Remote Sensing in Multi-Risk Assessment

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***Abstract*—Scientific literature reports several possible ways for remote sensing contribution to risk assessment of natural disasters, not only in a theoretical perspective but also in concrete applications. However, the typical remote-sensing-scientist approach to risk assessment has so far reflected one of the main limitations of the general risk assessment process where several natural disasters are concerned. In order to avoid facing the sometimes unmanageable complexities arising from inter-hazard/vulnerability dependencies, indeed, risk assessment activities tend to focus on one hazard at a time, sometimes leaving dangerous gaps in understanding the real risk pending on a community or an economic system. Given the current trend, in the risk assessment community, to move from a sum-of-hazards to a multi-hazard approach, this paper intends to build on previous scientific literature to bring the same perspective to remote sensing. The importance of the subject is supported and explained; a comprehensive review of the existing multi-risk assessment approaches is provided, and tangible contributions of space-based Earth observation is highlighted in the different phases of the disaster management cycle. Different strategies are discussed and one specific example is presented more in depth as one of the most promising approaches.**

***Index Terms*—multi-risk assessment; multi-hazard assessment; vulnerability mapping; geo-spatial data fusion**

I. INTRODUCTION

Natural and man-made disasters have steadily increased the toll they collect worldwide, in terms of human lives, financial damage, and in terms of delayed economic recovery of the affected countries [1]. The problem is increasingly perceived at a global level. On the one side, rapid increase of world population, manifested in the sprawling of inhabited areas, is widening the extent of vulnerable areas; on the other side, technological activities have broadened the hazard spectrum, affected the intensity and the frequency of several event types, and have raised significantly the overall vulnerability of societies. Consequently risk assessment has attracted attention as a crucial constituent to mitigate and if possible avoid disruption of societal activities at large [2]. Furthermore, the study areas are often subject to several types of risks (e.g. earthquakes, floods, landslides, tsunami, or technological risks) thus a multi-risk assessment, rather than a single-risk assessment would offer a more advanced approach in solving real world problems. However, multi-diciplinary terms, such as risk and multi-risk, often exhibit overlapping, diverging, and some times contradicting definitions. Thus establishing a standard reference for the definitions would create shared understanding of terms, avoid terminology confusion, and maintain the study consistency. The topic at hand is on multi-risk assessment which forms the core of disaster risk reduction practices. Therefore, the glossary of terms from the United Nations International Strategy for Disaster Reduction (UNISDR) [3] was taken as a reference source for the definitions of this document (see Table I).

The document is organized as follows: Section two introduces the risk concept with its two essential elements - hazard and vulnerability - and gives an overview on methods for risk assessment in literature. Section three illustrates the shift in paradigm from risk to multi-risk assessment stating the importance of the approach and highlighting a number of related general challenges. The existing multi-risk mapping strategies are underlined in Section four. Section five highlights the remote sensing contributions to the risk components and the disaster management cycle of different types of hazards. Finally, Chapter six summarizes and concludes the report.

II. THE RISK CONCEPT

This section is a preface on the concept of risk. In recent times, the gradual switch of people's perception from being disaster-reactive to disaster-proactive is the prominent lesson learned by experience for the attainment of sustainable development [4]. In that context, the concept of risk has been evolving during the last five decades and risk-models extended from being hazard-dependent to include other componenOverviewts e.g. vulnerability, exposure, and capacity (see Table I). Moreover, the relationship among the risk components have attracted significant attention leading to broad varieties in the proposed models, where several research groups presented their conceptual holistic framework of risk [5], [6], [7], [8], [9], [2].

Several risk models, in presenting the holistic risk, introduced exposure and capacity as parts of vulnerability whereas others present them as separate components. While the conceptual frameworks present tools for a general understanding of risk elements, risk assessment would require assessing the components to facilitate the risk computation and consequently simplify comparison and ranking of the risk-prone areas. Therefore risk can be formulated as a result of the multiplication between the potential damaging phenomena (hazard component) and the degree of susceptibility of the exposed elements, [3].

Risk notation:
$Risk = Hazard * Exposure * Vulnerability$

A. Hazard

As defined in Table I, hazard is the potential damage emerging from a physical phenomenon that can disrupt the functionality of a society. Hazards are often categorized according to their origins into two broad groups: natural or technological hazards. Moreover, natural hazards are classified into three branches: hydro meteorological (with atmospheric origin), geological (with tectonic origin) and biological (e.g. outbreak of epidemic diseases) [3]. However, specifying a

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Table I
THE RELEVANT UNISDR DEFINITIONS [3].

Hazard	A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation.
Exposure	Exposure is defined as: People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.
Vulnerability	The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards.
Physical vulnerability	The term is determined by aspects such as population density levels, remoteness of settlement, the site (*UNISDR indicating the asset location as a physical vulnerability proxy), design and materials used for critical infrastructure and for housing. Conventionally risk is expressed by the notation: Risk = Hazard*Vulnerability. Some disciplines also include the concept of exposure to refer particularly to the physical aspects of vulnerability.
Capacity	A combination of all the strengths and resources available within a community, society or organization that can reduce the level of risk, or the effects of a disaster.
Risk	The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions.
Risk assessment	A methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend.
Disaster reduction	The conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks throughout a society, to avoid (prevention) or to limit (mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development.

hazard category is often not a straightforward decision due to the compound relationship among the categories themselves. For instance, landslides might have geological (Earthquake or volcanic eruption) or hydro-meteorological (Floods, precipitation) origin, but they can also be induced by human activities as deforestation.

