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Article

Critical Data Source; Tool or Even Infrastructure? Challenges of Geographic Information Systems and Remote Sensing for Disaster Risk Governance

Alexander Fekete [1,*], Katerina Tzavella [1,†], Iuliana Armas [2], Jane Binner [3], Matthias Garschagen [4], Carlo Giupponi [5], Vahid Mojtahed [5], Marcello Pettita [6,7], Stefan Schneiderbauer [7] and Damien Serre [8]

[1] Institute of Rescue Engineering and Civil Protection, Cologne University of Applied Sciences, Betzdorfer Str. 2, Köln 50679, Germany; E-Mail: katerina.tzavella@th-koeln.de

[2] Faculty of Geography, Department of Geomorphology-Pedology-Geomatics, University of Bucharest, NicolaeBalcescu 1, Sector 1, 010041 Bucharest, Romania;
E-Mail: iulia_armas@geo.unibuc.ro

[3] Department of Finance, Business School, University House, University of Birmingham, Birmingham B15 2TT, UK; E-Mail: j.m.binner@bham.ac.uk

[4] Institute for Environment and Human Security (UNU-EHS), United Nations University, Bonn D-53113, Germany; E-Mail: garschagen@ehs.unu.edu

[5] Venice Centre for Climate Studies, Department of Economics, Ca' Foscari University, Venice 30121, Italy; E-Mails: cgiupponi@unive.it (C.G.); v.mojtahed@unive.it (V.M.)

[6] Amigo S.R.L., *via* flaminia 48, Roma 00196, Italy; E-Mail: mp@amigoclimate.com

[7] European Academy-EURAC, Institute for Applied Remote Sensing, European Academy of Bozen/Bolzano, Viale Druso 1, Bolzano 39100, Italy, E-Mail: stefan.schneiderbauer@eurac.edu

[8] UMR ESPACE 7300 CNRS, Université d'Avignon et des Pays du Vaucluse, Case 19, 74 rue Louis Pasteur, 84029 Avignon Cedex, France; E-Mail: damien.serre@univ-avignon.fr

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: alexander.fekete@th-koeln.de;
Tel.: +49-(0)-221-8275-2604.

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Abstract: Disaster risk information is spatial in nature and Geographic Information Systems (GIS) and Remote Sensing (RS) play an important key role by the services they provide to society. In this context, to risk management and governance, in general, and to civil protection, specifically (termed differently in many countries, and includes, for instance: civil contingencies in the UK, homeland security in the USA, disaster risk reduction at the UN level). The main impetus of this article is to summarize key contributions and challenges in utilizing and accepting GIS and RS methods and data for disaster risk governance, which includes public bodies, but also risk managers in industry and practitioners in search and rescue organizations. The article analyzes certain method developments, such as vulnerability indicators, crowdsourcing, and emerging concepts, such as Volunteered Geographic Information, but also investigates the potential of the topic Critical Infrastructure as it could be applied on spatial assets and GIS and RS itself. Intended to stimulate research on new and emerging fields, this article's main contribution is to move spatial research toward a more reflective stance where opportunities and challenges are equally and transparently addressed in order to gain more scientific quality. As a conclusion, GIS and RS can play a pivotal role not just in delivering data but also in connecting and analyzing data in a more integrative, holistic way.

Keywords: disaster risk management; geographic information systems; remote sensing; volunteered geographic information; crowdsourcing; critical infrastructure; crisis mapping; civil protection

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1. Introduction

Geographic Information Systems (GIS) and Remote Sensing (RS) have become recognized and utilized as critical tools, methods, and data sources for locating, monitoring, and analyzing human crises and natural hazards in the past decades, particularly boosted by the International Decade for Natural Disaster Reduction (IDNDR). In addition to GIS, data fusion between optical, radar, and thermal imagery is recognized as playing a major role in each of the four phases of disaster management cycle (mitigation, preparedness, response, and recovery), by providing up-to-date geospatial information [1]. The most important application of remote sensing is assessing the extent of damages suffered by an area affected by disasters, and monitoring its recovery. Synthetic Aperture Radar (SAR) data can be used to measure changes in topography and building damage through multi-temporal analysis of pre- and post-disaster imagery [2]. Differential SAR interferometry (DInSAR) is considered one of the best available techniques when ground deformation mapping is needed in earthquake- or landslide-prone areas [3–5]. The accuracy of this technique depends on many parameters, like ground and atmospheric conditions, wave-band, incidence angle, and backscatter variance and intensity [6]. The success of these technologies cannot be gauged only by the proliferation of papers but also by the number of institutions founded for the specific purpose of utilizing these tools for disaster risk management.

In this article, we use GIS and RS both as prominent examples of tools and models for spatial assessment. In many sections, we use them synonymously for data gathering techniques, data sources, and methods of data processing and displaying as well as data analysis (tools) and research on the two. GIS comprises software tools for spatial data processing and RS comprises analysis and a process of data gathering through remotely facilitated sensors. From data types and sources, to processing methods, there are certain overlaps, but also many differing characteristics. It is not the purpose of this article to describe, or even analyze, these differences; it is rather our task to show what they have in common when it comes to certain specific examples of current applications in the field of disaster and risk research, for instance, spatial vulnerability indicators. GIS and RS do not equivalently contribute to processes of spatial assessments and analysis (in terms of processual chains); for example, certain GIS data, such as interview data, is not related to RS sensors but GIS can combine both.

Apart from technical differences, there is also data acquisition and processing that, for both GIS and RS, are highly dependent on financing, and for both, the heterogeneity of availability and accessibility to communities and decision-makers has even widened which would deserve an assessment and article on its own. The (continuous rise in) variety of almost cost-free open access data and acquisition, especially in the fields of humanitarian assistance, is addressed in our article (in a limited way), as are constraints by still highly costly data and software, and educational costs. By broadening the scope from a technical to a more integrative view, we wish to outline how science in the fields of GIS and RS can be connected to the burgeoning fields of Disaster Risk Management (DRM) and Risk Governance, both of which are more integrative in the sense that they go far beyond the data and methods perspective towards involving user needs and decision processes. This article therefore uses GIS and RS often synonymously in order to reveal the possible acceptance perspectives from the field of DRM.

