Event-Based Approach to Multi-Hazard Risk Assessment

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Abstract. This work presents an event-based spatially-distributed dynamic multi-hazard risk model for the objects of critical infrastructure. The multi-hazard spatially-distributed risk model is based on the five-level spatial model, as well as the dynamic models of the socio-economic system, vulnerability, and event-based scenario model of multi-hazards represented on macro and micro levels. Each hazard on micro level can be represented as a sequence of events plunged into a certain context, where each event can initiate scenarios describing the multi-hazard dynamics. The risk for a certain object at a certain time point is a combination of the following components: the object state, disaster threat, the vulnerability of the object, and the potential damage. Thus, the area of interest at a certain time point will be characterized by integrated dynamic spatially-distributed assessments of the multi-risk in the conditions of multi-hazards.

Keywords: Multi-hazard risk, Model, Events, Scenario, Hierarchy, Critical infrastructure, Socio-economic infrastructure, Socio-economic system

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1 Introduction

Economy and society in the globalized world are increasingly dependent on the reliable availability of essential goods and services provided by technical and socio-economic infrastructures. Industrial facilities and critical infrastructure are vulnerable to the impact of hazards that can generate cascading effects. Different sectors of the infrastructures are interdependent. Being under influence of hazards or multi-hazards such interdependencies extend affected area and increase damage. Climate change also gives rise to the increase in the frequency, intensity, spatial extent, and duration of extreme events [1].

Disaster prevention and mitigation require analysing risks from hazards and multi-hazards, as well as their cascading effects to critical infrastructure elements. A subject matter of such analysis is not only single hazard but also chains of hazards. At that, one specific event can trigger different possible paths of hazard chains. The effects from hazards can also be cascading. Cascading effects are associated with the level of vulnerability and interdependency of critical infrastructure objects being at risk.

The chains of events are usually represented using event-tree structures, also called event trees [2] where the nodes are associated with the events, and the arcs are

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associated with the conditional probability of the next event occurring given that the previous event occurred.

2 Related works

Much has been done in the field of single- and multi-hazard risk analysis [3]. The classical definition of risk maintains that risk is a probability of occurrence of an unwanted event multiplied by the amount of loss [4]. In disaster risk case, unwanted event is disaster that can't be represented as a single event, and disaster risk analysis can't be assessed using classical approach. There are several reasons for this. At first, unwanted event (hazard or multi-hazard) is dynamic spatially-distributed process spreading in uncertain conditions. At second, disaster risk is analysed to protect some objects of critical infrastructure influenced by disaster that are also spatially-referenced and can be interrelated [5-12].

In recent years a range of approaches has been developed to disaster risk analysis. They are as following: quantitative (deterministic and probabilistic), indicator-based approaches, risk matrix approaches, event-tree approaches [13], data mining approaches.

Quantitative deterministic approach allows considering only one individual hazard (such as landslides, floods, wildfires, etc.) or a small subset of potential hazardous events and can't be applied to a wide range of hazards, as well as their interactions and cascading effects. However, in real life most of the regions are prone to multiple hazards that can lead to cascading effects. Quantitative probabilistic approach is that risk is assessed quantitatively taking into account a given set of hazard scenarios and the probabilities of their occurrence, at that each hazardous scenario is treated as an undivided whole. However, probability is associated to frequency of hazards, and the researcher faces an issue where the event of interest is quite rare. To cope with this issue and to increase the representativeness of posterior statistical samples, large territorial entities and big-time intervals (10-100 years) are considered [14]. In most cases, probabilistic approach is based not on imitation of many thousands of events using Monte Carlo method, which is connected with high computational complexity.

Indicator-based approach allows to carry out relative holistic risk assessment divided into a number of components such as hazard, exposure, vulnerability and capacity. The relative risk assessments don't provide information on actual expected losses.

The risk matrix represents semi-quantitative approach to risk analysis focusing on categorizing risks by comparative scores. Such matrix is made of classes of frequency of the hazardous events and the expected losses. Risk is represented as a combination of these two dimensions.

Existing event-tree approaches allow analyzing disaster chains. The nodes correspond to hazards, and the links between nodes depict the situations when one hazard causes another. The main drawbacks of existing event-tree approaches are as follows: each hazard is treated as undivided whole without referencing to spatial locations.

Data mining approach to risk analysis work well in conditions of incompleteness, inaccuracy, ambiguity and uncertainty of both the initial data and the rules for their transformation and can be an important tool in finding the correlation or uncertainty of risk factors [15]. In spite of flexibility of data mining methods, they are characterized by high computational complexity and can't be used for risk analysis in real-time decision making.

