Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2025, 13(1), 178-214
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Concepts and Misconceptions in Climate Change Risk Assessment: Considerations for Sea Level Rise and Extreme Precipitation Risk

Efthymia Koliokosta

School of Business, University of the Aegean, Chios, Greece
Email: efigrx@yahoo.com

How to cite this paper: Koliokosta, E. (2025). Concepts and Misconceptions in Climate Change Risk Assessment: Considerations for Sea Level Rise and Extreme Precipitation Risk. *Journal of Geoscience and Environment Protection, 13,* 178-214.
https://doi.org/10.4236/gep.2025.131010

Received: February 20, 2024
Accepted: January 17, 2025
Published: January 20, 2025

Abstract

Flood extremes due to sea level rise and extreme precipitation are expected to increase in frequency and intensity. However, despite the need for accurate climate change risk assessment, significant misconceptions in key risk terms, including vulnerability and impact, could lead to risk miscalculations. These misconceptions around risk concepts derive from the lack of risk terms' standardization and the gaps in an integrated and widely accepted methodology for assessing climate change risks. Risk assessment frameworks should follow the specialties of each element/sector it is applied on and the special features of each climate hazard. Also, risk assessment matrix should not follow specific design settings but it should better follow the needs of each study, so as to optimize the understanding of each risk. Through an extensive literature review, this is the first paper that identifies gaps, inconsistencies and misuses of climate risk concepts and suggests specific systemization and standardization of risk terms definitions. Finally, it develops a climate change risk assessment framework and matrix, focusing on sea level rise and extreme precipitation, which could be widely implemented in risk assessment of all elements at sea level rise and extreme precipitation risk.

Keywords

Risk Concept, Risk Misconceptions, Impact, Vulnerability, Climate Change, Sea Level Rise, Extreme Precipitation, Risk Assessment, Risk Ranking

1. Introduction

Earth's climate has changed several times over the past 400,000 years, passing through four glacial cycles (Le Treut et al., 2007). A combination of natural variations in solar irradiance and orbital parameters of earth, volcanic activities (Lean, 2010), anthropogenic emissions of greenhouse gases, such as CO_2, CH_4, water vapor, N_2O, O_3, HFCs, PFCs and SF_6 (Myhre et al., 2013), have resulted in the increase of global mean atmospheric and surface ocean temperature (IPCC, 2018). The continuous rise of global mean temperature has affected climatic patterns (IPCC, 2014), increasing the number, frequency and intensity of extreme weather occurrences (Le Treut et al., 2007), including climatological, hydrological and meteorological events and phenomena such as heatwaves (IPCC, 2014), sea level rise (IPCC, 2014), floods, ice thawing (IPCC, 2012), heavy precipitation, storm surges, tropical storms and hurricanes/cyclones (IPCC, 2014).

The economic impact of extreme climatic occurrences follows the trend of the frequency of the occurrences over time (Koliokosta, 2017), and the total damage of climate extremes shows increasing trend over the years counting billions of dollars in global economy (Mirza, 2003; EM-DAT) (**Figure 1**). As global mean temperatures increase, the probability, the duration and the magnitude of these extreme events are projected to rise (IPCC, 2013).

Among climate change hazards, floods associated with extreme precipitation and coastal flooding, are the most significant in terms of frequency, economic burden (Koliokosta, 2023c; Gangwal and Dong, 2022; Koliokosta, 2017) and number of fatalities (EM-DAT).

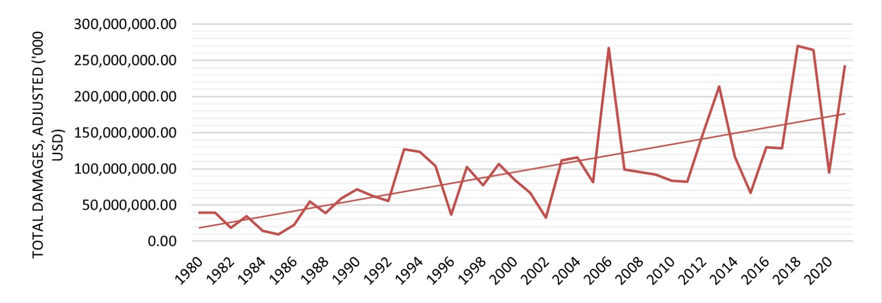


Figure 1. Economic damage over time (scaled to 2018) of extreme climate occurrences after 1980. Source: Author's calculations from EM-DAT.

2. Problem Statement

Risk assessment theory and methods, generally, perform high level of fuzziness, deriving from 1) the variability in risk definitions and assessment methods (i.e. Simmons et al., 2017; Coleman and Marks, 1999; Adams, 1995; Aven, 2012), 2) ambiguities and inconsistencies in the definition and interpretation of risk concepts (Christensen et al., 2003; Campbell, 2006; Nathan et al., 2021), especially vulnerability and impact (IPCC, 2014; Koliokosta, 2023b; Voskaki et al., 2023), 3) lack of criteria that define risk determinants, 4) the misuse of return periods in assessing likelihood of flood occurrences (Koliokosta, 2023a), 5) the risk subjectivity to personal perceptions (Renner et al., 2015; Brown, 2014), 6) the lack of methods for assessing all elements susceptibility to climate extremes, 7) the uncertainties related to risk (Benke et al., 2007; Chapman and Ward, 2003; Bowyer et al., 2014), 8) the uncertainty derived from the lack of data and knowledge regarding adaptation measures effectiveness and failure during climate extremes, 9) variability in risk assessment methods that conclude in different risk assessment outcomes. These problems are obvious in most research studies that discuss risk, resulting in a huge variability in risk assessment methods and outcomes (**Figure 2**).

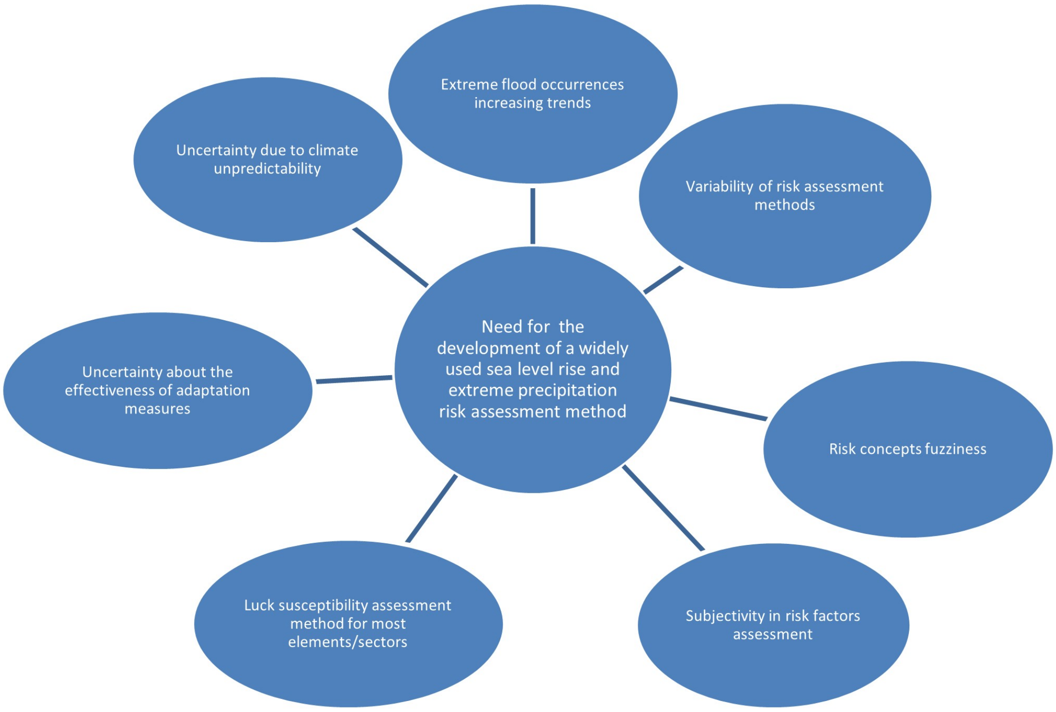


Figure 2. Problem statement.