By Disaster Risk Management (DRM) we mean the multidisciplinary process leading to the planning and application of policies, strategies, instruments, and direct intervention measures that favor the prediction, reduction and control of the effects of dangerous physical phenomena on populations, production systems, infrastructure, goods, services, and environment. The sum of actions that favor risk prediction, reduction, and control using prevention, mitigation, preparedness, rehabilitation, reconstruction, and recovery methods [7]. Risk governance is part of the disaster risk management: The totality of actors, rules, conventions and mechanisms relating to the collection, analysis and communication of information on risk and to the processes of management decision making [8]. Many phases of the often seen process cycles of DRM and risk governance overlap at least (compare the process cycles in ISO 31000 [9] and IRGC 2009 [10], for instance, and a further overview on current uses in [11]). We understand Disaster Risk Management as an integrative process(ISO - International Organization for Standardization 2009) consisting of the phases of preparation, analysis, evaluation, decisions, and communication. Risk Governance is a synonym for this process [10], while it points even more to the involvement of political actors. Risk Governance places even more emphasis on communication between all actors, between all phases, and underlines a political aspect. In the field of Disaster Risk Science, or as it is more commonly known, Disaster Risk Reduction, both concepts, DRM and Risk Governance are pivotal to understand the connection between risk processes, resilience and vulnerability, and tools such as GIS and RS.

This article builds upon research and practice of the authors in the field of Disaster Risk Management from the last 15 years. It is thereby a subjective view and comment on a selected number of aspects that prevail in areas that represent only a small fraction of the overall utilization of geo-information and remote sensing. Moreover, within the field of disaster risk science and management, this perspective is further limited to experience with national civil protection authorities in Europe and certain United Nations and international development organizations.

Regarding the broadness of services which GIS and RS can deliver, this article is limited to spatial indicators, early warning mapping/systems and communication, since these are of most direct relevance for DRR applications. Other services for risk reduction of more general type, such as GNSS (global navigation satellite system providing global coverage through a constellation of satellites providing signals from space transmitting positioning and timing data) as well as atmospheric, hydro-meteorological or oceanographic measurements, are excluded since they would exceed the length and purpose of this paper.

The paper will first describe spatial indicators in Chapter 2 as one prominent example of methodology in DRM. In Chapter 3 the paper highlights typical shortcomings of predominant data and methodology-driven approaches prevalent in GIS and RS communities. Chapter 4 discusses Volunteered Geographic Information and Communities in their role and growing use for disaster risk analysis and participation of users. Chapter 5 offers a holistic management approach used in disaster risk management for integrating all the different methods and concepts in GIS and RS. Chapter 6 then investigates whether GIS and RS services do not bear characteristics of other so-called Critical Infrastructure services in terms of having become a key resource for DRM.

2. Spatial Indicators

2.1. Proliferation of Vulnerability and Resilience Indicators

Planning and decision-making for sustainable development, which requires pro-activeness and making informed decisions, is a real challenge for decision makers due to the reactive approach of DRM. Therefore, with the help of GIS, spatial indicators, are widely applied for "measuring" (in a quantitative or semi-quantitative and relative sense) and communicating phenomena such as natural hazards, deforestation, land use change, wildfires, floods, earthquakes, tsunami, climate change. They have all been combined into concise indices with anthropogenic factors and variables, covering social, cultural, institutional, economic, and other sectors. Just to name one example from our experience: the social vulnerability [12,13] and socio-ecological indicators of resilience or vulnerability that have been connected with flood-area maps derived from RS, land use classifications, and precipitation data [14–16]. Drought, earthquake, tsunami, and storms are other areas where such spatial assessments are widely used [17–19].

2.2. Expanding Vulnerability and Resilience Indicators into Fields of Human Assistance, Conflict and Demographic Change

Indicators are not tied to a specific hazard, but some of them are more relevant to one than to another. This special issue for example, uses spatial social indicators to capture the additional impact of social vulnerabilities on the conflict in Yemen (see other article). Many more countries are currently affected by similar humanitarian conflicts and it will be worthwhile to undertake similar assessments and compare them. The Yemen example is not only a very timely application of this methodology, but also helps to provide valuable in-depth information about disaster risks and possible detrimental impacts that go beyond a mapping of hazard hot spots. The recent earthquakes in Nepal (25 April and 12 May 2015) provide another unfortunate case of how RS, GIS but also ground observations (GO) can contribute to disaster management and relief. Information loaded by multi-agency post-disaster efforts on the ground converged with remotely-sensed data on the "Nepal Earthquake 2015: Disaster Relief and Recovery Information Platform" (NDRRIP), a geoportal jointly developed by the Government of Nepal and ICIMOD, to map and assess the consequences of the earthquakes, and in particular landslides, rock falls, and avalanches [20] and orient relief efforts.

Furthermore, crisis mapping, itself, is conducted at an international level within the International Charter Space and Major Disasters initiated in 2000 by CNES (National Centre for Space Studies) and ESA (European Space Agency), joined by CSA (Canadian Space Agency), NOAA (National Oceanic and Atmospheric Administration), ISRO (Indian Space Research Organization), CONAE (Argentina Space Agency), JAXA (Japanese Space Agency), USGS (United States Geological Survey), BNSC/DMCii (Disaster Monitoring Constellation International Imaging Ltd.), CNSA (China National Space Administration), ROSCOSMOS (Russian Federal Space Agency), INPE (National Institute for Space Research of South America), DLR (German Aerospace Center), and KARI (Korean Aerospace Research), and the UN joining in 2003 [20], with the help of UNITAR/UNOSAT (The group of organizations and companies of this Charter coordinate the analysis and mapping of EO based information and provides integrated satellite-based solutions for human security, peace and socio-economic development). Several national space agencies, geoscience centers, institutions, and organizations, such as IPGP (France), INGV (Italy), NUA (Greece), BGS (UK), USGS, GFZ (Germany), DLR-ZKI (Germany), and KOERI (Turkey) alternate in providing rapid response to natural hazards and humanitarian crisis events in the form of satellite maps that designate hazard impact areas, evacuation sites, and other information.