Currently, individual hazards and risks are analyzed and treated by disaster risk managers separately, especially, natural, social, and technical risks are not combined. A severe gap is a fact that critical infrastructure is often recognized as important but treated only regarding its technical components without representation of the population and its vulnerability. When the vulnerability is captured, even in multi-risk analyses, it is done under static conditions, not in real-time. This emphasizes a knowledge gap in understanding the dynamic interaction of destructive processes with their potential receptors (the elements of CI, people) [16].

3 Materials and methods

Giving foregoing literature analysis, some gaps in the state of the art of multi-hazard risk analysis can be distinguished. Individual hazards and risks are analyzed independently. It's necessary to accumulate the knowledge about dynamics of multi-hazards, their interactions, and their cascade/simultaneous effects on CI elements.

Risk assessment is also usually represented as a static value. We propose to consider risk as a spatially-distributed process that provides a more comprehensive understanding of the multi-hazard risk concept. Spatially-temporal approach in multi-hazard risk analysis provides critical information on hazard areas, impact zones, and location of populations and vulnerable infrastructure within hazardous area.

Thus, the objective of this paper is to develop a model of spatially distributed dynamic multi-hazard risks for CI elements on different time and spatial scales, including cascading risks and risk-related processes driven by environmental and socio-economic changes, based on the models of socio-economic system (SES), multi-hazard dynamics, and vulnerability of CI elements.

3.1 Underlying models

Taking into account both temporal and spatial distributions of multi-hazard risks, the comprehensive approach to multi-risk assessment proposed in this paper is based on the dynamic models of the socio-economic system, vulnerability, multi-hazards, and spatially-distributed risks.

SES is a complex dynamic system resulting from the interaction between people, environment, technical and socio-economic infrastructures, which represent their interdependencies.

Technical and socio-economic infrastructure (SEI) is a dynamic spatially-distributed system of systems consisting of the elements important to the activity of people and society.

Critical Infrastructure (CI) is a part of SEI containing elements which are essential for the maintenance of vital societal functions. The damage to critical infrastructure, its destruction or disruption by natural disasters, terrorism, criminal activity, or malicious behavior, may have a significant negative impact on people's security.

3.2 Spatial model

All the above-mentioned models will be grounded on a multi-level spatial model (Fig.1). The lower level represents a system of geographic coordinates. On the second level, the spatial model is discretized by a grid of isometric cells, which makes it possible to model the dynamics of processes occurring within a certain territory. A cell is a homogeneous object of minimal size that can be variable.

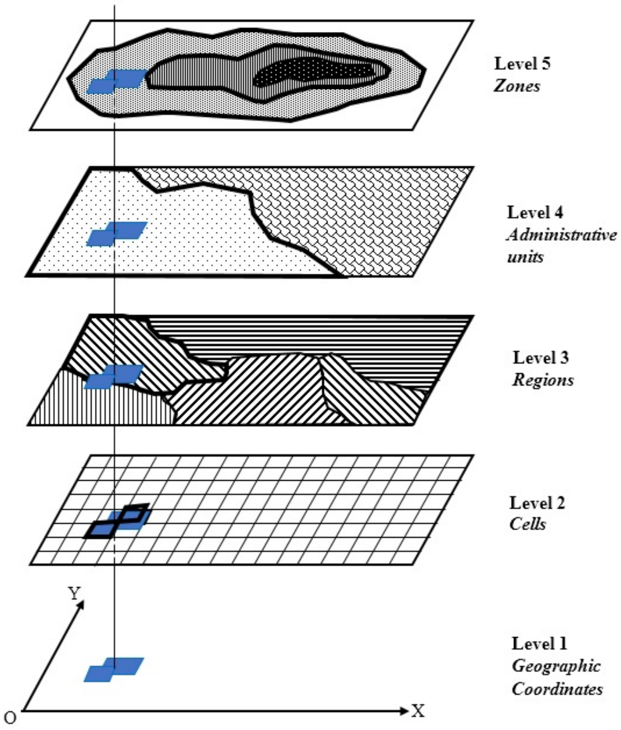

Fig. 1. Spatial model

On the third level, each considered territory can be divided into a finite set of disjoint spatial objects (geotaxons) representing geo-referenced natural parts of the terrain with homogeneous characteristics. Using this level, we can describe land-use objects that have a spatial extent, such as fields, forests, ponds, etc.

The forth level represents an administrative structure of the considered territory (municipalities, districts, provinces/regions, countries). Such hierarchy will be used to help stakeholders (risk managers, decision-makers, etc.) be aware of threatened areas and infrastructure elements being at risk from multi-hazards and make risk-informed decisions to forecast, prevent, respond, mitigate, adapt to multiple hazards, their chains and interactions.