3. Materials

For the purposes of this paper a systematic literature review has been conducted including 879 findings, 709 of which are peer review papers extracted from Scopus, Web of Science and Google Scholar and 170 reports extracted from google search engine. Using Boolean operators, the findings extracted are as following (**Figure 3**):

- “climate AND risk”: 88.932 findings
- “climate AND risk AND factors”: 26.045
- “climate AND risk AND vulnerability”: 9.660
- “climate AND risk AND impact”: 32.637
- “climate AND risk AND likelihood”: 1.749
- “climate AND hazard”: 22.105
- “flood AND risk AND assessment”: 16.664
- “vulnerability AND assessment”: 52,623
- “climate AND change AND impact AND assessment”: 37.236
- “climate AND change AND risk AND assessment”: 21,267

- “climate AND change AND adaptation”: 55.357
- “sea AND level AND rise AND risk’: 4.329
- “sea AND level AND rise AND vulnerability”: 2.623
- “extreme AND precipitation AND risk”: 3.991
- “extreme AND precipitation AND vulnerability”: 1.222
- “riverine AND flooding AND risk”: 344
- “climate AND risk ND uncertainty”: 7.430
- “exposure AND climate AND change AND hazards”: 2414
- “climate AND risk AND matrix”: 777
- “climate AND risk AND assessment”: 29.250
- “climate AND risk AND resilience’: 7002
- “climate AND risk AND susceptibility”: 1436
- “climate AND risk AND coping AND capacity”: 384
- “sea AND level AND rise AND coping AND capacity”: 27
- “extreme AND precipitation AND coping AND capacity”: 28
- “sea AND level AND rise AND infrastructure AND susceptibility”: 18
- “extreme AND precipitation AND infrastructure AND susceptibility”: 21
- “climate AND change AND risk”: 1.995
- “vulnerability AND climate AND change”: 571
- “impact AND climate AND change”: 9.101

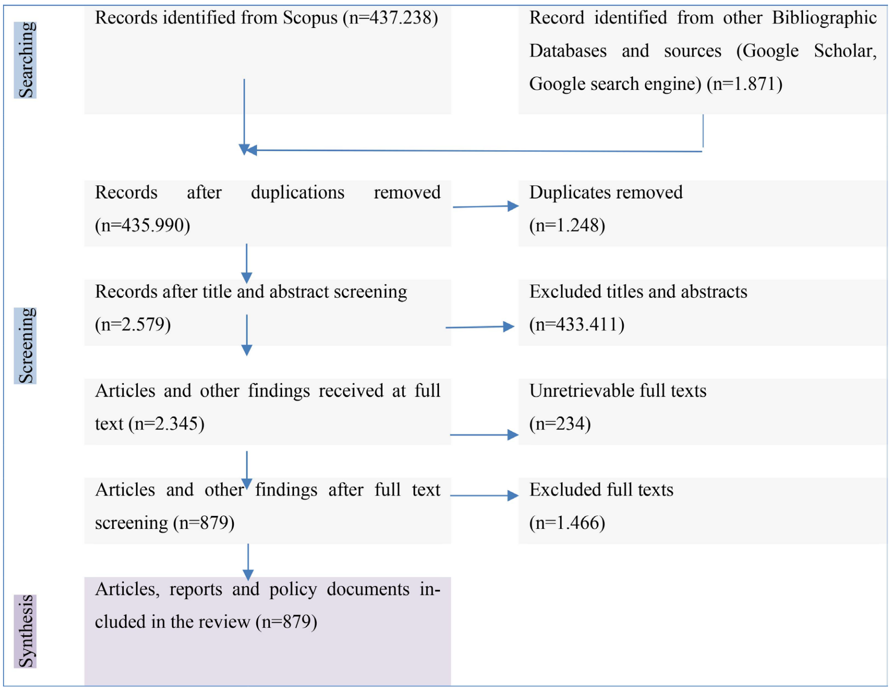


Figure 3. Reporting standards for Systematic Evidence Syntheses (ROSE) framework.

In this research, literature review studies the climate change risk concepts generally, identifies the failures in the use of climate change risk terminology, systematizes the risk terms in order to eliminate ambiguities and provides a clear basis, which can be widely and commonly used by all authors in climate change risk assessment science and suggests a climate change risk assessment framework that can be applied on all elements facing sea level rise and extreme precipitation hazards.

4. Concepts and Misconceptions in Climate Risk Assessment

4.1. General Concept of Risk

Risk is a very slippery concept (Coleman and Marks, 1999), that has been widely used in different disciplines and variously defined among authors over time (Aven, 2012). The simplest way to define risk is by the combination of the probability of a hazardous event and its consequences (i.e. Alexander, 2002; Knemeyer et al., 2009), where probability is the likelihood of occurrence and consequence is the severity, damage, loss or benefit driven by specific hazards (Dong and Cooper, 2016; Alexander, 2002). Risk in this case is expressed as:

$$\text{Risk} = \text{Likelihood of occurrence} \times \text{Impact} \tag{1}$$

A similar risk approach is suggested by Kron (2002) to assess flood risk, based on the fact that natural hazards manifest themselves in many different forms with an almost infinite number of variations instead of one single event with a given probability. Under this concept, risk may be assessed as:

$$R = \int_{QA}^{\infty} C(Q)\, f(Q)\,\mathrm{d}Q \tag{2}$$

where $C(Q)$ are the losses by a hazard Q, $f(Q)$ is the probability density function of the hazard and QA is the level of hazard for which losses start to occur. However, such calculations are rare as more simplified calculations are widely applied (Kron, 2002).

Although the above likelihood-impact approach is the most frequently used by authors, another also widely used expression of risk is the function of hazard, exposure and vulnerability (i.e. Alexander, 2002; IPCC, 2022) as following:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \tag{3}$$

This equation, however, encompasses some inconsistencies with respect to the definition of vulnerability and the consideration that exposure is independent from vulnerability. There are also some ambiguities associated with the subjective assessment of the exposed elements and which need to be furtherly concerned. How are the exposed elements defined and why exposure is not incorporated in vulnerability? Exposure is not an arbitral concept. It is measurable and needs to be severely concerned in vulnerability assessment (Koliokosta, 2023c). An extensive analysis of the exposure and vulnerability is discussed in the following sections.

Other authors (i.e. Blaikie et al., 2014; Taubenböck et al., 2008) use an alternative approach of the above risk formula (3), incorporating the concept of exposure into vulnerability, and suggest that risk is defined by hazard and vulnerability of the exposed elements in a particular period of time and space. They use the term vulnerability to imply impact and refer to risk as following:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \tag{4}$$

Another risk perspective is described by a combination of 1) the hazards, including the probability of occurrence, 2) the values at risk, including the buildings and structures, items and humans that are affected and 3) the vulnerability (Kron, 2002; IPCC, 2018) and is assessed as:

$$\text{Risk} = (\text{Hazard including Probability}) \times (\text{Values at risk}) \times \text{Vulnerability} \tag{5}$$

Considering that "values at risk" represents the impact of a specific hazard on the affected elements in monetary terms in case of physical assets, infrastructure and their operations or in term of fatalities and injuries, in case of peoples affected, the above equation can also be viewed as:

$$\text{Risk} = (\text{Probability of hazard occurrence}) \times (\text{Vulnerability}) \times (\text{Impact}) \tag{6}$$

(Koliokosta, 2023b)

This equation requires the assessment of both impact and vulnerability, by clearly distinguishing them in two different and vital concepts, which is very useful in decision-making procedure. Vulnerability assessment alone could be the initial step in identifying the elements with higher vulnerability and emitting the less vulnerable or resilient elements from impact and risk assessment procedure, gaining time and financial resources associated to the risk assessment action plans.

Apart from the risk definitions found in peer review papers they perform significant variability also between scientific Report findings. For instance, ISO Guidance for Risk Management (ISO, 2009), makes a more goal-oriented approach of risk involving the concept of uncertainties in risk definition as "the effect of uncertainty on objectives", where "the effect is the deviation from the expected positive and/or negative consequence" and "the objectives can serve different goals (such as financial, health and safety, environmental) and can apply on different levels (such as strategic, organization-wide, project, process)". This is a conceptual, goal-oriented definition of risk, which is largely compatible with the old event-oriented approach of risk that explains how to quantify risk by combining probability and severity (ISO Glossary 31000, 2018). According to this definition, risks are very likely to have either negative or positive impact and create new opportunities through adaptation measures and strategies (Nitkin et al., 2009).

The United Nations International Strategy for Disaster Reduction Report (UNISDR, 2009) defines risk from a disaster perspective as "the potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period". This definition is general, excludes any concept of vulnerability and focuses on the consequences of a disaster in a specific period of time.

In climate change risk assessment, Jones and Boer (2003) suggest that there are two approaches to assess risks:

a) the climate hazards-based approach, where the likelihood is attached to the hazard (Jones, 2003)

$$\text{Risk} = \text{Probability of climate hazard} \times \text{Vulnerability} \tag{7}$$

b) the vulnerability-based approach, where the likelihood is attached to the consequences due to high vulnerability level (Jones, 2003)

$$\text{Risk} = \text{Probability of exceeding one or more criteria of vulnerability} \tag{8}$$

According to the above risk definitions (7)-(8) impact is not considered as a key risk factor, but they imply that the impact is expressed through the concept of vulnerability. These definitions show clearly the interpretative issue with respect to the concepts of impact and vulnerability in risk assessment procedure.

4.2. Likelihood of Climate Hazards Occurrences

4.2.1. Climate Change Scenarios and Projections

The Intergovernmental Panel for Climate Change (IPCC, 2013), has adopted a greenhouse gas concentration trajectory, known as the Representative Concentration Pathway (RCP), which is used widely when making projections about future impacts of climate change. The RCP consists of four pathways, which describe four cases about future climate considering the levels of greenhouse emissions in the upcoming years. These are known as RCP2.6, RCP4.5, RCP6.0 and RCP8.5 according to the levels of radiative forcing (2.6, 4.5, 6.0 and 8.5 W/m^2) in the year 2100. The RCPs are used to create projections of global mean warming and global mean sea level rise in the mid-(2046-2065) and late-21st (2081-2100) century, as following (**Table 1** and **Table 2**):

Table 1. IPCC AR5 global warming projections (˚C).

	2046-2060		2081-2100	
Scenario	Mean	Likely range	Mean	Likely range
RCP2.6	1.0	(0.4 to 1.6)	1.0	(0.3 to 1.7)
RCP4.5	1.4	(0.9 to 2.0)	1.8	(1.1 to 2.6)
RCP6.0	1.3	(0.8 to 1.8)	2.2	(1.4 to 3.1)
RCP8.5	2.0	(1.4 to 2.6)	3.7	(2.6 to 4.8)

Source: IPCC, 2013.