Hazardous events are distinctive by type, intensity, frequency and their impact on the elements at risk. Moreover, each hazard type has a specific magnitude unit related to the amount of energy released during its physical process [10], e.g. the quake size is measured with moment magnitude scale (MMS) while floods with the discharge scale in m^3/sec. The historical archives on the features of previous hazards give better understanding of the phenomenon and enable predictions on a hazard intensity and the likelihood of its occurrence. Finally, human activities are affecting the natural system by enhancing the environmental degradations that changes significantly the facets of hydro meteorological natural hazards and consequently limits the efficiency of the forecasting models [11].

B. Exposure

Exposure is the set of valuable elements under potential loss in the hazard area, see Table I. The main essential values are people and their livelihood [3]. The mentioned vectors (population and livelihood) are obviously very difficult to map directly from remotely sensed data, however an indirect way to address the problem is through mapping of buildings or built-up areas.

C. Vulnerability and Capacity

The concept of vulnerability has been evolving since it was regarded as a risk element, thus it has assorted interpretations in the various disciplines. Birkmann referred to the paradox of aiming to measure vulnerability if we cannot yet define vulnerability precisely [8]. Despite the various interpretations of vulnerability in the literature, a set of shared characteristics for vulnerability are noticeable as being multi-dimensional, dynamic, scale dependent and site-specific [12].

The recent concept of vulnerability highlighted inverse proportionality between the susceptibility and the development of a community [13]. As the definition in Table I states, vulnerability is composed of four aspects:

- the physical factor often determined by material characteristics of the concerned assets e.g. population density and buildings properties,
- the social factor measured through the extent of well-being,
- the economic factor retrieved from the economic status, and
- the environmental factor deduced from the level of resource depletion in a society.

Moreover, the impact of a disaster on a community is directly dependent on its coping ability, thus the capacity building in the various vulnerability aspects (e.g. imposing building codes and raising public risk-awareness) would reduce the susceptibility of a community and meliorate the polices and measures of disaster risk reduction.

III. RISK ASSESSMENT

The section highlights the common approaches to risk assessment using its fundamental components: hazard and vulnerability. Risk assessment is usually done separately for the different potential losses e.g. number of fatalities, number of affected people, or economic losses. However the different methods share a common assumption that combine a hazard (through the probability of occurrence) to a vulnerability (through its corresponding consequences). This is summarized in Table II & Table III. Moreover, the analysis objective and scale, together with data availability are the chief points in selecting the method type. The estimation techniques are often grouped into three broad categories: **qualitative** (inventory and knowledge driven), **semi-quantitative** (partially data driven) and **quantitative**(data driven, deterministic, and probabilistic methods)[14], [15], [16], [17], [18], though the second technique tends to be a conjunction of the other two categories (see Figure 1).

Furthermore, a good representation of the spatial risk is often made through a combination of different intensity levels (hazard) and consequence categories through a risk ranking matrix (see Figure 1).

A. *Qualitative techniques*

These are flexible methods that give qualitative descriptions of the risk factors judged by experts (e.g. 'very high', 'high', 'moderate', 'low' and 'very low' risk). The qualitative techniques use experts' opinion in defining a set of ranked classes for risk intensity and its potential consequences [19], [20]. However, the qualitative methods allow comparison and ranking but without specifying the quantitative difference among the concerned levels. The methods are usually applied at large scales (national) where the absence of data details is tackled by moving towards a more qualitative approach. While the main advantages of these techniques are their simplicity, which facilitates the understanding process among stakeholders, and their applicability in scarce-data situations, the crucial drawback is their intrinsic subjectivity [14].

B. *Semi-quantitative techniques*

These methods are also flexible and enable lower levels of generalization and subjectivity compared to the qualitative methods. The main difference compared to qualitative approaches is that the classes' thresholds, for either the severity or the likelihood, are derived from the statistical analysis of historical events rather than being assigned qualitatively by experts [21], [22]. In these techniques the risk is often expressed in terms of indices, as proxies pointing at a generic risk level, with no direct physical meaning. Even though, the methods are appropriate for all scales of analysis, they are regularly applied to medium scale (regional) [19].

C. *Quantitative techniques*

These methods involve technical details and thus are often implemented by engineers. The techniques express risk quantitatively either as expected losses or probabilities [16], [9]. They can be deterministic/scenario-based or probabilistic and usually applied at local scale due to the process complexity as well as to the required detailed data. Quantitative risk assessment enable the computation of impacts for all potential scenarios which form the risk curves [23].

IV. FROM RISK TO MULTI-RISK ASSESSMENT

This section highlights the importance of multi-risk approaches and elaborate the general additional challenges they boost. The intrinsic connection between multi-risk concerns and risk management allowed the 'multi-risk' term to gain a growing attention in the international policy. For instance, several United Nations (UN) plans highlighted the importance of the multi-risk concept on human settlement planning and management in disaster prone areas [24]. Moreover, Federal Emergency Management Agency (FEMA) used a multi-risk approach in the US national risk mitigation strategy [25]. Additionally, the Hyogo framework of action adopted the appellation 'multi-risk' and stressed on its usage in disaster risk reduction [26].

