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Original Scientific Paper

THE ROLE OF HAZARD, VULNERABILITY AND DAMAGE IN THE GENERATION AND DEFINITION OF ECOLOGICAL RISK CAUSED BY NATURAL HAZARD SOURCES

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Amelija Đorđević, Jasmina Radosavljević, Aca Božilov, Danijela Stojadinović

University of Niš, Faculty of Occupational Safety in Niš, Serbia

Abstract. *In the 20th century, the study of ecological risk took precedence over studies of other risk types, giving rise to a new scientific discipline within environmental science – ecological risk. This paper presents a structural scheme with basic guidelines to be used when defining risk in general as well as ecological risk. Ecological risk focuses on determining the cause-and-effect relationship between stressors, as hazard elements, and the occurrence of unwanted ecological effects. It is a complex process involving all factors leading to phenomena and conditions that threaten the environment. The paper discusses hazard elements in terms of natural hazard sources, such as floods, landslides, droughts, or earthquakes, whose occurrence causes undesirable environmental effects and which are considered to pose ecological risks. Such risks are defined as a logical interdependence of environmental hazard, vulnerability, and damage.*

Key words: *risk, ecological risk, hazard, vulnerability, damage, flood, landslide, drought, earthquake*

1. INTRODUCTION

The term *risk* is used across scientific fields (social sciences and humanities, natural, medical, mathematical, and technical). Considering that different scientific fields focus on different research subjects, methods, and aims, each of them also has a different approach when considering risk, so risk may be viewed from a sociological, safety, ecological, professional, technogenic, bio-medical, military, or another standpoint.

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Corresponding author: Aca Božilov
University of Niš, Faculty of Occupational Safety, Čarnojevića 10a, 18000 Niš, Serbia
E-mail: aca.bozilov@znrfak.ni.ac.rs

In Europe, the term *risk* emerged in the late 15th century, when seafaring and sea trade were its chief domains of use. Introducing the term into the scientific discourse required a more precise definition. However, attempts to provide a unifying definition of risk, which would be applicable to any field of study proved to be futile. This is because the term *risk* is used in many natural and social sciences, each ow which has its own subject and aim when studying risk and its own methodology. Thus, there are technical, psychological, socio-psychological, economic, legal, medical, biological, and other aspects of risk.

Risk theory began to develop and be used more widely in the late 19th century, owing to advancements in mathematics, statistics, legal and economic sciences, as well as specific disciplines such as probability theory, game theory, disaster theory, and decision-making theory.

There are numerous difficulties in defining the term *risk*, as literature contains too many contradictory definitions. *Risk* is often used synonymously with *hazard*. Various sources provide numerous examples of risk definitions along the following lines: 'risk is the hazard of future damage' or 'risk is the hazard of occurrence of unwanted effects of a given event'. Another tendency when defining risk is to view it in terms of possibility or probability of an unwanted event or process. For instance, Merriam-Webster's dictionary defines risk as a "possibility of loss or injury", the French encyclopedic dictionary Grand Larousse defines it as "a possibility or probability of an occurrence or an event considered to be harmful or damaging", while the Russian *Environmental Encyclopedia* from 1994 defines risk as a chance that something undesirable might happen. Apparently, such a tendency of defining risk was inherited from the insurance practice, where risk refers to the probability (chance) of unwanted consequences. According to the International Organization for Standardization, risk is defined as the "effect of uncertainty on objectives", whereby uncertainty refers to events that may or may not happen but that may also be the result of ambiguity and lack of information. Uncertainty implies both the positive and the negative influence on objectives. This definition of risk covers a wide variety of fields, which means that risk assessment and risk management involve the same principles and concepts across different fields. Other definitions of risk also include terms such as hazard, potential, consequences, probability, uncertainty, and vulnerability.

2. Material and Methods

2.1. General approach to defining risk

Risk is a quantitative measure of hazard and its effects. The effects of hazards always cause damage, which may be economic, social, ecological, etc. In the risk characterization stage of risk assessment, the final risk evaluation should focus on damage assessment. The greater the damage, the more significant the risk. In addition, risk will be greater if the probability of a given hazard is higher. Thus, the term *risk* comprises the two terms – *hazard* and *damage*.

