model initially designed for disease prevention and health promotion. They find that both protective intentions and behaviours are facilitated by higher threat severity and vulnerability, higher self-efficacy, but also by decreasing rewards for maladaptive responses and costs for adaptive responses.

(Grothmann and Reusswig 2006) propose a psycho-social model of flood protection behaviours of residents of a flood-prone area in Germany, based on PMT, and evaluate it via a survey of residents of Cologne; they show that protective behaviours depend on factors such as previous flood experience, risk of future floods, efficacy and costs of self-protective behavior, but also on tendencies like wishful thinking; they conclude that in order to motivate residents, communication should not only be informative about risks, but also address the possibility, effectiveness and cost of protective measures.

(Siegrist and Gutscher 2008) compare people with and without flood experience, and find that if the latter are less motivated to take mitigation actions, it is because they strongly underestimate the negative emotional effects of floods; they conclude that flood communication should not only inform about technical aspects but also about potential emotional implications.

Other authors identify affective factors playing a role in protection motivation. For instance (Harries 2008) show a tendency to refuse to take protection measures ensuring physical security, in order to preserve a feeling of security (or ontological security). (Weinstein *et al.* 2000) interviewed survivors of tornadoes to identify the effect of recollections of fear from previous disaster experience on intended protective actions.

3.4 Trust

According to Slovic (2016), risk management has become much more “contentious”, with risk managers blaming the public for being irrational, and the public blaming the stakeholders for their poor management. In his view risk communication, aiming at aligning population and experts’ perceptions with experts, has failed due to the lack of trust: “if trust is lacking, no form or process of communication will be satisfactory” (p. 410). Slovic also explains that trust is “fragile”, builds up slowly but can be destroyed instantly and is then hard or impossible to regain (p. 319). He provides several reasons for this asymmetry. First, negative events are **more visible** than positive ones (one missed alarm stands out in many days of correct predictions). Second, negative events have **more weight** because they have lower probability and higher consequences (a flood is rarer than a “normal day” and it can do serious damage). Third, the media also tends to give **more coverage to bad news** than good news. Fourth, **sources of bad news are seen as more credible**, less likely to lie, than sources of good news. Finally, **distrust strengthens itself**, by limiting further interactions and biasing future interpretations towards the reinforcement of existing (distrustful) beliefs.

3.5 Impact for Vigiflood

Impact on our approach. Following this review of literature, our approach of proposing a serious game appears to be in line with the risk communication principles advocating transparency and empowerment of the population (Reynolds 2010), a field currently lacking research. The game format also favours engagement (Burke *et al.* 2009), which is important to maintain interest and vigilance over multiple crises (Attansey 2012), and repeated communication (Maidl and Buchecker 2015).

(Arvai 2003) concludes that public participation in decision-making about risks leads to higher quality decisions, with the resulting policies possibly being more acceptable. Our approach in this paper, consisting of surveying the population about the potential impact of such a game even before completely implementing it, is in line with participatory simulation (Becu 2020), which advocates to involve the stakeholders and final users right from the early stages of the design of the simulation. Our approach also facilitates a two-way dialogue with the population about flood risks; this is recommended by theory but not often enough observed in practice, according to a review of communication practices across Europe (Höppner *et al.* 2012)

Impact on our model. To make our simulated population an accurate representation of reality, each artificial citizen (agent) will perform their own subjective risk evaluation, based on their personality and experience (Infanti *et al.* 2013), as well as cognitive biases such as the *blasé* effect leading to dismissing low risks (Khan *et al.* 2012); they will update trust based on received communications (Slovic 2016), building it slowly and losing it fast when perceiving 'mistakes'; and they will also make a personal protective decision (evacuate or not) based on this risk assessment, their emotions and trust (Grothmann and Reusswig 2006). The full details of our agent-based model are discussed in Section 5.

Impact for cultural portability. Risk evaluation depends on culture (Douglas and Wildavsky 1983; Johnson and Covello 1987), as well as on the type of disaster. For instance (Adam and Bailly 2019) report no habituation phenomenon to fire alerts in Australia, maybe due to a different risk culture, where people in scarcely populated, fire-prone areas, feel more responsible for their own safety, than residents of flood-prone areas in France. Besides, our case study is strongly context-dependent as well, supported by real rain data from the South-West of France, and using the French weather vigilance system (see details in Section 4). As a result, the Vigiflood tool will probably not be usable beyond France or Europe. Our target is therefore limited for the moment only to the French population of flood-prone areas.

4. CONTEXT

This section provides some context about flash floods and their impact, and the specific events in the South-West of France in October 2018 that constitute our case study.

4.1 Flash floods

Flash floods generally occur due to rapid rain on an already saturated soil (after a particularly wet period) or on a soil with a poor absorption capability (such as concrete, as is often the case in urbanized settings), or due to extensive rain because of a storm or hurricane. They can also occur from more occasional events such as a glacier melting after a volcanic eruption, an ice dam melting, or a man-made dam failing. They are quite hard to predict (Duan *et al.* 2014). In this paper we focus on rain-induced flash floods, whose prediction is the responsibility of the meteorological services. The indicators used by forecast services include: forecast quantity of rain (radar or satellite or model based), soil absorption capacity, soil moisture or dryness level, topography, basin or catchment capacity, *etc.* (CEPRI 2008).

4.2 Facts and figures

The Centre for Research on the Epidemiology of Disasters publishes an annual report based on the EM-DAT database (CRED Center for Research on the Epidemiology of Disasters n.d.).

According to the its 2019 Review of Natural Disasters (Guha-Sapir 2019), in 2018, 315 natural disaster events were recorded, causing 11804 deaths, affecting over 68 million people, and costing 131.7 billion US\$ in economic losses across the world. This review also notes that floods are the disaster affecting the most people (50% of the total), even though they are less deadly than earthquakes (respectively 24% and 45% of total deaths). Indeed, floods are the most frequent natural disaster, representing 40% of all natural disasters between the years 1985-2009 (Svetlana, Radovan, and Ján 2015), killing an average of 12700 people worldwide annually, and affecting 60 millions others; their economic impact is huge, whether in Asia (Duan *et al.* 2016) or in Europe, with the 2002 floods in Central Europe costing about 20 billion US\$ (Svetlana *et al.* 2015).

The European Commission (2019) reports 213 recorded flood events between 1998-2009, causing 1126 fatalities, and costing about 52 billion €, making it the costliest type of disaster (followed by storms). There are also enormous stakes, with over 10 million people living in extreme-flood-prone areas along the Rhine river alone, and potential damage estimated at 165 billion €. Coastal areas are even more exposed, with economic assets located within 500 meters of the European coastline valued between 500 and 1000 billion €. (Paprotny *et al.* 2018) analyzed the HANZE database floods records in Europe between 1870-2016: they found 1564 records of floods, 56% of the total being flash floods (river floods under 24 hours); in southern Europe flash floods are even more prevalent, mostly between September and November. This is precisely the context of our case study: an extreme flash flood occurred in the South West of France in October 2018.

4.3 French flood vigilance system

French vigilance system. The current French vigilance system was designed in 2000 after the 1999 storms, and implemented in 2001 for a first set of meteorological events, then completed with heat waves in 2004, and combined rain-flood vigilance in 2007 (Degrace and Honore 2010). It is a meteorological watch and warning procedure where Meteo France, the national weather forecast agency, provides expertise to the prefects, the Civil Defence Organisation, the relevant stakeholders, and the general public. It is improved over time after feedback from events (Daupras *et al.* 2015).

According to Meteo France,² the agency in charge of rain forecasts, weak rain is defined as 1 to 3 mm/h, moderate rain is between 4 and 7 mm/h, and heavy rain is over 8 mm/h. Another agency is in charge of monitoring the main waterways and broadcast their expected height and debit 3 to 6 hours ahead of time: Vigicrues³. However, only part of the waterways is monitored, and the European Flood Risk Prevision Center (CEPRI⁴ notices that half of the 63 victims in

² <http://www.meteofrance.com/previsions-meteo-france/previsions-pluie>

³ www.vigicrues.gouv.fr

⁴ <https://www.cepri.net/>

the Languedoc-Roussillon region (south of France) alone between 1996 and 2006 died on catchment basins that were not monitored.

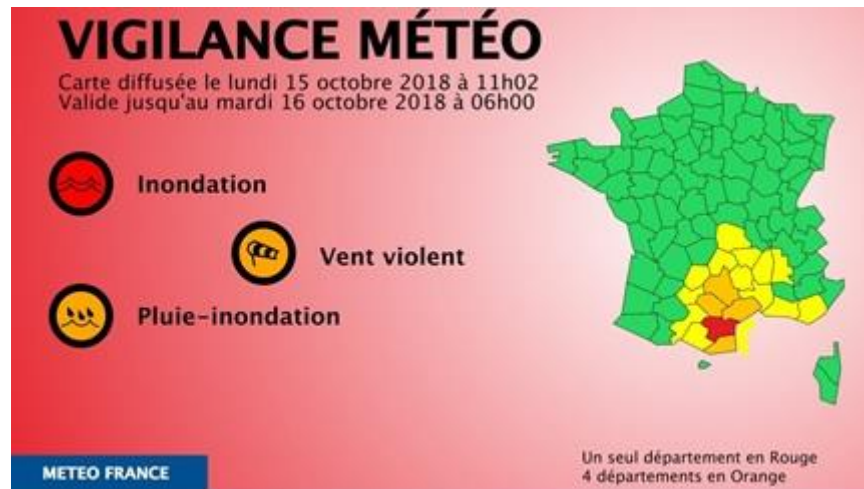


Figure 1. Meteo France vigilance map, 15 October, 11 am (source: Meteo France)

Vigilance scale. The meteorological services in charge of the area then analyses these clues (rain forecast, waterway height and debit, *etc.*) to define and announce a level of vigilance on a 4-colour scale, from green (no problem), yellow, orange, to red (higher risk). Table 1 gives the official⁵ definition of each level. This level of vigilance is publicly available online⁶ (example map on Figure 1). Each region has its particularities and can be more or less used to receiving heavy rain in a short amount of time, so that the vigilance thresholds are not the same everywhere.

Over-alerting (false alerts) vs under-alerting. But such extreme phenomena are hard to predict, and weather forecasting agencies are faced with a dilemma: alerting while uncertain about the occurrence of an event, with the risk of 'over-alerting' (or 'false alarm' as can be reported in the media (Le Monde 2018), meaning that the event forecasted does not happen; or waiting to have better certainty before alerting, with the risk of 'under-alerting', *i.e.* failing to alert before an actual event. Over-alerting is considered less risky in terms of immediate lives lost, and Météo France allows about 15% of over-alerts, while missed alerts can have very serious consequences, and only 2-3% of yearly events are missed (statistics provided by Météo France in an interview in the news after the 2018 floods (Le Monde 2018)). However, over-alerting can also be risky over the longer term by destroying the population's trust, as shown by the following case study.

⁵ Translated from French from: <https://vigilance.meteofrance.com/html/vigilance/guideVigilance/vigilance.html>

⁶ See: <http://vigilance-public.meteo.fr/or>: <http://vigilance.meteofrance.com/>

Table 1. Official definitions of flood vigilance levels (translated from Météo France)

Color	Definition
Green	No specific vigilance needed
Yellow	Be careful; if you engage in activities that are sensitive to the weather or near a shore or stream; common phenomena in the region but occasionally and locally dangerous are indeed predicted; keep abreast of developments.
Orange	Be very vigilant; dangerous phenomena are predicted; keep abreast of developments and follow the safety advice issued by the government.
Red	Absolute vigilance is required; dangerous phenomena of exceptional intensity are pre-dicted; keep abreast of developments and be sure to follow the safety instructions issued by the government.

4.4 Case study: Aude floods, October 2018

The Aude department in France (see map on Figure 2) depends on the CNP center in Toulouse; its critical rain threshold for the orange vigilance is 50-100 mm in 24 hours, with a regional record of 551 mm in 24 hours. On Sunday 14 October 2018 the meteorological station of Carcassonne received 139.8 mm of rain. The vigilance level was initially set to orange due to high uncertainty, then raised to red Monday 15 October morning at 6am. In the meantime, several towns were already flooded, roads and bridges destroyed, and some people had died. The final toll of these floods in the Aude department is 15 dead and 99 injured people, 204 towns classified as hit by “natural disaster”, and a total cost of damages estimated to 220 M€.

As a result, Météo France vigilance system was harshly criticized in the media (Libération-AFP 2018).

The representative of the French Ministry of the Interior, Frédéric de Lanouvelle, interviewed on LCI-TV, evoked a “*weakness in the orange vigilance level which is used very often and when there is a real problem, people do not take it into account anymore*” (our translation). He adds that based on residents’ statements, the red vigilance level was indeed raised too late, but he explains that it is due to the difficulty in forecasting such a powerful episode. However, as noted by the Major Risks Institute (IRMA) (Gominet 2018), there had only been 3 orange vigilances raised in 2018 in the Aude department for rain-floods before October 14: January 7-8; 28 February and 1st of March; and the last one on October 9-10, immediately following an orange vigilance for thunderstorms on October 8-9. Besides, this last episode probably influenced the dramatic floods of October 14-15 by saturating the soil with water. (Gominet 2018) therefore concludes that the general public must be made aware of their responsibilities, and be taught that several orange vigilance events in a row should make them

particularly vigilant, instead of the opposite, dismissing the last vigilance because nothing serious happened during the previous ones.

Our approach precisely intends to favour this empowerment of the population, raising awareness and instilling responsibility, by letting them take on the role of a weather forecaster in order to understand the difficulties faced. The next section describes our serious game and underlying model.



Figure 2. Map of the flooded area, with victim counts and evacuated towns.
Source: Préfecture de l'Aude.

5. VigiFlood

The VigiFlood serious game is implemented in Python (Adam and Andonoff 2019). It is based on actual rain and vigilance data, and on a conceptual agent-based model of human behaviour in flash floods grounded on the literature described in Section 3 above. This section provides a quick overview of the interface of the game, the scenario and data, and the underlying conceptual model, before we proceed to describing its evaluation.

5.1 Game interface and gameplay

The idea of VigiFlood is that the player takes the role of risk communicator, having to decide the vigilance level (color between green, yellow, orange, red), based on uncertain clues (rain forecast). Their actions influence the population, whose trust and subjective risk level evolve over time, and who might or might not evacuate when floods are announced; they can also

trigger various events simulating the reactions of institutional actors to the vigilance level (closing schools, stopping school bus services, closing roads, *etc.*) and the impact of rain or floods on the environment (collapsed bridge, *etc.*). The player can observe the impact of their actions through various information panels. The following paragraphs detail the narrative and interface of the game.

5.1.1 Game narrative

The game loop proceeds in the following phases:

1. The date of the day is displayed, as well as the observed amount of rain that day (in mm).
2. The residents react to the observation of the rain: they compare it with the current vigilance level (set the day before) to update trust, and they might evacuate if needed.
3. The player is provided with feedback about the population: average trust and its explanation (in terms of how much rain they expected based on the vigilance colour); and percentage of evacuated residents.
4. The weather forecast service announces a forecast amount of rain for the next day.
5. The player is asked to set a vigilance colour based on this forecast.
6. The population reacts to this vigilance level: compute subjective expected rain based on previous similar alerts, and might evacuate if this is above their risk aversion threshold;
7. The player receives feedback about the population's risk awareness percentage; their average expected rain (in mm); their average trust (in %); and the percentage that evacuated as a result of the alert.
8. Daily rain and vigilance are stored in game history, time moves forward to the next day.

5.1.2 Interface

The interface (shown on Figure 3) comprises several parts. The **weather tab** (white, left side panel) reminds the date, the observed rain, the forecast for the next day (mm of rain), and the last announced vigilance colour. The **population tab** (light blue, center panel) details the average subjective risk (expected rain) in the population for each vigilance colour, the average trust in vigilance messages (with its last evolution due to the last message sent by the player), the percentage of population that is unaware of risk (*i.e.* their subjective risk evaluation is lower than the objective risk), and the evacuation percentage. The **communication tab** (green, right panel) provides communication statistics, namely the number of days played, and for each colour of vigilance, the number of vigilances raised, the number of over-alerts (raised, but observed rain was lower than expected/announced), and the number of under-alerts (missed, *i.e.* not raised but the observed rain was higher than expected/announced). Four **vigilance**

buttons at the bottom of the window allow the player to select the desired vigilance colour (green, yellow, orange, or red). Finally, **popups** can appear on top of the main window to display various events triggered by the player's actions.

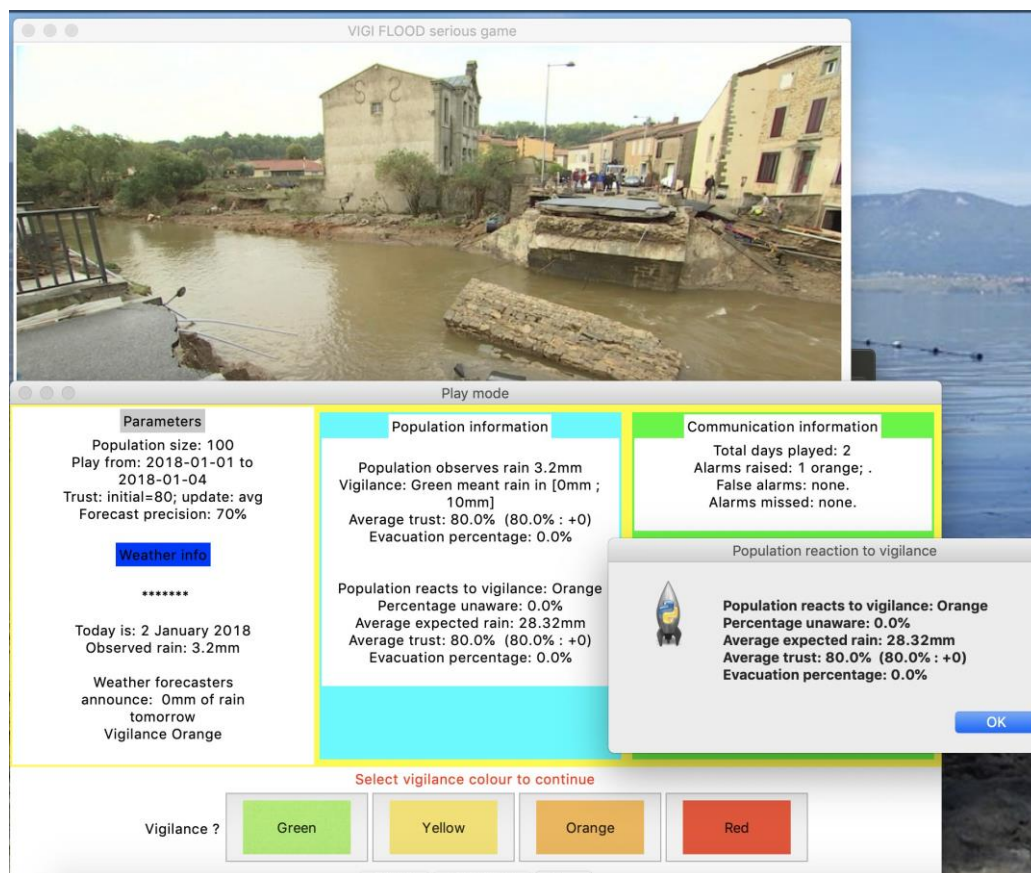


Figure 3. Screenshot of the game interface

5.2 Scenarios and data

The game can be played either with a realistic scenario using actual rain and vigilance data, or with a generated pedagogical scenario that places them in specific intended situations aimed at testing their reactions. The advantage of the generated scenario is to accelerate the game and control the desired pedagogical sequence. Real data was extracted with Python scripts, from public meteorological archive websites.