In addition to this charter, similar products are generated by the Emergency Management Service (EMS) of Copernicus. Copernicus is the European Union's Earth Observation program and EMS is one out of six services that integrates satellite-derived data with *in situ* data for the analysis and the monitoring of issues relevant for environment and security. Hand in hand with the development of these Copernicus Services, the European Commission together with the European Space Agency (ESA) launched its own dedicated constellation of satellites—the Sentinels. It is foreseen to give the user—under certain and still-to-be-defined conditions—free access to Sentinel data. If this is going to be realized, one constraint hampering the wider use of satellite-derived information for disaster risk management will be eliminated: the costs for EO data.

Eliminating these costs will enhance the role of emergency services, government, and even international humanitarian organizations. Government and all government agencies have played a major role in saving lives, preserving properties, prevented damage and breakdown of Critical National Infrastructure (CNI). However, the 9/11 incident, Asia Tsunami (2004), complex disaster in Japan (2011) and Christchurch earthquakes (2010, 2011) to mention but a few, have proved that the capacity of CNI, emergency services or governmental agencies are insufficient in facilitating effective response to complex, major or unprecedented incidents. Perhaps this reality or continued CNI failure across the world have forced the general public to self-organize, draw from survival instinct or empathize with one another in the face of death [21], For example, "the Red Cross was already working on mapping Nepal in preparation for an event like the earthquake in April of 2015", says Dale Kunce, senior geospatial engineer for the American Red Cross based in Washington DC. He also mentions that they are using the maps after the earthquake to guide teams on the ground about things like which routes might be prone to landslides, where possible distribution centers could be based, and where banks are.

Remaining challenges are the extension of spatial indicators and assessments on hazard types that are more difficult to map, including rare events, hard-to-spatially-detect information, such as certain supply infrastructure or cyber-attacks, but also many of other forms of sabotage or intentional small-scale and spatially-distributed events. Certainly, spatial information, such as that extracted by RS sensors, offer excellent and unparalleled data and proxy indicators, constraint by definition, play a key role in advancing our understanding about uncertain and complex phenomena, such as vulnerability. However, there remain certain challenges regarding causality and methodological analysis [22]. For example, the area affected by a power failure is often not the area affected by the hazard, such as a flood. There are spatial patterns of relevance for DRM for that direct indicators are difficult to find, namely those of the anthropogenic type. Aspects such as the economic situation, the cultural identity or social networks are only detectibly by remote observations to a limited extent but are the key for understanding vulnerabilities or resilience. In addition, one needs to remember that it remains very hard to directly capture many of the soft components and drivers of vulnerability and resilience through GIS or RS tools. Vulnerability outcomes can often be analyzed with such techniques, e.g., through the mapping of squatter settlements with sub-standard housing quality in areas exposed to floods, storms or landslides. Such methods have proven to be of great support for disaster prevention and relief. However, the institutional and economic driving forces that cause such vulnerability outcomes can, of course, not be captured with GIS and RS tools, limiting their capacity for long-term vulnerability reduction.

Apart from being able to capture the content, another challenge is continuous financing for such GIS or RS services. When it is based upon third-party research projects, then the existence and maintenance of services and platforms often finishes shortly after the project ends. Funding by national bodies of civil protection for example, is also at risk from budget costs and shifts in direction, especially in the field of DRM, which itself is subject to political scrutiny and strategic decisions. Funding can be motivated by certain major disastrous events at one time but at another same time diverted to other events or political processes.

3. The Tool Perspective

3.1. Maslow's Hammer Perspective—Top-down Methodologies of Classifications and Technocentric Perspective of Algorithms

Maslow's Hammer Effect

Research within RS appears often to be driven by a technological perspective, where the sensors, the satellites, the data, the methods to filter them or algorithms to process data often dominate the research carried out.

There is much less focus on the often limited consideration of the impact on potential end users, or evaluations other than statistical sensitivity tests. In certain GIS and RS studies, publication discussion chapters are lacking that are debating the pitfalls in the analysis design, model process or applicability of the results.

While this is a typical characteristic of many other natural science or technical studies, research in RS is typically focused on demonstrating and justifying its power by focusing on technical aspects or applications of algorithms. This observation is based solely on personal observations and it should not necessarily point to critique. However, there appears a need for more studies thinking and discussing

GIS and RS usage in DRM, and, papers analyzing pitfalls within the analyses, as well as in application. This is apparent in the field of spatial vulnerability indicators, where paucity exists on studies critically thinking and discussing challenges and pitfalls of methods or trans-disciplinary operationalization.

GIS and RS are often data-driven research, but also methodology, or algorithm-driven research, and in this respect are subject to Maslow's Hammer effect. Since when we have a GIS at hand not only are spatially-explicit data preselected, but also other types of data are made spatial and conforming to the data representation in a GIS.

On the other hand, this is, at the same time, a necessary prerequisite for data integration, which is a key opportunity offered by GIS technology to the management of RS data and GIS. Different types of scales (temporal, spatial, administrative, *etc.*) and different levels (local, regional, national, international *etc.*) have distinct, specific effects on permitting identification and measurement of, for example, social vulnerability [15,23]. Opportunities and challenges of scale, up-scaling, dis-aggregation, identification of proper research area boundaries, units or auto-correlation effects and tools to analyze and compensate auto-correlation are beyond the scope here and have been intensively discussed elsewhere [17,18,24,25].

3.2. Maslow's Swiss Army Knife—Triangulation of Methods, Embracing Interdisciplinarity

GIS is also not just a hammer, but in fact a Swiss Army Knife version regarding its versatility in combining and analyzing information, gathering and aggregating it. For instance, spatial vulnerability indicators can integrate RS data with demographic, environmental, and structural information, in a GIS environment.

