Interpretation of the Natural Hazards Parameters for the Purpose of the PSA

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Abstract. The contemporary regulations concerning the elaboration of Probabilistic Safety Analysis (PSA) for the Nuclear Power Plants (NPP) require that all the external hazards are assessed appropriately. The IAEA safety guide SSG-18 *Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations* recommends a general procedure for the assessment of meteorological hazards. It includes collection of observations of the considered hazard parameter for the specific region, their statistical processing and assessment of the values for different annual frequency of exceedance. Nevertheless, the direct statistical approach should be applied with caution for the assessment of values with very low frequency of occurrence.

The current paper considers the estimation of the natural hazards parameters with very low annual frequency of occurrence (below 10^{-5}) and proposes an approach for analytical interpretation of the parameters for the purpose of the elaboration of PSA Level 1 of a NPP. The proposed approach is verified by a detailed analysis of a set of observations, following the SSG-18 general procedure and direct extrapolation of the parameters to the very low frequency range. A comparison of the results is made and some relevant conclusions are drawn concerning the applicability of the proposed approach in the PSA Level 1.

Keywords: data analysis, extrapolation, natural hazards, probabilistic safety analysis, statistical distribution

1 Introduction

Probabilistic safety assessment (PSA) of nuclear power plants complements the deterministic safety analysis and is a widely recognized approach to identifying accident scenarios and deriving numerical estimates of risks of undesirable consequences concerning nuclear power plant operation and associated plant vulnerabilities. As per the IAEA Specific Safety Guide No. SSG-3 "*Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants*" [1] and the relevant regulatory documents and guides [2–8], the PSA should cover all the external hazards, originating from the sources located outside the nuclear power plant site. These hazards are generally defined as natural and human-induced hazards. The external natural hazards include the seismic hazards, external fires, external floods, high winds, biological phenomena and extreme meteorological conditions. The group of external human-induced hazards includes off-site explosions, off-site toxic substance releases, aircraft crashes. The current paper considers the group of external natural hazards, in particular the extreme meteorological conditions and external floods.

The assessment of the hazard parameters is a crucial stage of the elaboration of the PSA. The process includes the selection of a unique and representative parameter for the considered hazard, an appropriate collection and processing of representative data and a generation of the relation between the annual exceedance frequency/probability and the value of the parameter, used to quantify the considered hazard (generation of the so-called "hazard curve").

The current regulatory guide SSG-18 [2] recommends a general procedure for the assessment of the external hazards parameters. Nevertheless, the proposed procedure should not be adopted a-priori. It is pointed in the safety guide that the estimation of the parameters for return periods well beyond the duration of the observations should be made with caution. Several researches have been elaborated, regarding the estimation of extreme hydrological parameters [9–13]. The authors distinguish between the methods and quality of the parameters estimation regarding the different annual exceedance frequencies in direct relation with the properties of the collected data, the sources of data and observations. The authors consider a so-called "credible limit of extrapolation", which bounds the estimation with a large but justifiable uncertainty. Beyond this limit, the trend describing the observed data might be violated so the procedures, applicable for the estimation of the values in this frequency range are on a rather pragmatic base. In this regard, a distinct procedure is acceptable to be used, if adequately verified. This matter is considered in a statistical point of view by the authors of Ref. [14].

The assessment of the extreme meteorological and hydrological parameters for the extremely rare events (annual frequency of exceedance below 10^{-5}) through an interpretation of the values, estimated for the frequent events, based on the statistical processing of a set of observations, is considered in the current paper. The estimation of the parameters is made for the purpose of the elaboration of the PSA Level 1 of a NPP. The proposed procedure is verified by a comparison with the estimations made, adopting the procedure recommended by the SSG-18 [2].

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2 Regulatory Requirements

The general procedure for the estimation of the natural hazard parameters, recommended by the current regulatory requirements of SSG-18 *"Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations"* [2] includes the following steps in brief:

- A study of the representative data series (on-site and regional data from meteorological and hydrological stations, historical data, reports, etc.) available for the region under consideration and an evaluation of its quality (representativeness, completeness, effectiveness of the quality assurance program, homogeneity, etc.);
- Treatment of the extreme annual values of the meteorological parameters as samples of random variables and selection of the most appropriate statistical distribution for the data set. Usually, a set of statistical distributions (candidate distributions) is fitted to the samples of the considered parameter and the most appropriate of them is selected. The choice usually is based on the best fit of the sample. Widely used in meteorology are the generalized extreme value distributions of Type I (Gumbel), Type II (Frechet) and Type III (Weibull) or other distributions, proved to be appropriate (Figure 1);
- Processing of the data to evaluate moments of the probability distribution function of the parameter under consideration (expected value, standard deviation and others if necessary), from which the mean recurrence interval and associated confidence limits may be estimated.