A. *Importance of multi-risk assessment*

Well-founded risk identification and assessment are the fundamentals of a coherent risk management plan. Disaster risk management is regularly implemented on segregated spatial units (e.g. province, region, country, continent, or planet), but often the exposed elements of a territory are vulnerable to more than one type of hazards.

While single-risk approaches, i.e. risk considering a single type of hazards, may not provide sufficient information for risk management decision, the multi-risk concept forms a better tool for understanding and demonstrating the complexity of danger issues of a given area. Additionally, a multi-risk method enables a considerable participation of decision makers and offers an objective-based guidance of the analysis. As a result, the integrated risk prioritization would lead to improved flexible risk models.

The real-world problems made the multi-risk approach critical for an effective risk management [21]. Each type of hazard leads to a hazard map and by overlaying the spatial distribution of the elements at risk we can specify different risk levels. The multi-risk approach is important in depicting the aggregation of risk maps with diverse geographical extents (e.g. the wide-area effect of an earthquake compared to the often local impact of landslides). As a result, comparison among spatial patterns of risks can be carried out both to determine the crucial risks of the exposed elements and to afford guidance in emergency situations [23].

Multi-risk maps should not be considered alternatives to single-risk maps since they reflect different types of information. While single-risk products offer a detailed assessment of a hazard and its potential consequences, multi-risk products result from the agglomeration of more than one risk affecting an area and especially integrate cross-dependencies. Consequently, multi-risk maps represent an important but supplementary decision-level tool that consider the local importance of hazard types and serves as a common communication language between experts and stakeholders.

B. *General challenges of multi-risk approach*

Whereas the literature contains deep-rooted techniques for single risk approach [27], studies on multi-risk are relatively

Table II
EXAMPLE ON THE QUALITATIVE AND QUANTITATIVE DEFINITION FOR THE PROBABILITY OF OCCURRENCE OF AN EVENT.

	Rare	Unlikely	Possible	Likely	Certain
Qualitative	Events virtually never occurred	Events are unlikely to occur, but has to be considered as being possible	Unlikely but may occur when considering several similar situations	May occur once during the total studied period	May occur several times during the studied period
Quantitative	Event probability is $< 10^{-4}$ per 25 years	Event probability is between 10^{-4}&10^{-3} per 25 years	Event probability is between 10^{-3}&10^{-2} per 25 years	Event probability is between 10^{-2}&10^{-1} per 25 years	Event probability is $>= 10^{-1}$ per 25 years

Table III
EXAMPLE ON THE QUALITATIVE AND QUANTITATIVE DEFINITION FOR THE SEVERITY OF EVENT AS A RATIO OF LOSSES TO NATIONAL GDP.

	Negligible	Low	Moderate	Significant	Catastrophic
Qualitative	Negligible economic loss	low direct impact economic loss which can be easily restored	Moderate economic loss, still can be hardly restored	Large economic loss which cannot be restored	Catastrophic economic loss which cannot be restored
Quantitative	Event Severity is $< 10^{-4}$ of National GDP	Event Severity is between 10^{-4} &10^{-3} of National GDP	Event Severity is between 10^{-3}&10^{-2} of National GDP	Event Severity is between 10^{-2}&10^{-1} of National GDP	Event Severity is $>= 10^{-1}$ of National GDP

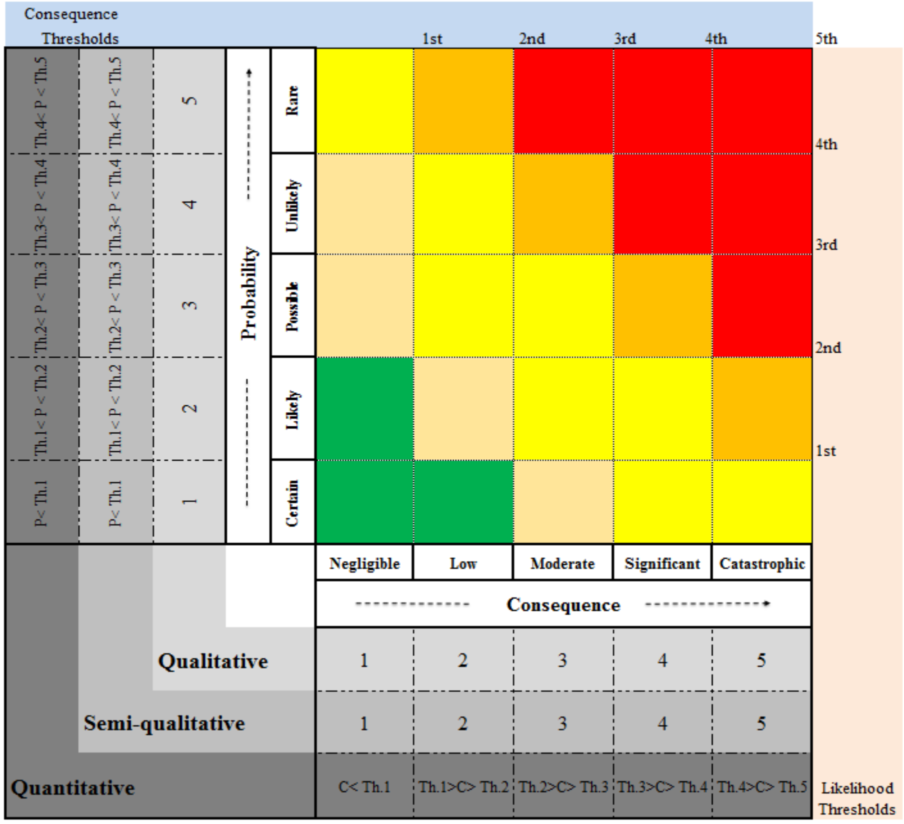

Figure 1. The risk matrix shows the three risk assessment techniques, where P and C indicate the probability of occurrence and the consequence of an event respectively.