Rain data was extracted from Infoclimat⁷, which provides archives of daily, monthly and yearly meteorological data (temperatures, wind, rain, *etc.*) since 1973. We focused on Carcassonne-Salvaza, a meteorological station of the town of Carcassonne, the prefecture of the Aude department that was the most impacted by October 2018 floods. We extracted the following data for the years 2010-2018: normal monthly rain (seasonal norms computed by

⁷ Infoclimat: <https://www.infoclimat.fr>

Infoclimat between 1981-2010), number of days of rain (at least 1 mm) per month, and actual daily readings of rain amounts.

Vigilance data was extracted from Vigilance Public Meteo⁸ which provides maps and details of daily departmental vigilance alerts: time, level (green, yellow, orange, red), emitting agency (each covering a different region; Aude department depends on the CNP agency in Toulouse), and phenomenon concerned (floods, high winds, waves and coastal submersion, snow and black ice, *etc.*). We extracted the daily rain and floods vigilance colours for the Aude department between 2010 and 2018 (green if no bulletin; higher colour if multiple ones).

5.3 Underlying conceptual agent model

Our approach is to use an agent-based model of the population and their reaction to their environment (vigilance level, observed meteorological events). The validity of this behaviour model is ensured by its grounding on psychological and sociological theories of trust and risk communication described in Section 3. The physical model of flood on the other hand need not be extremely realistic to reach an educational goal, in line with (Axelrod 1997). This conceptual model has already been described in (Adam and Andonoff 2019). This section reminds the characteristics of the agents representing the residents: their attributes, how they subjectively evaluate risk, how they update their trust, and how this subsequently impacts their behaviour.

5.3.1 Attributes

The population is composed of a number of heterogeneous resident agents, that have the same attributes (summarized in Table 2) but differ by their values.

5.3.2 Subjective risk evaluation

Residents receive vigilance alerts, which indicate an 'official' level of risk, but not all residents equally believe in this level of risk. Indeed, each resident first subjectively evaluates risk (*i.e.* expected rain) based on their **memory depth** and on their **risk evaluation strategy** which reflects their personality. **Optimistic** residents consider the minimum amount of rain observed during past events where the same vigilance colour was raised; if a false alarm was raised in the past this can lead them to expect no or very little rain. **Pessimistic** residents consider the maximum amount of rain; this is very forgiving to false alarms. **Rational** residents consider an average of observed rain on remembered past occurrences of the same vigilance level. Finally, **short-memory** residents consider only the last occurrence of the same vigilance level; this simulates the loss of risk memory observed over time when no significant disaster happens (Fanta *et al.* 2019).

⁸ <http://vigilance-public.meteo.fr/>

Table 2. Attributes of agents in the simulated population

Attribute	Value	Details
Subjective risk	Float, 0 to 1	Can be over-estimated or under-estimated compared to -inaccessible- objective risk)
Risk aversion threshold	Float, 0 to 1	What level of risk they can tolerate before they choose to evacuate
Trust in vigilance messages	Float, 0 to 1	How much they believe the level of risk announced by the authorities
Memory depth/experience	Integer	How many past flood or vigilance events they remember
Risk evaluation strategy	Optimistic, pessimistic, rational, short-memory	How they evaluate risk based on these events, in line with psychological theories saying that humans evaluate risk based on previous experience and emotions (Reynolds and Seeger 2014)

5.3.3 Interleaving with trust

Trust and risk are interleaved in the individual assessment process. On the one hand, trust mediates subjective risk assessment: each resident ponders their personal risk assessment vs the official communicated risk based on their (dynamic) level of **trust** in the vigilance alerts. Concretely, if trust is 100%, the resident will fully trust the official risk and expect exactly the amount of rain corresponding to the vigilance colour; if it is 0%, they will fully trust their own judgement and expect exactly the subjective value resulting from their past experience. On the other hand, residents then observe real rain and compare it with their expectations. If they are surprised by the actual amount of rain (either because it is higher or lower than expected / announced), their trust in the forecast will decrease (more if a flood was un-announced than in case of false alarm; and more for higher impact events). On the contrary if the observation is in line with expectations, trust will only slightly increase, as this is judged as being normal.

5.3.4 Biased decision making

Finally, the residents' decision to evacuate early is based on the comparison of their subjective risk value with their personal risk aversion threshold. They can also evacuate after directly observing high amounts of rain (exceeding their aversion threshold), but this often happens too late, hence the importance of maintaining trust in pre-flood warnings. Loss of trust pushes residents to neglect the official communicated risk, which can lead to two opposite situations. After **over-alerting** (false alerts), personal risk assessment is low (memory is full of events with high vigilance but low rain); neglecting official risk conduces to under-estimating risk. Potential consequences can be serious, such as a failure to prepare and evacuate

in time. On the contrary, after **under-alerting** (missed alerts), personal subjective risk assessment is high (memory contains events with low vigilance but high rain); neglecting official risk conduces to over-estimating risk. Potential consequences include over-reacting or panic (P. Sandman 2003); it can also lead stakeholders to take unnecessary measures.

6. EXPERIMENTAL EVALUATION

The game described above is designed to induce a change of perspective, where normal residents are put in a decider's shoes and faced with the responsibility to set the vigilance level themselves. We now want to check if such a change of perspective does actually improve users' awareness of the difficulty to set vigilance without mistakes, and of their own responsibility for being vigilant; and if it does trigger a shift of behavioural intentions towards more protective actions. In order to test the impact of our game, we have designed a questionnaire simulating the role-playing experience, and administered it online in order to reach a wide audience.

The following paragraphs describe the questionnaire, the recruitment of participants, and the results along 2 axes: the (objective) impact that the game had on awareness and protective intentions; and how the participants (subjectively) judged the game.

6.1 Questionnaire

The questionnaire is written in French. The complete list of questions, translated into English, is available in Annex 1. It was proof-read by a linguist, and validated by an ethics and data privacy consultant. It has also received the agreement of University Grenoble Alpes ethics committee⁹. It is designed to proceed in the following six phases:

1. Assess the responders' previous experience, knowledge of and trust in the French vigilance system.
2. Assess the responders' awareness of risk, challenges, own responsibility; and behavioural intentions in case of floods (before playing).
3. Change of perspective: role-playing exercise of setting the vigilance level, in different more or less complex situations, with different clues.
4. Subjective evaluation of the game by responders: interest, usefulness, willingness to use it.
5. Re-assess the responders' awareness of risk, challenges, own responsibilities, and their behavioural intentions in case of floods (after playing).
6. Demographic questions to categorize responders.

⁹ Agreement number CER Grenoble Alpes-Avis-2019-09-24-5

The comparison of scores between phase 2 and phase 5 will allow us to measure the impact of the role-playing experience (phase 3) on the indicators measured. The scores in phase 4 allow to gather the respondents' opinions about such a game, in line with a participatory approach. Answers to phase 1 and phase 6 will let us categorize responders in terms of their experience and demographic characteristics, to ensure representativity and to compare impact on different categories.

6.2 Recruitment of participants

We recruited adult participants by broadcasting the link to the questionnaire via email, through the author' professional and familial networks. The goal was to reach a wide audience, avoiding a classical bias of only testing software with computer scientists and students, and get answers from people with and without flood experience to enable comparisons.

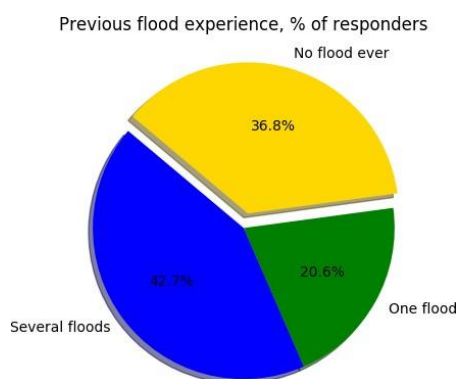


Figure 4. Experience

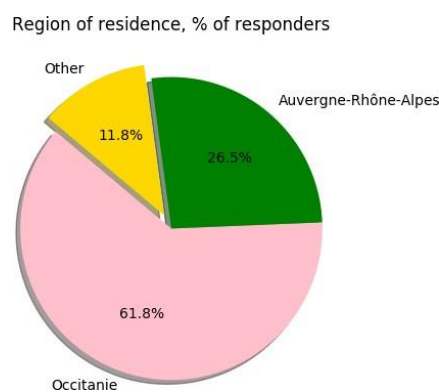


Figure 5. Residence

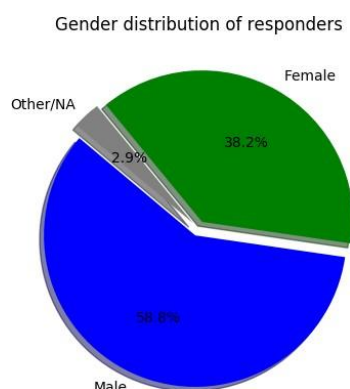


Figure 6. Gender

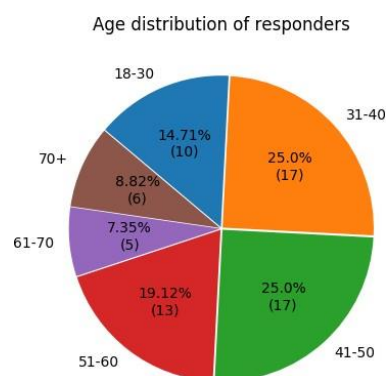


Figure 7. Age

The online questionnaire has received 80 answers. The pie charts in Figures 4 to 7 show that our sample was rather representative with responders from all age groups, slightly more males than females, and having different levels of experience with floods. Due to our mode of recruitment, the responders mainly live in 2 regions: Occitanie (South-West region of France

where the October 2018 floods occurred, reached via familial network) and Auvergne-Rhône-Alpes (South-East region of France where the author works, reached via professional network).

6.3 Results: objective impact of the game

The main goal of this questionnaire was to assess how role-playing and changing perspective (through a simulation of the Vigiflood game) can impact the players' attitudes. We measured a number of criteria defined in Section 3: **awareness of risks** (is the person aware of the risk of floods in the area) and of own **responsibility** (does the person feel responsible for their own safety in case of floods); impact of events interpreted as 'false alarms' on trust (does the person lose **trust** when an orange vigilance is not followed by a significant flood?) and on **vigilance** (is the person more or less vigilant after repeated 'false alarms'); and **intended protective actions** in case of orange or red vigilance (what does the person intend to do in case of high vigilance). We measured these criteria both before (phase 2) and after (phase 5) the change of perspective induced by the core of the questionnaire (phase 3).

6.3.1 Impact on awareness

Figure 8 shows how awareness scores evolved between before and after the role-playing sequence. We can see that risk awareness increases for orange vigilance events (that tend to be ignored when too frequent), which is a good thing. It does not increase for red vigilance events, which are already alarming enough.

The awareness of own responsibility in self-protection does not change significantly after the game, probably because the focus was more on the alert phase, and the game does not show actions of the population; further developments of the software will try to focus more on the population side.

Finally, awareness of the difficulty of setting the right level of vigilance does increase, less people feel that a forecast should only be announced when it is certain, and the minimal reliability for announcing a vigilance also decreases. This is in line with serious game research showing that a change of perspective does induce a better understanding of the other role: after being faced themselves with the dilemma of potentially under- or over-alerting the population, the players seem to reduce their expectations. We hope this should limit the subsequent loss of trust induced when the vigilance colour is perceived as wrong: errors are easier to forgive when the difficulty of the task is known.

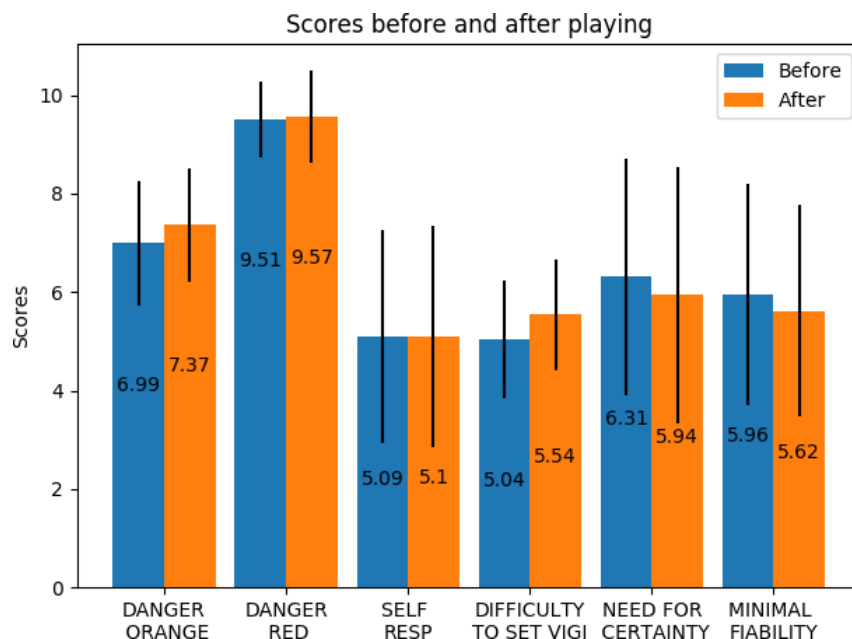


Figure 8. Evolution of awareness scores before/after playing

6.3.2 Impact of 'false alerts' on vigilance

As suggested by (Attansey 2012), vigilance can fade after several occurrences of a same disaster. This is confirmed by our survey. Figure 9 illustrates the dynamics of population vigilance over multiple alerts. It shows that before playing (blue bars) 17.65% of responders report being less vigilant after what they perceive as a “false alert”, while 14.71% report never being vigilant anyway. This is worrying for several reasons. First, “false alarms” can be quite frequent, because it is hard to predict such phenomena, and because the vigilance is set at the entire department level. Therefore, even if a flood does indeed happen locally, it is possible that a large part of the department is spared and left to believe that it was a false alarm. Second, even if it is actually a false alarm and no flood happens this time, intense rain might leave the soils saturated and river levels very high, thus favouring future floods if more rain happens later. As a result, past alerts should increase vigilance rather than decreasing it.

Our main idea was to reduce this loss of vigilance by explaining that vigilance announcements are necessarily probabilistic, and that some errors are unavoidable. Figure 9 indeed shows that after playing (orange bar) there is a significant increase of people stating that they will be “always vigilant” when under orange vigilance even after several 'false alerts' (rising from 58.82% to 67.65%). In contrast, there are less people stating they would be “less vigilant”, “more vigilant”, or “never vigilant” after “false alerts”. This is an important impact of our role-playing experiment, since we have seen that the key issue during the October 2018 floods in Aude was this habituation and loss of vigilance (Le Monde 2018).

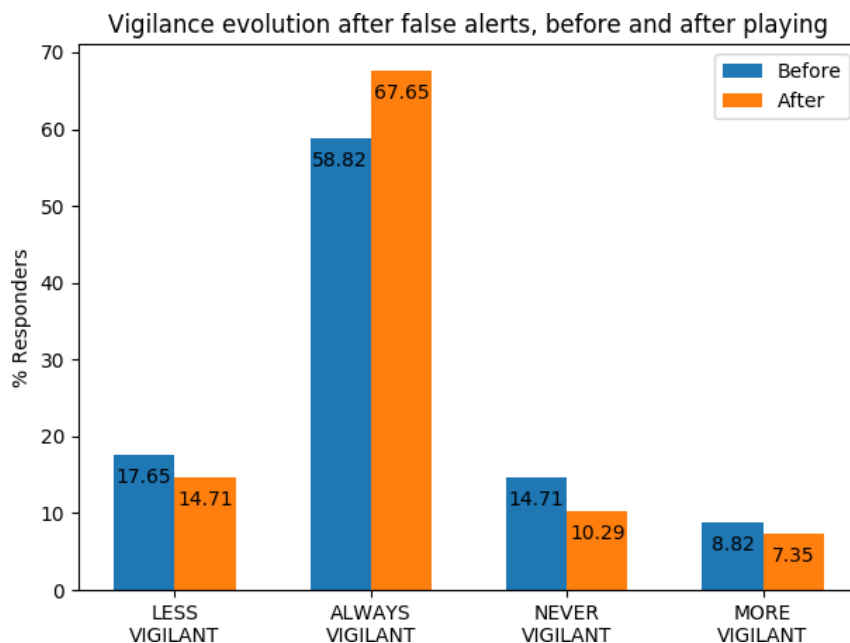


Figure 9. Evolution of loss of vigilance with false alerts, before/after playing

The survey was administered to many people having recently lived the October 2018 floods, which explains why most users in our sample are already very vigilant. Further analysis is required to compare the dynamics of vigilance in responders with or without flood experience. It would also be interesting to compare with people having a less recent flood experience, as the literature reports how humans tend to cyclically forget about risk until a new crisis occurs.

6.3.3 Protective measures taken

Figure 10 illustrates the percentage of responders taking various protective measures, before (questions in phase 2 of the questionnaire) vs after playing (same questions in phase 5 of the questionnaire). The actions mentioned in the survey are: search information (INFORM); share information (SHARE); prepare house; gather with relatives and family (GATHER); park one’s car on higher ground (PROTECT CAR); evacuate; or do nothing special. In the figure, each bar shows in orange the percentage of responders saying they would take this action when an orange vigilance is announced, and in red at the top the additional percentage of responders saying they would take this action only when a red vigilance is announced. The left part (uniform colour) of each bar is before the game, while the right part (starred colour) is after.

The left bar measures the percentage of responders doing “something” at all. We can see that about a quarter of the population would do nothing at all in case of orange vigilance (24% before the game, 22% after); very few would do nothing if there was a red vigilance (8% before the game, 6% after). This high level of behavioural intentions is probably due to our sample comprising more people with flood experience (and therefore more prone to take protective actions) than the general population.

The most frequently intended action is to search for information: 78% will try to get more information in case of an orange vigilance, and an additional 10% (so a total of 88%) in case of a red vigilance. These percentages rise to 82% and 91% after playing the game. We see a similar impact on the actions of sharing information, gathering with family, or evacuating (which is mostly envisaged in case of red vigilance). On the other hand, intentions for preparation actions (preparing house and protecting car) decrease slightly in case of orange vigilance, but increase in case of red vigilance.

This hence shows that changing perspective through the questionnaire has modified the protective intentions of the responders. These are only declared intentions and might be influenced by a willingness to give the “right” or expected answer. But in that case, it shows an improvement after the game of the awareness of actions that should or should not be performed. Declared intentions might also be actual intentions but not lead to actions once under stress in a real flood situation. It is nevertheless encouraging, and such communication should be repeated to further motivate protective behaviours.

6.4 Results: subjective evaluation of the game

The objective evaluation above is encouraging, but to have an impact, such a role-playing experience needs to be actually played by people in flood-prone areas, possibly in a repeated manner. This will require it to be interesting, engaging, motivating. We therefore asked the responders to score VigiFlood (in its simulated version administered via the online questionnaire) on 5 criteria: how **interesting** was it to answer or play; how **boring** is the current gameplay; how **useful** is VigiFlood to learn about floods, forecast and communication; are they willing to see such a game offered as training by the **town council**; are they willing to see such a game integrated in **school programs** about natural hazards.

