sustainability

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Organizational Aspects of Sustainable Infrastructure Safety Planning by Means of Alert Maps

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Abstract: Road infrastructure safety is a key issue in urban planning for numerous agencies, authorities, central and local administrations, road operators and contractors, in addition to researchers and technology experts. The present study describes a theoretical framework and examines coordination models highlighting how the integration between agencies can be developed with a supporting methodology. By means of alert maps derived from the elaboration of DInSAR (differential interferometry synthetic aperture radar) data, the study defines the actors involved, the alert level for each road infrastructure and the rationale for centralized or flexible coordination models. The potential applications of the approach are tested on a case study in Italy, in an area with about 1600 km of roads in Rome. The study aims to promote synergy between the various agencies for more sustainable infrastructure safety planning and governance.

Keywords: organization; infrastructure; sustainable safety planning; DInSAR technique; alert map

Citation: Troisi, R.; Arena, L. Organizational Aspects of Sustainable Infrastructure Safety Planning by Means of Alert Maps. *Sustainability* **2022**, *14*, 2335. https://doi.org/10.3390/su14042335

Academic Editor: Giovanni Leonardi

Received: 20 January 2022
Accepted: 16 February 2022
Published: 18 February 2022

1. Introduction

A change in perspective is currently taking place in relation to road infrastructure safety management. The focus has shifted from individual infrastructure safety issues with implications limited to each specific infrastructure, to a more integrated approach. Integration takes into account a number of infrastructures that share critical safety issues as a result of their proximity and their interrelation with repercussions at a societal level [1,2]. Thus, integration has two main characteristics. First, it considers a range of infrastructures and the various actors entrusted with their management such as the public authorities, central and local administrations, road agencies and operators. Second, it examines the consequences of safety issues, ranging from the domino effects among interrelated infrastructures to the factors undermining the integrity of the surrounding territory.

The integrated approach is becoming more and more widely adopted in planning and academic research. Bridge management systems (BMSs) are a significant example of integrated strategies adopted by private and public actors. By means of visual inspection-based decision-support tools, socio-economic and engineering factors are analysed to gain an in-depth understanding of how and when to make decisions on infrastructure maintenance. At the same time, planning is aimed at bringing together different actors, both public and private, based on the idea that safety issues have an impact on a more extensive area than just one specific infrastructure.

In terms of academic research, two separate approaches have been adopted. The first approach consists of theoretical work developing frameworks that justify the integration between actors, using models of multi-level governance [3] or organizational patterns [4]. In the second approach, most of the empirical analysis relies on methods and techniques emphasizing the integrated dimension of infrastructure safety. Most of the methodologies depend on multi-informative databases employing digital techniques (e.g., the geographic information system (GIS)) with monitoring technologies (i.e., on-site measurement and remote sensing).

In this connection, in relation to the social implications de Mendonca and Gullo [5] have contributed to planning in areas susceptible to natural disasters (landslides) by means of surveys to estimate risk perception by the general public. As for the identification of multiple structures with common safety issues, Török et al. [6] propose a territorial investigation using a GIS technique to identify improvements in the planning of industrial areas. Other researchers, such as Claudia et al. [7], and Hossein and Sachio [8], have designed risk maps, typically in a GIS environment, for safety planning considering different infrastructure systems. Each approach offers a partial view of the phenomenon, but the link between the theoretical work on how integration can be developed and the supporting methodology is still not well defined.

The present study aims to bring the two approaches together. The focus is on the integration of multiple road infrastructures (including the point elements such as bridges and viaducts) affected by the same critical safety issues rather on their integrated effects. The aim is to understand how to identify road infrastructures affected by common critical safety issues in a geographical area and, in this way, the agencies dealing with the shared problems. The next step is to understand how to coordinate actors to enable them to make decisions in a synergic way.

The identification of the actors involved and of the related circumstances is mainly related to the methodology adopted.

In this connection, researchers have shown an increasing interest in remote sensing, especially satellite techniques, such as the techniques making use of data retrieved from the space-borne synthetic aperture radar (SAR) [9]. Among these, the differential interferometry synthetic aperture radar (DInSAR) is a promising resource [10].

In this study, deformation time series derived from DInSAR data are retrieved from a satellite constellation, the Italian COSMOSkyMed. Specifically, data obtained by means of satellite technology make it possible to consider the effects (displacements) on a set of road infrastructures characterized by geographical proximity in relation to certain hazards (e.g., earthquakes or subsidence, slow landslides, seasonal or temperature phenomena, structural deterioration effects, soil-structure interaction effects [11]). Note that other hazards (e.g., anthropic) and safety aspects are not considered. Furthermore, the elaboration of DInSAR data in a GIS environment makes it possible to create alert maps relating to multiple infrastructures.

This methodology presents two main advantages. First, it deals with multiple road infrastructures that are geographically and functionally interrelated due to their proximity. In this sense, any critical issue is unlikely to be an independent variable, as it could be generated by the surrounding territory and thus concern the interrelation between infrastructures. Second, it makes it possible to determine the alert level for each infrastructure. As a result, alert maps can indicate the agents to involve, since they are responsible for the management of the specific infrastructure, and, according to the alert level, have roles in decision-making (see Section 4). This information can be incorporated into the proposed theoretical framework aimed at explaining how to coordinate the actors involved.