limited due to the absence of standard aggregation techniques. However, multi-risk modeling raises additional issues for the already intricate risk assessment task. The principal challenge is how to integrate diverse technical approaches and terminologies within a unifying loss-calculation framework.

Moreover, shifting the representation from single- to multi-risk raises another considerable challenge related to the interpretation of the maps. On one hand, creating several single risk maps has the traditional drawback of information dissociation resulting into difficult comprehension of the overall risk. On the other hand, the presentation of several risks in a final map will shrink a lot of information into a single output, which poses issues on readability and interpretation for different stakeholders. Therefore several previous studies suggested risks partitioning, to alleviate the visualization problem, by establishing classes with more than one hazard type pending the objectives, e.g. UNISDR categories [3]. As a result, the multidimensional problem is divided to empower a smoother communication and a better understanding of the geographical correlations among risks.

Multi-risk approaches have intrinsic subjectivity as they require an extensive field knowledge on the crucial factors and risks. As a result, a multi-risk assessment would be only transferable after adapting the scoring system accordingly.

V. EXISTING MULTI-RISK MAPPING PRACTICES

This section gives an overview on the existing multi-risk frameworks and highlights some of their specific complications. Multi-risk assessment is a result of studying the potential impacts of a set of individual risks acting on an area. The review on the existing multi-risk frameworks highlights two main strategies for creating representable multi-risk maps. The first strategy suggests concatenating the different hazards and their corresponding vulnerabilities separately and then using the two created layers (overall hazard and vulnerability) to assess multi-risk (see Figure 2). On the other hand, the second scheme proposes integrating the products of individual risk assessment of each hazard in order to obtain the multi-risk maps (see Figure 3).

A. Multi-risk assessment as integration of hazards and vulnerabilities separately

The principal difficulties for this approach can be summarized in the aggregation process of multi-hazards and vulnerabilities independently.

1) Multi-hazard Assessment: The main challenges that appear in multi-hazard assessment are the comparison and the dependency among the hazards.

a) Hazards Comparison : The problem raises challenges in the assessment, comparability and ranking among hazards of different types that have diverse measurement units. The dilemma originates in the different units used to describe hazards with distinct characteristics and the absence of a standard reference unit.

b) Hazards Dependency : The correlation between multi-hazards acting on a geographical pattern, due to their spatial and/or temporal overlapping, may create a hazard level that differs significantly from their linear combination. Moreover the geographical overlapping of various threats adds further complications such as:

1) A single hazard might create several threats i.e volcanic eruption leading to ash and lapilli fallout, lava flow, or lahars [14].
2) The primary hazard triggers successive hazards (the dynamo effect). For instance landslides can be a consequence of an earthquake, heavy precipitation, or deforestation [20], [28].
3) The simultaneous occurrence of completely irrelevant hazards.

However, the field remains restricted to few research studies due to its complexity, deriving from the significant increase in the number of the possible overall hazard scenarios [9], [14], [23].

2) Overall vulnerability assessment : The difficulties that arise in vulnerability assessment extend on its various components (physical, social, economic, and environmental). Additionally, the assessment of the coping capacity in the context of multi-risk becomes more complex. However here we will highlight only the constraints that arise on the physical vulnerability factor.

a) Physical Vulnerabilities Comparison : The assessment, comparability and ranking of different types of the exposed elements vulnerabilities add principal obstacles for the approach [19], [29]. The same assets show diverse vulnerabilities for different hazard types, thus the exposure sensitivity of an exposed element has to be considered for a consistent multi-risk assessment. The exposure of the elements at risk to diverse threats creates a hazard-dependent vulnerability features. Therefore, a new issue appears when comparing vulnerabilities of the exposed elements to different hazards as their measures vary significantly. For instance, while the vulnerability to seismic risk can be measured by the physical damage it leaves, the vulnerability to a chemical, biological or radiological accident is measured through the evacuation and decontamination durations. Therefore common units of measurement are required for overall vulnerability estimation. Moreover, the physical characteristics of an exposed element contribute variously to its susceptibility to different hazards. As an illustration, building features as: location, height, density, and construction material would affect distinctly their physical vulnerability to earthquakes, wind storms, or floods.

b) Physical Vulnerabilities Dependency: The elements at risk have changing characteristics for co-occurrence or re-occurrence of hazards which have to be considered in their overall vulnerability assessment. The relationship among hazards prevails to alter the overall physical vulnerability levels of the exposed elements through two main layouts:

1) simultaneous hazards: The overall vulnerability of the elements at risk can show drastic increase due to co-existence of several independent hazards. In particular, the impact of an earthquake would raise if it occurred