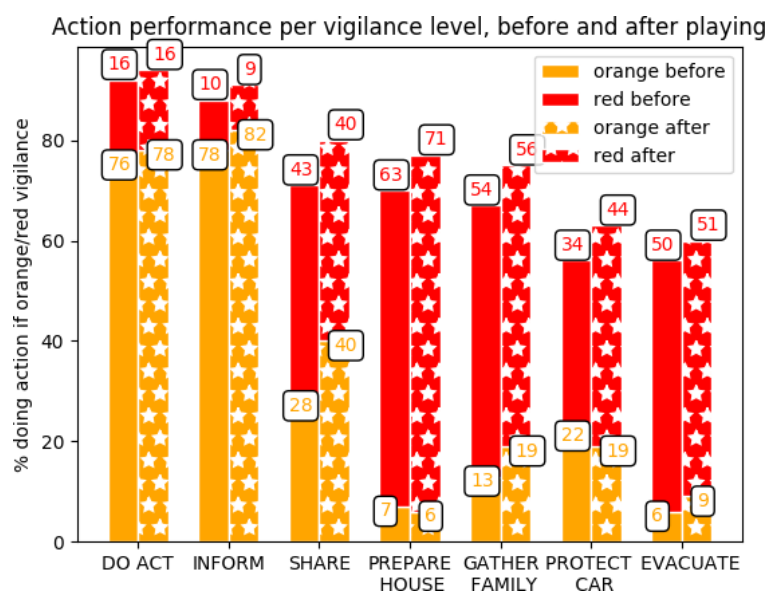


Figure 10. Evolution of actions performed/intended if orange/red vigilance, before/after playing

Figure 11 summarizes the results in the form of a boxplot diagram: the boxes extend from lower to upper quartile values of the scores, with a line at the median; the whiskers extend from the boxes to show the range of the data; outliers are not shown here.

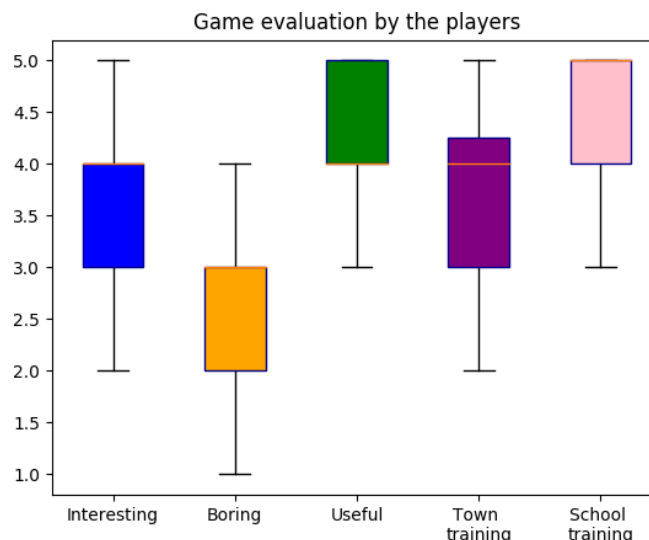


Figure 11: Evaluation of the game (5-point scale scores): interest, boredom, usefulness, willingness to use it for training of town residents (by town council), or for training of school children (by professors).

We can see that responders find the game very useful (avg=4.18; stdev=0.98). They are willing to have it offered by their town council as training (avg=3.79; stdev=1.08), and even more willing to see it offered to children as part of school programs about natural hazards (avg=4.35; stdev=0.84). However, even though they found the concept of the game quite interesting (avg=3.65; stdev=1.04), they also judge the gameplay rather boring (avg=2.51; stdev=0.95). Future work is therefore needed to improve immersion and engagement with the game; this is the current direction of the project. We will also further analyze if these scores are different between people with or without flood experience.

6.5 Conclusion of the evaluation and future work

This survey was intended to show the potential of such a serious game for getting the population of flood-prone areas to change perspective. Since the software is still under development, and to allow for a wider participation in different regions, it was decided to run the survey online via a questionnaire that simulates the intended functioning of the Vigiflood game. This is a first limitation, since we evaluated a slightly different process than that of the actual game. However, we believe that both versions do induce the same change of perspective, which is the key element of our approach.

Besides, we believe it is important to get feedback from target users very early in the development process, in line with a participatory research approach. As such, the subjective evaluation is very important to validate the idea of this game before putting efforts into implementing it completely. The results are encouraging, proving that such a serious game would be welcomed by the population of flood prone areas. They will also orient further developments towards improving the gameplay and immersion in the game.

The survey measured the impact of this role-playing exercise on the users' awareness, vigilance, and protective actions intentions. Our results show a positive impact on these indicators, which is encouraging. Another limitation of this survey comes from our sample of responders. The survey was broadcast through personal networks in the affected areas. Besides, only people who felt concerned with floods and motivated by the topic would take the time to answer the survey, given its repetitiveness and lack of engaging features. We hope that the final software, once we make it less boring and more immersive, will do even better in allowing the users to change perspective and to gain insight about flood risk communication. The gameplay design and implementation is the subject of ongoing work; we then aim to use this serious game with high school students and evaluate its impact.

Further analysis will also be performed on the answers, to categorize the users' risk evaluation strategies (what strategy do they use to choose a vigilance level), or to compare answers of different profiles of responders (with or without flood experience; by age or gender; *etc.*). This should lead to a better understanding of the population's subjective risk analysis and the factors influencing it. Such insight will be important to inform communication strategies of emergency managers. We are working with Météo France towards this goal.

This is in line with (Yamori 2012) who found that participative approaches promoted the population's engagement and responsibility, compared to vertical knowledge-passing approaches. The difference is that they designed a card game while we implemented a computer game; further research would be needed to compare engagement of the different formats, maybe depending on the target users. Our target being students, the engaging potential of digital games has already been proven (Bottino, Ott, and Tavella 2014).

7. CONCLUSION AND PROSPECTS

In this paper we presented Vigiflood, a serious game for raising awareness about the challenges of flood risk communication. It relies on an agent-based model of the population's trust and decisions, itself grounded in psychology and sociology of human behaviour. A first prototype of the game is implemented and functional. It lets the player choose the flood vigilance colour (green, yellow, orange, red) based on the weather forecast (generated from real meteorological data extracted from archives for the target area). It is therefore a role-playing game where the users (residents in flood prone areas) take on a different role in the game (that of weather forecasters) than in real life. The main idea behind this game design is that the change of perspective induced by playing a different role will lead to a better

understanding of the difficulties of this role, specifically here the challenges of announcing the “right” level of vigilance.

The main contribution of this paper is the evaluation of the concept of the game. We ran an online survey replicating the role-playing part of the game, preceded and followed by questions evaluating the user’s awareness of risks, understanding of difficulties, vigilance, and behavioural intentions in case of flood risk. This evaluation shows encouraging results, where the change of perspective does induce better awareness of risks, more protective actions intentions, and better vigilance and trust in the forecast. However, only very motivated users would answer the survey or play with the prototype, due to its boring and repetitive design. More work is needed to improve the game design and playability to make it more engaging (Brandtzaeg, Folstad, and Heim 2006), and allow it to be played by the general public and in particular by high school students. This is essential to guarantee that this serious game has an actual beneficial impact during future flood events. We are working with high school teachers to use our serious games in their courses about natural hazards.

The underlying population model can also be turned into an interactive simulator to train weather forecasters to apply crisis communication principles, and to take the subjective reactions of the population into account when announcing a forecast. This alternative version of Vigiflood is also under work in collaboration with Meteo France and the national school of meteorology. At a time when more and more floods are expected to happen in some parts of the world (Roudier *et al.* 2016; Kerr 2007; Schiermeier 2011), we believe that agent-based simulation can provide very useful tools to train and educate both the population and the deciders in order to reduce impact of these floods.

ACKNOWLEDGEMENTS

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Annex1: list of questions (translated from French)

- Phase 1: experience, awareness and trust
 1. Have you experienced floods before?
 2. Did these floods affect your residence?
 3. Were these floods announced in advance?
 4. Did these floods require your evacuation?
 5. Do you know about Meteo France vigilance system?
 6. Do you know about Vigicrues monitoring website?
 7. Do you trust these meteorological forecasts in case of floods?
 8. Do you trust the local authorities to warn and protect you in case of floods?

- Phase 2: awareness of risk, challenges, and self-responsibility; intended actions (BEFORE)
 9. Who do you think is responsible for your information and protection in case of floods?
 10. How easy/hard do you think it is to announce the right level of vigilance?
 11. What information do you think the authorities rely on to set the vigilance level?
 12. How important is it to be certain of a forecast before announcing a vigilance level to the population?
 13. What is the minimal reliability required before announcing a level of vigilance?
 14. In your opinion, what level of danger does an orange flood vigilance indicate?
 15. In your opinion, what level of danger does a red flood vigilance indicate?
 16. In case of orange/red flood vigilance, what do you do? (check all actions among: search information, share information, prepare house, gather with relatives, park car higher, evacuate, nothing special)
 17. During the last 2 orange vigilances, there were no flood in the end. What is your reaction to the next orange vigilance? (trust it anyway, distrust it anyway, trust it more, trust it less)

- Phase 3: change of perspective, setting vigilance in different situations:

18. Series of questions of the form: the weather forecast services announce XXX mm of rain with a confidence index of XXX %. Which vigilance colour do you wish to announce?
 19. Series of similar questions with additional contextual elements
 20. Series of similar questions with additional information about previous false alarms and population trust
- Phase 4: evaluating the game (rate on a 5-point scale):
 21. Such a game would be interesting to play
 22. Such a game would be boring and repetitive
 23. Such a game would be useful to learn and understand the vigilance system
 24. You would like your town council to offer such a game as part of its flood risk prevention plan
 25. You would like schools to offer such a game to children as part of their program about natural hazards
 - Phase 5: re-assessing awareness and intentions (AFTER):
 26. Same questions as in phase 2
 27. Have you discovered new criteria for the definition of the flood vigilance level that you had not considered before? If yes, which ones?
 28. Free comments
 - Phase 6: demographic questions: region of residence, age, gender, job (if related with weather forecast or depending on weather conditions)



Original paper

Towards Optimal Architectures for Hazard Monitoring Based on Sensor Networks and Crowdsensing

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Abstract The monitoring of hazards through the ability to detect events and predict spatial and temporal evolution of dynamical hazards still remains a big challenge for dynamic disaster risk assessment and mitigation. The goal of this paper is to show how well established methods arising from the control theory can positively contribute to dynamic risk assessment improvement through an effective hazard monitoring. More precisely, the objective is threefold. Firstly, the design of an optimal monitoring architecture is proposed based on the combination of optimal sensor placement and receding horizon observer design. In this paper, the focus is only made on model-based and data-driven approaches. The benefit of using sensor networks and crowdsensing techniques is also discussed. Secondly, the paper seeks to identify the application areas that can benefit from both optimal sensor location techniques and receding horizon observers, while reviewing already existing references. Thirdly, some personal contributions illustrating the proposed approach are presented. In particular, two case studies are presented: one considers the dynamic positioning of drones for monitoring air pollution, the other is dedicated to the early detection of a wildfire outbreak.

Key words: Natural and technological hazard monitoring, optimal sensor location, receding horizon observer.

1. INTRODUCTION

The early detection and the ability to predict spatial and temporal evolution of natural or technological hazards still remain a big challenge for disaster risk assessment and mitigation

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[Zio (2018)]. Designing effective monitoring architectures for that purpose is of great concern for natural hazards such as landslides, earthquakes, flooding, wildfires, air pollution, for critical infrastructures [Alonso *et al* (2018)], such as power, gas, water, oil, traffic and transportation networks, for engineered structures of bridges, buildings and other related infrastructures submitted to various stresses (earthquakes, structural ageing, attacks), or for pandemic detection and prediction. Another big challenge in risk assessment is to be able to predict cascading effects when, for instance, a natural hazard triggers a technological disaster. The current covid-19 crisis shows that it is more necessary than ever to have numerical tools to predict the evolution of a crisis so as to be able to anticipate decision-making.

Nowadays the development of the Internet of Things increases the availability of various sources of spatio-temporal data, thanks to the design of more and more autonomous and miniaturized systems capable of self-powering and communicating, and increasingly dense and high-speed communications networks (see the current deployment of 5G technology). This allows the deployment of wireless sensor networks which are made up of embedded and spatially distributed sensors with communication capabilities. The development of unmanned aircraft systems (UAS) allows the sensor networks to become mobile and reconfigurable. In the same way, static or moving individuals carrying or using smartphones can be viewed as parts of a static or mobile wireless sensor network. The involvement of a large number of individuals which collectively share data and extract information is called crowdsensing [Capponi *et al* (2019)], [Zhang *et al* (2019)]. Some successful applications of crowdsensing or crowdsourcing based on social media data are now available: For instance, in the domain of seismic risk reduction and awareness [Bossu *et al* (2018)] with LastQuake app, and with the tuning of influenza spreading models using tweeter data [Levy *et al* (2018)] or, more recently, the development and use of mobile applications for the mapping of persons infected by the COVID-19.

In this paper, a model-based framework arising from control theory to design a monitoring architecture based on wireless sensor networks and crowdsensing for dynamical monitoring is discussed. The central idea is to design a digital architecture which is optimal in the sense that it ensures the best possible use of data provided by sensors in order to provide the most accurate online information about a dynamical hazard evolving in both space and time.

In this paper, a mathematical model of the phenomenon generating hazards is assumed to be available together with a set of static or mobile sensors providing on-line measurements. The proposed approach relies on two key components:

- (1) Firstly, the optimal placement of sensors that can be either static [Georges (1995)], [Wouwer *et al* (2000)], [Ucinski (2005)], [Lou *et al* (2003)], [Kang *et al* (2011)], [Mallardo (2013)], [Spinelli *et al* (2017)], [Tang *et al* (2017)], or mobile [Demetriou (2008)], [Georges (2013a)], to ensure the best possible observation of the hazard to be monitored. In this paper, the problem of optimal sensor location is addressed using the so-called observability theory [Besançon (2007)]. It consists in maximizing a measure of the observability of some partial differential equations governing the spatial and temporal dynamics of physical hazards. Observability is the structural property of a

system that makes it possible to estimate the current system state using only the information from outputs (measurements provided by sensors).

- (2) Secondly, the design and use of an observer that is an algorithm used to process the distributed data delivered via sensor or crowd networking, whose goal is to detect unexpected events or to estimate or predict the spatial and temporal dynamics of the hazard. In this paper, the focus is made on the on-line model-based receding or moving horizon estimation algorithm [Michalska *et al* (1995)], [Muske *et al* (1995)], that can be viewed as the deterministic implementation of a nonlinear Bayesian filter allowing more flexibility (for instance to take constraints into account). It belongs to the class of model-based and data-driven state estimators such as Kalman filtering, extended Kalman filtering, unscented Kalman filtering, particle filtering, (see [Rawlings *et al* (2006)] for Kalman filter related approaches, and [Besançon (2007)] for other nonlinear state observer design).

The paper is organized as follows. In section 2, some background is provided on the central notion of dynamical system observability and a review of criteria providing a measure of observability is proposed. The formulation and solution of some optimal sensor location problems are discussed and a review of existing applications is provided. In section 3, the notions of both sensor networks and crowdsensing are presented and a discussion is provided on how to use these techniques for hazard monitoring. Section 4 is devoted to receding horizon observer design. Both the formulation and solution of the related optimization problem are also discussed. In section 5, an optimal architecture design based on the combination of both optimal sensor location and receding horizon observer techniques is presented. Section 6 considers two case studies -the dynamic positioning of drones for monitoring air pollution, and the early detection of a wildfire outbreak- to illustrate the proposed framework. Finally, the last section sums up the conclusions and perspectives.

2. OBSERVABILITY, OPTIMAL PLACEMENT OF SENSORS OR HOW TO INCREASE MONITORING CAPABILITIES

Monitoring of spatio-temporal dynamical systems consists in processing various data collected through time and space to estimate the past and current parameters or states of the system. Based on the estimation of future events or inputs affecting the system, monitoring may also allow the prediction of the spatio-temporal dynamics of the system. Monitoring of large-scale dynamical systems is a big challenge for risk management and safety since it provides a way to isolate or estimate system vulnerabilities or the occurrence and evolution of a (natural or man-made) hazard. In this paper, we will focus on model-based approaches, i.e., approaches requiring the a priori knowledge of the mathematical representation of the system dynamics. In system control theory and physics, modelling is based on state-space representation (those properties have been studied by Kalman for linear systems, see [Ogata (2010)] for an introduction to linear control theory) or partial differential equations (PDEs) for spacetime distributed systems. Most of the applications are governed by PDEs and complex

networks that require high level of computational complexity. However in many cases PDEs or networks can be well approximated using finite-dimensional state-space representations via model reduction techniques.

The major property required for the successful monitoring of a dynamical system is *Observability*, i.e. basically *the ability to recover the initial state of the system through the knowledge of some output measurements (obtained from sensors) collected over a time interval*.

Mathematically, Observability is defined as *the injectivity of the operator initial state to output, that can be also reformulated as the preservation of initial state distinctness or the nonzero output sensitivity to initial state (see [Besançon (2007)] for more details)*.

$$y_1(t, x_1(t_0)) = y_2(t, x_2(t_0)), \in [t_0, t_0 + T] \Rightarrow x_1(t_0) = x_2(t_0) \quad (1)$$

In the case of parameters estimation, there is a related notion: *The Identifiability of parameters θ* :

$$y_1(t, \theta_1) = y_2(t, \theta_2) \Rightarrow \theta_1 = \theta_2. \quad (2)$$

This fundamental property opens the way to the development of algorithms for reconstructing the initial state of a system from measurements obtained over a time interval.

2.1 Measuring the degree of observability

The effective model-based monitoring requires optimal configuration of a limited number of sensors to ensure the best possible state/parameter estimation. *The Optimal Placement of Sensors* will here consist in seeking an optimal configuration of a fixed number of sensors in order to maximize a measure of Observability/Identifiability.

Gramian-based measures of Linear System Observability

Consider the class of linear finite-dimensional systems defined by the following linear state-space representation :

$$\begin{aligned} \dot{x}(t) &= Ax(t), x \in \mathbb{R}^N, x(0) = x_0, \\ y(t) &= Cx(t), y \in \mathbb{R}^P \end{aligned} \quad (3)$$

where x is the state, y is the output vector corresponding to measurements obtained by sensors.

If the measurement vector $y(t)$ is known over time interval $[0, T]$, the so-called *Output Energy generated by any initial state x_0* is given by

$$E_0 = \int_0^T y^T(t)y(t)dt = x_0^T \left\{ \int_0^T e^{A^T t} C^T C e^{At} dt \right\} x_0 \quad (4)$$

since $y(t)=Ce^{At} x_0$. nonnegative-definite symmetric matrix $W(T)=\int_0^T e^{A^T t} C^T C e^{At} dt$, called *the Observability Gramian*, can be isolated (see also for instance [Kailath (1980)]).

$W(T) = W^T(T) \geq 0$ can be obtained as solution of the following differential Lyapunov equation:

$$\dot{W}(t) = A^T W(t) + W(t)A + C^T C, W(0) = 0. \quad (5)$$

This approach was extended to the case of algebraic-differential (singular) systems in [Marx *et al* (2004)].

It appears that $W(T)$ is a measure of the sensitivity of output y with respect to initial state x_0 (which can be interpreted as a Fisher Information Matrix (FIM) (see [Ucinski (2005)], and [Song *et al* (2009)] for interpretation of FIM): Indeed, the sensitivity of state $x(t)$ with respect to x_0 is given by

$$\frac{d}{dt} (\partial_{x_0} x(t)) = A \partial_{x_0} x(t), \partial_{x_0} x(0) = I_d \quad (6)$$

$$\partial_{x_0} y(t) = C \partial_{x_0} x(t) \Rightarrow \partial_{x_0} y(t) = C e^{At} \quad (7)$$

Then

$$\int_0^T \partial_{x_0} y^T(t) \partial_{x_0} y(t) dt = \int_0^T e^{A^T t} C^T C e^{At} dt = W(T), \quad (8)$$

where $\partial_{x_0} x(t)$ denotes the Jacobian matrix of partial derivatives $\frac{\partial x_i}{\partial x_{0j}}$.

The observability gramian is therefore a mathematical way to characterize the sensitivity of the system outputs to any initial state x_0 , allowing the development of a methodology to optimally locate sensors. Another interesting feature is that the notion of observability gramians can be extended to the case of nonlinear systems.