The present study is founded on certain principles that are widely applied in emergency management to support efficient models of integration between the actors involved dealing with a general emergency originating from critical infrastructure safety issues. In its most basic sense, two competing models were identified. In the first model, the focus is on a centralized system based on a command-and-control approach [12]. This is supported by a stringent use of administrative coordination rules and works well provided that two main conditions are met: first, a limited number of agents to coordinate, and second, a degree of predictability of events, in our case a low degree of alert.

The second model is based on a flexible strategy [13] with decentralized decision-making based on a 'loosely coupled' approach. Coordination rules turn into forms of partnership allowing for significant leeway at the individual level [14], particularly well suited to cases in which large numbers of actors are involved, along with unpredictability and large-scale events, in connection with a high alert level.

The choice between a centralized or decentralized model has implications for efficiency and synergy in the management of safety issues. In addition, it aims to determine investment priorities and improve the territorial resilience of the infrastructure.

The alert maps and subsequent coordination models were determined in the present study for a specific Italian area (i.e., a territory with about 1600 km of roads in Rome) by adopting specific alert thresholds in a GIS environment. Bringing together a theoretical framework and a monitoring technique, the results obtained could help to integrate current practices for more sustainable planning.

The idea of sustainability we refer to is multi-criteria and thus it involves economic aspects (mainly expressed in terms of scale economies in reducing costs), social (in terms of increase in security and thus well-being in facing a wider issue instead of a detached one) and environmental (preserving and being preserved by the natural environment in a more complete fashion). Developing each dimension necessarily requires multiple actors. In a virtuous circle, integrating the actors allows for sustainability that in turn generates the need to establish coordination models among the actors to ensure a degree of coherence and synergy among choices.

The remainder of the article is as follows: Section 2 outlines the main features of strategies and plans for infrastructure safety, whereas Section 3 considers insights from the crisis management literature and specifically organizational principles relating to the coordination models. Section 4 examines remote sensing and alert maps, and Section 5 discusses our approach to determining the alert maps. Section 6 describes a case study and discusses preliminary results, whereas Section 7 concludes.

2. Infrastructure Safety Strategies and Planning

Strategies and planning are essential tools for dealing with infrastructure safety. The authorities and operators responsible for road infrastructures can ensure appropriate safety levels by means of effective management strategies. A number of management strategies for infrastructures have been developed, ranging from relatively simple databases with data on bridges and other structures, to more sophisticated approaches. These strategies can help to determine maintenance programmes with the selection of interventions based on financial or economic analyses [15]. Data inventory, inspections and repairs are common factors in all the strategies. In fact, bridges or viaducts represent very important and strategic point elements of the road network and their safety aspects strongly influence the safety issues of the road infrastructures.

Strategies under the heading bridge management systems (BMSs) are particularly relevant in this connection. They deal with all the activities throughout the life-cycle of the infrastructure from design and construction to replacement and are aimed at ensuring safety and functionality [16]. The BMS model is outlined in Steele et al. [17], with activities for database, management inputs and engineering inputs for the BMS Analytical Process systematically linked to outputs. The model aims to determine the most beneficial strategy for bridge maintenance by means of a life-cycle cost-benefit analysis. Strategies may be determined annually or over a number of years for the entire network, or simply for a sub-set. In addition, taking account of budgetary constraints, the BMS model provides an indication of the effects of delayed maintenance on the future condition of the infrastructure and the financial implications of this delay.

Several forms of the BMS strategy have been developed and adopted with varying degrees of success around the world as discussed below.

Two BMSs have been developed and promoted in the U.S., known as PONTIS [18] and BRIDGIT [19]. They have been widely adopted by the majority of bridge management authorities. PONTIS is probably the most advanced BMS. With its top-down approach, PONTIS can be adopted to optimize financial planning for bridge maintenance, rehabilitation and repair, as well as also for improvements to bridge structures at the network level within a specified budget [16]. However, the limitations of the PONTIS system have been identified in Das [20], such as the lack of investigation of the resilience of the infrastructure network at a territorial level.

In Europe, the member states of the European Union have established a programme known as BRIME (Bridge Management in Europe) to develop a comprehensive strategy to deal with the specificities of the European Road Network. The project was undertaken by the national highway research laboratories in a number of countries in the European Economic Area (the United Kingdom, France, Germany, Norway, Slovenia and Spain) [16]. In Italy, different BMSs have been developed by agencies responsible for bridges and infrastructure, such as the Autonomous Province of Trento (http://www.bms.provincia.tn.it accessed on 17 July 2012), ANAS, and Concessioni Autostradali Venete S.p.A. [21]. More recently, the Italian Ministry of Infrastructure and Transport (MIT) has recommended implementing BMSs integrated with structural health monitoring (hereinafter, SHM) as part of a safety management system [22]. The process of SHM typically involves monitoring a structure over a period of time, either short- or long-term, using an appropriate array of sensors and devices (e.g., accelerometers, displacement transducers, strain gauges and thermometers). In a subsequent phase, it tracks the extraction of damage-sensitive features given by the measurements obtained from the sensors, with data analysis to determine the current state of the infrastructure [23].

One important aspect of the various strategies is the question of "top-down" or "bottom-up" implementation. In general, this concerns the source of the standards defined from the top and applied to the entire network, or defined for a single infrastructure typically in compliance with general guidelines for the entire network. However, the indication of the approach is essentially limited to the level that the strategy can adopt, where guidelines on the optimal conditions for the two options are lacking.