It is also pointed in the safety guide, [2] that caution should be exercised when fitting an extreme value distribution to a data set representing only a few years of records. If extrapolations are carried out over very long periods of time by means of a statistical technique, due regard should be given to the physical limits of the variable of interest. Care should also be taken in extrapolating to time intervals well beyond the duration of the available records, such as for "return" periods greater than four times the duration of the sample and the extrapolation method should be documented. The current paper gives a consideration of this remark by a specific case, applied in the elaboration of the PSA Level 1.

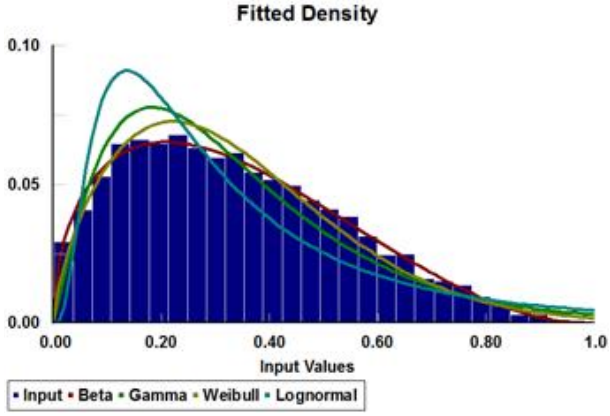

Figure 1. Fitted probability density to a histogram of the variable samples.

3 Considered Case

The current paper presents a particular case concerning the estimation of the natural hazards parameters (excluding earthquakes) for the purpose of PSA Level 1 elaboration. The parameters considered include extreme wind speed, extremely high/low natural water level/quantity of the river, extremely high/low temperature of the river water, extremely high/low air temperature, extreme thickness of ice/frost, deposited on wires and elements and extreme snow cover thickness. The specifics of the analysis requires that the parameters should be estimated for the range of exceedance frequencies covering the frequent and rare events (1.10^{-1} - 1.10^{-8}).

Estimation of the abovementioned parameters for the site considered has been elaborated as part of a previous analysis of the site, concerning the construction of a new NPP. The applied method is in full compliance with the general procedure of SSG-18 [1,2]. The estimation is based on contemporary, representative and complete database for the site considered, covering a period of around 100 years (1916-2011) and including observations from stations, situated in and out of the site, historical data, reports and other relevant information. The observations have been statistically processed, treated as random variables and representative statistical functions are fitted to

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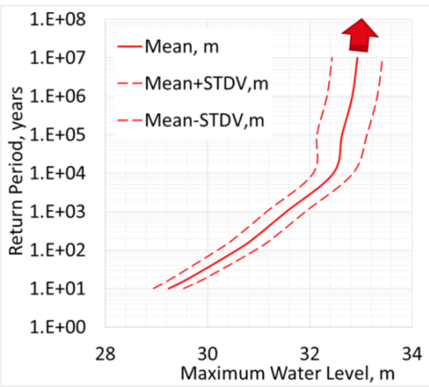

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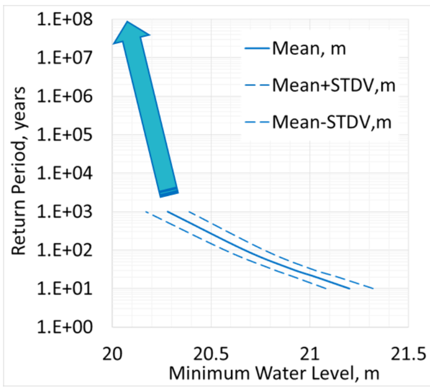


Figure 2. "Main model" curves for: a) maximum water level of the river, b) minimum water level of the river.