This versatility poses certain problems. One is the risk of overlooking the limitations of the capabilities of GIS and another of disregarding the hazards emerging from the aggregation of data. One is the aggregation problem, which is well known from spatial risk or vulnerability indicators aggregated into concise indices that may blur the representation of reality and diminish the richness of information borne in its variables or individual indicators. Some of these effects are the modifiable areal unit problem, ecological fallacy or spatial autocorrelation, but in this paper we will not go deeper in these issues [26,27]. On the other hand, the advantage of GIS is to map individual indicators, and to allow for multiple layer representation and analyses depending on how the database is structured. Aggregation methods are rarely considered with adequate care by scholars, often overlooking effects of normalization and internal compensation, and neglecting the opportunities offered by the algorithms developed by the literature on Multi-Criteria Analysis (MCA). Another risk stems from data sharing and communication; from an end-user perspective of civil protection bodies that need to take care of possible theft of data that could be misused by saboteurs for planning attacks on the identified vulnerable hotspots, be it people or critical infrastructure.

A greater awareness and transparency on the pitfalls of the usual methodological approach would be useful for the community applying GIS for DRM. Second, a greater awareness of security concerns of end-users or public bodies, or industry would be instrumental in improving the wider acceptance, and effectiveness of GI and RS data and tools. We believe that GIS and RS are indispensable tools and such pitfalls will and should not delimit their potential. However, a certain awareness of pitfalls and maturity in terms of discussion of challenges will be beneficial especially when it comes to interdisciplinary research projects and transdisciplinary collaborations with policy and practice.

In addition to the differences of GIS compared to RS the approach is still technology-driven. Scientists working with these tools, scrutinizing their potential, and developing codes for improved analysis usually do not consider user needs in the first place.

This fact hinders the wider use of RS and GIS products and has the potential to frustrate users by a lack of appropriate "expectation management" [28].

3.3. Bottom-Up Methodologies Based on GIS and RS

The potential role of GIS and RS in DRM must be augmented when they are used with certain models that describe an underlying spatial process. Together, they can be an invaluable tool for assisting policy makers to build adaptive or coping capacity *ex ante* or *ex post* disasters.

GIS and RS can be coupled with other methodologies to simulate and study the socio-economic behavior of individual or group of agents in a complex system, such as cities, in response to climate change or different natural and manmade disasters. An important methodology of coupling Bottom-Up research with the help of GIS maps is the spatial agent-based (ABM) models and as an example we recommend the article of Darvishi and Gholamreza [29]. ABMs are becoming the dominant paradigm in social simulation since they suggest that complex systems emerge from the bottom-up, are highly decentralized, and are composed of a multitude of heterogeneous objects called agents. Sources of heterogeneity can come from the multi-layer geographical characteristics of agents that are provided by the GIS maps. The agents act given their objectives and they interact, usually through time and space, which generates emergent order, often at higher levels than those at which such agents operate. There have been many applications of the spatial ABMs in DRM. For instance, authors in [30,31] provided models of emergency evacuation for urban area. These models provide estimates for the evacuation time given GIS inputs on roads, buildings, and population density. Kwan and Lee [32] used 3D GIS for an intelligent emergency response system based on ABM and network theory aiming at making quick emergency response easier during terrorist's attacks such as 9/11.

A different attempt has been made to make the use of GIS maps collaborative, multimodal, and interactive during the emergency management situations. Rauschert [33] developed a new GIS interface that overcomes problems with unimodality, personal, and unidirectional usage of GIS. The development of these interfaces brings the complex GIS databases directly to the emergency control rooms without the need of the GIS analysts.

4. Volunteered or Commanded Geographic Information?

4.1. Top-down Dissemination of Results and Gaps between Knowledge Production and Decision Making—False Expectations on the Decision Makers and End-Users

Another development is crowdsourcing of Geo-Information (GI). "It had been used in previous emergencies, such as the Wikis created to map Hurricane Katrina and bird flu, but none seemed to have a life beyond the particular incident", said Microsoft's Nigel Snoad, an adviser to the ICT4Peace Foundation, "but in Haiti, Ushahidi and its partners seemed to have a real impact on the way the humanitarian response worked," (NAIROBI, 5 July 2010, IRIN). By far the most known online platform is Ushahidi, which was initially developed to map reports of violence in Kenya after the post-election fallout at the beginning of 2008. Some others such as OpenDRI (https://www.gfdrr.org/opendri), ArcGIS.com (http://www.arcgis.com/features/), Sahana (http://sahanafoundation.org/), Google Crisis Response (https://www.google.org/crisisresponse/), as well as the UN Secretary-General's innovative Global Pulse project (http://www.unglobalpulse.org/) and the Humanitarian ID (http://humanitarian.id/) provide outlets for individuals and organizations to engage with each other to capture real-time issues and risks—ultimately to save lives and strengthen resilience to shocks and disasters.

Improvement of web-based mapping, invention of cell phones and devices that are equipped with Global Positioning System (GPS), PDAs, and digital cameras have made it possible for ordinary people to collect spatial data, which are then shared and disseminated on the Internet using web map services, especially Web 2.0. Producing maps and Geographic Information by non-expert people without academic studies and with local knowledge about their environment and, generally, the world, is preparing a phenomena that is named in general as "citizen science" and, more specifically, by different terms in geographic researches such as Neogeographic, Public Participation GIS, Ubiquitous cartography and, in general, the collection of spatial data and dissemination of them on the Internet by citizens were named by Goodchild [34] as Volunteered Geographic Information (VGI). Web sites such as OpenStreetMap (OSM) and Wikimapia, aiming to produce a free and editable map of the world, are examples of VGI.

For the most part, research on disaster response has assumed that states or other quasi-governmental entities (e.g., the United Nations) would be the primary actors in disaster relief, with NGOs playing a secondary role. Therefore, it comes as no surprise that the role of IT was primarily viewed as a means to enhance the command, control, and dissemination of information [35–38]. First and foremost, there is a need to consider which scientific questions can be answered by citizen science according to the patterns of data collection, the ability to recruit and train volunteers, the suitable participation level, and other aspects of VGI. Second, there is a need to overcome the cultural issues and to develop an understanding and acceptance of citizen science within the scientific community. This will require challenging some of the deeply held views in science, such as viewing uncertainty not as something that can be eliminated through tighter protocols but as an integral part of any data collection and, therefore, developing appropriate methods to deal with it during analysis. Moreover, the view of science as separate from societal and ethical concerns is also a challenge especially at higher levels of engagement between scientists and participants [39].