Extension of observability gramians to Nonlinear Systems

Consider systems described by the following nonlinear state-space representation

$$\begin{aligned} \dot{x} &= F(x,t,\theta), x \in \mathbb{R}^N, x(0) = x_0, \\ y &= H(x,t), y \in \mathbb{R}^P, \end{aligned} \quad (9)$$

where x denotes the state vector, y , the output vector, and θ , the vector of model parameters, and F is supposed to continuously differentiable.

Again the application of the sensitivity analysis is possible, which leads to the following sensitivity equations:

$$\frac{d}{dt} (\partial_{x_0} x) = \partial_x F(x,t,\theta) \partial_{x_0} x, \partial_{x_0} x(0) = I_d, \quad (10)$$

$$\partial_{x_0} y = \partial_x H(x,t) \partial_{x_0} x; \dot{x} F = (x, t) \quad (11)$$

Formally the nonlinear Observability Gramian can be defined by:

$$w(x_0, T) = \int_0^T \partial_{x_0} y^T(t) \partial_{x_0} y(t) dt. \quad (12)$$

It is worth noticing that the linear observability gramian defined by (8) appears to be a special case of this general formalism. However, the gramian depends on initial state x_0 in the nonlinear case.

It is also worth mentioning that a similar approach can be used to study parameter identifiability by introducing the sensitivity of the state with respect to the vector of system parameters θ :

$$\frac{d}{dt}(\partial_{\theta x}) = \partial_x F(x, t, \theta) \partial_{\theta} x + \partial_{\theta} F(x, t, \theta), \partial_{\theta} x(0) = 0, \quad (13)$$

$$\partial_{\theta} y = \partial_x H(x, t) \partial_{\theta} x; \dot{x} = F(x, t, \theta). \quad (14)$$

Then *the nonlinear Identifiability Gramian* can be defined by:

$$W(\theta, T) = \int_0^T \partial_{\theta} y^T(t) \partial_{\theta} y(t) dt. \quad (15)$$

In practice, the computation of sensitivity equations (10)-(11) or (13)-(14) can be highly complex, especially for systems with a large number of states or parameters. Indeed, a N -dimensional system with M parameters to identify (or N initial states to estimate), requires the integration of a sensitivity system in a space of dimension $N \times M$ (or N^2). To overcome this drawback, empirical computation of the observability gramian has been proposed that requires only simple simulations of the system.

Empirical observability gramian [Lall *et al* (1999)]

The empirical gramian is obtained by applying some small perturbations to each component of the initial state and performing time integrations to get the output trajectory corresponding to each perturbed initial state. For (nonlinear) dynamical systems, the empirical observability gramian can be defined as

$$W = \sum_{l=1}^r \sum_{m=1}^s \frac{1}{rsc_m^2} \int_0^T T_l \Psi^{ilm}(t) T_l^T dt$$

where $\Psi^{ilm}(t) \in \mathbb{R}^{N \times N}$ is given by $\Psi_{ij}^{ilm}(t) = (y^{ilm}(t) - y^{ilm,0})^T (y^{ilm}(t) - y^{ilm,0})$, and y^{ilm} is the output obtained with perturbed initial condition $c_m T_l e_i + x_0$, and $y^{ilm,0}$ refers to the output obtained with unperturbed initial state x_0 ; T_l is a perturbation direction, and e_i is a standard unit vector in \mathbb{R}^N . For more details, the reader is invited to refer to [Lall *et al* (1999)].

Some other approaches for the characterization of system observability

The observability gramian-based approach is not the only way quantify observability. Other observability indices may be derived by using the injectivity property (an observability inequality) that can be reformulated as follows:

The system $\dot{x} = F(x, t)$, $y = H(x, t)$ is observable in time T if there exists $C > 0$ such that

$$C \|x_1(0) - x_2(0)\|^2 \leq \int_0^T \|y(t, x_1(0)) - y(t, x_2(0))\|^2 dt \quad (16)$$

for any pair of initial state $(x_1(0), x_2(0))$ in the estimation space (included in the state space). Here $y(t, x(0))$ denotes the system output generated by initial state $x(0)$.

A similar observability inequality can be formulated when dealing with partial differential equations (see for instance Privat *et al.* (2014)).

The authors in King *et al.* (2014) proposes to exploit this definition by defining an unobservability index as follows:

$$\varepsilon^2 = \min_{\delta x_0} \delta X_0^T P_1 \delta X_0 + \int_0^T \|y(t, X_0 + \delta X_0) - y(t, X_0)\|_{P_2}^2 dt \quad (17)$$

s. t. $\|\delta X_0\| = \rho$, $\delta X_0 \in W$

where W is the estimation space, and P_1 and P_2 are weighting matrices. The ratio $\frac{\rho}{\varepsilon(\mu)}$ denotes the unobservability index. A good observability is obtained when the ratio is minimal, i.e, when ε is maximal.

One can also directly work on the performance of state observers or data assimilation problems by considering the state estimation error, for instance, using the Kalman filter (see [Tang *et al.* (2017)] for a description of this approach in the infinite dimensional framework), based on the covariance matrix P of the observation error defined by

$$trace[P] = trace[E\{(x - \hat{x})(x - \hat{x})^T\}], \quad (18)$$

where P is the nonnegative-definite symmetric matrix, solution of Kalman filter stationary Riccati equation

$$AP + PA^T - PC^T R^{-1} CP + Q = 0. \quad (19)$$

One of the three metrics (20), (21), or (22) can be used with covariance matrix P to measure the degree of observability.

A similar approach based on a norm of the state estimation error, is used for instance in Demetriou (2008) for the location of a mobile sensor and in Lou *et al.* (2003) for the optimal sensor location of a system governed by a nonlinear partial differential equation. For data assimilation problems, a similar approach is also proposed in Herzog *et al.* (2017).

For Riesz-spectral linear partial differential equations or finite-dimensional systems, eigenvalue/eigenfunction decomposition allows to use the modal components of the measurement/output operator to measure the degree of observability (see section 6.1.2). This kind of approach is used in structural health monitoring (see [Mallardo (2013)] that also provides an extensive review of optimal sensor locations techniques.

Frequency-based approaches have been also proposed (see [Demetriou *et al* (2014)]) that exploit the spatial H_2 norm of the transfert function of a 1D diffusion-advection partial differential equation. The spatial H_2 norm can be used as a measure of sensor sensitivity over the spatial domain.

The question is now to examine how observability gramians / FIM or other approaches can be used to design an appropriate observability metric, usable as a cost function for solving an optimal sensor location problem.

2.2 Observability gramian-based cost functions for optimal sensor placement

Three classical metrics based on the spectral analysis of observability gramian / FIM $W(T, \mu)$, where μ is a given sensor configuration corresponding to specific choices of state measurements or physical locations of the sensors are here recalled (see also [Herzog *et al* (2017)]):

$$c(\mu) = \text{trace}(W(T, \mu)) = \sum_{i=1}^N \lambda_i(\mu), \quad (20)$$

$$c(\mu) = (\log) \det(W(T, \mu)) = (\log) \prod_{i=1}^N \lambda_i(\mu), \quad (21)$$

$$c(\mu) = \underline{\lambda}(W(T, \mu)) = \min_{i=1, \dots, N} \lambda_i(\mu), \quad (22)$$

where the λ_i 's, $i = 1, \dots, N$, denote the eigenvalues of symmetric (N, N) -matrix $W(T, \mu)$.

The trace of the observability gramian (20) does not guarantee full observability, since some eigenvalues of W can be equal to zero. These null eigenvalues correspond to non observable state components. However, for exponentially stable systems, at least detectability (a weak form of observability where at least one stable state component is non observable) is ensured, meaning that asymptotic observers (such as Kalman filters) will converge. This metric only tends to improve observability of the dominant modes of the system. If metric (20) is used as a cost function to be maximized, an optimal sensor configuration achieves the maximum observability in average. In contrast, strictly positive values of metrics (21) and (22) guarantee that all the state components are observable.

2.3 Other cost functions for optimal sensor placement

ε^2 given by (17) can be used as a cost function $c(\mu)$, solution of a minimization problem, if one considers parametrization of the measurement operator C in function of sensor location μ :

$$c(\mu) = \varepsilon^2(\mu) = \min_{\delta X_0} \delta X_0^T P_1 \delta X_0 + \int_0^T \|y(t, X_0 + \delta X_0, \mu) - y(t, X_0, \mu)\|_{P_2}^2 dt \quad (23)$$

$s. t. \|\delta X_0\| = \rho, \delta X_0 \in W$

Notice that the use of the cost function will lead to the solution of max-min optimization problem.

In the same way, (18) defines a cost function $c(\mu)$, whose computation is obtained by solving the following algebraic equation parametrized in μ :

$$AP(\mu) + P(\mu)A^T - P(\mu)C^T(\mu)R^{-1}C(\mu)P(\mu) + Q = 0. \quad (24)$$

For data assimilation problems, a similar approach is also proposed in [Herzog *et al* (2017)].

2.4 Formulation of an optimal sensor location problem OSPP

It is now possible to define a generic Optimal Sensor Placement Problem OSPP which consists in maximizing one of the presented observability metrics:

$$\max_{\mu \in \mathcal{D}_\mu} c(\mu), \quad (25)$$

where \mathcal{D}_μ defines a set of constraints such as density constraints, communication range constraints, placement constraints. OSPP is usually a non convex optimization problem. Also notice that index (22) is not differentiable, leading to additional complexity that can be overcome by using subgradient optimization techniques [Bertsekas (2015)], [Karmitsa (2016)].

Solving OSPP can be a complex task especially for large-scale systems and in the case of sensors configurations constrained to belong to a set of discrete values (defining an integer programming problem). This is for instance the case when the OSSP consists in determining the location of a set of sensors. A big issue is the so-called curse of dimensionality since OSPP usually relies on exponential N^2 -complexity computations where N is the dimension of the system state space. In order to limit this complexity, model-reduction techniques have been proposed for large-scale systems (especially systems governed by partial differential equations), see for example, [Antoulas *et al.* (2006)] for large-scale finite-dimensional systems or [Benner *et al* (2017)] for systems governed by partial differential equations. Furthermore, a mixed integer programming OSPP has to deal with combinatorial explosion. The interested reader is invited to refer to appropriate references such as [Burer *et al* (2012)] which discuss the algorithmic techniques available to overcome the limitations due to combinatorial complexity.

In many situations, it is important to adapt the locations of the sensors, especially when the dynamics of the monitored phenomenon is time-varying (for instance, air pollution or wildfires with changing meteorological conditions). The OSPP for M mobile sensors can be formulated as an optimal control problem, where the dynamics of the mobile sensors can be also taken into account together with energy consumption:

$$\min_{u_i(t)} \sum_{i=1}^M \int_0^T \underbrace{[z_i^T(t)Qz_i(t) + u_i^T(t)Ru_i(t)]}_{\text{energy consumption}} dt - \underbrace{c(\mu_1(T), \dots, \mu_M(T))}_{\text{observability index}} \quad (26)$$

subject to

$$\dot{z}_i(t) = G_i(z_i(t), u_i(t)), i = 1, \dots, M, \quad (27)$$

$$\alpha \leq d_{ij}(t) \leq \beta, i = 1, \dots, M - 1, j = i + 1, \dots, M, \quad (28)$$

where $z_i = (\mu_i(t), \dot{\mu}_i(t))^T$ denotes the position and velocity of sensor i at time t . $u_i(t)$ is the navigation control input of sensor i . Q and R are weighting matrices. $d_{ij} = \|\mu_i(t) - \mu_j(t)\|_2$ is the euclidian distance between sensor i and sensor j . (27) represents the state-space equations of the dynamics of sensor i . Inequality constraints (28) are introduced for mutual collision avoidance purpose and mutual communications.

Provided that cost function c is differentiable, a less demanding navigation approach is the kinematic approach (i.e., without introducing the sensor dynamics, see for instance [Georges (2013a)]) may consist in using a gradient-based method of the form:

$$\dot{\mu}_i(t) = \rho [\nabla_{\mu_i} c(\mu_1(t), \dots, \mu_M(t)) + \delta \sum_{j=1, j \neq i}^M \left\{ \frac{(\mu_i(t) - \mu_j(t))}{d_{ij}^2(t) - \alpha^2} - \frac{(\mu_i(t) - \mu_j(t))}{\beta^2 - d_{ij}^2} \right\}], \rho, \delta > 0. \quad (29)$$

The trajectory of each sensor i follows the direction imposed by the gradient of $c(\mu_1(t), \dots, \mu_M(t)) + \delta \sum_{i=1}^{M-1} \sum_{j=i+1}^M \{\log(d_{ij}^2 - \alpha^2) + \log(\beta^2 - d_{ij}^2)\}$ with respect to μ_i , where $\sum_{i=1}^{M-1} \sum_{j=i+1}^M \{\log$

$(d_{ij}^2 - \alpha^2) + \log(\beta^2 - d_{ij}^2)\}$ are the sum of barrier functions (that can be viewed as repulsive potentials) introduced to avoid mutual collisions and ensure maximal interdistance. ρ controls the velocity and δ is a weighting coefficient used to adjust the importance of mutual avoidance constraints.

In fact, (29) can be viewed as a gradient method used for solving the maximization problem

$$\max_{\mu_1, \dots, \mu_M} c(\mu_1, \dots, \mu_M) + \delta \sum_{i=1}^{M-1} \sum_{j=i+1}^M \{\log(d_{ij}^2 - \alpha^2) + \log(\beta^2 - d_{ij}^2)\} \quad (30)$$

In [Demetriou (2010)], an approach based on Lyapunov stability arguments is proposed to control collocated actuator-sensor mobile networks for improving control and estimation of systems governed by diffusion partial differential equations.

2.5 Some existing OSPP applications

Table 1 provides some already implemented examples of (OSSP) for hazard monitoring.

Table 1. Applications of OSPP for Hazard Monitoring.

Hazard	Sensors	Some References
Weather	Meteorological stations, satellites, crowdsensing	[Demetriou <i>et al</i> (2014)]
Overland or urban flooding	Water level or flow rate sensors	[King <i>et al</i> (2014)], [Nguyen <i>et al</i> (2016)], [Ogie <i>et al</i> (2017)], [Park <i>et al</i> (2017)]
Landslides, avalanches, lava flows, mudflows	LIDAR, satellite, stress sensors, crowdsensing	[Terzis <i>et al</i> (2006)], [Thuro <i>et al</i> (2017)]
Pollution	Pollutant sensors, crowdsensing	[Georges (2011)], [Georges (2013a)], [Georges (2013b)], [Boubrima <i>et al</i> (2015)], [Kouichi <i>et al</i> (2016)], [Georges (2017)]
Epidemics and pandemics (including rumor propagation)	Crowdsensing, hospitals and medical centers	[Spinelli <i>et al</i> (2017)]
Critical infrastructures (water, gas, oil, energy, traffic flow networks), industrial facilities or processes, buildings ...	Physical sensors depending on the infrastructure, crowdsensing	[Nguyen <i>et al</i> (2008)], [Mallardo (2013)], [Georges (2014)], [Qi <i>et al</i> (2014)], [Casillas <i>et al</i> (2015)], [Herzog <i>et al</i> (2017)], [Khorshidi <i>et al</i> (2018)], [Summers <i>et al</i> (2014)], [Zan <i>et al</i> (2018)]

3. SENSOR NETWORKS AND CROWDSENSING

A Wireless Sensor Network (WSN) is a set of embedded sensors, spatially disseminated, able to use wireless communications with each other and to send data to a sink station (see Fig. 1). The WSNs are used to collect physical data, such as temperature, sound, pollution concentrations, humidity, wind velocities, and so on. The WSNs offer several interesting features, such as flexibility (no expensive infrastructure is required) and measurement redundancy offering more robustness to node failures. However they are often subject to power consumption constraints, except if they are equipped with energy harvesting devices. For a recent survey, see [Mostafaeia *et al* (2018)].

Some WSNs can be mobile. However, in this case, the management is much more complex since the sensors have to be coordinated in order to ensure connectivity and the energy

management of the sensors is also more demanding. Navigation approaches (26) or (29) are some examples of techniques that can be used to coordinate mobile sensor networks.

Crowdsensing is a technique where a group of individuals uses mobile or static devices capable of sensing and providing qualitative or quantitative data (see Fig 2 and [Capponi *et al* (2019)]). Today most smartphones are equipped with sensors such as cameras, microphones, GPS and accelerometers, temperature sensors, which can be used to provide quantitative data, for example to detect or locate earthquakes or to monitor traffic congestion in real time.

Crowdsensing can be classified into two classes: the opportunistic crowdsensing, where the data is collected without user intervention via specialized samrtphone applications, and the participatory crowdsensing, where many users voluntarily provide information through social networks or specialized applications. Both approaches can give access in addition to a huge number of qualitative data, which can be very relevant to reinforce physical knowledge in vulnerability or hazards after adequate processing. Or course, crowdsensing (even in the participatory case) is less suitable for the implementation of observability maximisation techniques such as (25), as it can be difficult or even dangerous to ask a large number of people to position themselves in order to increase the observability of a natural hazard (such as a flood or a forest fire). However, this defect can be compensated by the fact that the number of sensors is potentially higher and the coverage is therefore potentially wider.

Advances in Artificial Intelligence offer highly effective machine learning techniques for extracting quantitative data from qualitative data (for the goal of pattern recognition and classification for instance) (see [Zhang *et al* (2019)] for a recent survey).

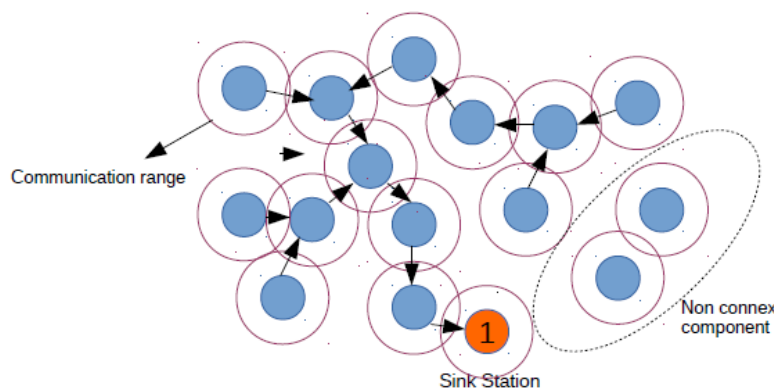


Figure 1. WSN structure - each node in blue is a wireless sensor. Some unconnected part of the WSN may exist. The communication range is limited and here depicted by a circle.

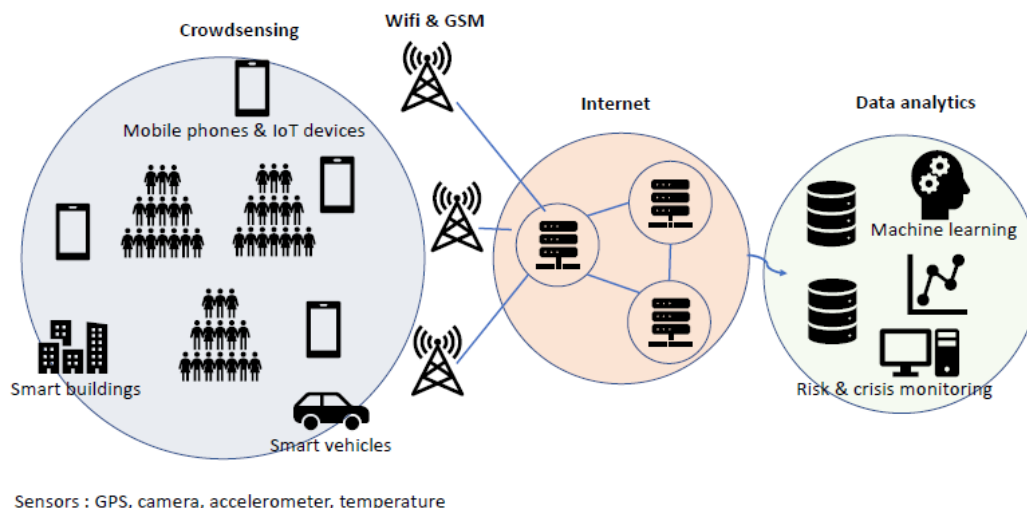


Figure 2. Crowdsensing (see also Alsheikh (2017)).