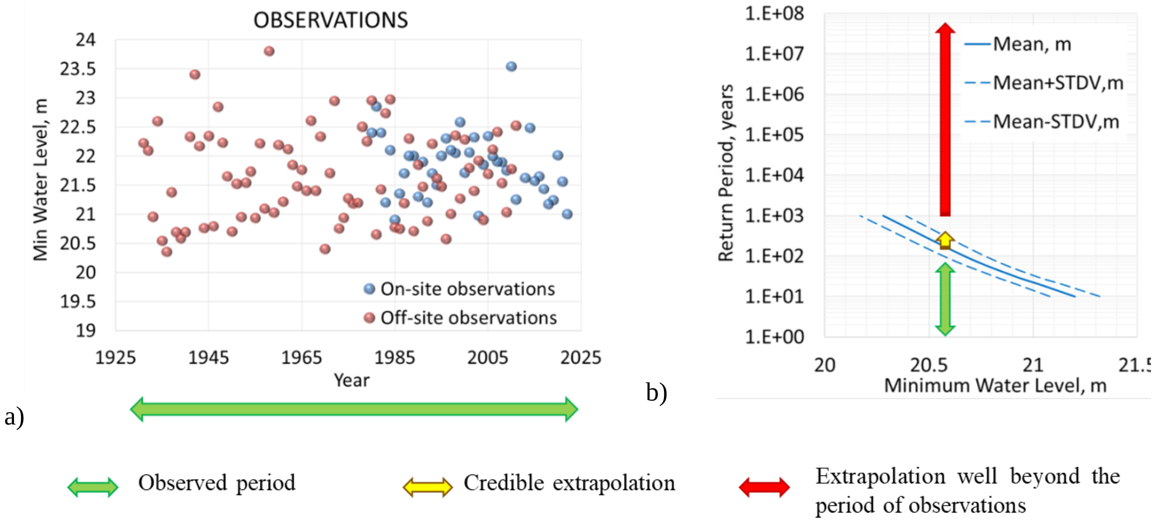


Figure 3. Observed data for the minimum water level of the river: a) discrete samples, b) best fit to the "main model".

them, allowing the analytical evaluation of the parameters for different frequency of exceedance. The parameters values have been estimated for probabilities of exceedance higher than 10^{-5} and were provided as input data. These values are accepted with no reassessment, nevertheless extrapolation of the estimations is needed for exceedance frequencies in the range of $(10^{-6}$–$10^{-8})$. The moments of the representative probability distribution functions of the parameters under consideration were not provided, so the extrapolation is not achievable in a direct manner.

With this regard and with regard of the specifics of the considered extremely rare natural events, an interpretation of the provided parameter values is proposed. The relation between the provided parameter value and the frequency of exceedance is named hereafter "main model" (see Figure 2) and is used in the estimation of the parameters values for the very rare events (up to once in 100 000 000 years).

Some considerations are accounted for in the process of the interpretation of the natural hazards parameters values as follows:

1. *The return period of the values to be estimated significantly exceeds the period of the observations*

The exceedance of the return period of the values that should be estimated is in the range of 10^4–10^6 times the observed period, as shown in Figure 3. Therefore, in compliance with the SSG-18 [2] requirements, such extrapolations should be made with caution. The data used in the analysis provide the only basis for verification of the analysis or modelling results, and as such, extensions well beyond the data period cannot be confidently verified.

2. *The extrapolation frequencies of occurrence cover the tails of the statistical distributions*

As illustrated in Figure 4 (the hatched zone) this is the range of four to six times the standard deviation of the sample from the mean, which implies that the estimation of the values is characterized with a large uncertainty.

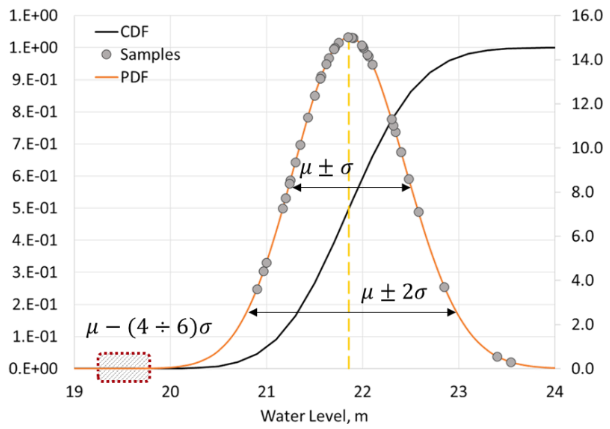


Figure 4. Probability density function (PDF) and cumulative density function (CDF) of the lognormal fit of observations.