Table 2. IPCC AR5 global mean sea level rise projections (m).

	2046-2060		2081-2100	
Scenario	Mean	Likely range	Mean	Likely range
RCP2.6	0.24	(0.17 to 0.32)	0.40	(0.26 to 0.55)
RCP4.5	0.26	(0.19 to 0.33)	0.47	(0.32 to 0.63)
RCP6.0	0.25	(0.18 to 0.32)	0.48	(0.33 to 0.63)
RCP8.5	0.30	(0.22 to 0.38)	0.63	(0.45 to 0.82)

Source: IPCC, 2013.

All RCPs conclude that global mean warming is expected to increase by 0.4˚C to 2.6˚C by the mid-21st century and by 0.3˚C to 4.8˚C by the late-21st century. Similarly, the maximum increase in global mean sea lever rise is projected to reach 0.32m in the period 2046-2060 and 0.82 m in the 20181-2100 period (IPCC, 2013). Most authors, thought, agree that the sea level will increase by at least 1m by the end of the 21st century (i.e. Kontogianni et al., 2014; Garner et al., 2018; Hallegatte et al., 2008). However, these projections are subject to volatile values, which may change over time either positively with the strict implementation of climate change mitigation measures or negatively with further environmental degradation and increase of climate change impacts.

There is growing amount of research that discuss potential climate change effects in all continents (i.e. Brown et al., 2017; IPCC, 2014; IPCC, 2013; Villarini and Denniston, 2016; Mastrandrea et al., 2010; Hawcroft et al., 2018). The majority of the research, despite the different methods and approaches used, have concluded in similar results with respect to the climate projections by region, and which are briefly provided in **Figure 4**.

Moreover, Knutson et al. (2020) have found that an increase of global mean temperature by 2˚ could also increase the frequency of the most intensive tropical cyclones (4 - 5 category) and extreme precipitation occurrences, globally increasing flood extremes especially in the Northern Hemisphere. Moreover, as atmospheric temperature rises, ice and glaciers in polar regions thaw and mean temperature of the oceans increases, causing seawater expansion and accelerating sea level rise (Widlansky et al., 2020).

Figure 4. Global climate change projections map. Source: Author's map from IPCC, 2014; IPCC, 2022; IPCC, 2023.

IPCC AR6 Report adopts another approach of climate change scenarios, using the Shared Socioeconomic Pathways (SSPs), which project the socioeconomic factors changes by the end of the 21st century, including population, urbanization, economic growth and technological development.

According to IPCC Sixth Assessment Report (IPCC, 2021), the SSPs temperature projections are described in **Table 3**. According to the SSPs scenarios, the increase of the temperature will very likely range between 1˚C - 1.8˚C under the very low GHGs scenario SSP1-1.9 and 3.3˚C - 4.6˚C under the very high emission SSP5-8.5 emission scenario. Similarly to the RCPs, the SSPs are used to project the contribution of each SLR driver to global mean sea level rise in the year 2100, as shown in **Table 4**
(https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?type=global).

Table 3. SSPs Projections about global temperature.

SSP	Scenario	Estimated warming (2041-2060)	Estimated warming (2081-2100)	Very likely range in ˚C (2081-2100)
SSP1-1.9	very low GHG emissions: CO_2 emissions cut to net zero around 2050	1.6˚C	1.4˚C	1.0 - 1.8
SSP1-2.6	low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7˚C	1.8˚C	1.3 - 2.4
SSP2-4.5	intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0˚C	2.7˚C	2.1 - 3.5
SSP3-7.0	high GHG emissions: CO_2 emissions double by 2100	2.1˚C	3.6˚C	2.8 - 4.6
SSP5-8.5	very high GHG emissions: CO_2 emissions triple by 2075	2.4˚C	4.4˚C	3.3 - 5.7

Source: IPCC, 2021.

Table 4. SSPs projections about Sea level rise projection (year 2100) based on sea level rise contributors.

	SSP1-1.9	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6 Low Confidence**	**SSP5-8.5 Low Confidence**
Thermal Expansion	0.12 (0.09 - 0.15)	0.14 (0.11 - 0.18)	0.20 (0.16 - 0.24)	0.25 (0.21 - 0.30)	0.29 (0.24 - 0.36)	0.14 (0.11 - 0.18)	0.29 (0.24 - 0.36)
Glaciers	0.08 (0.06 - 0.10)	0.09 (0.07 - 0.11)	0.12 (0.10 - 0.14)	0.16 (0.13 - 0.18)	0.18 (0.15 - 0.20)	0.09 (0.06 - 0.12)	0.17 (0.11 - 0.21)
Greenland	0.04 (0.00 - 0.09)	0.06 (0.01 - 0.10)	0.08 (0.04 - 0.13)	0.11 (0.07 - 0.16)	0.13 (0.09 - 0.18)	0.09 (0.01 - 0.30)	0.18 (0.09 - 0.59)
Antarctica	0.10 (0.03 - 0.25)	0.11 (0.03 - 0.27)	0.11 (0.03 - 0.29)	0.11 (0.03 - 0.31)	0.12 (0.03 - 0.34)	0.10 (−0.01 - 0.27)	0.19 (0.02 - 0.56)
Land Water Storage	0.03 (0.02 - 0.04)	0.03 (0.02 - 0.04)	0.03 (0.02 - 0.04)	0.04 (0.02 - 0.05)	0.03 (0.02 - 0.04)	0.03 (0.02 - 0.04)	0.03 (0.02 - 0.04)

Source: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?type=global.

The RCPs and the SSPs perform significant similarities in the trends of global sea level rise and global temperature projections. However, Schwalm et al. (2020) consider that RCP8.5 is the scenario that best describes the emissions accumulations from 2005-2020.

4.2.2. Climate Extremes Probabilities

Extreme weather events occur rarely and should not be more frequent than those in the 10th or the 90th percentile of probability density function (Kostopoulou and Jones, 2005; Schär et al., 2016). The probability of climate extreme occurrences depends on change in the mean, standard deviation, and even the symmetry of the climate variability distribution (e.g. temperature and precipitation) (Lavell et al., 2012). **Figure 5** shows that when there is a change in the mean and as a result a shift of the distribution (**Figure 5(a)**), then there will be an increase of extreme events in the one end and a decrease at the other. Besides, an increase of the standard deviation of future climate results in changes of extreme events in both sides of the frequency distribution and produces larger impact on the frequency distribution than a change in the mean (**Figure 5(b)**). Finally, a concurrent change of mean, standard deviation and symmetry of the distribution, affects the extreme occurrences in different ways (**Figure 5(c)**) (Lavell et al., 2012).

When performing measurements, statistical distributions can give us the degree of uncertainty (Taylor, 1997). This can be also applied in climatic measurements. As the number of measurements increase, the degree of uncertainties reduces. If we take *N* climatic measurements of a certain climatic size x, e.g. temperature, the mean value gives the actual level of the measurements, as: $\overline{x} = \frac{\sum_{i=1}^{N} \overline{x}}{N}$. The error and the uncertainty thus of climatic measurements $x_1, x_2, \cdots, x_N$, may be estimated by standard deviation (Taylor, 1997) (**Figure 6**) using the form

$$\sigma_{\chi} = \sqrt{\frac{1}{N-1} \sum_{\iota=1}^{N} \left(\chi_{\iota} - \overline{\chi} \right)^2}$$

This is a simple statistical approach of measuring the uncertainties. When considering climate phenomena, the analysis of uncertainties is much more complex and needs deep analysis, which exceeds the scope of this research.

Projections, thus, as per the climatic occurrences, are produced using complex ocean-atmospheric-climate system simulating models. These models are used to project how these physical processes that govern climate system and changes in sea level respond to different greenhouse gas emission scenarios (Kirshen et al., 2014). These methods reduce uncertainties and are often provided in qualitative terms with respect to the likelihood of predictions (IPCC, 2014; Le Treut et al. 2007). The degree of uncertainty may be communicated either a) qualitatively, expressed by the *confidence* in validity of a finding, based on the amount, quality, and consistency of evidence; or b) quantitatively, expressed *probabilistically* based on statistical analysis of the evidence, observations or model results (Mastrandrea et al., 2010; IPCC, 2014) (**Table 5**). The qualitative approach of likelihood of climate extremes, systematizes the probability levels in terms that are common for all those who are engaged in climate change issues.