Planning to protect infrastructures and urban communities from tidal rise, storm surges and flooding consequential to climate changes [24] as well as from geological hazards is not dealt with in depth by these strategies.

The need for planners to promote protection of infrastructure has been considered in relation to criteria ranging from their capacity to reduce risk, to their sustainability over time [25], and their capacity to develop best practices [26].

Similarly, the question of the agencies responsible for planning has been explored in two ways. The first concerns the multi-governance approach, considering the public bodies involved, together with laws and instruments at different levels [27]. The second concerns private actors involved in the development and implementation of measures deemed to be equally important to reduce risks relating to the safety of infrastructure and to improve efficiency [28]. In this connection, collaboration between civil society groups and other actors (e.g., technical staff, public administrators and other institutions) is recommended [29].

Despite the need to establish multiple levels of governance and actors in planning activities, to the best of our knowledge, insights into how to coordinate them seem to be lacking. The analysis by Troisi and Alfano [4] provides some organizational insights into the safety of road transport infrastructure, mainly based on organizational studies as a framework to provide a systemic analysis in which interdependent actors contribute to overall system performance. This can be intended as the sum of the activities of multiple actors guided by normative and cultural principles at a societal level, in the four different safety stages to be examined below.

3. How to Coordinate Agents: Insights from Crisis Management

Crisis management consists of a sequence of stages (prevention, preparedness, response and recovery) to deal with a crisis. Although in this study the focus is on "alert", concerning one particular stage of potential damage related to prevention, these stages can be considered useful for decision-making purposes.

3.1. Command-and-Control Model

In the early stages of crisis management studies at the end of the 1990s, the focus was mainly on specific interventions based on a command-and-control model, using administrative models with an hierarchical approach, mainly entrusted to the central government [30].

This model assumes that central governments are the key players and the most reliable actors in crisis management, mainly due to the need for financial planning, human resources, and technical and administrative capacity, together with an in-depth understanding of the social and political context to address complex emergencies and risk management issues.

The main features consist of a centralized source of intervention and decision-making, established plans, and an extensive communication and information network mainly in the public sector [31]. This model has the aim of ensuring top-down coordination to facilitate the flow of information and the proper implementation of standard procedures.

The command-and-control model has three main advantages. First, the concentration of decision-making is particularly efficient on a small spatial scale, since it enables a single actor to determine priorities with a degree of certainty of implementation. Second, it ensures open lines of communication and information with a low margin of error due to the small number of agents involved. Third, it guarantees integrated and centralized planning, particularly at the prevention stage [12].

In terms of the disadvantages, the lack of flexibility can lead to unsatisfactory adaptive responses to highly unpredictable events. The rigidity of planned procedures and standards tends to slow down response operations, whereas in some cases ad hoc choices would be more suitable. Moreover, a number of studies have underlined that such a rigid approach results in a strict division of labour, excluding other actors potentially involved in emergency management. In particular, it could reduce the scope of community initiatives [32], overlooking the social contribution and its essential role in the event of a disaster. Finally, considering its overall characteristics, its area of application has been mainly related to events with a low level of unpredictability, typically natural disasters on a small spatial scale, characterized by low agent involvement and a set of standard operations.

Applying these principles to road infrastructures in close geographic proximity characterized by an alert level that is not severe, it is possible to highlight the following points. In the case under examination, the decision-making agent does not necessarily correspond to a public agency, as private actors such as contractors or infrastructure operators may have the necessary resources to play a key role in the management of a crisis. This key role may depend on a higher alert level relating to the infrastructures managed in comparison to others, albeit not severe. The centralization of decision-making in the hands of a single actor managing a particular infrastructure characterized by a higher alert level than the others could result over time in a domino effect on other infrastructures in the vicinity.

At the same time, the general low alert level of the specific infrastructure and others in the vicinity would allow the chain of command to function properly. On the whole, the conditions for the proper functioning of a centralized coordination model consist of a limited number of agents and infrastructures and a certain degree of predictability of events, in this specific case, a general low degree of alert.

3.2. Flexible Model

Since the end of the 1990s, the command-and-control approach to emergency management has been called into question, mainly due to its inability to deal effectively with highly unpredictable and fast-changing crises [33,34]. The command-and-control approach appears to be less effective in terms of the essential function of deviating from established plans, adapting policies and interventions in response to the evolution of the event.

As a result, a more flexible and adaptable model has been proposed in the literature and in emergency management. This model brings together the autonomy of the agents and compliance with joint guidelines. Moreover, it can involve a wide range of agents, regardless of whether they are in the public or private sector, provided they are recognized as key agents in managing the crisis [35].

This model is intended to deal with emergencies as a challenge for society as a whole, with interventions considered as systemic rather than the responsibility of just one agent. The advantages are two-fold: first, the loosely coupled nature of the relation between the agents involved, and second, the adaptive approach mainly relying on a set of flexible coordination mechanisms according to the degree of uncertainty of the event, giving rise to the need for a rapid response. Furthermore, it is particularly well suited to responding to a crisis that has never previously happened, since coping with a disaster gives rise to the need to adjust to rapidly changing events. The key challenge for this model is a right balance between autonomy and interaction; however, once developed, it is particularly well suited to responding to a crisis that has never previously happened, since coping with a disaster gives rise to the need to adjust to rapidly changing events. In such a scenario it should be employed both quickly and in coordination with other approaches [36].