"It is sobering to be reminded that one of the basic instincts of human nature mutual cooperation for no cost—is thriving on a global scale", mentions Keegan [40].

VGI data are sometimes called "asserted" because there is no standard for checking their quality and there is no reference or citation for them, in divers the official data are called "authoritative" because their quality is checked with standards [34]. Although the quality of VGI data might not be clear, in emergency situations, such as forest fires, where we have no official data, using volunteered data with quality vagueness is better than waiting for better data to arrive [41]. The most significant advantage of VGI is that they can be up-to-date in less time than traditional data, so for the projects that have time limitations, such as updating the streets of a city in few weeks, the local citizens are the best source to collect data and update information about the streets [42]. On the other hand, some monitoring systems are more and more exposed to the risks of budget cuts and volunteered systems are liable to fluctuations of people and their motivations.

Crowdsourced data, in general, and volunteered geographic information, in particular, are becoming the huge source of data. VGI has enormous advantages such as: it's free, has the ability to produce large amounts of data in short period of time, and collect local data that are, in some cases, impossible to obtain by traditional methods of mapping. Despite its benefits, volunteered geographic information cannot be used in many applications because its quality is not determined and there is vagueness about it. Therefore, much research has been carried out so far to determine the quality of VGI [43].

In some specific cases, the problem of the VGI quality could be not crucial and the lack of precision can be used for other purposes. For measuring environmental parameters, VGI data usually do not satisfy the requirements of precision, accuracy, and error. Nevertheless, with appropriate means, VGI can become usable and produce relevant environmental data. For example, in case measures from conventional instrumentation are available and, at the same time, a large amount of VGI can be collected, despite the scarce accuracy of the latter, the high accuracy of the standard measurements tool can be used to correct the bias and to use the VGI as a measure of the spatial variability of the measure. In this case, the accuracy does not play a relevant role because we are interested in the spatial variability of the measured field.

Similarly, VGI data have the problem of "False Observation", which are wrong data collected by users (deliberately or accidentally), but also in those cases, when the concurrent number of VGI is large, False Observations can be easily invalidated with standard techniques of large-deviation filtering.

Participatory GIS (PGIS), Public Participation GIS (PPGIS), and community-integrated GIS are newer and issue-driven approaches of volunteer-based community participation (insiders) for the creation of geographical information to be fed into a GIS. The difference lies in the coordination of this participative process by the researchers (outsiders) through various methods: sketch mapping, transect walk, Internet-based mapping, scale mapping and enhancing spatial accuracy of end-products [44,45]. The concept of participative mapping has been around since the 1980s, as a fast way of extracting indigenous spatial knowledge when adequate cartographic materials were missing. PGIS is currently used on a wider scale in democratic spatial decision-making, because it loads a given space with socio-cultural, economic, or ecological value. PGIS is enhanced VGI because it helps the community identify and better define a common interest problem and generate possible solutions, while supporting self-confidence and determination, community cohesion and identity consolidation [46,47]. PGIS produces maps that represent interactive vehicles for learning spatial analysis [48], helping information exchange and analysis, decision-making, and promotion of community interests through various forms of lobby and advocacy. PGIS is, at the same time, a method of involving local communities in hazard management, a precondition for sustainable disaster risk reduction, bringing with it the deep local knowledge that may differ from scientific of official knowledge [49].

4.2. Crowd-Sourcing as a New Risk?

The proliferation of crowd sourcing, particularly loose networks in disaster communication, may even increase risk. In Section 1.21 of the UK National Security Strategy the potential impact of a new "mass of connections" upon security was highlighted.

It was argued that networks, including social networking technologies and 24 hour news media, could impact security as interest groups become more able to pressurize governments and a wide range of ideas easily proliferate, globally [50]. A recent article on ZDNet covered national "unfriend day", which argued that loose connections on Facebook lead to increased risk of terrorism [51]. Loose networks can lead to the propagation of both intentional and unintentional rumors. In January 2010 a Twitter rumor led to the evacuation of Grand Central Station in Manhattan [52]. Finally, at The Red Cross-hosted Emergency Social Data Summit a key conclusion was that "the major obstacle to the use of social media in crisis situation is the same obstacle to adoption we've seen since the beginning of the technology: a hesitation to shift from broadcasting information to engaging," [53]. Getting emergency managers in particular to embrace and adapt to these new technologies in an age of not only uncertainty but resource scarcity may be a key challenge. There is also the danger that feedback loops between new technologies and the media escalate rumor and speculation as is evident in the work of [54] through the development of the notion of "spectacle" in the media coverage of disaster events (see also [55]).

However, despite reservations around particular technologies, findings in Preston *et al.* [56] show how social networking technologies around transport attacks are potentially transmedia orientated and make use of sentiment. In particular, authors in [56] specifically looked at the characteristics of daily social media conversation and how this may react to specific events through automated content and sentiment analysis of Twitter data. Geo-tagged social media data was used by Schmidt and Binner [57] as a proof of concept for the development of an early warning tool to help first responders and emergency management personnel to quickly assess the scope and location of a current crisis, and to quickly summarize the state of affairs [57]. A related study by Preston *et al.* Authors in [56] carried out an initial manual content analysis on a Tweet dataset to understand how the attack on Domodedovo airport had been discussed in the UK Twitterverse. From a dataset of over 300,000 tweets posted from 24 to 27 January 2011, we extracted tweets that contained the following keywords: "bomb", "explosion", "Moscow", "Domodedovo", "airport". Of the 198 posts retrieved, 61 were directly related to the attack, 17 referred to other attacks and 120 were of "conversational" nature (e.g., "calm as a bomb"). It was noted that all the data directly related to the attack could be grouped into the following four categories: (1) Broadcasting, (2) Fact-finding, (3) Reacting, and (4) Projecting. The categories closely match the three-step cognitive process of SA theory [58] as each step seems to emerge in chronological order and it coincides with a deeper understanding of the event. For example, first the news is broadcasted "Russian media reporting that at least 23 people were killed and 100 injured in Moscow airport bombing". As the news is being broadcasted, people look for more information—a transmedia interaction between old (broadcast) and new (social) media—"Any word on number of bombs? News reports saying possible multiple". Once the gravity of the situation is understood (comprehended), the public react with emotional posts: "Very sad about bombings at Moscow Domodedovo airport (...)". A few final tweets contain references to past experiences and "projections" of future threats "Need to find my blog from years ago about suicide bombs (...)" "Have FIFA said anything on the Moscow bombing? Tragedy all round. Questions over airport security ahead of WC that relies on them so heavily".