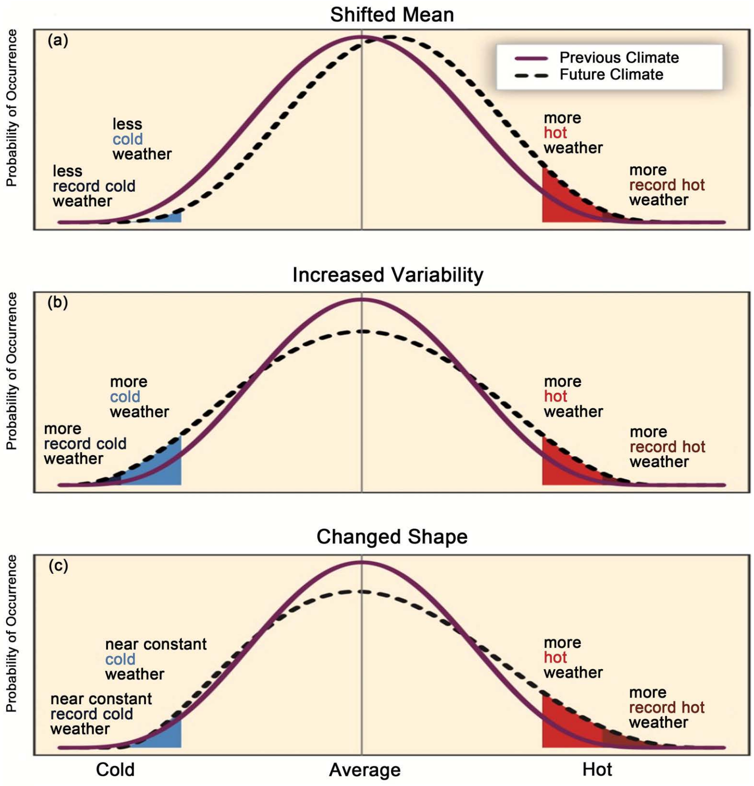


Figure 5. Probability of climate extreme occurrences. Source: Adjusted to Lavell et al., 2012.

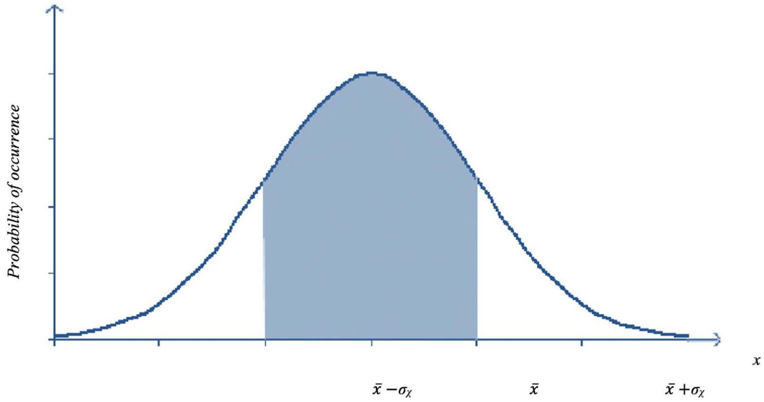


Figure 6. Probability distribution and uncertainties. Source: Taylor, 1997.

Table 5. Likelihood of occurrence and degree of confidence definition. Source: IPCC, 2014.

Term	Likelihood description	Term	Confidence level
Virtually certain	>99%	Very high confidence	At least 9 out of 10 chance
Extremely likely	>95%	High Confidence	About 8 out of 10 chance

Continued

Very likely	>90%	Medium confidence	About 5 out of 10 chance
Likely	>66%	Low confidence	About 2 out of 10 chance
More likely than not	>50%	Very low confidence	Less than 1 out of 10 chance
About as likely as not	33% - 66%		
Unlikely	<33%		
Very unlikely	<10%		
Extremely unlikely	<5%		
Exceptionally unlikely	<1%		

4.2.3. Return Periods in Assessing Sea Level Rise and Extreme Precipitation Likelihood of Occurrence

Most Authors use return periods (Ts) to assess the likelihood of a hazard occurrence, which despite they have been successfully used in assessing the likelihood of storm surges, high tides and extreme precipitation, they are not adequate to assess the probability of sea level rise and inundation due to extreme precipitation (Koliokosta, 2023a). Sea level rise is a long lasting and slow phenomenon that differs from the sea level rise due to storm surges and high tides (Koliokosta, 2023a), which despite contributing to temporary sea level (Marcos et al., 2019) they perform significant regional variability in terms of frequency, duration and intensity and definitely do not define the global mean sea level (Ezer, 2023). In addition, the return period of extreme precipitation occurrences is not equal to the return period of extreme flood occurrences due to extreme precipitation (Vangelis et al., 2022). Thus return periods should be very frugally used in hydrological hazards (Koliokosta, 2023a) suggests that the combination of likelihoods and confidence levels can provide with adequate information about future climate extremes, which can be assigned with values ranging in a [1, 10] scale as in **Table 6**. The combined likelihood and confidence level can increase the accuracy of future climate extremes likelihood assessment, eliminating the inconsistencies derived from the use of return periods, that are usually used to assess climate extremes likelihood of occurrence (Koliokosta, 2023a).

Table 6. Numerical scale for probability of occurrence.

Qualitative Assessment Prediction Term	Associated likelihood	Degree of confidence	Proposed Probability Scale (PPS)
Virtually certain/Extremely likely	>99%/>95%	Very high/High confidence	10
Very likely	>90%	High confidence	9
Likely	>66%	High confidence	8
		Medium confidence	7

Continued

About as likely as not	33% - 66%	High Confidence	6
		Medium Confidence	5
Unlikely	<33%	Medium Confidence	4
		High Confidence	3
Very unlikely	<10%	High Confidence	2
Extremely unlikely/Exceptionally Unlikely	<5%/<1%	High Confidence	1

Source: Koliokosta, 2023a.

4.3. General Concept of Vulnerability

The concept of vulnerability is fuzzy (Taubenböck et al., 2008; Birkmann, 2006) and encompasses a wide range of definitions (Proag, 2014; IPCC, 2014; Brenkert and Malone, 2005). The concept of vulnerability was initially associated with poverty (Imai et al., 2011) and physical fragility (Birkmann, 2007). Since then, the concept of vulnerability has been implemented in a wide range of subjects and disciplines (Bankoff et al., 2004), that is why the concept of vulnerability may vary according to the disciple, organization or among researchers (Birkmann, 2006).

The term vulnerability is widely discussed in literature and is used to describe:

- the susceptibility of human beings, assets or systems to the impact of hazards (Sayers et al., 2003; Cruz-Bello and Alfie-Cohen, 2022)
- the weakness and deficiency of assets and systems and the physical resistance of structures (IPCC, 2012)
- the resilience and coping capacity (Wisner et al., 2014)
- the exposure to hazards (Voice et al., 2006)
- the impact of hazards (Cutter et al., 2003) and
- the value of assets (Rezende et al., 2020)
- the risk to natural hazards (López Royo et al., 2016)

Such variability in the interpretation of the term "vulnerability" leads to misconceptions about the term and could result in inaccurate risk assessment. A variety of definitions that are found in literature are analyzed below. In order to identify the inconsistencies in the use of the term "vulnerability" the use of the original definitions is vital in order to avoid misconstructions derived from own words and personal views based on abstracts and summaries of the definitions.

Vulnerability in many cases implies primary the impact and secondly the susceptibility. For instance, Cutter et al. (2003) claim clearly that vulnerability defines "the potential loss", an approach that has been very widely accepted among Authors. Similarly, Buckle et al. (2001) enunciate vulnerability as "the degree of loss to a given element at risk or set of such elements resulting from the occurrence of a phenomenon of a given magnitude expressed on a [0, 1] scale", connecting vulnerability with the impact. In a like manner, Jones (2003) views the vulnerability *as* "the degree to which a system is susceptible to harm and is measured in terms that express a measure of monetary value or any other value-based criteria", associating systems susceptibility with the impact expressed in monetary terms and does not refer to physical damages. Gobbens et al. (2010) refer to the vulnerability of peoples as a dynamic state that harms one or more domains of human functioning (physical, psychological, social), resulting from the influence of a range of variables that increase the risk of adverse outcomes.

United Nations-International Strategy for Disaster Reduction associates vulnerability with "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) or "the processes or factors that increase the susceptibility of human beings, assets or systems to the impacts of hazards (UNISDR, 2009). In both definitions, the hazard seems to be external to the physical systems and livelihoods at risk, while vulnerability refers to the factors of these elements at risk that could affect them financially, physically or operationally (Birkmann, 2007).

Very similar are the definitions given by (Mechanic and Tanner, 2007), according to whom vulnerability is expressed by "the susceptibility to harm resulting from the interaction of risk factors and supports and resources available to individuals and groups" and Zarowsky et al. (2013), who view vulnerability as "a condition of heightened fragility of a population or specific group, and a process that is potentially reversible or avoidable through appropriate interventions".

In several cases, vulnerability is being viewed through coping capacity and resilience, which are actually negatively related to vulnerability (Hughes and Healy, 2014). More specifically, Buckle et al. (2001) expresses vulnerability as "the degree of susceptibility and resilience of the community and environment to hazards", while Wisner et al. (2014) give a human-oriented approach of vulnerability based on "the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard (an extreme natural event or process)" implying that the impact derived from vulnerability is a temporary situation that can be mitigated through resilience and coping capacity.

Moreover, Proag (2014) defines vulnerability as "the degree to which a system, or part of it, may react adversely during the occurrence of a hazardous event "and expresses vulnerability as a measure of the capacity of physical and socioeconomic system to address the risk, and emphasizes the importance of social and financial liability to cope with hazards.

4.4. Vulnerability to Climate Change

Dewan (2013) view vulnerability from another perspective, according to which vulnerability is a part of the following three premises (**Figure 7**). According to the first premise vulnerability is expressed by the outcome of hazards and determined by exposure, sensitivity and potential impact (Dewan, 2013). In this case, Dewan considers that the impact is a factor of vulnerability, which is very questionable as impact is a separate risk concept that may be affected by vulnerability but is not a factor of vulnerability, which is in detail discussed below. The second stem highlights the social, economic and cultural dimension of vulnerability, which derives from weaknesses in the economy, distribution of resources, political structure and the cultural characteristics of a community (Dewan, 2013). The third lineage refers to the role of resilience and coping capacity in managing the vulnerability to natural hazards and thus reduce the risks (Dewan, 2013).