However, the adaptive approach has certain limitations. First, an excessive focus on flexibility can underestimate the importance of key agents in the definition of policies and the provision of suitable resources for responding to and recovering from a disaster. Second, when priority is given to the bottom-up approach, emergency responses may differ from one area to another, leading to an excessive fragmentation of emergency responses not complying with the national standards, or even inequalities within the same State due to the disparity of resources at the local level [37].

Finally, considering the overall features, the flexible approach is considered more suitable for large-scale and geographically extensive events involving a large number of actors, and at the same time, for unpredictable and rapidly changing disasters. It seems to work best in cases in which there are large numbers of agents to coordinate, with an average alert threshold that is higher than it is in circumstances in which the top-down approach seems to be appropriate, since the greater degree of autonomy makes possible a timelier response to imminent danger.

4. Remote Sensing and Alert Maps

To date, the monitoring techniques supporting the integrated dimension of road infrastructure safety can deal with the dimension relating to the integrated effects, and hence the multiple implications of a particular security issue. The main limitation lies in the fact that they are developed by different actors separately for each infrastructure. A mix of motives relating to the costs and exclusive competence supports this tendency. Particularly in terms of costs, it is important to consider the SHM that are implemented by means of on-site sensors, which are extremely expensive when utilized for more than one infrastructure due to the large number of devices required for each infrastructure.

As a result, the separate management of data from different sources by various actors is in contrast with the idea of coordination among the actors and in this way with sustainable safety infrastructure management. In order to deal with these limitations, the present study proposes the use of satellite observation techniques (i.e., the DInSAR technique) with a view to defining alert maps in GIS.

This section outlines the satellite technology and its potential benefits in terms of shared monitoring and supporting coordination among a range of actors. The first subsection describes the relevant technological aspects of satellite monitoring, whereas the second one illustrates the effectiveness of alert maps in a GIS to protect infrastructure from natural hazards.

4.1. DInSAR Technique

Remote sensing is a valuable method to observe the surface of the earth from outer space using satellites (space-borne) or from the air using aircraft (airborne). A major application of the SAR technology is represented by the differential interferometry synthetic aperture radar (DInSAR) technique, which in its basic form exploits the phase difference of (at least) two complex-valued SAR images, acquired by different sensors along lower earth orbits (LEO), between 500–800 km, following polar orbits (ascending and descending, with opposite ground-facing directions) to ensure global coverage. As for the SAR sensors, they may differ mainly in terms of maximum measurable displacement, band, acquisition period, revisiting time, line of sight and resolution [38].

Since the early 2000s, multi-pass DInSAR algorithms (e.g., [39]) have been widely used to retrieve information on displacements of the topographic surface, and grouped into two classes: persistent scatterer interferometry (PSI) [10] and small-baseline subset (SBAS) approaches [39].

Moreover, as reported by Peduto et al. in 2015, numerous factors such as the wavelength, number of images, confidence level of the processing algorithm and overall temporal span influence the accuracy that can be achieved with DInSAR data. As noted in Peduto et al. [38], the accuracy is 1–2 mm/year and 5–10 mm, respectively, for the average velocity and the single displacement time series. In addition, the quality of each measurement is expressed by the coherence that can vary from 0 to 1 [38].

The potential applications of the elaboration of the DInSAR data are testified by the fact that they are increasingly widely adopted, as recorded worldwide with several different projects and case studies for the detection, mapping and monitoring of ground displacements resulting from hazardous events (e.g., [40]). This growing interest is due to several advantages afforded by the DInSAR-based techniques, namely: the extensive spatial coverage of SAR images, the subcentimetric accuracy of the displacement measurements. Finally, economic sustainability is fully ensured as for the cost-effectiveness of the monitoring.

4.2. Alert Maps

The elaboration of the DInSAR data makes it possible to retrieve useful information about road infrastructure by means of alert maps.

The forecast of time of failure and the definition of alert thresholds combined with fundamental aspects of natural hazards in an early warning system can help to reduce fatalities and economic losses. Their implications in terms of environmental sustainability are twofold as they represent a tool to protect road infrastructures from the surrounding and vice versa. As a consequence, they can help avoiding a greater number of safety problems, in this equally representing a mean of social sustainability.

Alert maps and thresholds have been investigated by many researchers, as discussed below. Segalini et al. [41] described a general criterion to define alert thresholds by means of a normalization procedure starting from the creation of a database of displacement data recorded for historical landslides. Mirus et al. [42] demonstrated that accounting for antecedent wetness conditions with direct subsurface hydrologic measurements can improve thresholds for alert systems, providing early warning of rainfall-induced shallow landsliding. In Segoni et al. [43], an early warning system for rainfall-induced landslides was set up in Tuscany. The system was based on a set of state-of-the-art intensity–duration rainfall thresholds combined with real-time rainfall data provided by an automated network of more than 300 rain-gauges. Various attempts to develop earthquake early warning systems have also been discussed in the literature (e.g., [44]).

Mention should be made of the fact that alert thresholds are employed in the methodologies adopted by civil protection departments in different countries to establish priorities, such as the AUGUSTUS approach proposed by the Italian Civil Protection Department.

In this analysis, alert maps, defined on specific thresholds, serve as the technical and administrative instruments to support the coordination models among actors for infrastructure safety planning.