Participatory crowdsensing can be very useful in providing information about hazard magnitude and location during an extreme weather event, flooding, earthquakes, or epidemics for example. A description of the process with illustrative examples is given by Fig. 3. The learning process relies on the availability of data sets obtained from past events or simulations. The data sets are used to learn a regression/classification model that will provide an estimate of the magnitude of an event occurring at a given time instant together with a degree of confidence. The processed data (estimated value + degree of confidence) then can be used for model-based monitoring as depicted in the section here-after.

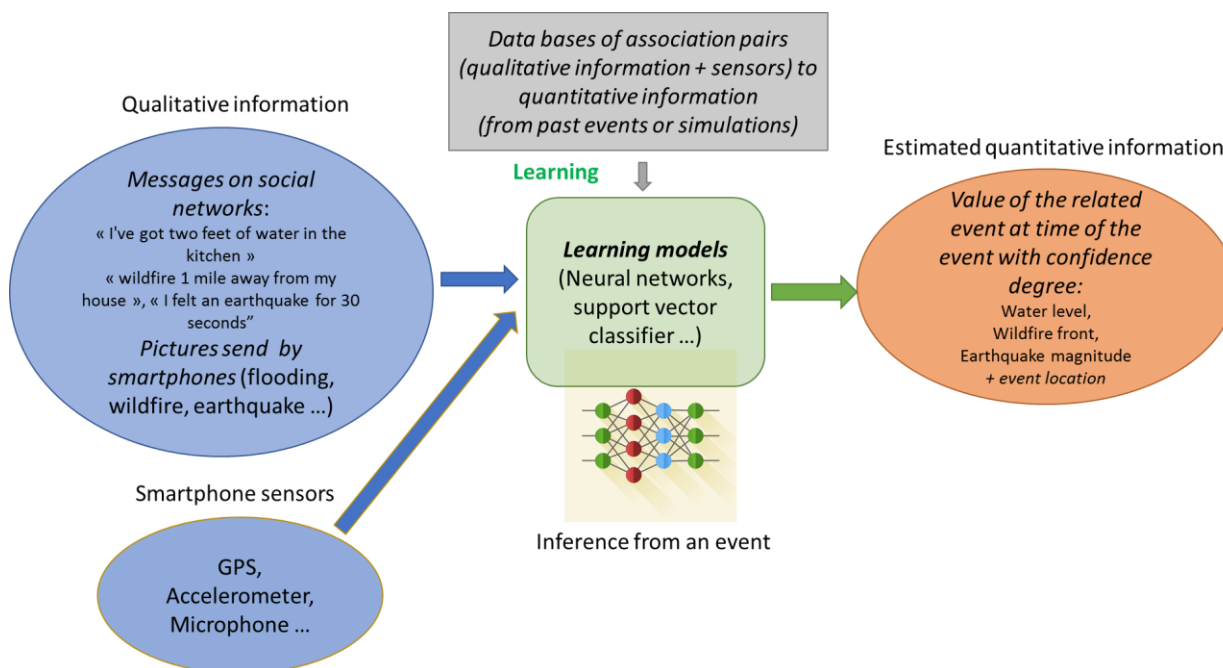


Figure 3. From qualitative to quantitative data through machine learning.

4. RECEDING HORIZON OBSERVERS FOR DYNAMIC HAZARD ASSESSMENT AND REAL-TIME MONITORING: AN OPTIMIZATION APPROACH

In this section, some background is provided on Receding or Moving Horizon Observer design. The main goal is to show how this approach can be useful to ensure real-time monitoring of an evolving hazard or to estimate vulnerability.

Hazard monitoring must be here understood as the online process described by Fig. 4 that consists in processing data provided by a large number of sensors on a time period $[t_k - T, t_k]$, called receding or moving horizon, at each sampling time denoted as $t_k = kT_s$, where T_s is the sampling period, in order to get estimate of both system state at $t_k - T$ and unknown system parameters. It is worth noticing that *this approach does not necessarily require a large and dense coverage with sensors to get relevant spatio-temporal information, thanks to the observability property.*

In this paper, one considers that the phenomenon to be monitored is described by the following nonlinear state-space representation

$$\begin{aligned} \dot{z}(t) &= F(z(t), u(t), \theta), z(t) \in \mathbb{R}^n, z(0) = z_0, u \in \mathbb{R}^m \\ y(t) &= H(z(t), t), y(t) \in \mathbb{R}^p, \end{aligned} \quad (31)$$

where $z(t)$ denotes the state vector, u is the vector of known exogenous inputs, y is the vector of measured outputs provided by the sensors, and θ is the vector of unknown parameters.

If the phenomenon is governed by partial differential equations, spatial discretization on a grid or model reduction techniques have to be performed in order to get form (31). In the case of systems governed by partial differential equations (PDEs), such as floods governed by the shallow water equations, pollution governed by several diffusion-advection-reaction PDEs or earthquake dynamics governed by 3D elastic wave equations for instance, the dimension of the state space can be very large. A big challenge in current research is to develop effective low-dimensional model reduction techniques (see [Benner *et al* (2017)] for a review of techniques as Proper Orthogonal Decomposition (POD), balanced truncation, tensor-based approaches).

The measurements are assumed to be obtained from physical sensors or from qualitative information provided by individuals via the social media (through crowdsensing), with a certain degree of confidence (see Fig. 3). θ can represent either physical parameters (such physical diffusion or source location) or information on particular dysfonctionning or failures in the case of critical infrastructures. The reader is invited to refer to Table 3 for concrete examples of what are state variables and parameters for various hazards.

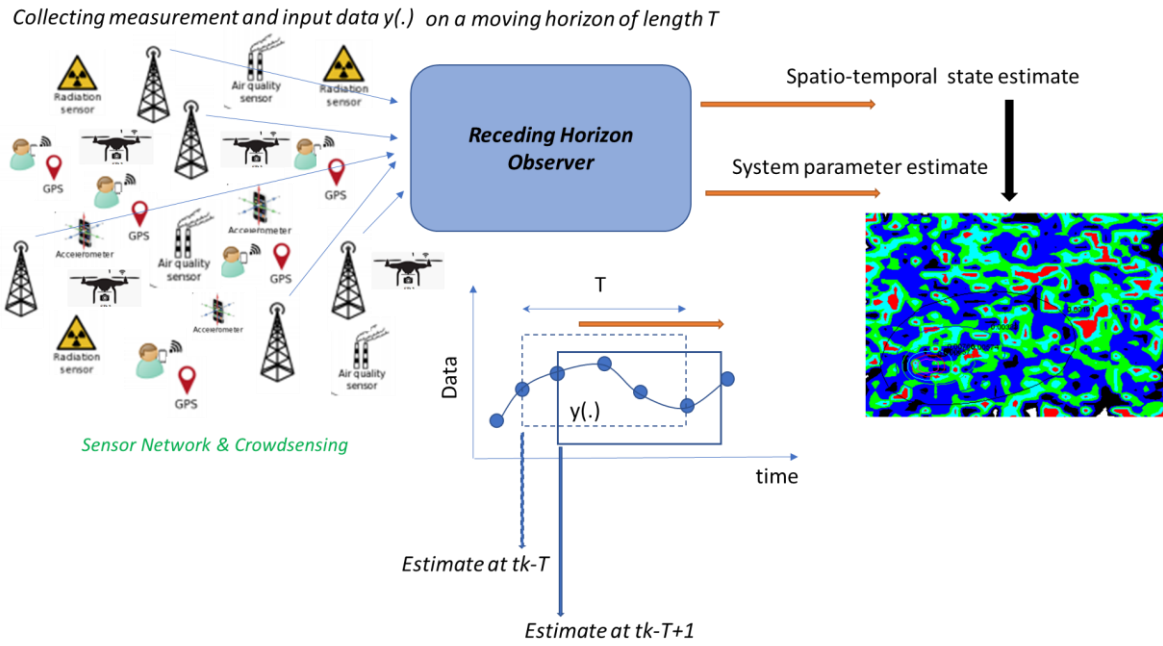


Figure 4. Principle of RHO with sensor network and crowdsensing.

4.1 The receding or moving horizon observer formulation

The following notation will be used in what follows to denote the forward solution of (31) at time τ , starting from state z at time t :

$$Z(\tau, z, u(\cdot), \theta), \tau \geq t. \quad (32)$$

State and/or Parameter Receding or Moving Horizon Observers RHO (see [Michalska *et al* (1995)], [Muske *et al* (1995)], [Kuhl *et al* (2011)], [Rangegowda *et al* (2018)]) provide an estimate of both x and θ of the true x and θ by minimizing the output prediction error in the least-square sense over a past receding horizon defined by horizon T , at each time t_k :

$$\{\hat{z}(t_k - T), \hat{\theta}_k\} = \arg \min_{z \in \mathcal{Z}(t), \theta \in \Theta} \int_{t_k - T}^{t_k} \|y(\tau) - H(Z(\tau, z, u(\cdot), \theta), \tau)\|_{R^{-1}}^2 d\tau + \|z - \bar{z}\|_{M_1^{-1}}^2 + \|\theta - \bar{\theta}\|_{M_2^{-1}}^2, \quad (33)$$

where $y(t)$ denotes the measured data at time t , weighting matrix R can be interpreted as the covariance matrix of a noise vector affecting the output measurement. H denotes the measurement operator. R^{-1} can also be used to reflect the degree of confidence in the measurements (particularly useful for data obtained from crowdsensing). R^{-1} can also depend on time to introduce some forgetting factor with respect to past measurements. M_1 and M_2 can be viewed as regularization matrices or the covariance matrices of uncertain variables z and θ . $\mathcal{Z}(t)$ is the set of admissible values of the state at time τ (often the set is used to impose the state remains positive, for instance, in the case of physical densities). Θ is the set of admissible values of the parameters. \bar{z} and $\bar{\theta}$ are guess values of initial state $z(t_k - T)$ and θ respectively, for instance estimated values obtained from the algorithm at previous sample time $t_k - T - 1$.

It is worth mentioning that (33) provides in fact an estimate of state z at time $t \in [t_k - T, t_k + 1]$, since it suffices to integrate (31) from estimate state $\hat{z}(t_k - T)$, knowing $u(\cdot)$ and the estimate of θ .

4.2 Relevance of the RHO approach

The main value of RHO lies in the fact that each new sample of the sensor measurements are used to provide an update of the state estimate thanks to the online solving of (33).

Measurement reliability is a big concern especially when low cost sensors are used in sensor networks, since indeed they can be prone to failure or lack of precision. The interest of using model-based estimation/filtering whose effectiveness relies on the fundamental property of observability, is the fact that estimation algorithms, such as the receding horizon which is based on optimal filtering, are able to provide estimates of the distributed states based on a limited number of well-placed sensor measurements which can be subject to measurements noise. Thus the covariance matrix of the measurement noise is explicitly taken into account in the minimized cost function (see eqn (33)), where R denotes the covariance matrix of noises affecting the sensors).

This approach also provides a lot of flexibility allowing inclusion of heterogeneous, sporadic or asynchronous data produced by static or mobile sensors, especially in the context of crowdsensing. In this case, the number of sensors can actually vary considerably over time. Think about the increasing number of posts in social media observed during a disaster. Furthermore, taking measurements delays due to limited transmission rates in some sensor network configurations, is important if the monitored dynamics has "small time constants" with respect to the measurement delays. The development of 5G technologies will soon make the problem of delayed data obsolete due to the gain in transmission rates (x10 compared to 4G). However, it is worth mentioning that there exist well-established results on the estimation of systems time-delayed measurements and data loss [Johansen *et al* (2013)]. Formulation (33) can be modified to include delayed data. However the computation of the optimization is more tricky. Finally, extension of the RHO have been proposed to hybrid dynamical systems [Ferrari *et al* (2003)]. A hybrid system is a dynamical system that exhibits both continuous and discrete dynamic behavior, i.e. a system that combines both differential equations and discrete event automats. The class of hybrid systems has to be considered with attention when dealing with cascading hazards such as natural hazards triggering technological disasters (Natech risks). It is worth noticing that such flexibility cannot be obtained using the Kalman filtering approach -and its variants- that cannot include constraints in particular in the estimation process.

It can be shown that the existence of a solution to (33) relies on both the state observability and parameter identifiability properties of system (31). Improving observability/identifiability by solving an OSPP (25) will increase the sensitivity of output measurements $y(\tau)$, $\tau \in [t_k - T, t_k]$ to state $z(t_k)$ which generated them. It can be shown that such sensitivity computations are involved in solving (33), for instance through the computation of an adjoint model.

Solving optimal problem (33) usually requires the computation of a large scale optimization problem in particular when dealing with discretized PDEs with a large number of state variables. Again the use of model reduction techniques is a key factor for reducing computational complexity. In addition, efficient solvers have been developed over the last decades to solve large-scale constrained optimization problems, such as solvers based on sequential quadratic programming techniques associated to quasi-Newton methods [Gould *et al* (2005)] or Limited Memory Bundle Methods for solving large-scale nonsmooth optimization problems [Karmitsa (2016)].

Due to its ability to cope with constraints and its intrinsic flexibility in the formulation, some particular formulations of RHO can be viewed as the generalization of Kalman filter that hold only for linear unconstrained systems subject to Gaussian noises. (see [Alamir (2007)]) .

4.3 Review of some existing or potential RHO applications

RHO implementations are still limited in environmental applications, despite the flexibility of the approach. However, many data assimilation techniques and Kalman filter variants have been developed in the literature, that are not reviewed here. However successful implementations of RHO are available in the literature related to the monitoring of industrial processes or facilities, that are listed here.

Table 2 provides some potential applications of RHO techniques for hazard monitoring.

5. OPTIMAL MONITORING ARCHITECTURE

In this section, the overall optimal architecture proposed in the paper is described and formalized.

Some additional notations are introduced.

The measurement operator related to static sensors and the locations of the static sensors are denoted as $y_s(t) = C_s(\mu_s)z(t)$, $y_s \in \mathbb{R}^{N_s}$ and μ_s respectively, where N_s is the number of static sensors.

- The measurement operator related to controlled mobile sensors, such as UAVs, and the time-varying locations of these mobile sensors are denoted as $y_m(t) = C_m(\mu_m(t)) z(t)$, $y_s \in \mathbb{R}^{N_m}$ and $\mu_m(t)$, respectively, where N_m is the number of mobile sensors.
- The measurement operator related to crowd sensors (individuals carrying smartphones), and the time-varying locations of these crowd sensors are denoted as $y_c(t) = C_c(\mu_c(t)) z(t)$, $y_c \in \mathbb{R}^{N_c}$ and $\mu_c(t)$, respectively, where N_c is the number of crowd sensors.

Table 2. Potential or Existing Applications of RHO

Hazard	States	Parameters	Sensors	References
Weather	temperature, wind velocities, pressure fields ...	extreme events	meteorological stations, satellites, crowdsensing	
Overland or urban flooding	water levels, flow velocity in time and space	friction coefficient, location of dyke failures	water level or flow rate sensors	[Pham <i>et al</i> (2013)]
Landslides, avalanches, lava flows, mudflows	flow thickness , flow velocity, in time and space	friction and stress coefficients	LIDAR, satellite, stress sensors, crowdsensing	
Earthquakes	displacement and stress tensor, in time and space	Lamé elastic constants, density of the elastic medium, seismic source location	seismometers, crowdsensing	
Wildfire	Temperature, fuel consumption in time and space	diffusion and reaction coefficients, ignition location	infra-red sensors, crowdsensing, satellite	See section 6.2
Pollution	pollutant concentration in time and space	diffusion and reaction coefficients, pollutant source location	pollutant sensors, crowdsensing	
Epidemics and pandemics	susceptible, infected, recovered individual density in time and space	disease diffusion, infection, recovery rate coefficients	crowdsensing, hospitals and medical centers	
Ecology (Predator/Prey models)	predators and prey density in time and space	diffusion and rate of increase and competition coefficients	biological field stations	
Critical infrastructures (water, gas, oil, energy, traffic flow networks), industrial facilities or processes, buildings ...	flows and physical potentials	fault detection and isolation	physical sensors depending on the infrastructure, crowdsensing	[Alamir <i>et al</i> (2003)], [Mohd Ali <i>et al</i> (2015)], [Range Gowda <i>et al</i> (2018)]

When one considers systems governed by PDEs, the individual measurement operator C_i^j , $i = s, m, c$, for any sensor j is defined as follows:

$$C_i^j(\mu_i^j z(t)) = \int_{\Omega_i} \Delta(\zeta, \mu_i^j) z(\zeta, t) d\zeta, \quad (34)$$

where $\Delta(\zeta, \mu_i^j)$ is the characteristic of a spatially averaged measurement around location μ_i^j

on domain Ω_i . Δ is often chosen as
$$\begin{cases} 1, & \text{if } \zeta \in [\mu_i - \varepsilon, \mu_i + \varepsilon], \\ 0, & \text{otherwise} \end{cases}$$

The way of deriving the optimal location of sensors depends on the nature of the sensors:

- For static sensor units, the OSPP is solved once and for all.
- For controlled mobile sensing units, an adaptive OSPP is implemented where the observability index is updated at each sample time t_k using both state $\hat{z}(t_k-T-1)$ and exogeneous inputs on horizon $(t_k-T-1, t_k-1]$ -for instance, weather forecasting information: wind velocity, temperature, pressure- or control inputs performed on the system -for instance, actions of fire fighting units in the case of wildfires- and estimated parameters provided by the RHO, and the sensor trajectories are updated accordingly.
- For crowdsensing units, usually the OSPP does not make sense since the individuals freely evolve on the field. However if parts of the individuals (in the context of participatory crowdsensing) accept to follow some prescribed trajectories in order to position themselves in order to maximize observability, they are assumed to belong to the category of controlled mobile sensors defined just before.

Based on (25), (29), (33), additional notations and previous assumptions, the overall iterative monitoring architecture can be formulated as follows:

Offline static OSP:

$$\max_{\mu_s \in D_{\mu_s}} c_s(\mu_s), \tag{35}$$

Mobile OSPP³ updated at each t_k , starting from $\mu_m^i(t_k - 1)$:

$$\begin{aligned} \dot{\mu}_m^i(t) &= \rho[\nabla_{\mu_m^i} c_m(\mu_m^1(t), \dots, \mu_m^M(t), \hat{\theta}_{k-1}, \hat{z}(t_k - T - 1), u([t_k - T - 1, t_k - 1])) + \delta \sum_{j=1, j \neq i}^M \frac{(\mu_m^i(t) - \mu_m^j(t))}{d_{ij}^2(\mu_m^i(t), \mu_m^j(t)) - \alpha^2}], \\ &\Rightarrow \mu_m^i(t_k), i = 1, \dots, N_m, \end{aligned} \tag{36}$$

Processing of crowd data $y_c([t_k - T, t_k])$ (37)

RHO with data assimilation with sensor measurements $y_i([t_k - T, t_k])$, $i = s, m, c$:

$$\begin{aligned} \min_{z \in \mathcal{Z}(t), \theta \in \Theta} & \int_{t_k-T}^{t_k} \left[\sum_{i=1}^{N_s} \frac{1}{r_s^i} \|y_s^i(\tau) - C_s^i(\mu_s^i(\tau))Z(\tau, z, u(\cdot), \theta)\|^2 + \sum_{i=1}^{N_m} \frac{1}{r_m^i} \|y_m^i(\tau) - C_m^i(\mu_m^i(\tau))Z(\tau, z, u(\cdot), \theta)\|^2 \right. \\ & \left. + \sum_{i=1}^{N_c} \frac{1}{r_c^i} \|y_c^i(\tau) - C_c^i(\mu_c^i(\tau))Z(\tau, z, u(\cdot), \theta)\|^2 \right] dt + \|z - \hat{z}(t_k - 1)\|_{M_1^{-1}}^2 + \|\theta - \hat{\theta}_{k-1}\|_{M_2^{-1}}^2, \tag{38} \\ & \Rightarrow \hat{z}([t_k - T, t_k]), \hat{\theta}_k \end{aligned}$$

³ Here, constraints $d_{ij}(t) \leq \beta$ are omitted.