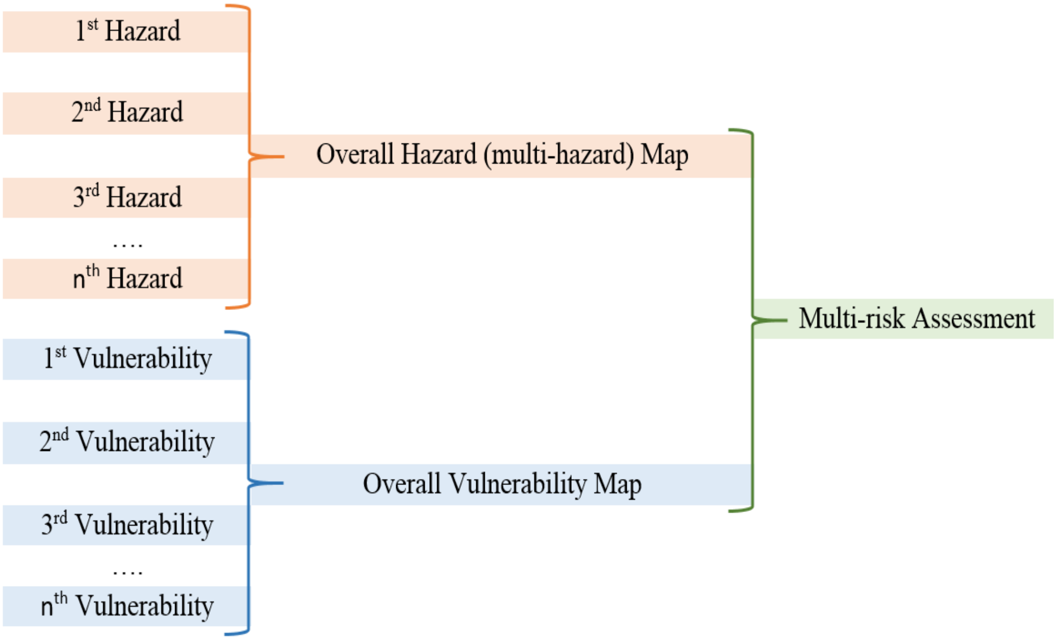

Figure 2. Chart on multi-risk assessment strategy as an integration of hazards and their vulnerabilities separately.

during a snow storm or a volcanic ash fall, as the effect would be amplified on buildings appended with loads as well as on death toll due to the high occupancy rate.

2) successive hazards: the successive occurrence of independent or triggered hazards sometimes accumulates the vulnerabilities of the exposed elements and increases significantly the impact of subsequent hazards on the assets, e.g. the damaging effect of a strong aftershock or a tsunami on buildings after an earthquake.

The interaction among vulnerabilities is rarely studied however the topic started attracting more concerns due to its high impact on the predictions of losses [14], [30].

B. Multi-risk assessment as integration of individual risks estimations

The scheme proposes the combination of individual risks estimations, where each risk is computed from a hazard type and its corresponding vulnerability. Although risks came from hazards of diverse physical phenomena, the risk metric can be a common unit describing an element of the potential direct losses e.g. estimated number on fatalities, number on affected people, or economic losses. As a result, risks aggregation phase is facilitated and the outputs are presented as simplified risk maps.

This approach enables an easier way to detect dominant risks of a region, as it would be easier for the stakeholders to prioritize and weigh the potential threats according to the final expected loss impact. The challenging factor would be in a reliable selection of the dominant risks for an area considering the stakeholders' prioritization and the dependency among the individual risks. Thus, a stress on the importance of integrating the stakeholders' perceptions in the definition of multi-risk maps incorporates more qualitative features into multi-risk assessment [9].

Even though the multi-risk notion inherits the dynamic property of single-risk assessment, often its estimation is not a direct combination of the separate risks [31]. Therefore the process of ranking and weighting the local risks has to be taken into concern. Moreover the single-risk inclusion in the assessment process has to be quantified by a minimum cut-off threshold for its expected losses (e.g. risks with potential fatalities exceeding 10 people) which have to be adjusted to the spatial scale of the study.

VI. REMOTE SENSING IN DISASTER MULTI-RISK MANAGEMENT

The section highlights how remote sensing (RS) can contribute - as a spatial data source - to a multi-risk approach of disaster management. 'Remote Sensing' in Earth observation usually refers to both of the two broad categories space/air -based; though, civil and environmental protection are increasingly relying on space assets both in the response and in the preparation phases. Let us consider for example, Copernicus [32] -formerly GMES- the joint initiative of the European Union and the European Space Agencies to build an integrated space-based system for monitoring the Earth. Of the 8 application domains of Copernicus, at least 5 are directly related to risk assessment and mitigation, i.e. “environmental protection”, “civil protection”, “public health”, “transport and safety”, “urban and regional planning”. In this section, we will thus concentrate mainly on the potential of the space-based systems in risk assessment. Broadly speaking, all data types that give a detailed understanding for at least one of the risk components (hazard and/or vulnerability and/or exposure) would be helpful for multi-risk assessment. Moreover, remote