5. Proposed Approach for the Definition of Alert Maps

Our proposal aims to achieve organizational improvements in road infrastructure safety planning with the support of the DInsAR data following the path shown in Figure 1. By employing the deformation time series derived from DInSAR data, in our case related to the Italian COSMOSkyMed satellite constellation, alert maps are defined in the GIS environment as instruments to promote the optimal coordination between the various actors (Figure 1).

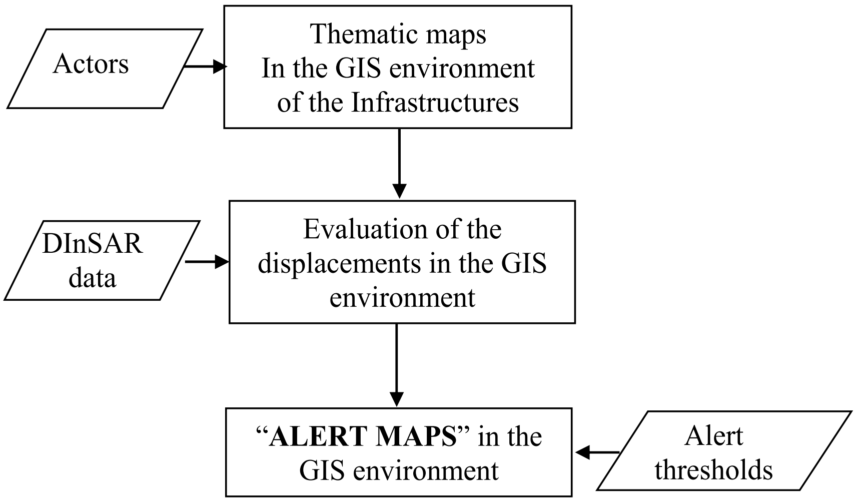

Figure 1. Proposed approach.

The proposed approach consists of three steps with different input data, as summarized in Figure 1:

- Thematic maps, outlining the geographical area and road infrastructure locations, are imported into the GIS environment; at the same time, the main actors are recognized as managers of each infrastructure;
- The DInSAR data are imported into the GIS environment to be processed and to retrieve ground velocity and displacement measurements of the points within a given timeframe. More precisely, the road infrastructures are divided into cells of specific sizes in the GIS environment to estimate the vertical (V) and horizontal (H) velocities and, consequentially, displacements;
- The H and V displacements are compared to corresponding alert thresholds [45], as shown in Table 1, to achieve the alert maps of the infrastructures in the GIS environment.

Table 1. Alert thresholds expressed as displacements.

Alert Thresholds	
Vertical Displacements (cm)	**Horizontal Displacements (cm)**
value > 25	value > 12.5
15 < value <= 25	7.5 < value <= 12.5
10 < value <= 15	5 < value <= 7.5
6.5 < value <= 10	3.25 < value <= 5
4 < value <= 6.5	2 < value <= 3.25
2.5 < value <= 4	1.25 < value <= 2
value =< 2.5	value =< 1.25

As shown in Table 1, with every decrease in the magnitude of the thresholds expressed as both vertical and horizontal displacements, the level of alert decreases. Alert maps have a two-fold benefit in supporting the coordination model among the actors involved. As noted above, alert maps together with the other information in the GIS environment make it possible to identify road infrastructures and in this connection the related agent, based on geographical and functional proximity. Then, in defining the degree of alert for each infrastructure, the maps provide an indication of the optimal coordination model among the actors. In practical terms, the alert map makes it possible, on the basis of specific circumstances, to apply two organizational criteria that are fundamental for choosing an efficient coordination model: the number of actors involved, and the alert level for each infrastructure. Moreover, as this model is based on the extension of data to multiple infrastructures in a given area instead of just one infrastructure, preliminary to establishing coordination models, it could be an important tool for reducing monitoring costs. As mentioned above, an important factor in the development of a system of coordination is the difficulty of finding a monitoring model with sustainable costs.

The output of the present proposal was defined for a case in Italy (i.e., an area of about 1600 km of roads in Rome), as discussed in the following section.

6. Case Study: Preliminary Results and Discussion

The proposed approach was applied to the area covering the municipality of Rome (Italy). The site under investigation is not always flat and some natural hazards (e.g., floods and landslides) characterize the geographical area. The road map in the analysis (implemented in the GIS environment and obtained from "openstreetmap") includes about 1600 km of road infrastructures classified as highways, primary and secondary roads, with different agencies responsible for their safety management.

The agencies responsible for safety management are: AutoStrade Per l'Italia—ASPI, Strada dei Parchi S.p.A., ANAS S.p.A., the State, the Region (Lazio), the Province and the Municipality. Under the supervision of the Italian Ministry of Infrastructure and Transport, AutoStrade Per l'Italia—ASPI and Strada dei Parchi S.p.A. are two private-sector agencies responsible for the management of many highways, alongside the Italian public-sector company ANAS S.p.A. The roads managed by these agencies are shown in Figure 2. Specifically, the figure reproduces the orthophoto of the geographical area and the infrastructure map highlighting the different agencies in the GIS environment.