Repeat the above steps for all t_k , using

$$\mu_m([t_k - T, t_k]), \mu_c([t_k - T, t_k]), \gamma_s([t_k - T, t_k]), \gamma_m([t_k - T, t_k]), \gamma_c([t_k - T, t_k]) \quad (39)$$

where the $1/r_i^j$, $i = s, m, c$ denote the degree of confidence in the sensor i j measurement or the quantitative data provided by crowdsensing.

Finally, Fig. 5 depicts the overall proposed scheme.

6. TWO ILLUSTRATIVE CASE STUDIES

The goal of this section is to illustrate how OSSP techniques (25), (29) and RHO approach (33) described in the previous sections, can be applied to realistic hazard monitoring problems.

The section is now dedicated to two main topics:

- (1) The management of both static and mobile sensor networks in the context of air pollution monitoring.
- (2) The early detection of fire ignition and the prediction of the spreading of wildfires based on a receding using low-cost temperature sensors deployed on the field. To the best of my knowledge, such a RHO has never been proposed before.

6.1 Optimal management and deployment of static or mobile Sensor networks for air pollution monitoring

This section sums up some contributions in ([Georges (2011)], [Georges (2013a)], and [Georges (2017)]) and presents the following results:

- The management of a WSN with static sensor nodes including lifespan concern;
- The illustration of navigation strategy (29) with a number of UAVs reaching 100 units;
- A modal observability metric not proposed in my previous publications.

Air pollution spreading is classically modeled by 2D or 3D advection-diffusion partial differential equations (ADPDE) (see [Zannetti (1990)] for example). For the sake of simplification, only a 2D problem is discussed here.

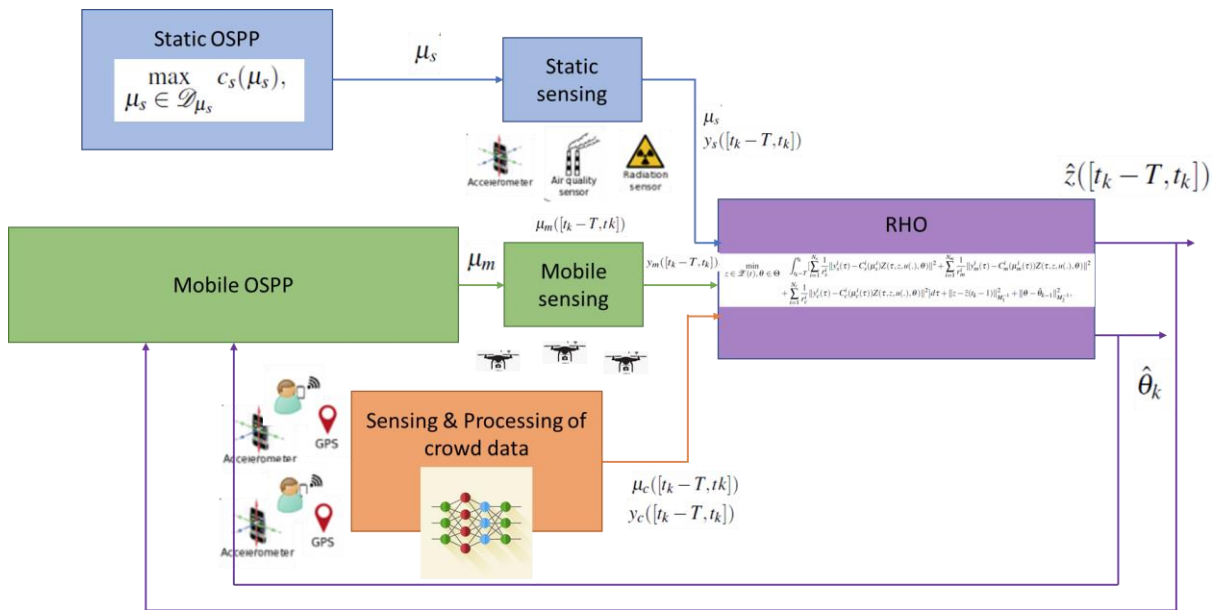


Figure 5. Optimal Monitoring Architecture.

$$\frac{\partial z}{\partial t}(x, t) + U(x, t) \cdot \nabla z(x, t) = k\Delta z(x, t) + D(x, t)S(t) - rz(x, y, t) \quad (40)$$

where $z(x, t)$ is the concentration of a chemical species, $U = (U_x, U_y)$ is the vector of wind velocities, k is the diffusion coefficient, r is the reaction coefficient, $S(t)$ represents the source of pollution assumed to be known, $D(x, t)$ represents how the source of pollutant $S(t)$ acts in a domain $\Omega = [0, L] \times [0, H]$, where L and H are the limits of the $2D$ domain. ∇ is the gradient operator, while Δ is the Laplacian operator.

Some initial conditions $z(x, y, t = 0) = z_0(x, y)$ and boundary conditions are needed for the well-posedness of the problem, for instance, Dirichlet boundary conditions:

$$z(x, y, t) = z_{bc}(x, y, t), \forall (x, y) \in \partial\Omega \quad (41)$$

In what follows, the source is supposed to be constant with a gaussian distribution located at (x_s, y_s) .

Three methods will be considered in the following sections to deal with a finite-dimensional system of form (31):

- A time-explicit finite-difference approximation [Georges (2011)];
- A spectral Galerkin methods [Georges (2013a)] using Legendre's orthogonal polynomials;
- A modal approximation based on the solution of the eigenvalue problem of the advection-diffusion equation (40) ([Georges (2017)]. More focus on this approach will be made in section 6.1.2.

6.1.1 Managing the trade-off between observability and energy consumption in static Wireless Sensor Networks

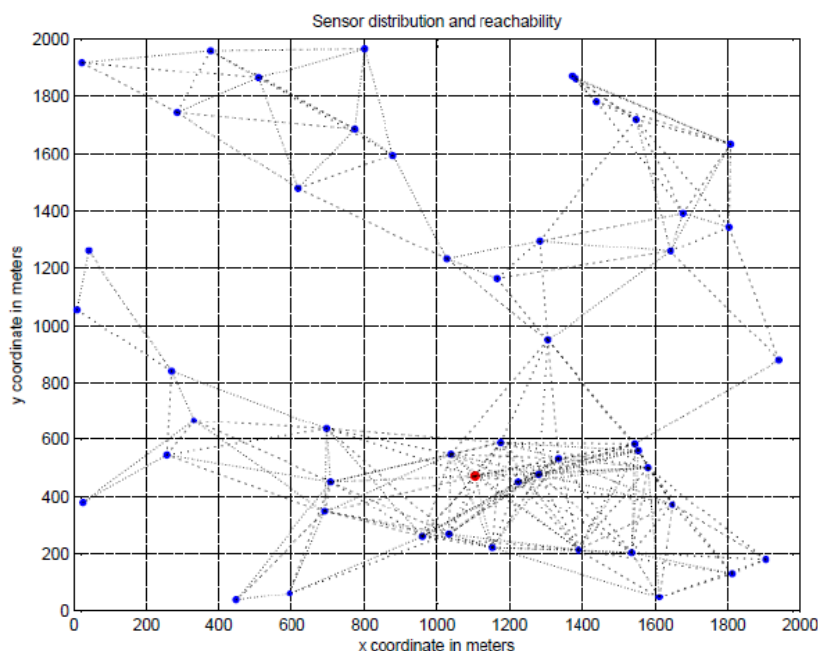


Figure 6. Static network of 50 randomly-distributed sensors with 296 communication links, on a monitored square domain of 2km side.

The dotted lines feature the existence of an effective communication link between two sensors (mutual reachability). The red dot is the sink station.

In [Georges (2011)], the problem of energy management in a static WSN, ensuring the best possible observability of air pollution, while maximizing the lifespan, was studied. This section sums up the contribution and the main results obtained. It can be regarded as a special case of OSPP (25) where constraints on energy and communications were taken into account.

The sensors were assumed to operate with limited energy harvesting and storage capabilities. The chosen observability metric was the trace of the observability gramian (20).

Two objectives were assigned:

- The first objective consisted in maximizing the observability index.
- The second objective was to maximize the lifespan of the network by minimizing the energy consumed by the sensors (due to communication and data processing).

It is worth noticing that these objectives are antagonistic and there is a trade-off to find, since observability is better if many sensors are active, but the price to pay is a greater energy consumption of the sensors.

The sensors were assumed to be equipped with a battery and a photovoltaic panel.

This problem was formulated in [Georges (2011)] as a two-objective optimization problem using a receding horizon optimization problem constrained by the topology of available communication links which depends on both the initial configuration of the network and the individual state of the sensors (the fact to be active in sensing or not).

The network structure is described in Fig. 6.

The incidence matrix M_I of the communication network is assumed to be known. It is derived from the connectivity matrix of the network, that depends on the interdistance d_{ij} between any sensor nodes i and j . If δ is the M_c vector of the δ^{ij} 's, where δ^{ij} denotes the average number of packets routed from the node i to the node j and $M_c = \sum_{ij} \beta_{ij} = \sum_{i=1}^M \text{card}(C_i)$, where for each

node i , C_i denotes the set of the nodes connected to i : $C_i = \{j, j = 1, \dots, M, j \neq i / \beta_{ij} = 1\}$, we get the following model of communications links:

$$M_I \delta + d\alpha - Hd_0 = 0_{M_c \times 1}, \quad (42)$$

where d is the maximum number of packets transmitted by any sensor node (routing information and measurement packets), d is supposed to be fixed. $H = (1, \dots, 0)^T$, and d_0 is the maximum number of packets received by the base station. Since all the packets are supposed to converge towards the base station, $d_0 = \sum_{i=1}^M d\alpha^i$.

Decision variable $\alpha^i \in [0, 1]$ was introduced to reflect the activity ratio of node i (when $\alpha_i = 1$, node i is fully active, while when $\alpha_i = 0$ it is in standby).

The amount of energy needed to send a packet of the measurement data, status and routing data between the node i and the node j is assumed to be available on request of the base station, and is given by a coefficient $k_{ij}^s > 0$. k_{ij}^s depends on the distance d_{ij} between node i and node j , since the emission power needed to send packets to node j increased as a function of the distance d_{ij} . On the other hand, the amount of energy needed to receive a packet from the node j is given by a coefficient $k_{ij}^r > 0$. The a model of energy consumption at each node i , $i = 1, \dots, M$ is given by:

$$\dot{e}^i(t) = -k_{ii} \alpha^i(t) - \sum_{j \in C_i} [k_{ij}^s \delta^{ij}(t) + k_{ij}^r \delta^{ji}(t)] + E^i(t) - p^i(t) \quad (43)$$

$$\underline{e}^i \leq e^i(t) \leq \bar{e}^i, \quad (44)$$

$$p^i(t) \geq 0, \quad (45)$$

where $e^i(t)$ is the available energy of node i at time t , e_i^i is the initial available energy stored in the node battery, and $E^i(t)$ is the energy provided by the solar cell of the sensor i at time t . The coefficient k_{ii} correspond to the energy consumed by the node i when it collects and computes

its own air pollution measurement. \underline{e}^i and \bar{e}^i are the discharge and full battery bounds, respectively. $p^i(t)$ is a energy "spill" variable to take into account the full battery state.

The OSSP may be now formulated as a two-goal receding horizon control problem as follows⁴

$$\min_{\delta(t_k), \alpha(t_k), d^L(t_k), p(t_k)} \int_{t_k}^{t_k+T} \left\{ \sum_{i=1}^M (k_{ii} \alpha^i(t) + \sum_{j \in C_i} [k_{ij}^s(d_{ij}) \delta^{ij}(t) + k_{ij}^r \delta^{ji}(t)]) + K_p \sum_{j=1}^M (p_j^j + d_j^L) - \sigma \text{trace}(W(t_k, T_0, \alpha(t))) \right\} \quad (46)$$

subject to constraints

$$M_l M \delta(t) + d \alpha(t) - H \sum_{i=1}^M d \alpha^i(t) - d^L(t) = 0_{M_c \times 1}, \quad (47)$$

$$\dot{e}^i(t) = -k_{ii} \alpha^i(t) - \sum_{j \in C_i} [k_{ij}^s \delta^{ij}(t) + k_{ij}^r \delta^{ji}(t)] + \hat{E}^i(t) - p^i(t) \quad (48)$$

$$e_0^i = e^i, \quad (49)$$

$$\underline{e}^i \leq e^i(t) \leq \bar{e}^i, \quad (50)$$

$$0 \leq \delta^{ij}(t) \leq \bar{\delta}^{ij}(d_{ij}), 0 \leq \alpha^i(t) \leq 1, d^L(t) \geq 0, p^i(t) \geq 0, \quad (51)$$

where $\sigma > 0$ is the "preference or arbitrage coefficient", and $K_p > 0$ is a large enough penalty coefficient, $W(t_k, T_0, \alpha(t))$ is the observability gramian of the discretized ADPDE obtained by finite-differences, computed on the time interval $[t_k - T_0, t_k]$, $\hat{E}^i(t)$ is a prediction (except at current time t) of the amount of energy provided by the solar cell (depending on both night or day time and weather conditions). $e^i(t)$ is the amount of energy stored in the battery, available for the node i at t . $\bar{\delta}^{ij}(d_{ij})$ is the maximum number of packets sent by the node i to the node j at every sampling time (a data flow rate limit), which will depends on the inverse of the distance d_{ij} since the transmission rate is affected by the quality of the wireless link. $d^L(t)$ is the M vector of packet losses at each node. Packet losses may occur, when some links are congested due to data flow rate limits.

Based on the parameters of the ADPDE, the 50-sensor network, and the optimization given in [Georges (2011)], Fig. 7a and Fig. 7b provide a comparison of the results obtained with two different values of preference coefficient σ , 2 and 0.1. The trade-off is in favour of the observability maximization when the value of σ is large (see the left column results compared to the right column results with the smaller value of σ). All the results are expressed in normalized units. The different figures show the evolution on 24 hours of the observability index, the evolution of the energy stored in each sensor, and the communication traffic in each active links of the sensor network. Not surprisingly, the observability index reaches its maximum value when a maximum of energy is available in the sensor batteries as expected. For $\sigma = 2$, the observability index value appears to be 5 times greater than when using $\sigma = 0.1$. Of course, the price to pay is a higher energy consumption of the sensors.

⁴ In the referenced paper, the formulation was originally made in discrete-time.

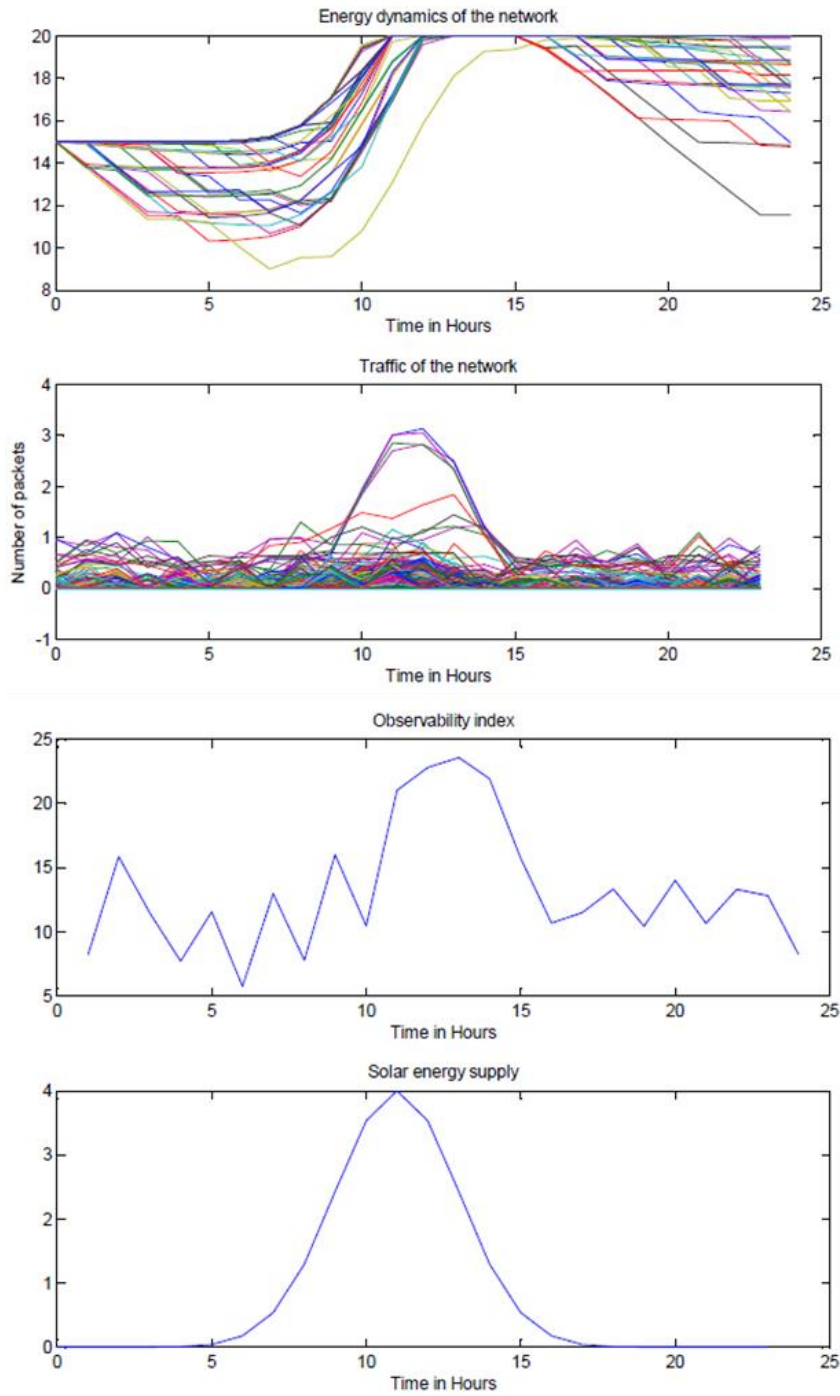


Figure 7a. Results obtained with $\sigma = 2.$,

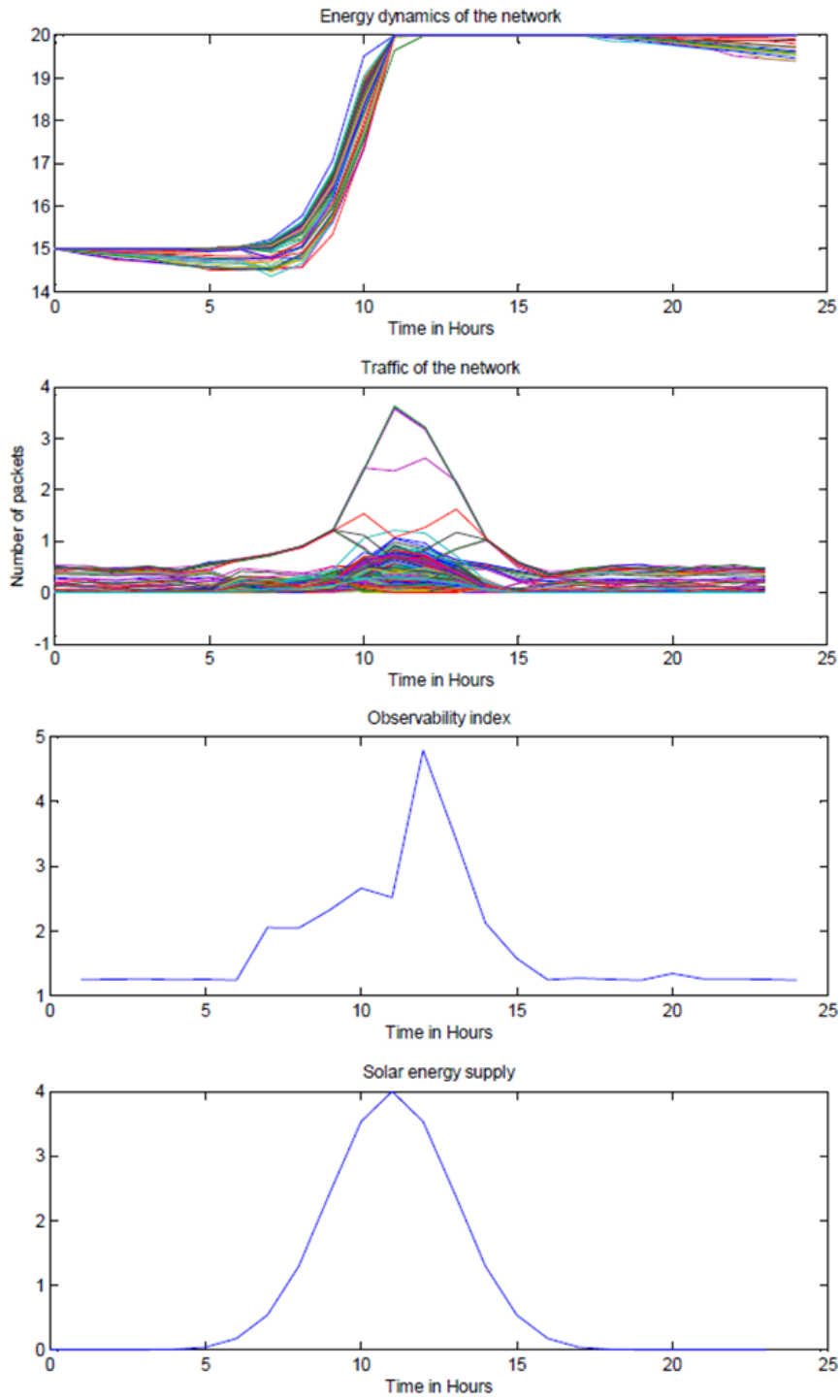


Figure 7b. Results obtained with $\sigma = 0.1$.

