Proceeding Paper

Return Periods in Assessing Climate Change Risks: Uses and Misuses [†]

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Abstract: Return periods (Ts) are used to estimate the interval of time between natural hazard occurrences of a certain size and assess the risks associated with hydrological occurrences, climate extremes, structural failures and seismicity. Despite *T*s being widely used, they are characterized by strong misconceptions and ambiguities. Moreover, although they have been successfully used when discussing storm surges, high tides and extreme precipitation, concerns arise from their use in assessing probabilities of future global mean sea level rise (SLR). Most papers discuss SLR return periods considering storm surges or high tides and not SLR itself, as a separate and unique hazard. Sea level rise due to storm surges or tides is regional and temporary and differs from the global SLR, which is a long lasting and slow phenomenon. This paper discusses these misconceptions and misuses of return periods in assessing flood risk and the probability of sea level rise at the global level and suggests a method for assessing likelihoods of climate change risks that can be widely accepted and commonly used by all stakeholders and decision makers for all types of climate hazards.

Keywords: return periods; sea level rise; storm surges; tides

1. Introduction

The return period (or recurrence interval) (T) is the "average time until the next occurrence of a defined event" [1] or "an estimate of the interval of time between events of a certain intensity or size" [2], and is expressed by the following formula:

$$T = 1/P(X \geq x) \tag{1}$$

where $P(X \geq x)$, is the probability of occurrence of a hydrological variable X of an equal or greater magnitude x in a given time interval [3].

Return periods have been widely used to assess the probability of occurrence of most natural hazards, such as earthquakes [4], tsunamis [5], extreme heat/cold weather occurrences [6–8], extreme precipitation [9,10], storm surges [11], tropical/extratropical cyclones [12], landslides [13].

Return periods are also used to assess (i) failures of hydrological safety systems due to extreme hydrological occurrences [14], (ii) failures of buildings [15] and critical infrastructure such as bridges [16] and highways [17] due to climate extremes, (iii) seismic resistance construction decisions [18], etc.

Despite the concept of return period being widely used in assessing the risks of hydrological and geophysical hazards, there are still strong misconceptions that could lead to wrong estimations [19]. Phrases such as "The 50-year return period flood peak of 100 $m^3 s^{-1}$ occurs once every 50 years" or "A flood peak of 100 $m^3 s^{-1}$" means that the value of 100 $m^3 s^{-1}$ has 50-year return period" are very common, but completely wrong [19]. The

return period does not mean that an event of a given size and magnitude will occur at intervals of T years on a regular basis, or that an event that has already occurred will not occur again in the next T years [3].

Return period estimation is based on the study of historical data of a specific event. An example of an extreme event is discussed below, so as to make clear what a return period is and what the probability of occurrence is for this specific event of this magnitude.

Let us assume a climate extreme X that exceeded magnitude *x* eight times during the period 1975–2018 (Table 1). According to Table 1, recurrence intervals range from 1 year to 16 years [20].

Table 1. Return period assessment.

Years When the Magnitude of Climate Hazard X Exceeded Level *x*, during 1975–2018	1980	1981	1982	1998	2001	2007	2012	2017	Average
Return Period (*T*)	4 years (1966–1970)	1 year (1970–1971)	1 year (1971–1972)	16 years (1973–1988)	3 years (1989–1991)	6 years (1991–1997)	5 years (1997–2002)	5 years (2002–2007)	5.1 years

By applying the average return period of X that exceeds *x*, which is equal to 5.1 years, to the return period formula, the probability of climate hazard X to exceed *x* is approximately 20%. This means that a 5.1-year event has approximately a 20% probability in any year and it is possible to have more than one such event within a year or even months [2]. The relation between the probability of occurrence of a value of a variable X equal to or greater than *x* in any year and the return period is given in Table 2 [1]:

Table 2. Return period and probability relation.

	Return Period (T)												
	10,000	2000	1000	200	100	50	20	10	5	3	2	1.5	1
Probability (%)	0.01	0.05	0.1	0.5	1	2	5	10	20	33	50	66	100

Based on the above, the return period is in fact nonsense when it is used to assess the probability of occurrence of an event that has large recurrence intervals, e.g., $T > 10,000$, as probabilities are eventually zero. As a result, the return period is not the appropriate tool for assessing risks of all climate hazards, as probability assessment is vital for accurate risk assessments and effective decision making. This paper aims to identify the ambiguities deriving from the use of return periods in the assessment of flood risks, driven from sea level rise (SLR), storm surges, high tides, tropical cyclones and extreme precipitation.

2. Materials and Methods

This paper concerns a review of 127 peer review papers from the Scopus database which use return periods as a tool for studying sea level rise impacts, coastal vulnerabilities, extreme precipitation impact, storm surges, high tides and flood risk.