A hazard is a probability category that may vary in time and space. A hazard associated with a specific event or process refers to the probability of the event or process proceeding in a given place and at a given instance. Hazards from various events or processes are determined using the mean values of the probabilities of their occurrence based on spatial and temporal parameters. If a hazard manifests itself under specific circumstances accompanied by the combination of events H_1, H_2, ..., H_n, then the probability can be expressed with the total probability equation [1]:

$$P = \sum_i P \frac{G}{H_i} \cdot P(H_i) \qquad (1)$$

where $P(G/H_i)$ – conditional probability of a hazard, G – hazard; $P(H_i)$ – probability of i^{th} event, H_i – i^{th} event, and P – probability.

A hazard can also be defined as a physical event, process, or phenomenon that may cause damage. According to its origin, it can be geological, hydrometeorological, or biological and it can vary in magnitude or intensity, frequency, duration, affected location, speed of occurrence, propagation, and the return period (UNISDR, 2004).

The term *damage* refers to actual and potential economic loss, human casualties and/or environmental degradation due to changes in our surrounding.

Unlike a hazard, risk should not be considered separately from the potential effects (damage) of the occurrence of a given hazard. The analysis of the explanation of the conceptual meaning of the term *risk* is based on the logical interdependence between hazard, vulnerability, and damage (Figure 1). Therefore, risk is a function of hazard, vulnerability, and damage – Risk = f (hazard, vulnerability, damage) [1].

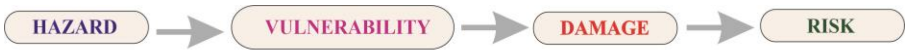

Fig. 1 Interconnection between hazard (hazardous event) and risk through vulnerability of an object and/or subject and the sustained damage

Vulnerability refers to the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UNISDR, 2004). Vulnerability is also defined as reduced capacity to absorb the effects of a disaster and to recover from it (UNDP, 2004). Vulnerability can be physical, social, economic, and environmental. A broader concept of vulnerability includes the capacity for recovery and adaptation of an object or subject exposed to a hazard. Within this concept, vulnerability is understood as a dynamic process (Cutter & Finch, 2008). The degree of vulnerability depends on the resilience and recovery capacity of objects or subjects that are or have been exposed to hazards.

It can be concluded that the risk pertaining to specific objects/subjects is manifested only in the presence of hazards and sustained damage. First, this implies the existence of a source of hazards, whether internal or external, related to a given object, or their combination; second, it implies its impact on a given object or the exposure of the object to that impact; and third, it implies insufficient protection or vulnerability of the object in relation to the negative impact. Thus, the presence of hazard and vulnerability is a necessary and sufficient condition for the generation of risk (Figure 2).

The aforementioned interpretation of the *risk* category allows the monitoring of its connection with other states and processes, which are of paramount importance for risk assessment and risk management, and especially with the states of *emergency*, *accident*, and *disaster*. All phenomena or circumstances of risk materialization lead to vulnerability of a given object/subject. Phenomena or states of risk materialization are those in which the force of a devastating impact of primary strength is such that it alters the current state (due to natural and/or anthropogenic influence), whereby the negative impacts on humans

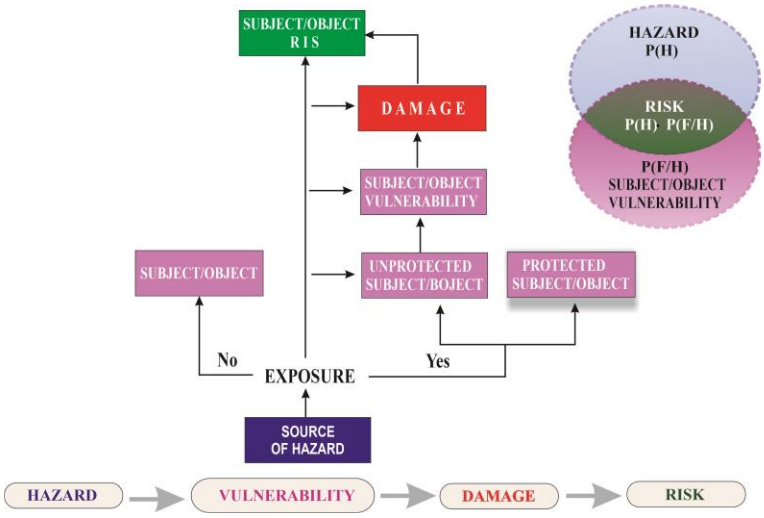

Fig. 2 General schematic of risk generation [1]

and/or structures exceed the available resources for their protection, which leads to their endangerment. Previous studies show that risks are inherently extremely versatile [3]. Depending on the risk source type and the spatial-temporal properties of negative impact manifestations, risks can be classified according to a series of characteristics. According to the object they threaten, they can be classified as follows:

- safety risks;
- health risks;
- environmental risks;
- public welfare/goodwill risks;
- financial risks.