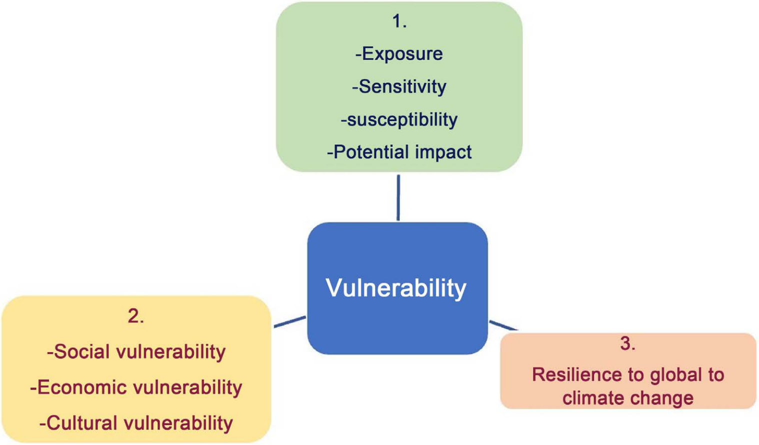


Figure 7. The three dimensions of vulnerability according to Dewan. Source: Dewan, 2013.

Vulnerability is dynamic and changes over time (Buckle et al., 2001). All factors that affect the level of vulnerability can affect the outcome of a hazard occurrence. Vulnerabilities deriving from political and economic systems, environmental forces, population demography, weaknesses and failures in structures and systems define the magnitude of the risk and the magnitude of a disaster (Blaikie et al., 2014; Dewan, 2013). That is why developing countries are considered more vulnerable to natural disasters than developed countries (IPCC, 2001).

Although vulnerability is a key factor in risk comprehension (IPCC, 2012), it cannot be easily assessed or quantified (Birkmann and Fernando, 2008). Literature discusses a variety of vulnerability assessment methodologies, according to the issue or discipline it is associated to. Some authors very often confuse vulnerability assessment with impact or risk assessment (Brenkert and Malone, 2005), something that needs to be clarified when studying risks.

With respect to vulnerability to climate change, IPCC has developed a variety of definitions. One of the first definitions, combines the susceptibility with the impact, exposure and adaptive capacity in an integrated definition as following:

"*Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.*" (IPCC, 2001)

Authors from different disciplines agree that vulnerability concept can be divided in three premises (Malone, 2009; Cutter et al., 2003; Dewan, 2013;

Taubenböck et al., 2008) exposure, sensitivity and copying capacity as following:

$$\text{Vulnerability} = \text{Exposure} \times \text{Susceptibility/Coping Capacity} \quad (9)$$

(Taubenböck et al., 2008)

4.5. Exposure

Exposure describes “the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected” (IPCC, 2012). Nicholls et al. (2008), who uses the term “Assets at risk”, “a combination of the exposed population, GPD per capita and the exposed assets, including transport, buildings and utility infrastructure”, defining exposure as a dominant element of vulnerability and connecting risk with vulnerability.

Exposure describes “the extent to which a unit of assessment falls within the geographical range of a hazard event. Exposure extends to fixed physical attributes of social systems (infrastructure) but also human systems (livelihoods, economies, cultures) that are spatially bound to specific resources and practices that may also be exposed. Exposure is then qualified in terms of spatial and temporal patterns.” (Birkmann et al., 2013).

Exposure is an important determinant of vulnerability (Koliokosta, 2023c). Voice et al. (2006) in their Report to the Australian Greenhouse Office, use an exposure-based approach in order to analyze coastal regions vulnerability to climate change and conclude that “any coastal community, ecosystem, economic unit or industry that is susceptible to, or unable to cope with the adverse effects of climate change impacts” are vulnerable to climate extremes, such as sea level rise, storm surges and strong winds. In a comparable manner, Nicholls et al. (2008) discuss the vulnerability of coastal “assets at risk” from an exposure perspective as “a combination of the exposed population, GPD per capita and the exposed assets, including transport, buildings and utility infrastructure”. Similarly, Boruff et al. (2005) consider exposure as dominant factor in assessing coastal vulnerability to coastal hazards, which is related to both inundation and erosion due to exposure (Bosom and Jiménez, 2011).

Besides, exposure is highly associated to vulnerability to climate extremes, as is the basic tool to identify, assess and map the vulnerability with the use of various geospatial tools and data (Koliokosta, 2023c). Thus, vulnerability to SLR and riverine flooding due to extreme precipitation is very reasonably expressed through a geospatial perspective, as all elements laying on areas close to seashore and rivers are exposed to the related hazards, including SLR, storm surges, extreme precipitation, tropical storms and glacier tsunamis and thus are vulnerable to them (i.e. Koliokosta, 2023b; Koliokosta, 2023c). Based on this approach the exposure to these hazards can also be implied by the term “geospatial vulnerability” (Koliokosta, 2022; Koliokosta, 2023c) or “regional vulnerability” (Swami and Parthasarathy, 2021), which eventually express the vulnerability to climate hazards that occur and hit specific areas and perform specific features.

4.6. Susceptibility or Sensitivity

Susceptibility or sensitivity refers to the degree to which a system will respond to a given hazard, including beneficial and harmful effects (IPCC, 2001; Brooks, 2003). “Sensitivity” refers to the “degree to which system or asset is susceptible when exposed to a specific climate hazard” (Forzieri et al., 2018).

When referring to populations’ sensitivity to climate extremes Koliokosta (2023b) suggests that population sensitivity can be assessed as:

$$V_{\text{POP}} = \sum_{1}^{n} V\left(xi\right) n^{-1}$$

where x represents population vulnerability factors, such as health conditions, age, physical and mental impairments, homelessness, wealth (Smith et al., 2014) and n is the number of factors. For example, in a [1, 5] scale, where 1 implies the lowest vulnerability and 5 the highest vulnerability, if 30% of the population has a type of impairment and 80% are displaced people and immigrants, then $V_{\text{pop}} = (V_{\text{disability}} + V_{\text{immigrants}})/2 = (30\% \times 5 + 80\% \times 5)/2 = (1.5 + 4)/2 = 2.73 \approx 3$, which is a moderate vulnerability (sensitivity) (Koliokosta, 2023b).

4.7. Coping or Adaptive Capacity

Coping or adaptive capacity is “the ability of a system to evolve in order to accommodate environmental hazards or policy change and to expand the range of variability with which it can cope.” (Adger, 2006). Although, in most papers there is no distinction between adaptation and coping capacity, Birkmann (2011) considers that coping capacity refers to the ability to manage the impacts during a disaster or crisis, adaptation refers to medium- and long-term organization that could reduce the impacts of a hazard. In this research, as it studies future hazards occurrences, coping and adaptive capacity are considered similar concepts, as present adaptation will define the future coping capacity. Generally, it’s very important for decision makers to understand long term impacts of climate change in order to develop the appropriate adaptation decisions (Kirshen et al., 2005).

In the case of climate change hazards, coping capacity is the ability of a community to respond successfully to climate extremes, associated with “adjustments in practices, processes and structures”, to moderate the potential damages and take advantage of opportunities or to cope with the consequences (IPCC, 2001). It mainly refers to the ability to manage effectively the adverse impact of crisis, natural hazards and disasters, so as to reduce risks. Adaptive capacity is considered to relate with the social and economic development of each community (IPCC, 2001). Indeed the socioeconomic and environmental conditions of each country may increase coping capacity as developed countries can spend higher amounts of money for adaptation and resilience to climate change and other natural hazards (Birkmann, 2006). However, reality debunks this myth, as even developed countries with high adaptive capacity are vulnerable to climate extremes and perform severe damages due to climate hazards (Koliokosta, 2023c; Koliokosta, 2022).

In AR5 Synthesis Report, vulnerability is reflected by *"the propensity or predisposition to be adversely affected."* (IPCC, 2014). This definition, is very general and "*encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.*"

The above IPCC definitions refer to all elements and does not focus on assets and structures specifically, as they did in the Fifth Assessment Report (IPCC, 2012), which separately referred to the physical structures vulnerability as "*the structural weaknesses and deficiencies that affected the physical resistance to climate extremes.*"

Brooks (2003) considers that vulnerability could cause both negative and positive results and refers to vulnerability as "*The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.*" This is actually more an impact definition rather than vulnerability definition.

Rezende et al. (2020) discuss the risk to flood extremes and concern that vulnerability of a socioeconomic system is a function of exposure, susceptibility and value, giving vulnerability a financial dimension, implying that adaptive capacity depends on the value of the assets and systems that will potentially be affected by flooding occurrences.

Vulnerability can be assessed either by using quantitative indexes (Boruff et al., 2005; López Royo et al., 2016) or vulnerability matrices (Koliokosta, 2023c). When assessing vulnerability of assets or regions to climate hazards, the use of geospatial data is essential (Sterr, 2008) in both approaches. All methods of vulnerability assessment aim to compare vulnerabilities and assess the resulting risks, in different areas, conditions or groups. Vulnerability assessment is a vital tool for promoting sustainability in societies by increasing resilience either by short-term recovery strategies or long-term adaptation measures (Moss et al., 2001). The results of the vulnerability assessment can be summarized by the vulnerability matrix, which is a useful tool for evaluating a systems behavior when exposed to hazards (Baker, 2005).