Although these were initial observations, it is clear that there is scope for applying automated content and sentiment analysis, within a transmedia context, to assist researchers and stakeholders in gaining a deeper understanding of the content and modalities of daily conversation and crisis communication. Our short-term plans include the incorporation of a variety of semantic algorithms, permitting the communications and graphs to be connected in more meaningful ways. This enhancement would also allow the graphs to be tagged to support, e.g., semantic search operations.

Adding a search tool or a watch-list of interesting terms would enable the utility to be used to display the results of simple searches. One simple extension to this concept is to collect geo-tagged results from commercial search engines, to better display those results. It would be interesting to revise the displays such that these technologies could be used in real time and be widely accessible. It would also be useful to experiment with adding these graphical concepts to small displays, such as cell phones and the latest generation of tablet computers.

5. Holistic Sensing, Knowledge and Management

Chapter 4, as well as Chapters 2 and 3, have only highlighted a few key tool characteristics and a relatively new field of research, crowdsourcing. These examples, spatial indicators, the general prevailing tool-pursuit in conceptual designs of spatial assessment research, and its current combination in the field of what is coined by some as Volunteered Geographic Information, only pinpoint some of the features by which GIS and RS tools and related models are currently used in relation to DRM and Risk Governance. The next question is how are these related to each other and which could be a framework for such tools and models? The following chapter and concurrent chapters will try to outline certain important fields and concepts that (a) might be an option and (b) are already used quite pervasively, for instance in the fields of resilience and vulnerability studies [11].

5.1. Lacking Integration of Product Thinking and Risk Analyses into a Holistic Risk Management Concept

Many risk analyses only cover individual processes of a risk management or governance framework and in most cases they directly start with the analysis itself. Not many papers using GIS or RS in the context of DRM are aware of integrated risk management frameworks, such as the one in ISO 31000 [9] or IRGC 2009 [10]. Building upon knowledge acquired from past events, forward-looking activities and related feedback loops set the context for decision-making and policy development in a strategic planning framework. Carried out by subject experts, forecasting and prediction in that concept have a strong modeling component and are focused on quantitatively assessing and measuring a certain near-future condition. Foresight processes strongly consider inter-related communication of various stakeholders and multidisciplinary experts with the objective of creating common visions and consistent scenarios and thus shape and construct long-term future developments in a favorable manner. Disaster risk mitigation, irrespective of hazard-specific characteristics, can be seen as the common overall goal spanning the entire timeline [59]. In such a risk management framework, the analysis is just one part, embedded in an overall process starting with a pre-analysis phase of identifying the objective possible stakeholders to involve methods to use. After the analysis, the phase of evaluation is separated in order to stress out the need to validate but also in order to highlight that the decision making process is often done by other persons and methods than the ones in the analysis. After that, the phase of identifying and then implementing measures to handle risks follows, and while in some, especially of the older versions of such frameworks, communication and dissemination of results is often the last phase, before the risk management process starts all over again. However, this top-down thinking has been criticized and communication in some frameworks is now put at the core of risk management, taking part in all phases of the process. Applying this risk management process to many GIS and RS studies which are dealing with risks will help to align it with other stakeholders. Such stakeholders can be the decision makers who can be better involved in the process right from the phase of pre-analysis.

5.2. Technical and Social Sensors: Geo-Information as a Vital Part of Risk Management Culture (and not Just as a Tool)?

Another idea to transform the top-down and technocentric culture of GIS and RS, as is often still the case, is offered by bottom-up decentralized crowd-mapping and use of social media (see previous sections of this paper). This is a strong trend and many scientists are eager to pick up the opportunity to integrate feedback on data they disseminated in the classic top-down dissemination chains of products, and others integrate the data itself that is fed back by people texting and mapping disaster information on the spot.

This is certainly becoming a new culture and it might be interesting to undertake studies on how to join remote sensing and local sensing, but also technological sensing and human or social sensing [60]. A new look at technical and social sensors could help to include the perspectives of people and dramatically expand the range of context information to any point of interest (POI) of a crisis area, for instance. In addition, it would help to better integrate social scientists and get their acceptance of this methodology. Overall, it will tremendously increase the accuracy of information on the ground, the context to human factors, and thereby the richness and validity of a risk analysis and thereby risk management process.

5.3. Not another Science Policy Platform—From DSS to Knowledge Management

One unsolved problem and challenge remains in how all the different results, data, and method developments are managed. This calls for a knowledge management concept for knowledge preservation, back-up, but also for a service provision how to make this knowledge available to a large variety of stakeholders and users. While there is an abundance of platforms designed for certain experts, or other vaguely-specified "end-users" for which an evaluation of their sustainability, efficiency, and acceptance would be valuable. Partly driven by the logic of funding institutions, be it national or EU, communication platforms and Decision Support Systems (DSS) proliferated to an extent where many of those end-users might lose oversight and interest. Research is needed to develop an overall knowledge management concept first rather than creating or connecting more and more products and communication platforms, once more.

6. GIS and RS as a "Critical Infrastructure" for DRM

RS offers a great variety of services to DRM, but overviews and analyses of such services and their range are often wanting. While such overviews are sometimes used to justify funding of RS projects or services, so far RS services are, to a lesser degree, analyzed in a scientific manner. One way to address RS could be to analyze the range and importance of services they offer for DRM. As an example, RS information systems could be scrutinized whether they are a Critical Infrastructure (CI), in the same sense as CIs are analyzed for the purposes of civil protection. CI policy and, concurrently, academic research, were stimulated by activities in the United States, such as the Presidential Commission on CI.