Risk can also be defined as a quantitative measure (quantitative indicator) of hazards and their effects [4]. Risk assessment should be related to damage assessment – the greater the expected damage, the greater the risk. In addition, risk will also increase as the probability of a given hazard increases. Therefore, with some simplification, risk *(R)* can be defined as the product of probability of a hazard of a given event or process *(P)* and the magnitude (scope) of expected damage *(W)*:

$$R = P \cdot W \tag{2}$$

Thus, the term *risk* merges the terms *hazard probability* and *damage*, whereby indeterminacies related to the quantities of probability and damage are also considered.

The indeterminacy and vagueness are caused by increased human activities, the complexity of environmental issues and ecological systems, as well as the lack of knowledge about the interrelations of these systems.

Risk (R_{ec}) as a statistically evaluable category, which is a vector quantity composed of several components, can be represented with the following expression [1]:

$$R_{ec} = \{S, P_s, W\} \tag{3}$$

where S – scenario description; P_s – probability of hazard occurrence; W – damage (loss).

3. Results and Discussion

3.1. Ecological risk due to natural hazard sources

System safety can be defined as a system property that, under specific operating conditions, provides the maintenance of a state in which there is a certain probability that risk events caused by the effects of hazard factors on unprotected elements of the system and its environment will not occur. The property of a system that ensures its safety is not solely related to the given system but also to its environment, and to the elements and systems constituting the immediate surrounding of the given system and the changes in their quality. Consequently, a given system may change its behavior and quality influenced by other systems, i.e., its safety may be affected by the surrounding systems. With such a framework of system safety, which regards the environment as a complex system, ecological risk is represented as an indicator of probability of loss of life, health or property damage, and environmental damage due to exposure to a specific ecological hazard. Ecological risk depends on *ecological hazard* (source of ecological damage or a negative effect such as toxic emissions from factories or toxic discharges into rivers) and *hazard exposure* (involving pathways between damage sources and the affected population or natural environment), albeit any of the two elements may independently affect the risk outcome. This actually means that a specific ecological hazard may be minor but at the same time affect a large portion of the population; conversely, certain toxic substances may pose a major ecological hazard but with limited exposure, which minimizes the risk. In keeping with the previous definition, ecological risk may be expressed using probability values or mathematical equations pertaining to the expected damage. When determining risk level, its value is generally expressed as the product of three components

$$R = R_1 R_2 R_3 \tag{4}$$

where R – risk level, i.e., probability of damage to humans and the environment; R_1 – probability (frequency in technogenic risk) of occurrence of events or phenomena that induce harmful negative factors; R_2 – probability of formation of specific burden areas with concentrations of harmful substances in different environments with a specific load, which is considered a favorable factor for the transition of harmful into hazardous substances that affect humans and other objects in the biosphere and are seen as chemical stressors; alternatively, probability of burden areas affected by physical stressors that cause environmental degradation; R_3 – probability of the abovementioned levels and burdens causing damage.

When assessing ecological risk, natural hazard sources are viewed as processes that lead to altered physical states of the environment resulting from unexpected events categorized as natural disasters. Professional and scientific literature often represents such risks as

$$R = H \cdot E \cdot V, \tag{5}$$

where V is the vulnerability of objects/subjects as a function of damage [4].