On the fifth level, the area of interest is subdivided into zones representing homogenous areas with respect to the definite assessments of some indicators such as danger, threat, risk, etc.

All levels of the spatial model can be implemented based on a multitude of corresponding layers within a Geo-Information System (GIS).

3.3 SES model

We will consider a novel SES model as a network of networks containing people, technical and socio-economic infrastructures such as food supply, health service, agriculture, forestry, energy supply, traffic, the economy as a whole, and others. Some subsystems of SES can be organized hierarchically. All of its infrastructures consume natural resources such as water, air, soil.

The proposed model of SES can reflect all kinds of possible relations between a large variety of its elements. It will be grounded on the GIS-based spatial model of the territory. Thus, all objects of SES can be referenced spatially using this model.

3.4 Vulnerability model

Since decision-makers are interested in the protection of some valuable elements of SEI exposed to hazards and minimizing their risks, we need to use corresponding models of the dynamic vulnerability of various elements of infrastructures against hazards of different classes.

We consider the interaction of SEI elements in dynamics to take into account various short-term (meteorological), mid-term, and long-term (climatic, migration processes) impacts, as well as the influence of people on the vulnerability of the objects. A property of vulnerability accumulation and the possible existence of recovery function should be also taken into account.

4 Event-Based Multi-Hazard Model

We propose to consider multi-hazard model on macro and micro levels. On the both levels multi-hazard model is represented by even-tree [17, 18]. On the macro level, the nodes of event tree are associated with the hazards as a whole, and the arcs represent the facts when one hazard causes another. Each node of event tree built on the macro level can be represented as more detailed tree on the micro level. The trees on the micro level represent the model of each hazard spreading within the grid of isometric cells (the first level of spatial model) (Fig. 2).

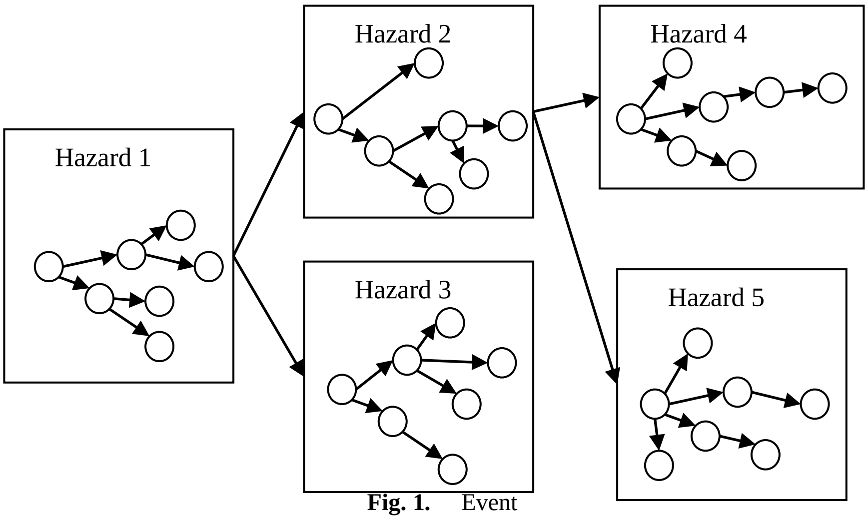

Fig. 1. Event

Fig. 2. Macro and micro levels of multi-hazard model

We propose to consider every occurrence of an observed hazardous process on the micro level as a certain kind of dynamic case, so we can use a case-based approach to accumulate and store the scenarios of dynamics of various hazards and multi-hazards on the micro level, as well as their combination, and chains on the macro level. Each case can be represented as a sequence of events plunged into a certain context, where each event can initiate scenarios describing the multi-hazard dynamics.

One of the important properties of the models mentioned above is that any object has its state available for the use of threat/risk assessment methods. This applies to any building, any infrastructure component, any element of any group, or ever any hierarchies within the models, including areas of any level of the spatial model.

Further, we will consider a generalized concept called “object” against all above-mentioned. Thus, the object O_i has its state $w_t^{O_i}$ at the time t represented by a subset of attributes $w_t^{O_i} = \left\{a_{ij},...a_{im}\right\}$. Suppose $W = \{W_0,...W_F\}$ is an ordered set of the object state classes. Clearly, a variation of the value of any attribute $a_k \subseteq A_D$ of the object O_i at the time t can change its class. We consider this is an event denoted by y, so that $y : w_t^{O_i} \to w_{t+1}^{O_i}$, where $w_t^{O_i} \in W_j$, $w_{t+1}^{O_i} \in W_k$, $W_j, W_k \in W$, and $W_j \neq W_k$.