Notably, vulnerability is influenced by many factors. The main factors to consider with respect to climate change impact on physical assets, is the resistance to climate extremes, its durability and the exposure to climate hazards (Cardona and Carreño, 2011). As structural resistance and durability are related to the particularities and characteristics of each structure, vulnerability in this research is assessed based on exposure and, more specifically, exposure to flooding since this is the major impact of sea level rise and extreme precipitation.

4.8. Adaptation and Resilience towards Extreme Flooding Events

Sea level rise and extreme precipitation already occur and are projected to increase more in the future and thus contribute to increased flooding that could affect all critical infrastructure, services and livelihoods. Past and recent flooding occurrences around the world, in both developed and developing countries, prove that there is a huge gap in managing effectively riverine flooding after extreme precipitation occurrences, as well as coastal flooding during tropical or extratropical storms, monsoons and tsunamis after earthquakes (Koliokosta, 2022; Koliokosta, 2023c).

In a dynamic and continuously changing climate, where flooding from climate extremes result in huge economic and physical damages (Resio and Irish, 2015), effective climate risk management, including adaptation and resilience building, is crucial for the sustainability and durability of infrastructure, systems and societies (Zhang et al., 2022). Adaptation can be generally concerned as a response to repeated natural disasters, which requires the adoption and implementation of measures, strategies and tools that aim the reduction of vulnerability and impact mitigation (Nohrstedt et al., 2022). Effective adaptation requires 1) information about vulnerable systems exposed to certain hazards, including data collection, research and simulations and 2) the prioritization of investments and other financial resources for the preparation the most vulnerable to prevent the adverse impacts of climate change (Füssel and Klein, 2006). Effective adaptation aims to build resilient systems and societies by increasing "*capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance*" (IPCC, 2022). However, the knowledge with respect to the effectiveness of adaptation to climate change remains limited (Magnan et al., 2022) making the adaptation assessment a difficult task.

When referring to resilience, it can be considered as the flip side of vulnerability (Rose and Krausmann, 2013) and can be described as "*the ability of the physical system*(*s*) *to perform to an acceptable*/*desired level when subject to a hazard event*" (Bruneau et al., 2003). Resilience also, refers to a) the level that a system can absorb a shock with the minimum changes in the given state, b) the ability of the system to build capacity and adaptation and c) the capability degree for self-organization (Folke et al., 2002).

There have been several tools developed and adopted with respect to pluvial, fluvial and coastal flood risk management, including flood projection maps, structural flood protection measures, early warning systems, risk-informed land planning, nature-based solutions, social protection and risk financing instruments (Aerts et al., 2014). Although they are vital tools for reducing flood risk, in practice they might be inadequate (Koliokosta, 2022; Nateghi et al., 2016) to prevent large flood disasters and their failure might result in larger adverse impact (Barnett and O'Neill, 2010). Moreover, flood projections are described by "tremendous uncertainties" making it very difficult to make accurate predictions about future flood impacts and map vulnerability to flooding extremes (Muñoz et al., 2021). Such uncertainties need to be translated and incorporated into flood risk assessment by hydrologists (Neale and Weir, 2015).

Despite the difficulties in optimizing adaptation effectiveness to flood extremes, adaptation measures have been adopted around the world aiming to reduce the vulnerability of peoples, societies, systems and infrastructure that are exposed to flood associated hazards, such as sea level rise, storm surges, high tides, tsunamis and extreme precipitation. The most common adaptation tools and measures against floods are the following:

a) Levees: are natural or artificial constructions that have been traditionally used to protect waterfront areas from flooding (Ohtsuki et al., 2022), by disconnecting them from floodplains and thus preventing water from penetrating protected areas (Knox et al., 2022).

b) Dykes: are also built to prevent flooding with the difference that they protect areas that would normally be inundated, while levees protect areas that under normal conditions would be dry (Serre et al., 2017).

c) Wave walls and seawalls: are constructions designed to reduce the amount of wave overtopping and keep it to a minimum level, with wave walls to be smaller structures than seawalls (Qiang et al., 2021). Experiments and studies have proven that wave and sea walls reduce significantly the run-up momentum and can minimize the impact of large and strong waves (Thieu Quang & Nguyen Van, 2014).

d) Drainage systems: in urban regions, artificial drainage systems are significant facilities for controlling and decline the propagation of flood waters (Qiang et al., 2021), where natural drainage is very frequently replaced by impervious drainage channels and paved areas (Piadeh et al., 2022). Despite their contribution in mitigating the impacts of flooding events, in several cases they are not considered adequate to resist the increased intensity of extreme precipitation and storm surges (Lee et al., 2016).

e) Flood Early Warning Systems (FEWS): consist of a set of capacities that are required to produce prompt and important information that warn people, communities and organizations to get prepared to address a hazard by properly acting in sufficient time, aiming to prevent losses and reduce injuries and physical damages (Chaves and De Cola, 2017). Their effectiveness relies on four core components that consist of 1) disaster risk knowledge based on accurate disaster risk assessments, 2) identification, monitoring and analysis of the hazards and assessment of their potential impact, 3) risk communication and dissemination of accurate warnings by official sources and competent authorities regarding the risk, 4) preparedness to respond to the warnings received (UNISDR, 2009).

f) Relocation: the accelerating SLR rates, the enhanced storm surges built on higher sea levels and riverine flooding due to extreme precipitation have already urged people to relocate from the affected areas and move to less vulnerable areas, which offer higher level of life quality and prosperity (Arnall, 2019).

g) Flood projection maps: illustrate the expected extent of inundation after extreme precipitation or other natural or anthropogenic factors (Antzoulatos et al., 2022). Several organizations and institutions around the world, (i.e., NASA, NOAA and FEMA) have developed flood projection maps (interactive and not) that illustrate the potential extent of a future flooding event, under different flooding scenarios. These maps are developed using complex hydrodynamic models and simulating flood inundation in both simple and complex areas, taking into account flow data, meteorological data, remote sensing data and other supplementary terrestrial data that provide significant information for flood mapping and assessing potential impacts (Skilodimou et al., 2021; Qiang et al., 2021). Recently, methods such as Deep Learning (Bentivoglio et al., 2022), Machine Learning (Ighile et al., 2022) and Big Data (Yu et al., 2018) have also been used in flood mapping procedures, which assess the risk towards climate and other natural hazards and contribute to building capacity and risk mitigation decisions.

Flood maps provide visual illustration of flood extent, which is stronger than other types of presentation, such as analytical or oral (Merz et al., 2007). Thus, flood risk maps provide adaptation planners, stakeholders and decision makers with significant information with respect to hypothetical flooding patterns and geospatial features that are essential for setting adaptation, insurance and land development priorities, which is necessary for flood management (Chen et al., 2022).

Although adaptation measures are generally considered to increase resilience and safety against floods, reality shows that not all measures are adequately effective to prevent flood disasters (Nateghi et al., 2016; Piadeh et al., 2022). The most important thing is the effectiveness, the accuracy and the performance of these adaptation measures during flood extremes and not their existence alone (Koliokosta, 2023c; Piadeh et al., 2022, Perera et al., 2019; Zhang et al., 2022). Due to the uncertainties derived from the gaps in literature and lack of knowledge in the assessment of the performance of these measures, their incorporation in assessing vulnerability and risk should be furtherly concerned (Koliokosta, 2023c).

4.9. Impact

Impacts, consequences or outcomes are *the effects on natural and human systems*. (IPCC, 2014; IPCC, 2018). The term impact refers to economic, human and environmental consequences of a hazardous event, and may include death, injuries, damages on physical structures and human systems, ecosystems, cultures, well as diseases and other negative effect on mental and social well-being (UNGA, 2016). The impact of a specific hazard depends on the vulnerability profile of a society, system, infrastructure or network (Omena Monte et al., 2021), related to the level of adaptive capacity and sensitivity. Despite hazards usually result in negative impacts, in some cases, they may have some positive impacts that derive from systems transformation after adaptation and mitigation measures (Hallegatte and Dumas, 2009).

Natural hazards impact can be distinguished between direct and indirect consequences (Brown et al., 2018). Direct impacts are the damages on physical structures, raw materials, natural resources, disruption of services, injuries, diseases and deaths, which occur directly after a hazard's occurrence or disaster (UNGA, 2016; Bednar-Friedl et al., 2015). Indirect impacts are principally associated with the financial or other losses and refer either to first order impact or higher order impacts (Al-Amin et al., 2019). Economic losses due to the direct damages can also be considered as direct losses, and "they represent the monetary value of the damages" on physical settlement and livelihoods (UNGA, 2016). Indirect economic losses, on the other hand, including microeconomic and macroeconomic impacts, are produced due to "a decline in economic value added as a consequence of direct economic loss and/or human and environmental impacts". Indirect losses may happen beyond the affected area with time lag (UNGA, 2016). Due to the above characteristics of the impacts of natural hazards, it is very difficult to measure the total impact.