6.1.2 Management of mobile sensors for air pollution monitoring

This section sums up the contribution in [Georges (2013a)], where the goal was to manage mobile sensors to ensure the best possible observability of air pollution when the meteorological conditions (essentially, the wind velocity field) vary. A group of mobile sensors (UAVs) was coordinated to adapt their positioning in order to always maximize the trace of the observability gramian, while maintaining wireless communication through the group, together with mutual obstacle avoidance.

20 mobile sensors follow navigation strategy (29) that consisted in maximizing the trace of the observability gramian (20) of a reduced model of ADPDE obtained with a spectral Galerkin method using 20 Legendre’s orthogonal polynomials. The individual trajectory of each sensor towards an optimal sensor configuration was constrained to guarantee mutual collision avoidance and to maintain the communication connectivity with all the other members of the group.

Table 3 shows the parameters retained for the case study presented here-after.

Table 3. ADPDE parameters

U_x	U_y	diffusion k	B.C.	$D(x, t)$
10km/h	10km/h	1	$\mathcal{Z}_{bc}(x, t) = 0$	$e^{-\frac{\ x - x_s\ ^2}{2\sigma^2}}, \sigma = 0.01$

The source of pollutant was assumed to be defined by a Gaussian distribution, where x_s is the source location here situated at the center of the square domain.

Fig. 8 and 9 show the trajectories of the 50 sensors to reach optimal location maximizing the observability index. The sensors start from a random initial position. On Fig. 9, the wind velocity has changed (from (10km/h, 10km/h) to (−10km/h, 5km/h)) and the sensors automatically reposition themselves to maximize the observability index corresponding to this new situation.

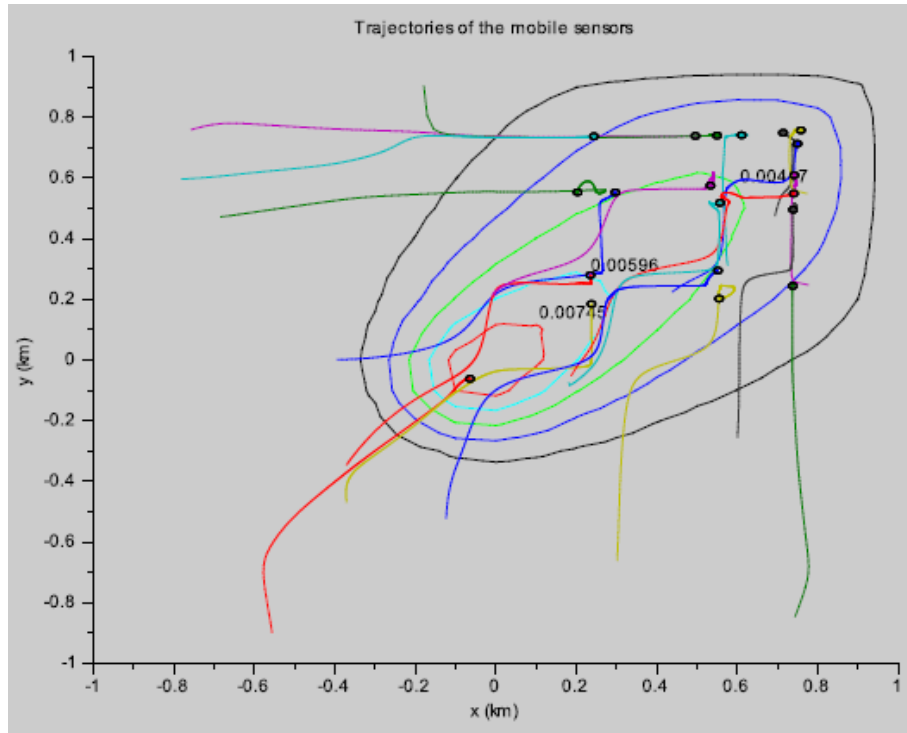


Figure 8. The "o"s feature the optimal location of the sensors. The coloured curves represent levels with identical pollutant densities.

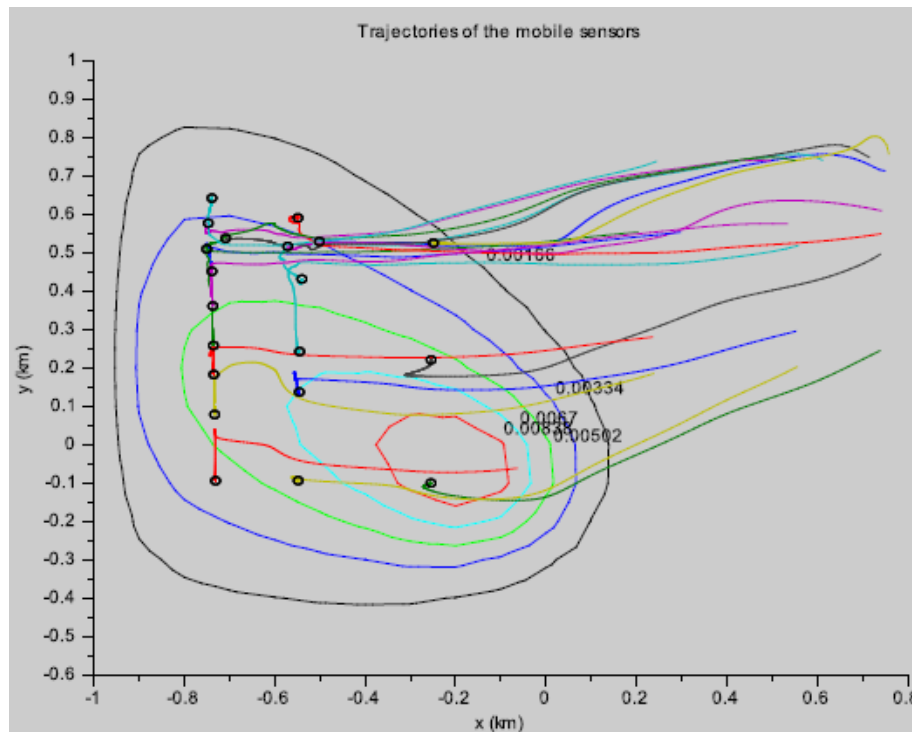


Figure 9. New trajectories of the sensors obtained after wind velocity changes.

6.1.3 OSPP with a modal observability gramian

Following [Georges (2017)], the air pollution model (40) may be represented in abstract form by

$$\dot{z}(t) = Az(t), \tag{52}$$

$$y(t) = Cz(t), \tag{53}$$

where A is the infinitesimal generator of a C_0 -semigroup $T(t)$ on a Hilbert space Z , and C is an output linear and bounded operator from Z to a Hilbert space Y ; define for some finite $T_0 > 0$, the observability map of (A, C) on $[0, T_0]$, as the bounded linear map $C^{T_0}: Z \rightarrow L_2([0, T_0]; Y)$ given by $C^{T_0}z = CT(\cdot)z$.

Here the output operator C is given, as in (34), by

$$y = Cz = \int_0^L \int_0^H \Delta(x - x_l, y - y_l)z(x, y, t) dx dy, \tag{54}$$

where $\Delta(x - x_l, y - y_l)$ is a shaping function of a sensor l located at position $\mu_l = (x_l, y_l)$.

Here

$$\Delta(x - x_l, y - y_l) \begin{cases} 1, & \text{if } (x, y) \in [\mu_l - \varepsilon, \mu_l + \varepsilon], \\ 0, & \text{otherwise.} \end{cases} \tag{55}$$

The observability gramian of (A, C) is defined by the linear self-adjoint operator $W^T = C^{T_0*}C^{T_0}$.

In order to get an explicit form of the gramian, the following procedure was proposed in [Georges (2017)]:

- (1) Transform the ADPDE (40) into the following diffusion equation:

$$\frac{\partial v}{\partial t}(x, y, t) = k \frac{\partial^2 v}{\partial x^2}(x, y, t) + k \frac{\partial^2 v}{\partial y^2}(x, y, t) + S'(x, y, t) - qv(x, y, t), \tag{56}$$

with $q = r + \frac{1}{4}(\frac{v_x^2}{k} + \frac{v_y^2}{k})$, thanks to the change of coordinates $z(x, y, t) = v(x, y, t)e^{p_1x + p_2y}$ where $p_1 = \frac{v_x}{2k}, p_2 = \frac{v_y}{2k}$.

- (2) Compute the well-known eigenvalues and eigenfunctions of the diffusion equation using Dirichlet's boundary conditions:

$$\mu_n = \frac{\pi^2 n^2}{L^2}, \phi_x^n(x) = \sin(\frac{n\pi x}{L}), \tag{57}$$

$$v_m = \frac{\pi^2 m^2}{H^2}, \phi_y^m(y) = \sin(\frac{m\pi y}{H}), \tag{58}$$

$$\phi_{nm}(x, y) = \phi_x^n(x) \times \phi_y^m(y). \tag{59}$$

(3) Get the modal solution of ADPDE (40) with input $S(x, y, t) = 0, \forall t \geq 0$:

$$z(x, y, t) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} c_{nm} e^{(-q-k(\mu_n+v_m))t+p_1x+p_2y} \phi_{nm}(x, y), \tag{60}$$

where c_{nm} denote the modal coordinates of the initial conditions.

(4) Compute the output map using (54):

$$C^{T_0} z = \sum_{n,m=1}^{\infty} c_{nm} C_{nm}(\mu_l) \times e^{(-q-k(\mu_n+v_m))t},$$

where

$$C_{nm}(\mu_l) = \int_0^L \int_0^L \Delta(x - x_l, y - y_l) \sin\left(\frac{n\pi x}{L}\right) \sin\left(\frac{m\pi y}{H}\right) e^{p_1x+p_2y} dx dy \neq 0, \forall n, m, \tag{61}$$

Since operator A is exponentially stable, the trace of the truncated observability gramian (20) is defined when $T_o \rightarrow +\infty$ as follows [Georges (2017)]:

$$W^\infty(\mu) = \sum_{n=1}^N \sum_{m=1}^M \frac{C_{nm}^2(\mu)}{2(k(\mu_n + v_m) + q)}, \tag{62}$$

where (M,N) are the numbers of modes retained for the approximation.

Fig. 10 shows the value of the observability index for a pollution distribution with constant wind velocities according to the sensor location in the domain.

Fig. 11 shows the mobile OSPP of a network of 100 mobile sensors using navigation strategy (29) with the cost function $c(\mu_1, \dots, \mu_{100}) = \sum_{i=1}^{100} trace \{W^\infty(\mu_i)\}$ on a given time period.

According to the classical theory of Riesz-spectral operators, ADPDE (40) is approximately observable if and only if all the $C_{nm}(\mu)$ are different from zero, for a sensor located at μ (see [Curtain et al (1995)]).

Then an observability index ensuring approximate observability on the basis of the first (N,M) modes can be defined by

$$c(\mu) = \min_{n=1, \dots, N, m=1, \dots, M} |C_{nm}(\mu)|. \tag{63}$$

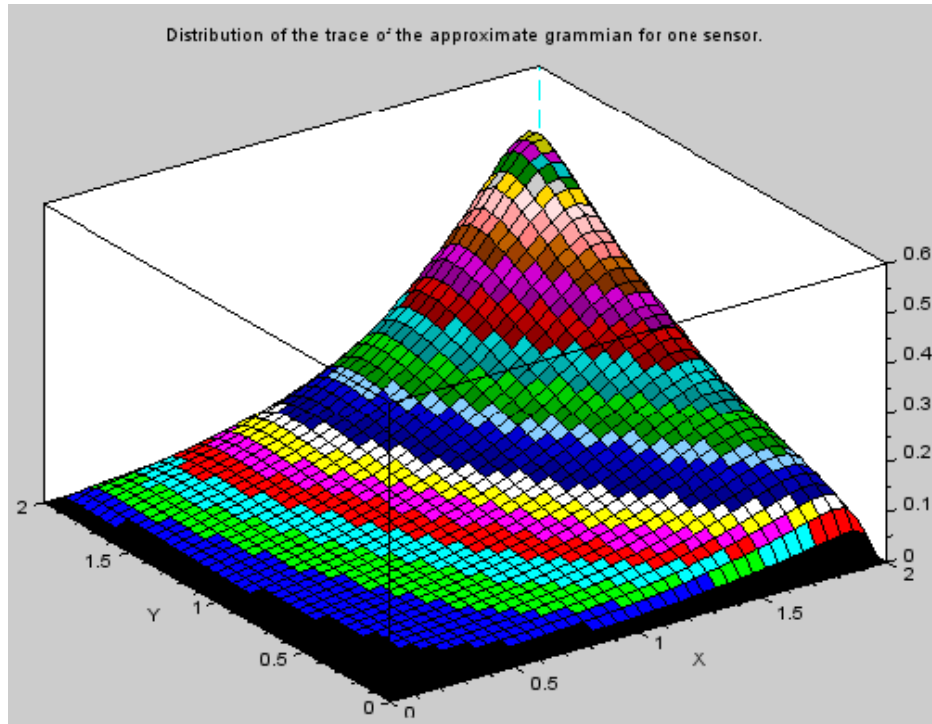


Figure 10. Observability index given by the trace of the observability gramian with $N = M = 20$ for one sensor according to its location in the domain, for $(U_x = 50\text{km/h}, U_y = 25\text{km/h})$.

Fig. 12 shows all the values of this new index and therefore the locations of sensors ensuring observability ($c(\mu_l) \neq 0$), with $N = M = 30$. The maximum values of the index are obtained at the top-right corner of the domain. Compared to Fig. 10, it immediately appears that metric (63) is more demanding than (62). With (63), navigation strategy (29) is no more directly applicable since the index is not smooth. It should be modified to ensure that some optimal locations of the N_s sensors $\mu_l^*, l=1, \dots, N_s$, solutions of a static nonsmooth OSPP, for instance:

$$\max_{\mu_l \in D_\mu(\mu_1, \dots, \mu_{N_s}), l=1, \dots, N_s} \min_{n=1, \dots, N, m=1, \dots, M} \sum_{k=1}^{N_s} |C_{nm}(\mu_k)|, \quad (64)$$

are reached, for instance, by replacing the gradient $\nabla_{\mu_i} c$ by $-\gamma (\mu_i^* - \mu_i)$, $\gamma > 0$ in (29). $D_\mu(\mu_1, \dots, \mu_{N_s})$ is the set of constraints intended to avoid sensor clustering and to ensure inter communications between the sensors.

6.2 Early detection of a wildfire ignition and fire prediction using a receding horizon observer

In this section, some new results on the use of a receding horizon observer RHO (33) are presented, based on the adjoint method proposed in [Georges (2019)]. The objective is to be

able to detect and locate early fire ignition using a sensor network constituted with ground-layer temperature sensors (see Fig. 13).

The model of a wildfire propagation can be well described by 2D coupled partial differential equations, which define the energy balance and fuel reaction rate for a wildfire in a ground layer of some given finite small thickness, on a rectangular domain $D = [0, L_x] \times [0, L_y]$ (see [Mandel *et al* (2008)]):

$$\begin{aligned} \partial_t T &= \partial_x(k\partial_x T) + \partial_y(k\partial_y T) - v_x\partial_x T - v_y\partial_y T + A(Sr(T) - C(T - T_a)), \\ \partial_t S &= -C_s Sr(T), \end{aligned} \quad (65)$$

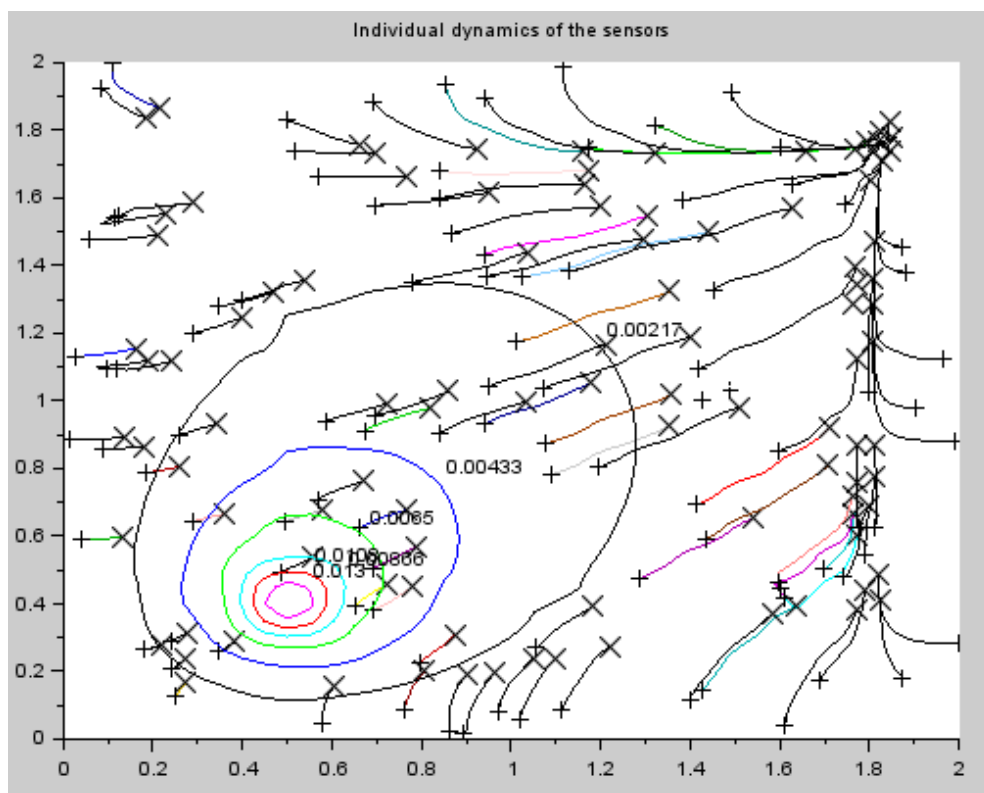


Figure 11. The 100 sensors tend to move towards locations on the right side of the domain. The sensors initially are randomly distributed in the domain. The initial locations are marked by "+", and the final ones, by "X".

with Arrhenius reaction rate from physical chemistry

$$r(T) = \begin{cases} e^{-B/(T-T_a)}, & T > T_a, \\ 0, & T \leq T_a, \end{cases} \quad (66)$$

and where $T(x,y,t)$ is the distributed temperature in the ground layer, $S(x,y,t)$ is the distributed mass fraction of fuel. k is the coefficient of temperature diffusion. $v = (v_x(x,y,t), v_y(x,y,t))$ defines the velocity field of the air, supposed to known from meteorological data. A, B, C, C_s are some

physical coefficients. T_a is the ambient temperature. ∂_t , ∂_x , and ∂_y denote the partial derivatives with respect to time t , and spatial coordinates x and y , respectively.