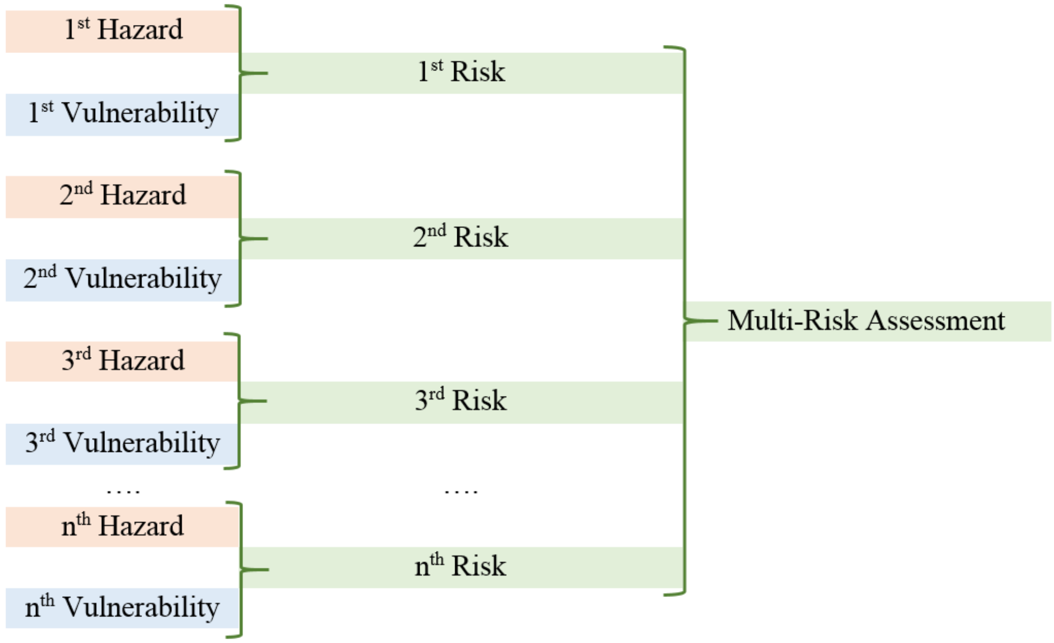

Figure 3. Chart on multi-risk assessment strategy as an integration of individual risk estimations.

sensing as a geo-spatial data source offers a peculiar value in granting low-cost and broad-coverage data acquisitions, useful in the different phases of a disaster cycle even if the accuracy of the information may not be always guaranteed as it is in e.g. direct ground surveying.

A. *Remote sensing in the different risk components*

The space based applications for mapping elements at risk at different scales (e.g. individual structures, urban blocks, agricultural areas, coastal land...) are gaining a growing attention [33], as remote sensing can contribute in extracting information on the different terms of risk (hazard, exposure, and vulnerability). Moreover, space-based technology does not only serve in collecting data for multi-risk assessment models but also in validating these models [34], [35].

1) RS in hazard analysis: In principle, RS systems are helpful in delineating the hazards extents (Landslides, floods, tsunamis, earthquakes...) [36], [37]. Many hazard types are visually observable through sensors operating in the visible bands (e.g. lava flows, landslides, lahars tracks...), however, this presents a concise notion on what remote sensing can provide in the context of multi-risk assessment. For example, infra-red sensors enable monitoring the thermal variations which can be used for tracking hazards like volcanic activities, flood extents, wild fires, desertification, heat and cold waves. However, the usability of the optical (visible and infrared and LIDAR) remote sensing might face weather problems (which often accompany meteorological and volcanic hazards). RADAR sensors overcome the mentioned weather restrictions and thus it has many applications for tracking water bodies after a disaster. As is well known, flooded areas appear as weak backscattering areas resulting from mirror reflection, scattering the incident wave nearly exclusively away from the sensor [38]. Moreover, radar interferometry applications are highly appreciated in geological hazard assessment for accurately measuring changes in topographic maps (down to mm) which has wide applications in multi-risk assessment [39]. For instance, radar interferometry is used in landslides (slope instability features), earthquakes (land surface displacement), ground subsidence, volcanoes (linking physical deformation to volcanic eruptions), soil degradation, erosion, landscape changes[12].

Additionally, several remote sensing systems (e.g. aerial LIDAR, aerial RADAR, satellite RADAR, UAV cameras) are efficient in estimating the land topographic parametrization used to build 3D terrain models (e.g. Digital Elevation Model (DEM) and Digital Terrain model (DTM)) that helps in monitoring hazards and understanding the dynamics of their physical phenomena [39]. These models are becoming indispensable for assessing different hazard types (floods, volcano, landslides...) [40]. Therefore, the ability to offer a monitoring tool on the fine variations of Earth surface provides knowledge on the current state and when combined with the historic data it enables creating more accurate hazard models in hazards like volcanoes, landslides, floods hazard assessment. For instance, the elevation information of 3D terrain models from stereo-photogrammetric, RADAR and LIDAR (highly accurate estimations) techniques enable to delineate the spatial extent of a flood and to estimate its intensity (inundation depth) [41]. Thus RS is particularly useful for hydrological models as these models need a large amount of detailed topographic information and other surface properties (e.g. humidity, emissivity) provided effectively through RS [41], [39].