The analysis of the research papers using return periods (both bivariate and univariate) in the study of flood related vulnerabilities, impacts and risk, generates a series of inconsistencies and ambiguities that are further discussed below. The return period's misuse in scientific research highlights the need for a widely accepted method that could be easily comprehended and used by all risk managers, stakeholders and decision makers when assessing climate change risks.

3. Results

The majority of the papers (57%) concern SLR and extreme precipitation (40%). The largest portion of the papers (86%) concerning SLR return periods (T_{SLR}) mainly discuss re-

turn periods of storm surges ($T_{storm\ surge}$) and high tides ($T_{high\ tide}$) (Figure 1). Storm surges alone, separate from SLR hazards, are studied in 31% of the research papers, while flood return period studies cover 28% of the total studies. The return periods of combined SLR and extreme precipitation risk was studied by 18% of the papers, but SLR is also discussed mainly from storm surges perspective. River water rise due to extreme precipitation is very rarely discussed, despite the fact that riverine flooding is widely discussed (Figure 1).
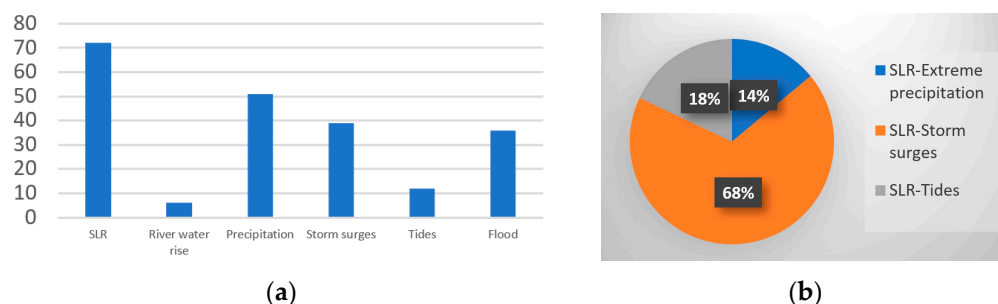

Figure 1. Peer-reviewed papers concerning the return period of flood-related hazards. (**a**). Papers distribution by climate hazard; (**b**) Papers studying combined hazards.

According to the literature findings, although extreme precipitation is one of the basic factors of inundation, the return periods of precipitation and flooding occurrences are not equivalent [21]. For reasons that have not yet been well comprehended or scientifically proved, the return period of inundation is always greater than the return period of precipitation [22]. In order to display similar return periods, they have to occur only under very low probabilities and under exactly the same conditions [21]. Among others, regional climatological features, soil moisture characteristics before the rainfall and soil evaporation, soil water storage capacity, precipitation spatial distribution, precipitation intensity and duration are factors that effect the relationship between precipitation and flood return periods [21,23].

Moreover, in most cases, when discussing SLR return period, authors refer to storm surges, high tides or waves and not the sea level rise itself [24,25]. Indeed, storm surges, high tides and wind waves contribute significantly to the level of the sea [26], but they do not define the global mean sea level, as they display high variability from place to place and follow the specific climatic features of each region and specific duration, intensity and frequency [27,28]. Ice and glaciers thawing are the primary contributors to global SLR acceleration [29], which will cause the most significant impact on future coastal populations, systems and infrastructure [30], and not storm surges or high waves, which are regional and temporary climate extremes.

Sea levels have changed dramatically through five glacial cycles [31] (Figure 2), ranging from approximately −120 to approximately 10 m, with zero sea level to represent the present years (Figure 2a). Based on the sea level cycles of the previous 500,000 years (Figure 2a), sea level takes several thousand years to reach present sea levels, and SLR remains a phenomenon that has been progressing slowly over the years [32]. More precisely, existing (present) sea levels were exceeded sometime during the last 1000–3000 years, and once again approximately 120,000 years ago. There are no data for the years before the last 500,000 years, which means that it may have occurred even millions of years earlier. Thus, sea level rise itself (not storm surges or high waves) displays very large return periods, and the probability of occurrence is close to zero. More precisely, P(SLR $\geq SLR_{present}$) ≈ 0, for any $T > 1000$ years