In Serbia, the most frequent natural hazard sources include floods, landslides, droughts, and earthquakes. Flood risk is the probability of a flood event with a specific return period that is a potential threat to human health, the environment, cultural heritage, and economic activity. In the context of flood risks, a flood risk is considered a hazard. Flood risk depends on many parameters and is determined for each separate receptor. Receptors are all those entities that can sustain damage in the hazard zone and when exposed to the hazard, such as general population, buildings, material and non-material resources, services, states, and processes. A receptor that sustains damage during a flood event but, due to the change of its state, emits the harmful effects onto other receptors is called an emitter (Figure 3). Flood risk of the i^{th} receptor (Figure 3) is expressed as [5]

$$R_i = f\,(P_m, Z_i, E_i, S_i, T_i, t_i, t_{gi}...) \qquad (6)$$

where P_m – design probability of an event, Z_i – depth sensitivity of receptor i, E_i – exposure of receptor i, S_i – security of receptor i, T_i – duration of the flood over receptor i, t_i – daily time determinant of flooding occurrence, t_{gi} – annual time determinant of flooding occurrence.

Flood risk can be defined according to the schematic shown in Figure 3, which is compatible with the general risk schematic shown in Figure 2.

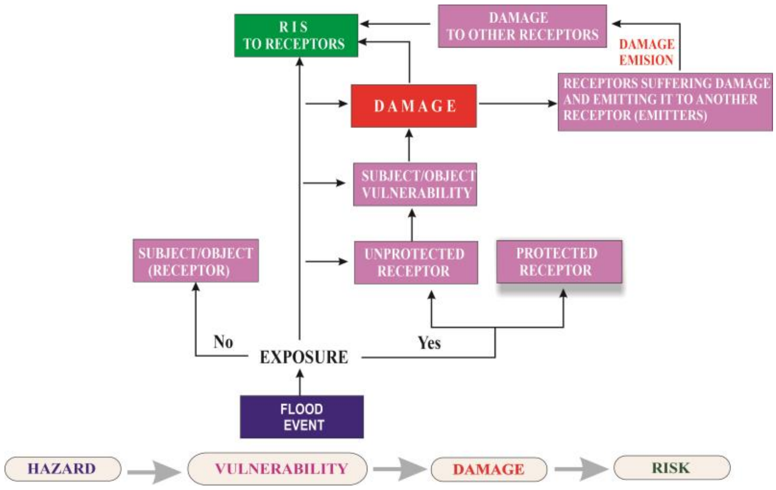

Fig 3 Schematic of flood risk generation

According to the basic methodological framework of landslide risk assessment, the first step is to identify the hazard that initiates the landslide. Hazard refers to the probability of an event or process at a specific location with a specific magnitude/intensity over a specific period of time. In hazard zones affected by the consequences to the objects/subjects (elements), vulnerability is characterized using the time and intensity of their exposure. Landslide risk can be defined as a combination of probability of a process (Figure 4) that initiates a hazard and its negative effects (damage) on the exposed unprotected elements (subjects/objects) over a specified time period. It is expressed using the equation [6]

$$R = P(H) \cdot P(S\,/\,H) \cdot V(P\,/\,S) \cdot W \qquad (7)$$

where R – risk; $P(H)$ – annual probability of a landslide; $P(S/H)$ – probability of spatial impact of a landslide; $V(P/S)$ – vulnerability; W – element at risk (damage).

Such a general definition of landslide risk is also compatible with the general risk definition schematic (Figure 2).