Thus, during the lifecycle, each object can pass through a sequence of different classes of its states.

In our model, the event is a basic concept that reflects causality and is referenced in space and time. Accordingly, each event has its “cause” influenced by a natural phenomenon or an anthropogenic action that induce a hazard, and “effect” resulted in a change of the state of some object.

Consider a threat as a result of the hazard materialization that leads to the event occurrence. Let us describe the threat τ_k as a couple

$$\tau_k = \langle t_k, l_k, c_k, m_k \rangle , \tag{1}$$

where t_k is a reference of τ_k in time, l_k is a reference of τ_k in space, c_k is a class of τ_k , and m_k is its magnitude.

5 Spatially-Distributed Dynamic Risk Analysis

Risk should be assessed for each SEI object that has a spatial reference. To analyze the dynamics of risk for a certain object, it is necessary to analyze state transitions for the cell within which the object is located. Under the influence of multi-hazard, the cell passes from one category of state to another. Each category of states can be attributed to the degree of undesirability with regard to the decision-maker. Then risk will be a likelihood of the transition from a less undesirable state to a more undesirable one.

The risk $R_i(t)$ for the object o_i at the time point t is a combination of the following components: the object state, disaster threat, the vulnerability of the object, and the potential damage [19]. The threat to an object results from the presence of disturbance events. The threat can be expressed as a likelihood that a system will face a particular type of disturbance event at a specific target location in a given period. An object´s vulnerability to particular disturbance events determines the likelihood that damage will occur if it takes place at a specific object location. Vulnerability is determined by the nature of the system (e.g. technical infrastructure, socio-economic infrastructure) and the set of baseline coping capacities that are already in place to protect the objects. Consequences refer to the nature of the damage (e.g. injures or death of people, property damage, economic damage) that will occur if the disturbance succeeds. The consequences of a disturbance event can impact either people or the functioning of the system (as damage and/or business interruption).

Thus, the area of interest will be characterized by integrated dynamic spatially-distributed assessments of the multi-risk in the conditions of multi-hazard at the time t: $\left\{ R_i(t) \middle| \forall o_i \in O^*(t) \right\}$.

6 The Results of the Research

The proposed models have been implemented in multi-hazard risk analysis framework using Python programming language, as well as the framework Django, its GIS extension GeoDjango, DBMS PostgreSQL, and geospatial extension PostGIS to implement a GIS-based risk management environment. The event-based model, event structures, and hierarchies are based on the double indexed lists and provide enough performance of the framework for the multi-hazard risk assessment.

The proposed model and framework can be used for risk-informed decision support within spa-tially distributed SES of any level of complexity in conditions of spatially distributed destructive processes (such as flood, drought, epidemic spread, etc.) and their cascades under uncertainty.

The framework has been approbated on the simulated area covering Okeshky Sands, Kherson region, Southern Ukraine. Oleshky Sands is the largest expanse of sand in Ukraine and the second in Europe. It's situated near the Dnipro river and the coast of Black Sea. In XX century moving sands was limited by planting artificial coniferous forest around sandy areas. Although a relatively small sandy steppe, the Oleshky Sands have sand and dust storms. Giving the fact, that at summer air temperature rises to 40°C, in summer this forest often catches fire. There is underground water reserve that forms an indispensable part of local environment as a source of fresh water [20].

Global warming leads to decrease in groundwater levels, forests are being affected by invasions of insects, they also become more prone to forest fires. All these factors can cause rapid destruction of forests in large areas, desertification of the territory, and the revival of sand movement.

A five-level spatial model of the territory was built. The third level of spatial model is shown in the Figure 3.

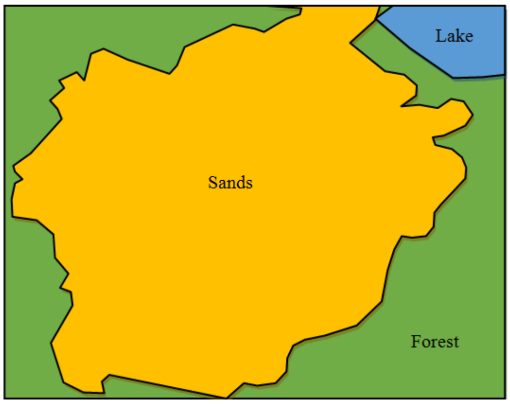

Fig. 3. Third level of Oleshky Sands spatial model

Figure 4 shows a fragment of the multi-hazard model on the macro level, connected to the region level of spatial model, and a fragment of SES model.