2) RS in exposure analysis: Extraction of built-up areas has gained importance from the early application of space-borne technology. The main interest was the ability of the extracted information to afford an efficient, low-cost assistance in urban planning and resource management. Earth surface exposure data has been tracked using different types of multi-spectral satellite sensors at various scales [42][43], [44]. At the global scale, space borne sensors like AVHRR and MODIS were widely used for urban area extraction. Later on, with the improvement on the spatial resolution, medium-scale sensors like Landsat family provided higher accuracy and enabled the estimation of more exposure indicators like cartographic information [45]. Finally, the appearance of higher-resolution satellites sensors (e.g. IKONOS and QuickBird) gave further detailed information and enabled the derivation of a larger number of exposure indicators from remote sensing (e.g. building footprint and height). Extraction of these indicators has been carried out using different classification algorithms that use either pixels or objects (group of pixels) as the computational units.

3) RS in vulnerability analysis: Space-based observation can contribute in extracting a large set of either direct or indirect physical, social, economic, and environmental vulnerability indicators which can used in qualitative as well quantitative assessment of the term. [3]. Vulnerability is often expressed in the form of:

1) Vulnerability indices: In this case, vulnerability is estimated by means of indicators that are not directly related to the hazard intensity, and are generally useful to support a qualitative assessment [46].
2) Vulnerability curves: these curves specify a quantitative relationship between the intensity of the input generated from the considered hazard, and the level of damage. Vulnerability curves reflect the monotonic increasing relationship between the damage state and the intensity level of the "disaster input" (e.g. ground acceleration for earthquakes, inundation depth for flooding events, etc.) [47].

Particularly remote sensing can be of great help for physical vulnerability assessment through indices [33], [19]. Physical vulnerability can be measured through a wide set of indicators presented in the literature. The reader is referred to the products of the SENSUM project for a further highlight on remote sensing role in extracting vulnerability proxies [48]. Literature includes a large set of potential vulnerability indicators related to different types of natural hazards [49], [8], [33], [2]. Then, the indicators can be prioritized according to their possibility of being extracted from remotely sensed data (e.g. building footprint and height), and to their inter-dependence.

The adopted indicators for physical vulnerability should include two main features: they should reflect the difference in performance of buildings and infrastructure in disaster situations and should consider other affecting factors that enhance or decrease the direct physical losses (e.g. structure location). As buildings incorporate the main exposure assets, they are considered in estimating the physical vulnerability of population and their housing properties. Considering the spatial/spectral/temporal resolutions of the available sensors, remote sensing is used to extract a set of physical vulnerability indicators. With the introduction of high-resolution space-borne sensors (e.g. Quick Bird and TerraSAR-X) larger sets of geo-information indicators were made available with significantly higher information content [8]. For some of these indicators, however, crucial improvements on the result accuracy can only be achieved by integrating GIS-based data. The state-of-art on methods for extracting physical vulnerability indicators from remote sensing has been collected considering sensors with different capabilities and collecting different types of data (multi-spectral, panchromatic, hyper-spectral, LIDAR, and RADAR) [33], [46], [8], [50].

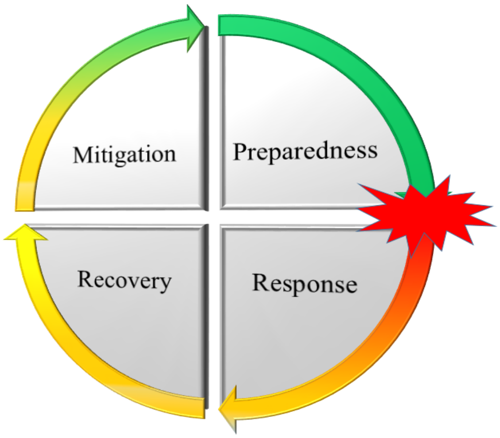

Figure 4. Remote sensing utility in the disaster management cycle.

B. RS in a disaster management cycle

Remote sensing technology represent a trustworthy data source for multi-risk models as it contributes in the different phases of a disaster cycle, see Figure 4.

1) RS in mitigation : The contribution of remote sensing in the hazard and vulnerability analysis helps in organizing effective actions for a disaster mitigation [51]. The intervention activities are mainly restricted on reducing the susceptibility of the elements of risk and building a coping capacity [52]. For instance, high spectral resolution sensor (e.g. super-spectral and hyper-spectral) enable a highly detailed monitoring of the changes in surface vegetation cover which correlate with the subsequent occurrence of different risks (e.g. wild fires and desertification) or ensuring appropriate crop yields consequently protecting the food security[53]. Other examples can be given on the utility of LIDAR or RADAR elevation data in tracking land erosion and subsidence with connected actions that mitigate their effect on the structures of interest [54], [55], [56], [57].

2) RS in preparedness and Early warning : One of the most promising application of remote sensing is detection of precursory signals which serves in short term hazard prediction and in the activation of early warnings. Technological developments have improved the early warning systems for several types of natural hazards (e.g. floods, volcanic activities, tsunamis, hurricanes, wildfires) [58], [59], [60]. For example, monitoring the volcanic activities through gas emission, thermal variations, elevation changes, or magmatic activity can give an accurate estimation on a potential volcanic eruption [61]. Another example is on monitoring the tsunami unfolding after an earthquake and thus estimating the ocean wave height and speed through remote sensing; this allows giving early warning to the potentially affected lands about the time of arrival and the height of the impending tsunami wave [59]. Additionally, a considerable research trend in remote sensing relies on satellite tracking of thermal anomalies in a seismic area as earthquake precursors [62].