(**a**) (**b**)
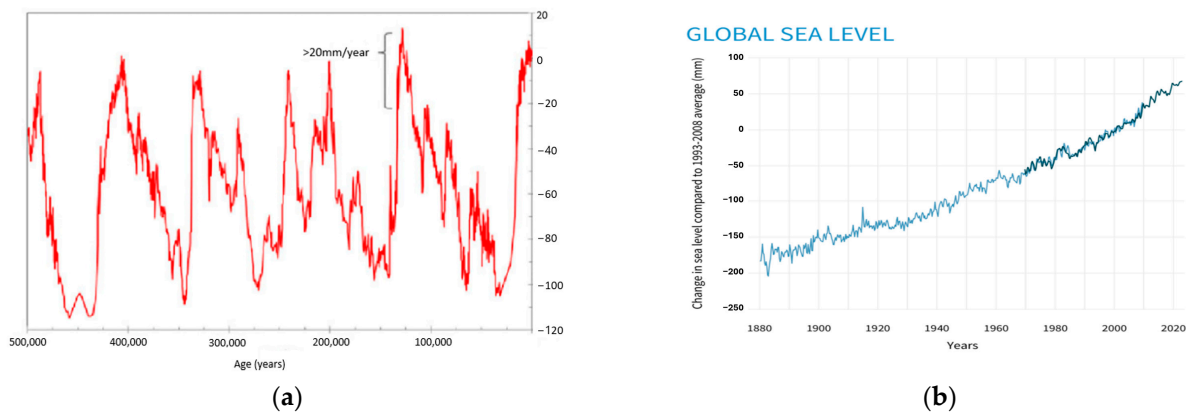
Figure 2. Sea level cycles [33,34]. (**a**). Sea level cycles during the past 500,000 years [33], (**b**). Global Sea Level Trend for the period 1980–present [34].

Even if it is considered that sea level has exceeded present levels during the last 2000–5000 years, approximately (Figure 2b), the fact that the previous interval occurrence lasted more than 120,000 years means that the average return period will be very high and the probability of occurrence will remain close to zero. On the contrary, storm surges perform higher frequencies and smaller return periods. For instance, in Northeastern USA, for a return period of 10 years, storm surge return levels could range from 0.9 to 1.5 m, while for a 50-year return period, the storm surge return level could range from 1.1 to 2.1 m [11].

Most hydrological series cover a period of about 30–50 years [35], while the same period does not provide the same important information about global SLR with respect to return periods. As illustrated by Figure 2b, there is no interval occurrence that can be assessed during the period of 50 years, 100, 200, or even 1000 years, as sea levels have never exceeded the present sea level over these periods. The SLR trend is increasing and is expected to increase more in the future due to global heating.

4. Discussion and Conclusions

According to the above, although return periods are a widely accepted tool for assessing flood-related risks, they cannot be used to define the probability of global mean sea level rise (MSLR). Giving a probability of MSLR occurrence close to zero means that SLR risk is negligible, which is an absurd and invalid concept. As the literature is mainly built upon the consideration that SRL, storm surges and high waves contribute similarly to SLR risk and coastal flooding, the above observation makes it necessary for researchers to re-define the use of return periods when assessing SLR risk.

In order to overcome the inconsistencies from the use of return periods in assessing flood risks, this research recommends that probabilities should follow the qualitative approach adopted by IPCC reports, ranging from "Exceptionally Unlikely" to "Virtual certain" [36–38], combined with the level of confidence [39], and which describes the validity of the related findings. A level of confidence that ranges from "Very high confidence" to "Very low confidence" can affect the meaning of the probability [40]. According to them, when an event is given a high or virtually certain likelihood, it must have a high confidence and never low confidence, or else it is not possible to be interpreted in a meaningful way. By assigning metrics on a scale [1,10] (Table 3), probabilities absorb degrees of confidence, increasing their accuracy.

Table 3. Numerical scale for Probability of Occurrence.

Qualitative Assessment of Likelihood	Associated Likelihood	Degree of Confidence	Probability Scale
Virtually certain/ Extremely likely	>99%/>95%	High confidence	10
Very likely	>90%	High confidence	9
Likely	>66%	High confidence/Medium confidence	8/7
About as likely as not	33–66%	High confidence/Medium confidence	6/5
Unlikely	<33%	Medium Confidence/High confidence	4/3
Very unlikely	<10%	High Confidence	2
Extremely unlikely/Exceptionally Unlikelly	<5%/<1%	High Confidence	1

So, when IPCC reports say that SLR in Japan is "likely" to occur with "medium confidence", the proposed probability scale level is assigned as "7", while, in the case of extreme precipitation that is "extremely likely" to occur with "very high confidence", the probability scale is equal to "10".

To summarize, instead of using return periods to assess flood risk, probability scales would result in more accurate risk assessment, as they are easy to comprehend and can be widely used by all stakeholders and decision makers. Return periods can be used to assess risk to extreme precipitation, storm surges and high tides but not future sea level rise at a global level. The use of probability scales could lead to more realistic results which are essential for coastal adaptation and resilience, by eliminating errors in calculation related to the more complex and ambiguous probabilistic approach of return periods.

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