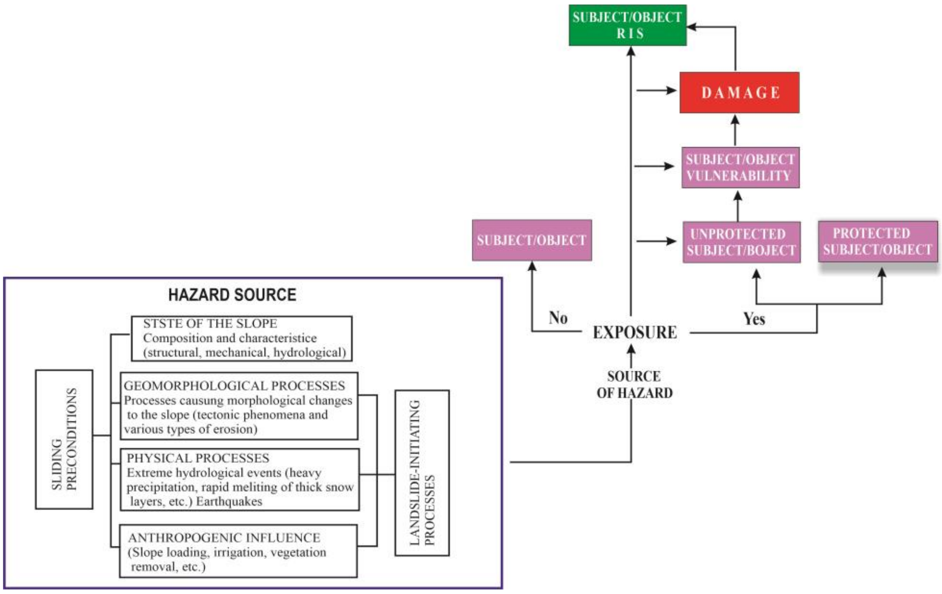

Fig. 4 Schematic of landslide risk generation

Drought risk is defined as the function of drought probability, exposure of an area to droughts, and drought effects due to vulnerability of the drought-exposed elements. Drought probability refers to how often droughts can occur within a given time period. Area exposure refers to the number, quantity, or monetary value of various types of material resources, infrastructure, or living organisms that are susceptible to unwanted outcomes. Drought effects refer to partial or total damage, injury or loss of human life, economic or financial indicators of drought impact on property, the environment, or business operations. Again, the provided definition of drought risk is compatible with the general risk definition schematic shown in Figure 2.

In a narrow sense, seismic risk usually refers to the level of potential loss of material resources in the event of an earthquake of specific intensity in a given area. It is most often expressed using relative numbers (in relation to the maximum possible loss). Seismic risk (R) is mathematically defined as a convolution of seismic hazard (H) and the function of vulnerability of the elements at risk (V) with consideration of potential damage due to earthquake [7]:

$$Risk = Hazard \times Elements\ at\ Risk \times Vulnerability\ of\ the\ Elements\ at\ Risk$$

The above definition of seismic risk is also compatible with the general risk definition schematic (Figure 2).

4. Conclusion

Environmental degradation has always been the result of uncontrollable hazards, which are scientifically defined as physical events, processes, or phenomena that can cause damage. The degree of sustained damage from a hazard at the level of the biosphere and/or the anthroposphere is considered in terms of defense, adaptation, or regeneration mechanisms. These mechanisms depend on the intensity, duration, and frequency of the hazard, so familiarity with the general as well as specific characteristics of a hazard is necessary to define the risk resulting from its negative environmental impact, i.e., to define ecological risk. Definition of ecological risk has to be compatible with the general definition of risk, which is a function of hazard, vulnerability, and damage. General risk of natural hazards is the level of expected loss or damage and it is predicted as a consequence of a natural hazard occurring in a given location at a given time. The factors involved in understanding and assessing risk include the following: assessment of the level of expected hazard; evaluation of all elements of human value susceptible to hazard actualization; evaluation of location or position of the elements of value in relation to the hazard; and assessment of physical, social, and economic vulnerability of the social community.

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OPASNOST, RANJIVOST I ŠTETA U FUNKCIJI FORMIRANJA I DEFINISANJA EKOLOŠKOG RIZIKA USLOVLJENOG PRIRODNIM IZVORIMA OPASNOSTI

U dvadesetom veku, izučavanje ekološkog rizika dobija primat u odnosu na druge rizike. S toga dolazi do razvoja nove naučne discipline, u okviru nauke zaštite životne sredine, ekološki rizik. U radu je data strukturna šema sa osnovnim smernicama koje treba koristiti pri definisanju rizika uopšte ali i ekološkog rizika. Ekološki rizik je usmeren na utvrđivanju uzročno-posledičnog dejstva stresora kao elementa hazarda na pojavu neželjenih ekoloških efekata. To je kompleksni proces koji obuhvata sve faktore koji uslovljavaju pojave i stanja koji ugrožavaju životnu sredinu. U radu su prikazani elementi opasnosti koji su sagledani sa aspekta prirodnih izvora opasnosti (poplave, klizišta, suše, zemljotresi) čije dejstvo dovodi do neželjenih efekata po životnu sredinu i koji se sagledavaju kao ekološki rizici. Ovi rizici se definišu kao logička međuzavisnost i uslovljenost opasnosti, ranjivosti (ugroženost) i nastale štete u životnoj sredini.

Ključne reči: *rizik, ekološki rizik, opasnost, ugroženost, šteta, poplava, klizište, suša, zemljotres*