Many other countries followed and classified supply infrastructure such as electricity, gas, mineral oil, water, food and also other services such as the financial system, government, school, media or national heritage and symbols as CI. Is RS a CI of national significance? Well, maybe it is wise to be more modest and start to analyze whether RS carries the characteristics to be critical for DRM. For this purpose, methods such as criticality assessment should be used, that identify the significance of a CI service to a certain customer, in this case, DRM.

RS is certainly interesting in this respect, since it is both a provider of critical services, such as GPS for navigation of rescue teams but, on the other hand, is critically dependent on many other CI services, such as electricity, IT and telecommunications, manpower, roads, *etc.* Such an assessment could help to identify the range and importance of RS for DRM in a more structured and in the end more visible manner.

Table 1 ([61]) gives and exemplary overview on just a few selected services that Earth Observation/Remote Sensing and Geographic Information Systems offer to risk governance bodies and people affected by risks and disasters. While certain qualities of these services are specific, overall, their character that could allow them to be classified as "critical" is based on the observation on the ubiquity and pervasiveness of GPS and similar navigation services amongst public and official navigation devices and practices.

Certainly, it remains open and debatable whether RS should bear the name tag "Critical Infrastructure", since this term is tightly coupled with the politically-driven field of Critical Infrastructure Protection (CIP). In fact, even within our consortium of authors, this terminology is debated. However, this is the purpose of this article, to stimulate discussion and trigger assessments, whether RS carries or not all the ingredients and is according to the criteria of a CI. It could be argued that such a scientific assessment bears its own merits while the political connotations and, therefore, also the usability of RS services for DRM and Risk Governance is another task for debate.

The selection of services builds up on our subjective observations of GIS and RS tools and data utilized by local and national disaster risk governance bodies, including ambulance and firefighting. For a thorough analysis of all services upon their criticality, we refer to national and international strategy papers and guidelines [62] and our previous publications where we have outlined a set of methods to analyze the goals of identifying a service as one of being of a critical infrastructure [63,64]. In this process that exceeds the scope and purpose of this sections, the societal values that are of interest would be identified (saving lives, health, the environment, economic interests, legal requirements, *etc.*), then the services that are related to it, then criticality criteria, such as number of people supplied by it, urgency, and other time dimensions and the specific quality that makes a service critical [65]. For example, the value "human lives" would be at risk from an interruption of navigation data when an ambulance is on the way to a major emergency. When a certain number of ambulances are reliant on such navigation data and time is critical to reach the target position, a certain number of victims of an accident are at risk. The specific quality of navigation data is its accuracy and availability, even for non-local helpers or locations that are difficult to find. It is exactly this combination of critical volume (of people using it and are dependent on it) with critical time frames and service quality that makes a service critical. From a disaster risk governance or economic management point of view it might be questionable whether it makes sense to identify more and more "critical infrastructures", but from a scientific point of view, this is more a question of whether the criteria we deploy and the concept behind it identify certain services as critical and sort out others sufficiently. This can be done for GIS and RS but demands for a more complete analysis than we suggest.

Table 1. Usefulness and critical infrastructure characteristics of selected GIS and RS services for civil protection and disaster risk management/governance.

GIS and RS Services (Selected Examples)	Usability for Civil Protection and Disaster Risk Management	Critical Quality *
Navigation: GPS, *etc*	Ambulance and firefighting services, police, location of disaster areas, people trapped under rubble, *etc.*	Life-saving reduction of response times
Communication: Satellite services, internet connectivity, telecommunications	Early warning services, communication between control rooms and remote teams and affected people, social media devices	Number of people reached by warning, better quality of information based on feedback possibility of people affected, more timely coordination of operations and therefore loves saved, effective risk and crisis communication improving public awareness, knowledge and learning
Monitoring: Natural phenomena and recovery progress Weather and climate monitoring	✓ Space Charter Calls for rapid production of disaster event overviews, long-term planning maps on hazard and risk zonation. ✓ Weather forecasts, Climate scenarios disaggregated on regions where civil protection forces are responsible for	Lives and health conditions improved for a large number of populations by better land use zonation and urban planning. Unparalleled overview and accessibility of data saving time to assess a risk or disaster
Surveillance: Humanitarian relief and refugee camps as well as forced displacement	✓ Rapid assessment of impacts and relief needs. ✓ Identification of refugee streams, possible locations suitable for refugee camps	Knowledge on quantity and geographical distribution of impacts is prerequisite for all other steps of response and relief.

* critical infrastructure meaning of such relevance for society that an interruption could cause human losses, serious health implications or devastating effects on the continuity of a community or society (based on and shortened after definition of national CI Criticality criteria in general linked to critical number, time dimensions and quality to be affected [61].

Satellites are not always ideally positioned at the time of the disaster event. However, some natural disasters may be, to some extent, forecasted, and thus satellites can be alerted and prepared to examine areas at risk. In some cases, core data and systems are unavailable. In others, Disaster Managers are unaware of the existence and utility of RS/GIS. If the data cannot be easily understood, processed, integrated, and presented in a timely manner, Disaster Managers will find other alternatives. Moreover, if society prevents Disaster Managers from acquiring RS/GIS data for public policy reasons (e.g., cost, privacy, security), the benefits will also remain illusory.

Table 2. Dependencies and interdependencies of GIS and RS with traditional National Critical Infrastructure.

GIS and RS Assets and Processes (Nodes and Vectors)	National CI Critical ** in the Sense of Causing Serious Impediment in Case of Failure	Mutual Feedback Loops (Physical, Geographic, Cyber and Logical) ***
Navigation: GPS satellite	Electrical power Oil and Gas Banking & Finance Continuity of Government	Physical, cyber, geographic, logical
Communication	Electrical power Oil and Gas Continuity of Government Transportation	Physical, cyber, geographic
Monitoring	Electrical power Oil and Gas Transportation Water Telecommunication Banking & Finance Emergency Services Continuity of Government	Physical, cyber, geographic, logical
Surveillance	Electrical power Oil and Gas Banking & Finance Continuity of Government Emergency Services	Physical, cyber, geographic, logical

** Infrastructures from the Executive Order 13010; *** interdependency criteria based on [61].

Table 2 provides an insight on the dependencies of GIS and RS services on other infrastructure services, often classified as National Critical Infrastructure (NCI). For a better general understanding of the classifying interdependency criteria listed in Table 2 consider the summer vacationers flocking to the highways when gasoline prices are low, resulting in increased traffic congestion. In this case, the logical interdependency between the petroleum and transportation infrastructures is due to human decisions and actions and is not the result of a physical process [61].