3. *The specifics of the considered events and their physical limits*

The estimated events are natural phenomena and as such, it should be realized that the parameters' values have some physical limits. The proper estimation of this limit is essential for the extrapolation of the parameters. It might be estimated by the historical records (considering the recorded extreme values worldwide) or by the meteorological predictions. According to the authors of Ref. [9] and Ref. [11], hydrological events might be classified into three groups depending on the annual exceedance frequency and nature of the events (Figure 5). In brief, the first group of events covers the period of observations (around 100 years) for which the parameters' values are estimated mainly through interpolation of the data and consequently the uncertainty of the estimation is moderate. The following event class is the class of very rare events, which covers the range between the frequency of the observations and the credible limit of extrapolation. Extrapolation of values in this range is characterised with a large uncertainty and it might extend from 4 to around 100 times the observed period, depending on the type, quality and

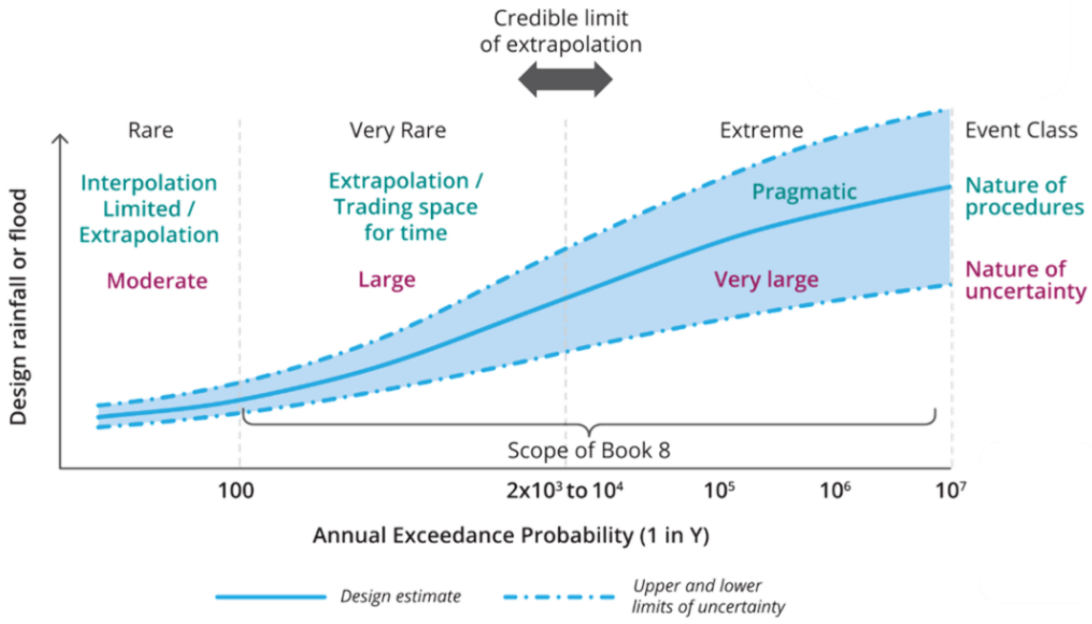


Figure 5. Characteristics of notional floods (source: [12]).

sources of the observations, as well as other available information for the extremes of the parameters (historical data, weather predictions). The range beyond the credible limit of extrapolation is distinguished with very large and practically unquantifiable uncertainty of the estimations and mainly pragmatic nature of the applicable procedures. This range includes the events of extremely low annual exceedance frequency which are to be estimated in the scope of the probabilistic safety analysis, being the subject of the current paper.

4 Proposed Approach

Considering the mentioned above specifics and the available input data, an approach for the interpretation of the values in the extremely low frequency of occurrence range is proposed. It aims at evaluating the high modelling uncertainty of the estimation in this frequency range, the physical limitations of the considered events, as well as their applicability to the PSA Level 1. The proposed approach includes the following steps:

- A selection of four statistical distributions widely used in meteorology and hydrology: Lognormal, Gumbel, Frechet, Weibull [14–16]. Each of the distributions is assumed as an equally possible distribution that appropriately describes the hazard parameter values in the very low probability of exceedance range (10^{-6}–10^{-8});

- Best fitting of each of the four cumulative density functions (CDFs) to the discrete values of the "main model" by minimizing the error and thus identification of the parameters of the distribution;

- Calculation of the extrapolated values using the specified parameters of the CDF for each of the four distributions;

- Each of the CDFs is assigned a weight factor, considering the physical bounds of the variables of interest and in search for convergence with the curve of the main model;

- The mean and standard deviation of the weighted values is calculated. The standard deviation is used as a measure of the modelling uncertainty. An assessment of the natural/aleatory variability of the events is made using the data available, as well as expert judgement.