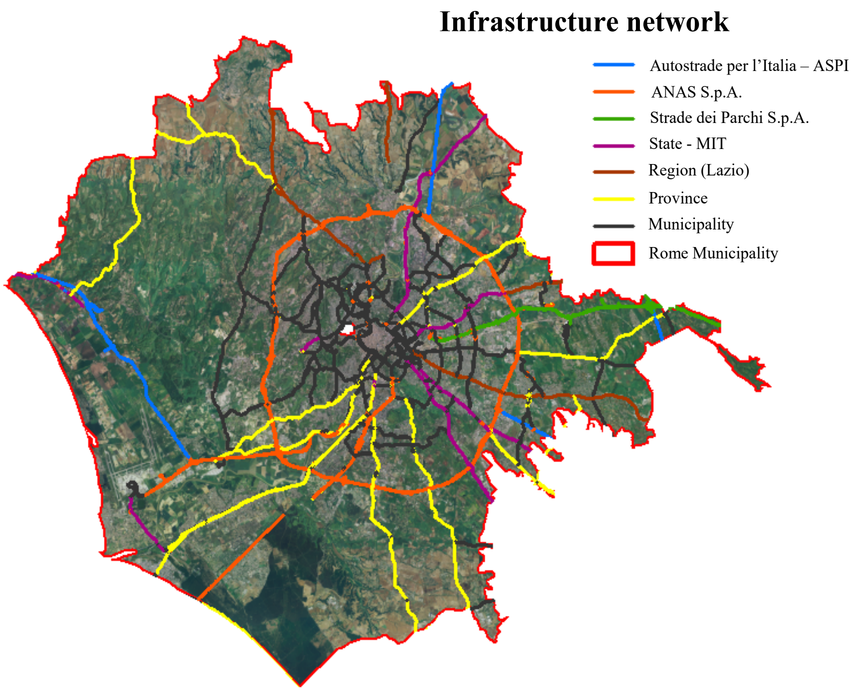

Figure 2. The various road infrastructures (highways, primary and secondary) with the agencies responsible for safety management.

In the present study, the DInSAR data are derived from the elaboration of very high-resolution SAR sensor images (COSMO-SkyMED) on both ascending (34° incidence angle) and descending orbits (29° incidence angle). In particular, 129 and 107 images were used, respectively, for the ascending and descending orbit.

The DInSAR data were then imported into the GIS to retrieve the ground measurements of the points as both velocities and displacements. The timeframe analysed was March 2011 to March 2019 (around 8 years). Selecting a high coherence value equal to 0.6 [46], in the area under investigation, more than six million monitoring points for the ascending orbit (Figure 3a) and more than eight million monitoring points for the descending orbit (Figure 3b) were available. Figure 3a,b shows the intensities of the average velocities in the timeframe under analysis (i.e., 8 years).

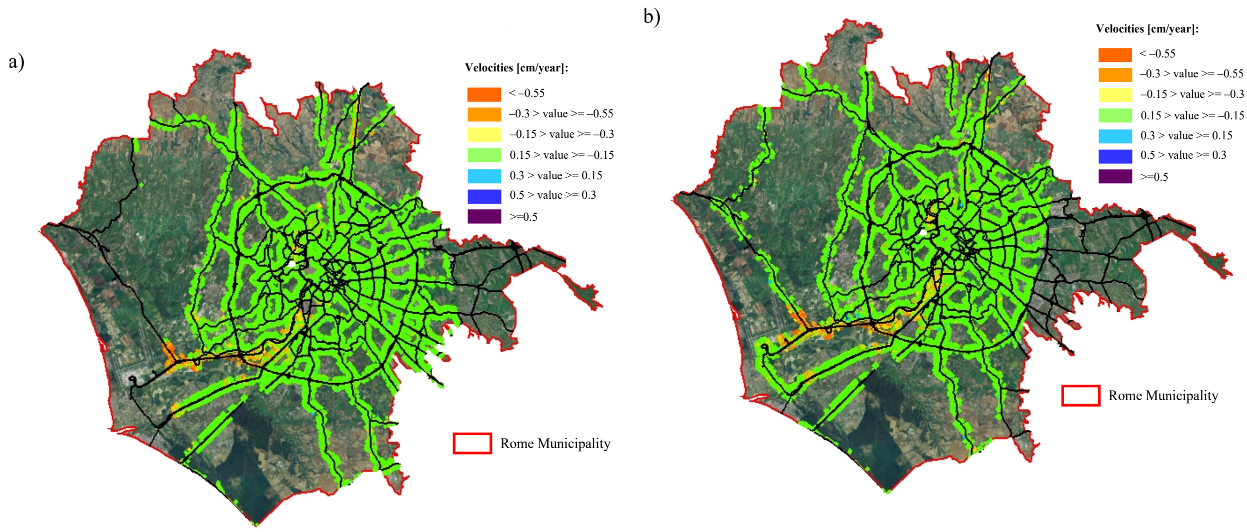

Figure 3. The monitored points with velocities (cm/year) corresponding to the ascending (**a**) and descending (**b**) orbit.

The next stage consisted of the division of the road infrastructures into regular cells measuring 50 × 50 m, as proposed by Calvello et al. [47]. Each cell was designated "covered" if at least one measurement point (with measurements associated to a 3 m × 3 m square) was within its perimeter, also taking account of localization error [38]. The cells covered by the two orbits (i.e., ascending and descending) amounted to about 2000 cells, as shown in Figure 4.