This section displays the ambivalent character of criticality—a service becoming so useful and used that if it fails will cause serious delays, impediments or even worse detrimental effects on all users who got accustomed to rely on it.

7. Conclusions

Geographic Information Systems (GIS) and Remote Sensing (RS) tools and services have become recognized and utilized as major tools for monitoring and analyzing human crises and natural hazards in the past decades. The compounded and complex difficulties described above in this use of GIS and RS tools in practice are both a communication and co-ordination problem.

Our conclusion is that digital technologies, such as these, have obvious capabilities in both dispersing information and coordinating responses in the event of a serious impediment or failure in the national critical infrastructure. The implementation of prototype models to serve as leading indicators and early warning systems in disaster management such as that described in detail in [57] are, at present, in their infancy and in need of further research to tackle situations of abuse and misuse, although we have provided examples of good practice. Ultimately, an interdisciplinary, and not simply technology-led, approach is required to investigate this issue in detail. Despite the technological advances in this area, we also need to understand both the mathematical structure of networks and the inter-relatedness of agent behavior, including the limitations of the models and associated barriers and obstacles in practical implementation. As our research to date shows, we also need to consider the role of sentiment and interactions between new and old media (transmedia) in solving these complex problems.

In this article, we could not address a range of issues that would deserve much more detailed explanation and analysis. As an example, the differential characteristics of GIS and RS and the concurrent implications for consideration within the DRM and Risk Governance fields we have indicated in Chapter 1 and have tried to showcase a few examples throughout the following chapters. One other issue related to this and, in fact, one of the major crosscutting themes of the applicability of spatial information is the question of scale. We did not have the space to cover the different implications of spatial, temporal and other conceptual scales such as administrative scales in this paper. In our previous research [66], based on key literature [23] we have shown at the example of spatial vulnerability indicators how differently in some and similarly in other respects data, assessment methodologies, and the relation to the analyzed objects on the ground interact regarding choice of scale, level, unit, and research area. Since this, itself, is nothing new to spatial sciences, even when related to disaster and risk topics, we have not elaborated on this. However, specifically, crowd-mapping and mobility tracking of individual mobile phone user feedback are adding very scale-specific opportunities for analysis, as well as decision making. The paper has, therefore, focused on these aspects but we acknowledge that we ourselves need and want to carry out more research on the scale effects. Specifically, it would be worthwhile to undertake scientific assessments on the reality of how different stakeholders and the so-called “decision-makers”, as well as so-called “affected people” truly utilize and perceive the products from GIS and RS assessments. While certain products are provided and considered for a specific user-group, it would be interesting to analyze if this is, in fact, useful and whether it is the appropriate group to target.

Just as one outlook, the task of developing user-centered and scale-specific concepts is in keeping with other similar developments such as the national alert system which is set to begin in New York City to alert the public to emergencies via cell phones. This new Personal Localized Alert Network (PLAN) will enable presidential and local emergency messages as well as Amber Alerts to appear on cell phones equipped with special chips and software. The Federal Communications Commission and the Federal Emergency Management Agency confirms that the system will also warn about terrorist attacks and natural disasters. There is clearly much work to be done. The goal is far more important than the mere display of message data on a graph or map. The ultimate objective is to create a reliable tool that allows first responders and others to leverage digital technologies to protect the public at large. The testimony of the value of such a tool occurs when those who use the prototypes designed for their work areas are able to claim these tools are directly responsible for lives being saved.

In order to achieve this, it is necessary to include users already in the design phase of a service in order to (1) be able to do expectation management in the sense that it is realistically described what EO technology can offer and what it cannot—and (2) to best fulfill the user requirements. These are ingredients towards a more participative DSS and processes, where GIS can play an important role with participative simulations, exercises and more coordinated decision based on collective spatial analysis.

Concluding, GIS and RS will be able to express and enhance their capabilities into the field of DRM and Risk Governance much more pointedly, when taking into account the user side. The user may be an individual affected by a disaster situation or a governmental institution responsible for crisis prevention or a risk manager in a company. In many of the examples we have shown, such as vulnerability indicators, crowdsourced or mapped from space, or spatial assessments of mobile phone users, the participation of the users or, people affected by disaster, is a paradigm changer that has prompted many scientists to embrace the opportunities provided. This is not only about delivering better data quality and resolution (spatial, temporal, and causal context quality) for the GIS and RS analyst. It turns the perspective from a product delivery mentality and therefore top-down data processing tool and model view towards an integrative, feedback-up taking concept view.

GIS and RS can play a pivotal role not just in delivering data but also in connecting and analyzing data in a more integrative, holistic way. There might be a path in development from a tool to a concept to even a perspective of infrastructure vital (or "critical") for improving understanding and actions of handling risks and disasters.

Author Contributions

Alexander Fekete has provided the majority of the research and text body for this paper. Katerina Tzavella wrote Section 4 and provided to Sections 1, 2, 3, 6 and coordinated the reviews. Iuliana Armas contributed mainly to Section 4.1. Jane Binner wrote a large section in Section 4.2 and wrote part of the conclusion. Damien Serre advised on sections in Section 3.2 and the overall document. Matthias Garschagen helped to focus the general title and added to Section 2.2. Carlo Giupponi contributed to Section 2.2 and Vahid Mojtahed contributed to Section 3.3. Marcello Pettita added to Section 4.1 and Stefan Schneiderbauer added to Section 2 and Section 3.2. All co-authors provided guidance and in joint meetings we discussed the research idea and structure to investigate this topic from a broader, multi-author perspective.

Conflicts of Interest

The authors declare no conflict of interest.

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