The particular success of remote sensing in this disaster phase enhance worldwide collaboration among private RS data providers, plus national, and international space agencies for establishing the International Charter on Space and Major Disasters since 1999 . The charter provides space acquisitions from various satellite missions (e.g. ERS and ENVISAT, SPOT and Formosat, and RADARSAT...) to relief organizations in the event of major disasters [63]. The charter was triggered for different types of disasters like Floods, oil spills, forest fires, tsunamis, major snowfalls, volcanic eruptions, hurricanes, landslides, and epidemic outbreaks.

However, human intervention should not be restricted to the existing elements at risk, but it should consider the quality of the future assets and their geographical distribution [64]. Thus, combining built-up expansion with multi-risk modeling may help to assist urban planning and direct the city's development in a way to consider the local prospective threats [65], [66].

3) RS in response: The rapid and efficient response activities after a disaster have a major impact on the number of fatalities after major disasters [67]. Remote sensing can play a guiding role in such emergency situations for offering a real-time synoptic views on the affected areas [68]. For instance, building damage is a conventional indicator on the extent of both social and physical direct losses after a destructive event [69]. Direct losses mainly include factors affecting human life as fatalities and injuries numbers, in addition to the physical destruction occurring to residential houses and industrial structures [49]. Therefore, the immediate knowledge of damage presence and its level is of particular interest for both humanitarian and financial help. However, usually the necessary damage-related information is difficult to attain from ground sources as in-situ data collection faces diverse hitches like time constraints, area accessibility, and the sheer physical safety of surveyors [49], [70]. Remote sensing provides an applicable and credible source of data which when acquired and analyzed properly can provide an invaluable knowledge about loss distribution [71]. Earth observation technology offers a variety of information sources that characterizes the objects' spectral, spatial, and geometrical properties. Diverse types of information can be extracted remotely from optical and radar sensors that work on different ranges of the electromagnetic spectrum and with changeable spatial resolution. As an application, is the usage of SAR technology in detecting both single building, and urban block damage which benefit from the superior ability of RADAR in capturing useful information about the 3-D geometric features of the observed objects [72], [73], [69].

4) RS in recovery : Remote sensing imagery can also be considered an important tool that offers a low-cost monitoring and evaluation of the recovery and reconstruction actions, which is often a systematic procedure required by national governments and donor agencies [74], [67]. The monitoring is carried out through the analysis of a time series of satellite imagery which can be used to track the post-disaster building reconstruction, the number of tents in the displacement camps, or the vegetation recovery after a wild fire [75], [76], [77].

C. Data suitability

This process defined the main outlines of the most desirable remote sensing data sources considering sensor type and scale. The geographical scale, as a product of the image resolution, determines the level of the spatial information of the mapping product. Data details are meant in four different ways: spatial (objects detectability and separability), radiometric (intensity differences), spectral (spectral distinction), and temporal (acquisition repeatability) resolution.

In literature, several efforts have been made to investigate the properties of the main data types of different resolutions [78], as well as the effect of selecting suitable sensors that best serve the imagery objective [79]. Others investigated the importance of relationship between scale and spatial resolution on producing thematic maps [80]. However, in multi-risk analysis, several objective-dependent factors have to be considered. For instance, in response and emergency activities weather conditions would add a constraint on optical data acquisition, and proper usage of complementary technologies like radar-based acquisition would offer a back-up data source in such situations.

D. Data integration

Data fusion process of spatial data types is an ongoing activity in different scientific fields [78], [81]. In geo-informatics, the integrated spatial data types are often archived either as vector data (points, lines or polygons) or as raster data (e.g. satellite images). The data integration can be made among the RS acquisition systems where the fusion process occur between data with different spectral and/or spatial resolution (e.g. different Radar scales, panchromatic with multi-spectral, LIDAR and multi-spectral, RADAR and multi-spectral... [82], [81], [83]). However, the data integration process is not only restricted to a single data source (e.g. RS) but often extends to include diverse data sources (e.g. tabular data, thematic data, topographic maps, and RS data) [84].

VII. CONCLUSIONS

Remote sensing as a geo-spatial data source offers a peculiar value in granting low-cost and broad-coverage data acquisitions. Consequently, RS has tangible contributions in all phases of a disaster risk management cycle at different scales with often acceptable information accuracy.

Multi-risk approaches are designed according to stakeholders' objective, data scale, and data availability. Literature on multi-risk assessment can be classified into two main branches. The first approach estimates the multi-hazard and their associated vulnerabilities separately and integrate the obtained overall hazard and overall vulnerability components to present a multi-risk assessment. The second approach presents the multi-risk assessment as the integration of a set of individual risks assessed distinctly. However, the single risk integration approach appears to have an evident privilege for introducing a unified risk metric of the elements at risk. Thus, it reduces the ambiguity in establishing the common units of hazard intensity and vulnerability from the different risk types. Moreover, the recent scientific trends, for both methods, are in creating generic and flexible multi-risk evaluation systems as well as in considering hazards' and vulnerabilities' dependency in the performed computations. However, the current approaches often remains to be applicable in the context they were designed for and consequently require further adjustments to be transferable.

Finally, the estimation of multi-risk losses often demands extensive and multidisciplinary spatial analysis that entail the integrity among remote sensing and in situ data sources. Thus,a risk manager has to consider availability, suitability and integration of the used data sources to extract risk-related information.

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