Some boundary and initial conditions have also to be defined to ensure the well-posedness of the problem. Neumann’s boundary conditions are used in this paper:

$$\partial_x T(0, y, t) = \partial_x T(L_x, y, t) = 0, \forall y \in [0, L_y], \tag{67}$$

$$\partial_y T(x, 0, t) = \partial_y T(x, L_y, t) = 0, \forall x \in [0, L_x], \tag{68}$$

$$T(x, y, 0) = T_0(x, y), S(x, y, 0) = S_0(x, y), \forall (x, y) \in D. \tag{69}$$

The interest of this model relies in the fact it is able to simulate heat travelling waves in a realistic way. In what follows, a normalized model is adopted (see (71) and (72)).

A network of temperature sensors is assumed to be deployed in the field. The location of the sensors is obtained thanks to a Sobol’s sequence (see [Georges (2019)]). The sensor location is assumed to be fixed and the effect of changes in wind direction is taken into account via the advection term of model (65) by using weather forecast data. A perspective would be to use mobile sensors (UAVs with infrared sensors) using a navigation strategy (26) or (29). Here it is assumed that the initial fuel distribution $S(x,y,0)$ is known from an a priori mapping of the field. Physical coefficients β and λ are also assumed to be known from the knowledge of previous wildfire occurrences with the same fuel characteristics.

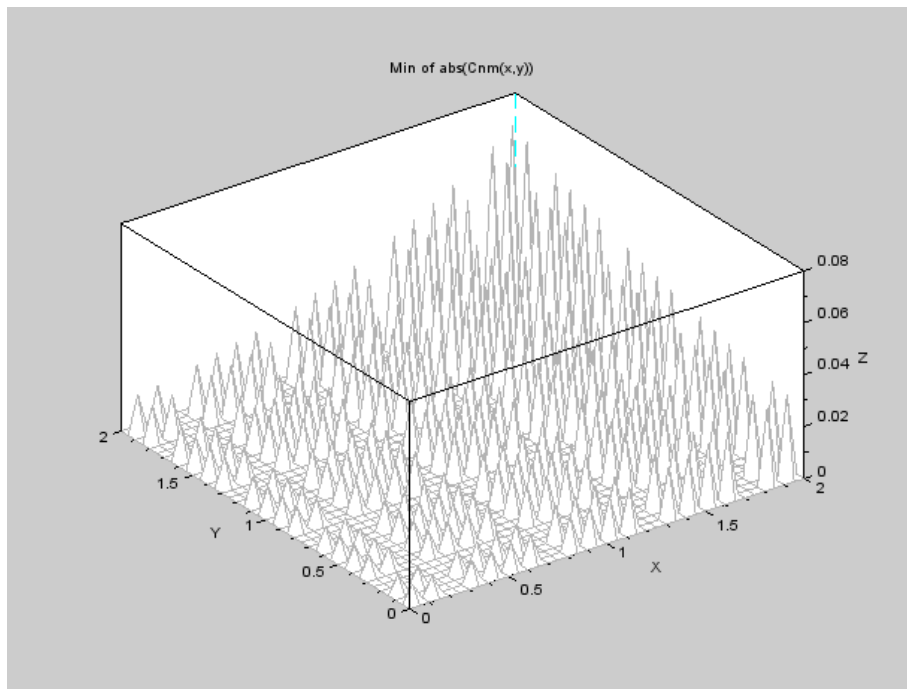


Figure 12. Alternative modal observability index over the domain. Observability for $N = M = 20$ is ensured only on very specific locations.

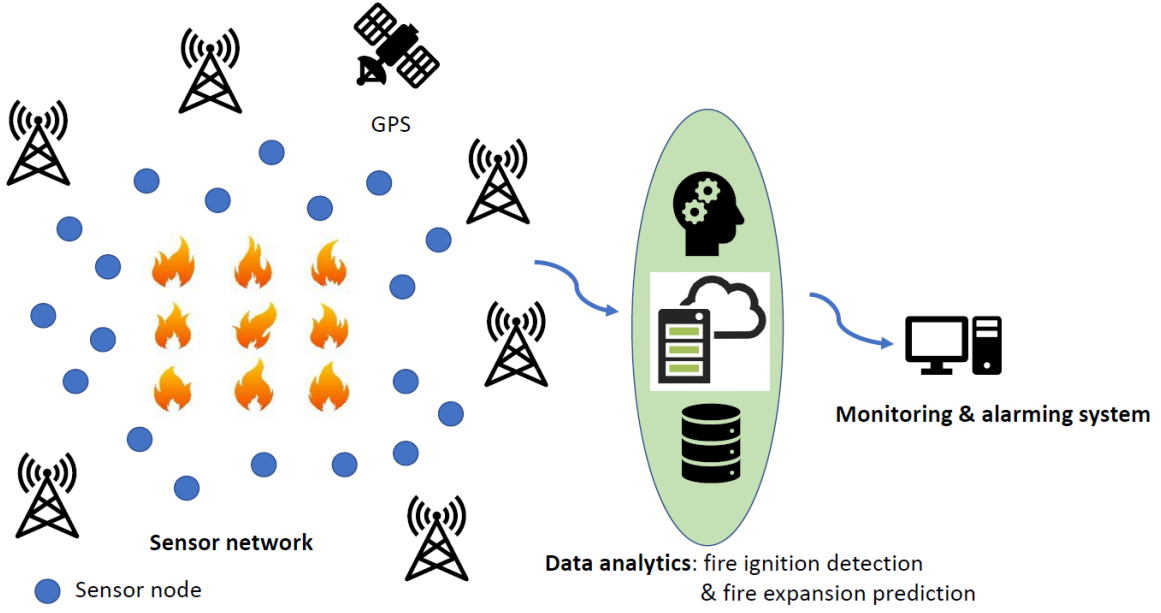


Figure 13. Sensor networks for wildfire monitoring (see also [Li *et al* (2006)]).

Similarly to (33), the moving horizon fire ignition estimation will consist in finding the distributed temperature at each time instant t_k over domain D . This can be formulated as solving the optimal least-square optimization problem defined for N_s sensors and on moving time interval $[t_k - T_f, t_k]$:

$$\min_{T(x,y,t_k-T_f) \in D} J(T_0) = \min_{T(x,y,t_k-T_f) \in D} \frac{1}{2} \sum_{i=1}^{N_s} \int_{t_k-T_f}^{t_k} (y_i(t) - y_i^m(t))^2 dt + \frac{a}{2} \int_0^{L_x} \int_0^{L_y} (T(x,y,t_k - T_f))^2 dx dy, \quad (70)$$

subject to

$$\partial_t T = \partial_{xx} T + \partial_{yy} T - v_x \partial_x T - v_y \partial_y T + S e^{-1/T} - \lambda T, \quad (71)$$

$$\partial_t S = -\beta S e^{-1/T}, T > 0, \quad (72)$$

where the measurement operator for each sensor i is given by

$$y_i(t) = \int_0^{L_x} \int_0^{L_y} \Delta(x - x_s^i, y - y_s^i) T(x, y, t) dx dy, \quad (73)$$

Where $y_i^m(t)$ is the temperature measured by sensor i at time t and pair $\mu_i = (x_s^i, y_s^i)$ denotes the spatial coordinates of sensor i in the reference frame. Δ is defined as (55). This problem was solved by using a adjoint-based method associated to a gradient iterative algorithm. The PDEs are discretized using a finite difference scheme on a 80×80 grid leading to a finite-dimensional system of 6400 states. The interested reader may refer to [Georges (2019)] for the derivation of the necessary conditions for optimality and the detailed computation of a closely-related state estimation problem without receding horizon technique.

In the simulation presented here-after, the receding horizon is equal to 160 time samples, and the domain is assumed to be a square of size 650 (in normalized units) for each side. The fuel is uniformly distributed over the domain, except for a fuel break featuring a river with no fuel. The fire ignition is detected when at least a sensor measures an abnormal temperature increase implying that the cost function of (70) becomes greater than a small threshold. The detection time is not the fire ignition time, since the fire wave reaches the closest sensor after a propagation time delay. Fig. 14 shows the fuel consumption after 160 time samples. The fire ignition was located at (450,350) and modelled by a gaussian distribution. Fig. 15 shows the location over the domain of the 50 temperature sensors used by the RHO algorithm (meaning that only 0.8% of the 6400 system states are supposed to be known). Fig. 16 shows a comparison between the estimated distribution of the fire ignition and the simulated one. Finally, Fig. 17 demonstrates that the RHO is able to predict the wildfire expansion, despite the fact that the data assimilation problem is known to be ill-conditioned. The optimization problem appears to be very sensitive to initial conditions that are generated randomly. Several trials (here 5) have to be performed at each sample time t_k and the solution corresponding to the minimum value of the cost function is retained.

7. CONCLUSIONS AND PERSPECTIVES

This paper was devoted to the design of optimal architectures for hazard assessment monitoring. Hazard assessment monitoring was viewed as the ability of estimating and predicting states of a dynamical system representing a natural or technological hazard. It was also considered to be the ability to estimate model parameters or changes in the model parameters. From the view point of risk assessment, the proposed approach can be used to detect vulnerabilities or locate failures or dysfunctioning, and to predict future behaviors of the hazard in time or space. In this paper, two approaches were discussed: firstly, the key notion of system observability was emphasized and some metrics for measuring observability were discussed. The use of these metrics was also investigated for solving the optimal sensor location problem for both static or mobile sensor networks. A survey of applications of such optimal sensor location problem was also provided. Secondly, the receding horizon estimation approach was presented. The relevance of this estimation technique was discussed and a survey of existing and potential applications of this approach was also proposed. Finally, some concrete applications illustrating optimal sensor location problems and receding horizon estimation were presented in the field of air pollution and wildfire monitoring.

The application of the framework described in this paper to large-scale cascading hazards is still a big challenge to be investigated. In that context, one key issue is the availability of effective model reduction techniques suitable for large-scale complex dynamics of coupled phenomena. Furthermore, the implementation and validation of the global architecture (OSPP and RHO together) remain to be studied in real situations.

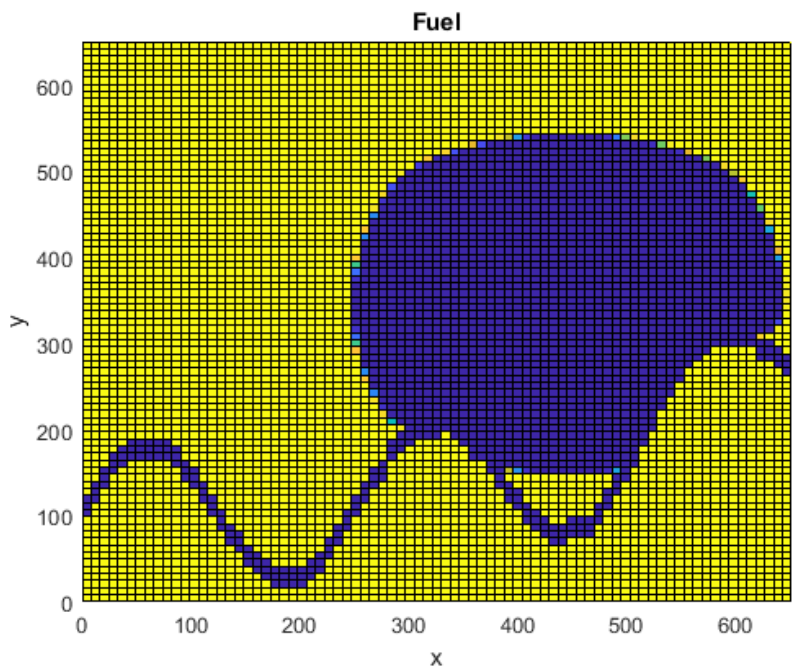


Figure 14. The burned area and the river are in blue color. The fuel consumption is given after 160 time samples.

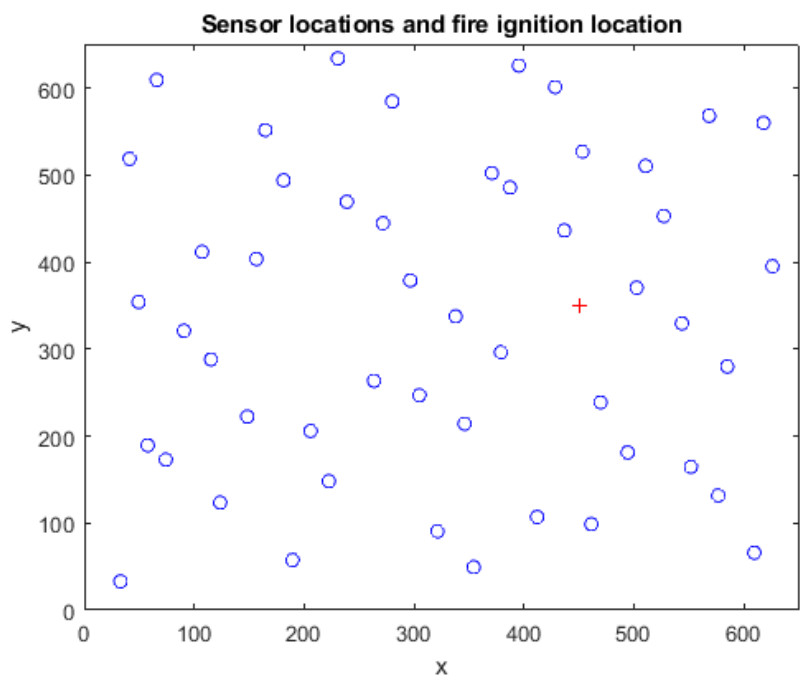


Figure 15. 50-Sensor location based on Sobol's sequence. The red "+" represents the location of the fire ignition.

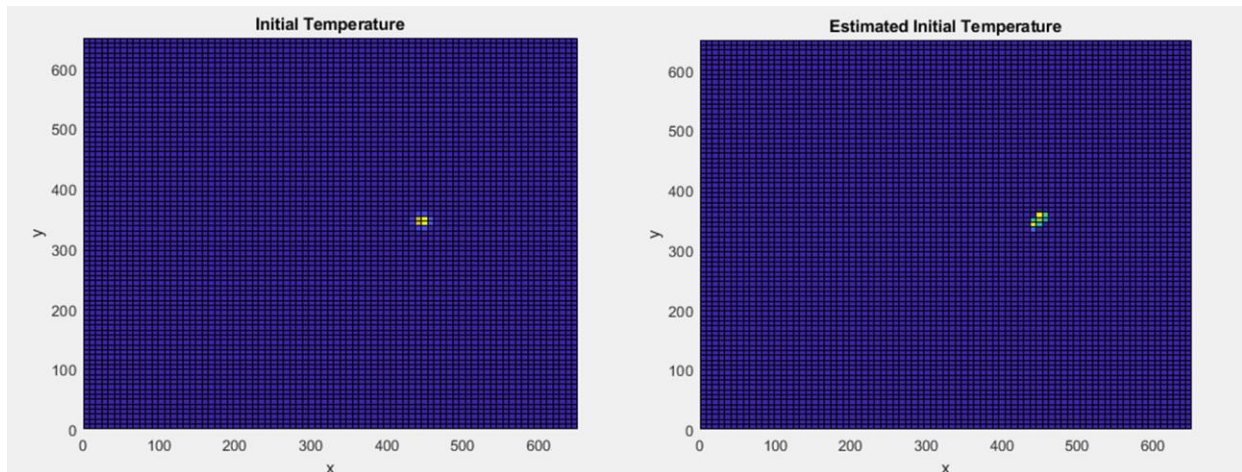


Figure 16. Comparison - Fire ignition.

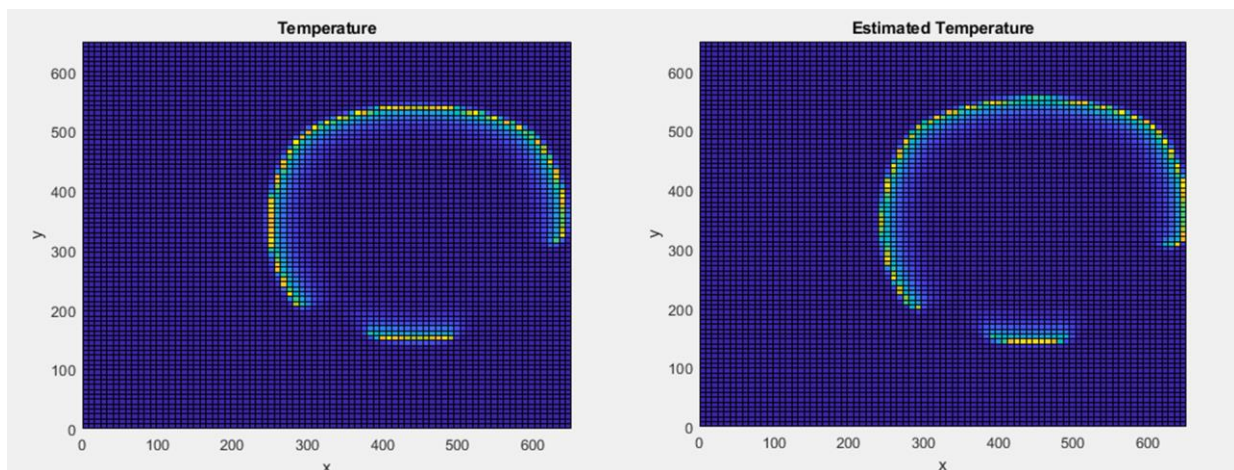


Figure 17. Comparison - Temperature distribution after $t = 160$ time samples.

The huge development of Internet of Things and machine learning techniques for processing data obtained by crowdsensing in the context of more and more powerful networking capabilities (5G technology) offers very large perspectives for the development of more and more accurate risk monitoring.

Such methods cannot be designed without a strong cross-disciplinary approach for including knowledge of fields, models, for qualification and preprocessing of available data, and finally developing adequate monitoring algorithms.

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