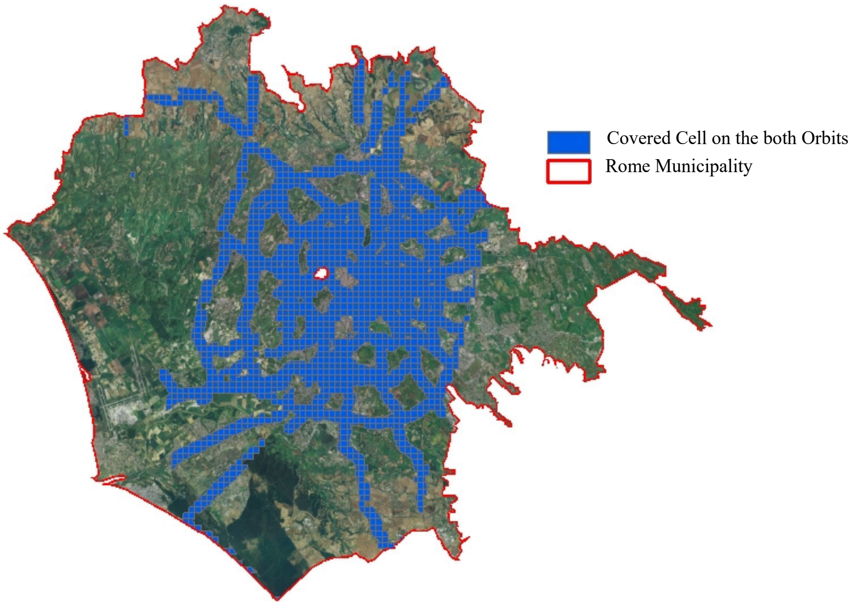

Figure 4. Cells covered by the two orbits.

In this way, the average velocity (in time and in space) value was calculated for each covered cell in accordance with Peduto et al. [38]. Then, combining both the ascending and descending data, the V and H velocities and, consequentially, displacements were determined. Finally, these values were matched with the alert thresholds (Table 1) to construct the alert maps plotted, respectively, in Figure 5a,b.

From the alert maps, it may be noted that both V and H displacements were observed in different road infrastructures. Specifically, severe alerts for both the vertical and the horizontal displacements were recorded for a number of infrastructures managed, respectively, by ANAS S.p.A., Autostrade per l'Italia—ASPI and the Municipality of Rome (Figure 5a).

At the same time, in the upper part of the map, a single infrastructure, managed by Autostrade per l'Italia—ASPI, the Province and the Municipality of Rome (Figure 5b) presented medium-level alerts with regard to horizontal displacements and a low- to medium-level alert with regard to vertical displacements, whereas the connected infrastructures all had low-level values with regard to both V and H alerts. Finally, for the other infrastructures on the maps, the alerts were low or very low for both horizontal and vertical displacements.

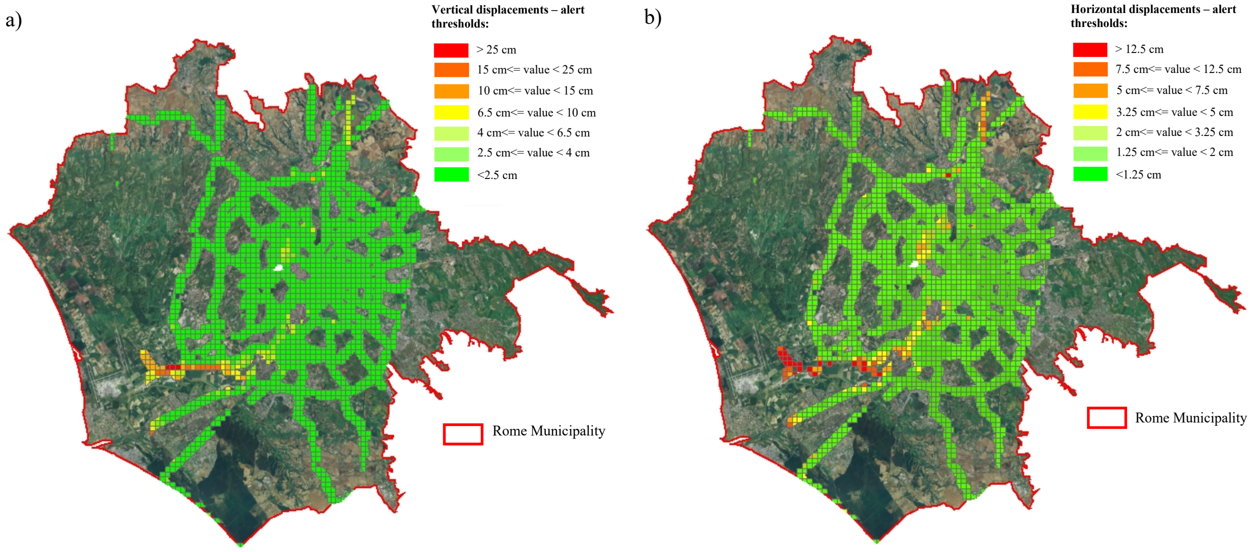

Figure 5. Alert maps of the road infrastructures relating to V (**a**) and H (**b**) displacements.

Two sub-scenarios can be highlighted in the alert maps to justify the application of the two different coordination models. In the first scenario, characterized by multiple structures affected by severe alerts, flexible coordination models appear to be preferable. Each infrastructure identified has an alert level that could rapidly escalate and spread to other infrastructures due to their connectedness and geographical proximity. A high degree of autonomy in decision-making makes possible rapid intervention without losing sight of general coordination. This should lead to the definition of shared guidelines in order to avoid acting in an uncoordinated manner in response to shared problems. The presence of a common alert of a severe nature that makes the sequence of events unpredictable can further justify the need for a mix of autonomous solutions and shared choices. For example, urgent requirements may justify autonomous decision-making within the framework of operational standards and controls.