The experiment has been conducted to evaluate query response time-varying the cell size within the spatial model from 5 m to 50 m. The results of the experiment are shown in Fig. 5.

The proposed model and framework make it possible to simulate emergencies that begin with forest fires, and then the chain of consequences may include tornadoes, sand and dust storms, floods, etc.

The results of the simulation experiment confirmed the adequacy of the proposed event-based model and the efficiency of the framework; the developed framework provides acceptable performance for the GIS-based multi-risk assessments.

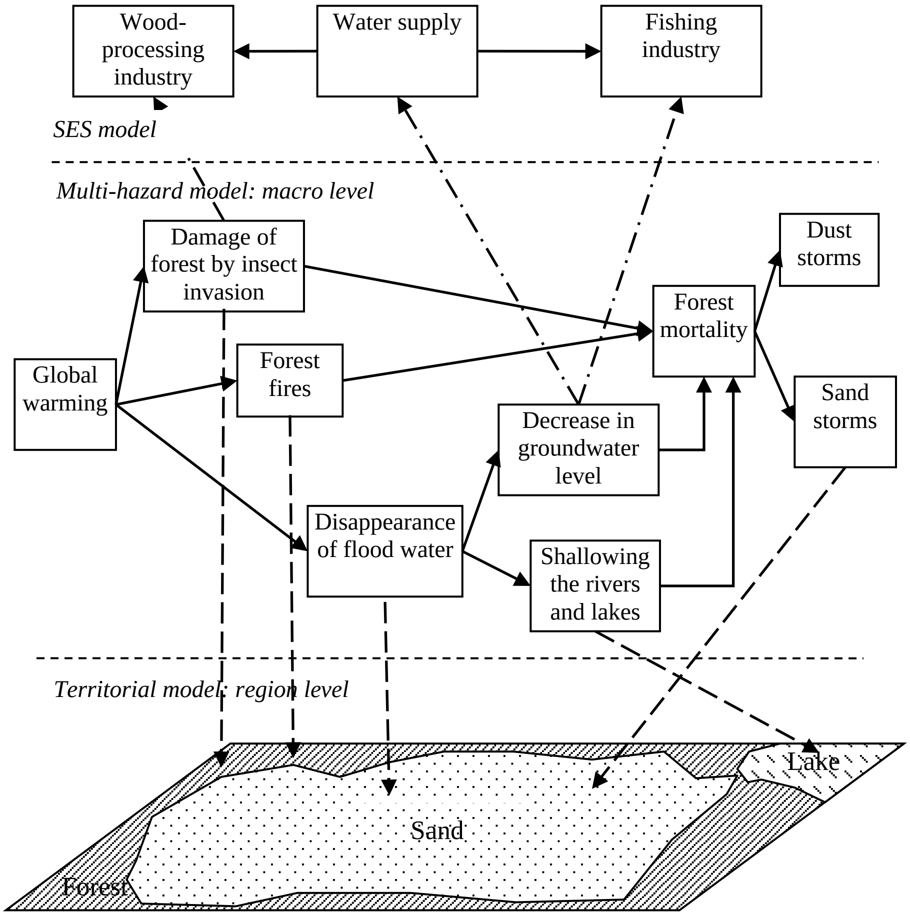

Fig. 4. Multi-hazard model

7 Conclusion

The proposed approach to multi-hazard risk analysis addresses the need of society to minimize the negative effects of disasters and climate changes through adequate adaptation actions. Our approach is primarily targeting the value of CI elements but it also takes into account the citizens' health and wellbeing by making the connection between the infrastructure monetary value and its perceived value for the citizens.

The proposed approach will contribute towards a more resilient and more sustainable society based on the concepts of increased awareness, better preparedness, information enhancement, appropriate behavior during disasters. This will result in fewer expenses related to fixing the hazards as well as in the improved quality of life and health of the citizens.

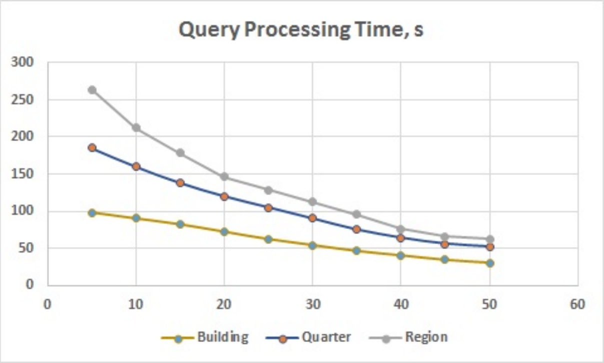

Fig. 5. The simulation results

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