As the number and the intense of natural disasters have dramatically increased (Le Treut et al., 2007; Coumou and Rahmstor, 2012) the magnitude of the impact tends to rise (IPCC, 2014). Factors, such as infrastructure development in areas vulnerable to hazards, population density, lack of disaster preparedness etc., contribute to further increase of natural hazards impacts (Brown et al., 2018; Padli et al., 2018). Based on the area's vulnerability, the impacts differ with respect to the specific geographical, geomorphological, demographical, technological and socioeconomical features of each area (Di Risio et al., 2017).

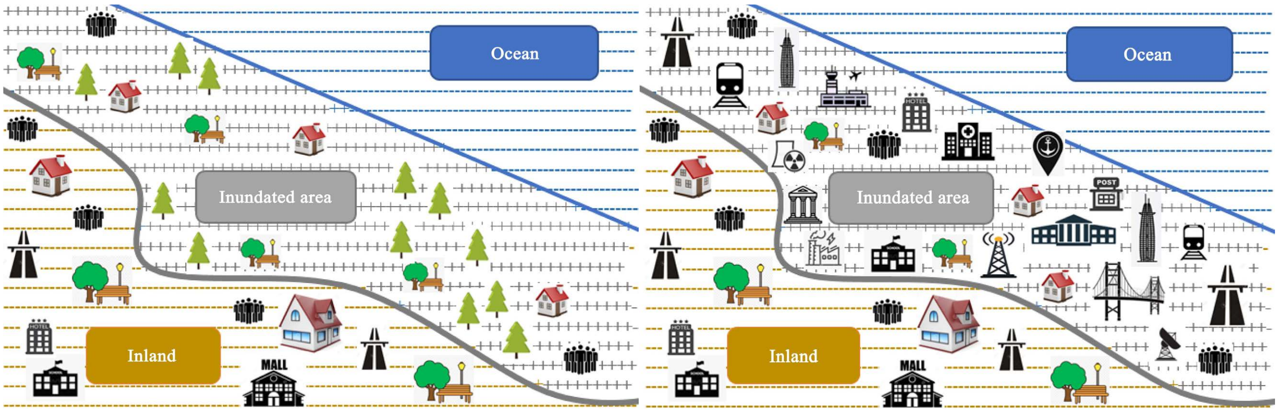
4.10. Impact vs Vulnerability

One of the most common misconceptions in risk management literature is the overlap between "impact" and "vulnerability" terms. Many authors use the term impact to imply vulnerability and vice versa, without making distinct reference to these two elements. In climate change risk assessment, the distinction of these terms is crucial and the ignorance of one of them could lead to wrong estimations and thus to misleading decisions.

Let's consider an inundated area (+++) due to SLR, storm surge or a tsunami (**Figure 8**). The inundated area represents the vulnerable area and the elements laying in it are the elements at risk or else the vulnerable elements. The type of the elements laying in the vulnerable area are those that define the level of the impact and not the vulnerable area itself. The more critical infrastructure, people, residential buildings, networks and systems laying in the exposed area the higher the impact (**Figure 8(b)**).

The impact of the flooding occurrences can be defined by the structural and operational damages. As there is little evidence on the economic impact of climate extremes on critical infrastructure (Koliokosta, 2017), the disruption of their operations reflects adequately the magnitude of the damage. The vulnerability of critical infrastructure on the other hand, is mainly defined by the exposure, as there is little evidence on adaptation and sensitivity data (Koliokosta, 2023c).

The structural vulnerability to flooding occurrences should be concerned by an engineering approach and should be assessed separately for each element at a second stage. There is no reason for elements that are not exposed to climate hazards to invest on climate adaptation measures, unlikely elements highly exposed to climate hazards, should invest on specific adaptation strategies according to the specific hazard and adaptation needs (Felio, 2015). There is also a necessity for individual elements to adopt adaptation measures combined with regional adaptation, so as to optimize the effectiveness of its adaptive capacity. For instance, a coastal airport that is expected to sink under water, would increase its adaptation to SLR if regional sea walls or other regional adaptation measures were also implemented.



(a)

(b)

Figure 8. Illustration of impact vs vulnerability. (a) Small impact due to inundation; (b) Large impact due to inundation. Inundated area +++; Ocean ---; Coastal (inland) area ---: 1) The vulnerable area is defined by the extent of the inundation; 2) The impact is defined by the elements laying in the vulnerable area; Source: Author's illustration.

5. Suggested Flood Risk Management Framework and Risk Matrix

The literature review concludes that there is a huge gap in the interpretation of risk concepts, which in result conclude in a variability in risk formulas, risk matrices and ambiguous risk frameworks. Based on the risk concepts definition above this research systematizes risk terms and provides the fundamental upon which a climate risk assessment framework and a risk assessment matrix is developed, focusing on sea level rise and extreme precipitation.

A general SLR and extreme precipitation risk management framework can be described by **Figure 9**.

This flood risk management framework incorporates all key risk elements, including likelihood, vulnerability and impact and excludes susceptibility and adaptive capacity from risk assessment process. This framework is general and can be adapted to the needs of each discipline or sector.

6. Suggested Definitions for Climate Risk Concepts

In order to assess and rank the risk to sea level rise and extreme precipitation, it is important to have concluded in the definition of each risk term that will be incorporated into risk assessment process. As such, this study consider that:

Climate change risk is a function of the likelihood of a climate hazard occurrence, the vulnerability of this climate hazard and the adverse impact of the specific climate hazard on all exposed elements, including people, properties, critical infrastructure, networks and systems.

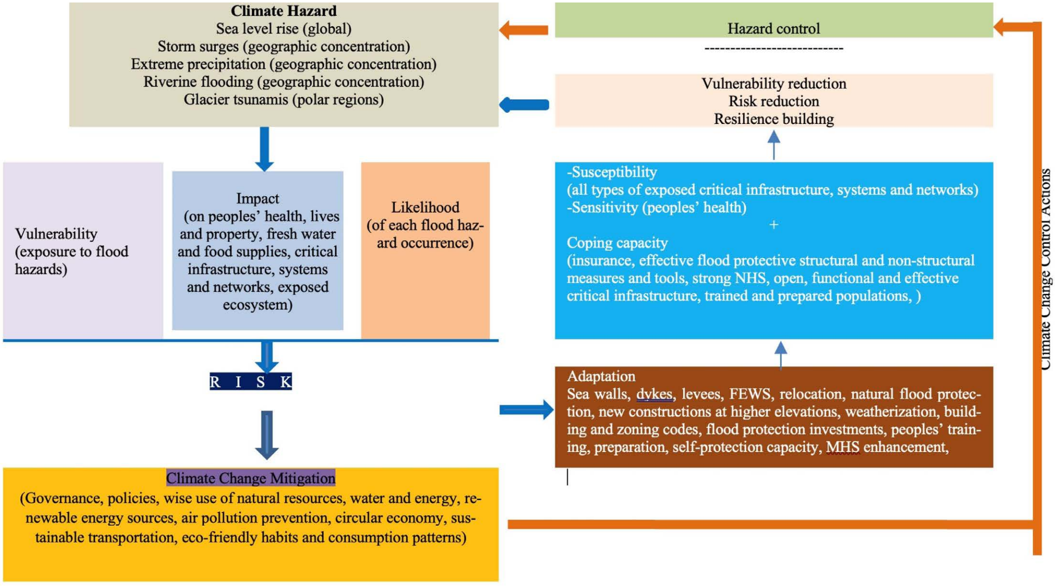


Figure 9. General flood risk management framework. Authors' General flood risk management framework.

A) The total climate change risk on all these elements is expressed by the formula:

Total Risk of Climate Hazard *x*:

$$R(x) = L(x)\Sigma V(x) \times \Sigma I(x) \tag{10}$$

where $R(x)$ is the risk of occurrence of climate hazard x, $\Sigma V(x)$ represents the vulnerabilities of all elements to climate hazard x and $\Sigma I(x)$ implies the total impact of climate hazard x on all the above elements (Koliokosta, 2023b).

B) The vulnerability to sea level rise (V_{SLR}) and extreme precipitation (V_{PREC}) is approached by an exposure perspective, based Birkmann et al.'s (2013) definition, considering elevation and distance from water-masses the primary exposure factors that define vulnerability (Koliokosta, 2023c). According to this approach, vulnerability is called *geospatial vulnerability* (*GV*) that implies the proximity of the elements to the water-masses that may flood the surrounding regions due to climate extremes (Koliokosta, 2022; Koliokosta, 2023c).

Susceptibility and adaptive capacity are not incorporated into the vulnerability assessment in all cases, due to the lack of adequate susceptibility assessment methods for most sectors and the lack of knowledge with respect to the effectiveness of the adaptation measures (Koliokosta, 2022). Sensitivity assessment is more clear when assessing e.g. health issues or when there are specific scientific criteria that define susceptibility, e.g. bridges to flood extremes. So:

Vulnerability to sea level rise (Koliokosta, 2023c).:

$$V_{\text{SLRi}} = GV_{\text{SLRi}} = (\text{Min}(E_i, D_{\text{Ci}})) \tag{11}$$

where E_i is the minimum elevation of the element i closest to the sea shore and Dci is the minimum distance of element i to/from the coastline.