The other scenario identifies infrastructures with a higher alert level, albeit contained, between geographically connected infrastructures with a lower alert level on average. The model of vertical coordination is effective in this case, albeit with some limitations. This cannot be considered a chain of command, properly speaking. Infrastructure managers have different functions, with some operating in the public and others in the private sector: they can hardly be coordinated in terms of an hierarchy. In addition, each agency invests financial resources of its own, making it difficult to delegate decision-making to other agencies. However, a higher alert level affecting one particular infrastructure has a greater chance of impacting on the infrastructure of another agency, causing damage as a result. It is possible to adopt a centralized model taking account only of how to manage the impact of the alert and how to contain its cascading effects. Centralized decision-making in dealing with a shared problem as a whole would provide benefits in terms of economies of scale, while facilitating the adoption of homogeneous measures for the same problem.

Considered overall, this approach can integrate current practices for more sustainable safety planning, improving the synergy between the agencies involved. The set of advantages in terms of sustainability are to be considered different in the case of economic sustainability and shared in the case of environmental and social sustainability. From an economic point of view, sharing activities such as a monitoring—as said—involves considerable cost saving although distributed differently in the case of the vertical or horizontal model. In the vertical model it is reasonable to imagine greater economic expenditure for the structure with a higher alert level. On the other hand, the economic sustainability stands also in economies of scale that could represent mainly a benefit for the actor in a centralized position.

At the same time, decisions regarding the planning of future monitoring activities, inspections and interventions should establish the priority for those infrastructures with the highest alert levels. Similarly, it is possible to plan the layout development of the infrastructure network referring to the lowest alert levels. Other advantages are in common. From an environmental point of view, the sharing of planning and coherent related interventions is preferable to single initiatives responding to different, but not necessarily compatible, logics both to protect and to be protected from natural risks. In addition, a common schedule in programming instead of temporally disconnected initiatives can equally produce positive effects at an environmental scale. Then social benefits should grow: as mentioned above, integrating security has a positive effect on the communities by widening the spectrum together with the kind of protection.

Finally, the way the coordination models outlined above can be put into practice depends on compliance with administrative and asset management requirements that are not necessarily an obstacle to moving beyond isolated management in favour of joint management.

Furthermore, this study offers some key elements that can help to put into practice the integrated management described above. On the one hand, the flat model can be implemented where many actors, thanks to a common low degree of alert of their infrastructures, have the time to establish parity rules in terms of both authority and responsibility that may turn into joint investment of resources, shared risk taking and mutual benefit.

On the other hand, it is possible to implement a vertical model that is based on a few actors and urgency of intervention that focuses on the infrastructure with the higher alert level.

Where there is a higher risk there is also a centralized position that is based on the combination of greater responsibility and greater investment. Many departments in the public sector have been frequently experimenting with forms of partnership with the private sector which put into practice these kinds of models and the benefits they derive, ranging from having greater resources than public budget constraints allow, to seeking innovation and to aiming for better risk management.

7. Conclusions

The present study outlined an integrated approach to road infrastructure safety considering multiple infrastructures affected by shared safety issues. It laid the groundwork for organizational improvements in the safety planning of road infrastructures through the elaboration of DInSAR data. The study focused on two main objectives.

The first objective was theoretical, aiming to bring together theoretical studies defining frameworks to justify the integration between the agencies involved in infrastructure management, with the empirical analysis mainly relying on methods and techniques emphasizing the integrated dimension of infrastructure safety. Alert maps make it possible to define the optimal model of coordination among agencies. The satellite-based analysis in the GIS environment aims at identifying all the agencies responsible for the infrastructures under examination, and at the same time the alert level of a specific infrastructure. By combining multiple infrastructures with the alert level, we can identify under what circumstances and how to identify infrastructures affected by common critical issues and, in this way, the agencies affected by a common problem. It is thus possible to understand how to coordinate agencies with a view to adopting synergic decisions. The study highlighted two potential scenarios in which centralized or flexible models can be efficiently developed.

The second objective concerns the lessons the approach can offer to stakeholders involved in infrastructure management to achieve more sustainable safety planning. In this connection, alert maps provide a useful instrument for planning activities to identify investment priorities determining the allocation of economic or financial resources where necessary for the prevention of emergencies. The potential applications of the approach were tested on a case study in Italy (i.e., an area with about 1600 km of roads in Rome) by defining alert maps in the GIS environment.

However, it is important to mention the limitations of the proposal. In particular, validation of the results obtained is always necessary, especially when severe alerts are identified, through on-site or structural engineering calculations. In addition, it is important to specify that the impact of other kinds of natural or anthropic hazardous events occurring suddenly and unexpectedly [48] cannot be captured by satellite sensors, and as a result, for these events other alert maps are required.

Finally, it is worth underlining the fact that the typology of the interventions is dependent on the expert judgement of engineers, and alert maps have to be updated within a specific timeframe in compliance with the specific characteristics of the site and the system of governance.

Author Contributions: R.T. conceived and designed the idea; L.A. collected the data and performed the analysis; R.T. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors wish to thank William Bromwich for his painstaking attention to the copy-editing of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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