Vulnerability to extreme precipitation (Koliokosta, 2023c):

$$V_{\text{PRECi}} = GV_{\text{PRECi}}(\text{Min}(D_{\text{Ri}})), \text{ for non-coastal or estuarial elements} \tag{12a}$$

$V_{\mathrm{PRECi}} = V_{\mathrm{SLRi}} = GV_{\mathrm{SLRi}}(\mathrm{Min}(E_i, D_{\mathrm{Ci}}))$, for coastal and estuarial elements distant from rivers and other water-masses rather than sea (12b)

where D_{Ri} is the minimum distance of the element i to a river or another water mass, under the restriction that elements laying at elevation higher than 4m from the river elevation are considered resilient to riverine flooding (Koliokosta, 2023c). For the coastal and estuarial elements, that lay far from rivers, their vulnerability equals to the vulnerability to SLR, when $V_{\mathrm{SLRi}} > V_{\mathrm{PRECi}}$, due to strong climatic hazards interconnection and interaction

C) The impact of climate change is defined by the structural/physical damages and the disruption of the operations of the elements/infrastructure/systems/networks laying on the exposed and thus vulnerable areas. In several cases, e.g. for critical infrastructure, there is no accepted methodology that could estimate the structural and physical damages due to climate extremes, and thus the disruption of the operations could represent the magnitude of the damage.

7. Risk Assessment, Risk Matrix and Risk Ranking

This research considers that R = Likelihood × Vulnerability × Impact, where likelihood is assigned a [1, 10] scale (Koliokosta, 2023a) and both vulnerability and impact range in [1, 5] scales (Koliokosta, 2023b). Thus risk ranges in [1, 250] = [1, 10] × [1, 5] × [1, 5]. Vulnerability and impact combinations conclude into the following products, which are then used to design the risk matrix:

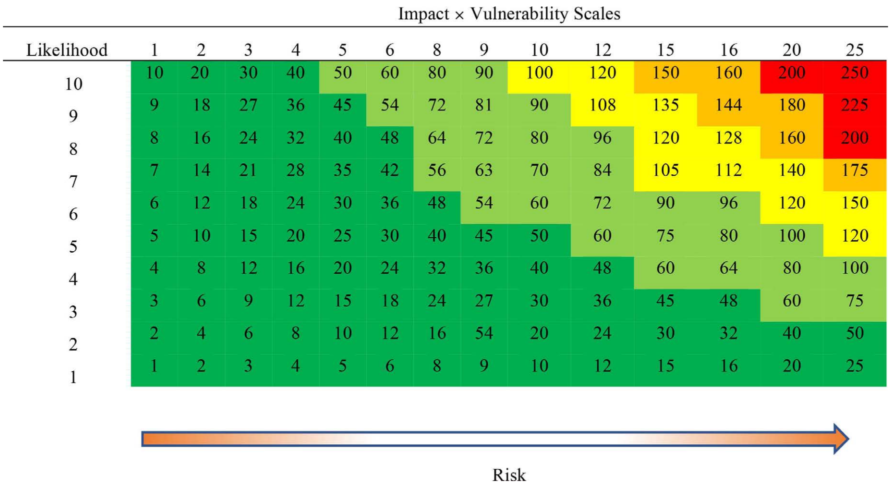
V *	I =		V *	I =		V *	I =		V *	I =		V *	I =	
5	1	5	4	1	4	3	1	3	2	1	2	1	1	1
	2	10		2	8		2	6		2	4		2	2
	3	15		3	12		3	9		3	6		3	3
	4	20		4	16		4	12		4	8		4	4
	5	25		5	20		5	15		5	10		5	5

The product combinations of vulnerability and impact give 14 scales/levels for $V(x)*I(x)$, which take the following values in the distribution: {1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, 16, 20, 25}.

These scales contribute to a 10 × 14 risk matrix (**Figure 10**). Any adjustment to a [10, 10] or [5, 5], could lead to loss of information and comparison ability, which is vital in making distinctions and supporting decisions. So, the [1, 250] scale is the most appropriate in climate change risk assessment and ranking.

The risk levels are described by relevant colors and are defined by dividing risk in five symmetric scales (i.e. adapted to Chen et al., 2023) as following:

- Extremely high risk: 5, when R ≥ 200
- High Risk: 4, when 150 ≤ R < 200
- Moderate Risk: 3, when 100 ≤ R < 150
- Low Risk: 2, when 50 ≤ R <100
- Very Low Risk: 1, when R < 50



Impact × Vulnerability Scales

Likelihood	1	2	3	4	5	6	8	9	10	12	15	16	20	25
10	10	20	30	40	50	60	80	90	100	120	150	160	200	250
9	9	18	27	36	45	54	72	81	90	108	135	144	180	225
8	8	16	24	32	40	48	64	72	80	96	120	128	160	200
7	7	14	21	28	35	42	56	63	70	84	105	112	140	175
6	6	12	18	24	30	36	48	54	60	72	90	96	120	150
5	5	10	15	20	25	30	40	45	50	60	75	80	100	120
4	4	8	12	16	20	24	32	36	40	48	60	64	80	100
3	3	6	9	12	15	18	24	27	30	36	45	48	60	75
2	2	4	6	8	10	12	16	54	20	24	30	32	40	50
1	1	2	3	4	5	6	8	9	10	12	15	16	20	25

Figure 10. Risk assessment matrix.

Risk ranking can then follow the risk rates, so when Risk = 250 risk ranking r = 1, when Risk = 225 then r = 2 etc. (Tadashi & Chutaporn, 2023). This risk matrix concludes into 59 risk ranking scales as illustrated by **Table 7**.

Table 7. Risk Ranking associated to risk assessment.

RISK LEVEL	*RISK RANKING*	RISK LEVEL	*RISK RANKING*	RISK LEVEL	*RISK RANKING*	RISK LEVEL	*RISK RANKING*
250	1	**100**	16	**48**	31	**16**	46
225	2	**96**	17	**45**	32	**15**	47
200	3	**90**	18	**42**	33	**14**	48
180	4	**84**	19	**40**	34	**12**	49
175	5	**81**	20	**36**	35	**10**	50
160	6	**80**	21	**35**	36	**9**	51
150	7	**75**	22	**32**	37	**8**	52
144	8	**72**	23	**30**	38	**7**	53
140	9	**70**	24	**28**	39	**6**	54
135	10	**64**	25	**27**	40	**5**	55
128	11	**63**	26	**25**	41	**4**	56
120	12	**60**	27	**24**	42	**3**	54
112	13	**56**	28	**21**	43	**2**	55
108	14	**54**	29	**20**	44	**1**	56
105	15	**50**	30	**18**	45		

8. Discussion

Risk and more specifically climate risk theory performs severe ambiguities derived from the huge variability of key risk definitions. Risk concepts are highly characterized by fuzziness, which is obvious among authors. Apart from the variability in risk definitions, there is also a considerable lack of consistency and lack of fixed patterns, among Authors, in understanding and comprehending key risk concepts, such as likelihood, impact, vulnerability and exposure. The lack of systemization and standardization of risk terms is widely disseminated in scientific risk assessment literature and other related publications.

The most common misconception found in literature is the overlapping between impact and vulnerability concepts. Several Authors consider vulnerability by an impact or loss perspective, considering that these two terms are similar or very close, while others view vulnerability as the value of assets, which actually reflects the impact and not vulnerability. Moreover, vulnerability is also used to describe the weaknesses and deficiencies of assets and systems, which is very general and cannot be applied on all hazards risk assessment. In other cases, Authors misinterpret vulnerability as risk, considering that all vulnerable elements to a specific hazard face similar risk to that hazard, without considering the potential impact.

Apart from the above, even the most common expression of vulnerability, where vulnerability is a function of exposure, susceptibility and coping capacity, performs also some severe ambiguities when assessing climate risk. At first, there is no commonly accepted method to assess the level of exposure, the level of susceptibility and the coping capacity of all elements, infrastructure and sectors, which are usually assessed based on personal judgements and perceptions. The assessment of vulnerability terms based on personal perceptions and not on specific criteria and methods, may affect significantly the accuracy of vulnerability assessment and thus the outcome of the risk assessment.

Another important issue that needs to be furtherly concerned is the incorporation of coping capacity in vulnerability assessment. In most cases, coping capacity is implied by the existence of adaptation and preventive measures, without considering their effectiveness, which may significantly affect the risk outcomes. Reality has proven that adaptation alone is not adequate to prevent large flood extremes. Failures in structural and non-structural adaptation measures and tools are very common and prove that preventive measures are not reliable and may increase vulnerability instead. As a result, there is an urgent need for further research on the effectiveness of adaptation measures, in order to fill in the gap in methodologies that provide accurate adaptive capacity assessments.

9. Conclusion

This paper discusses all aspects of climate change risk and ambiguities and inconsistencies in derived from the fuzziness of climate risk terminology. The contribution of this paper is significant as it 1) systematizes the key risk terms by defining the criteria for the assessment of each risk element, 2) incorporates both vulnerability and impact in risk assessment procedure and 3) emits susceptibility and adaptive capacity from vulnerability assessment due to the increased level of uncertainty, deriving from the lack of a widely accepted method for susceptibility assessment and the assessment of the effectiveness of adaptation capacity. This paper considers that geospatial vulnerability or exposure is the dominant factor for assessing vulnerability to sea level rise and extreme precipitation. With respect to SLR and extreme precipitation, this paper highlights the dominance of the IPCC likelihood/confidence scales, over return periods, in assessing the likelihood of hydrological hazards occurrences.

This paper also suggests that a [1, 250] risk assessment matrix, could contribute to better risk comprehension and understanding and facilitate risk ranking, which enables the prioritization of the needs for adaptation and resilience of the elements at highest risk.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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