The proposed approach for the interpretation of the natural hazard parameters for the range of very low frequency of occurrence is considered conservative and covering the sources of uncertainty in the estimation of the values for the extremely rare events, as well as the physical limitations of the events. A graphical illustration of the hazard curve for the minimal water level of the river is given in Figure 6.

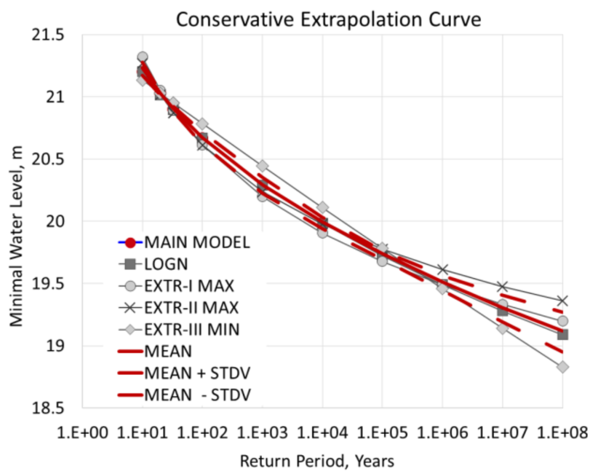


Figure 6. Conservative interpretation of the minimal water level of the river.

5 Extrapolation of the Fitted-Observed Data

In order to verify the proposed approach for interpretation of the natural hazards parameters, a comparison is made by direct extrapolation of the parameter values, estimated by the SSG-18 [2] general procedure. For the purpose, a set of observations of the annual minimum water level of the river, observed by the local hydrological stations at the considered NPP site is analysed and statistically processed. The period of observations covers 42 years and it should be noted that it is elongated with 10 more years compared to the data set, used for the estimation of the values in the "main model". The influence of the last 10 years on the estimation could also be assessed by the comparison.

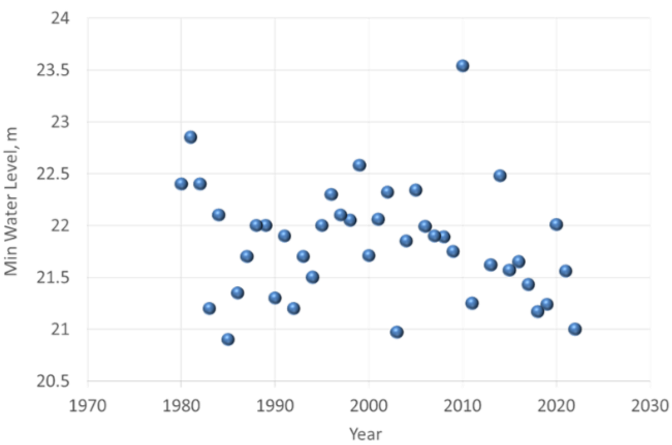
The data are treated as samples of a random variable and best-fitted to the Lognormal distribution and the Pearson III distribution using the standard methods of moments, maximum likelihood and the z-least squares. The histogram of the data indicates for slight skewness. An illustration of the discrete data and the histogram of the observations for the annual minimum water level of the river is given in Figure 7 and Figure 8. It can be observed that both of the distributions fits well to the data set.

6 Comparison between the Interpreted and Extrapolated Values of the Parameters

In order to evaluate the relevance of the values of natural hazards parameters, estimated by the proposed approach, a comparison is made with the values, estimated in compliance with the recommended procedure of SSG-18 [2] and a direct extrapolation to the extremely low frequency of occurrence range (between once in 1.10^5 and once in 1.10^8 years).

The comparison is made for the high-frequency range (the range of the "main model") and for the low-frequency range. The comparison between the fitted observations and the main model is performed in order to verify the relevance of the selected distribution functions (lognormal and Pearson III). Figure 9 illustrates the compared hazard curves for the high-frequency events. The comparison indicates that:

- The Lognormal distribution function fits very well to the curve of the main model;
- The Pearson III fitted curve deviates from the main model around 0.5–1% or 5–20 cm;



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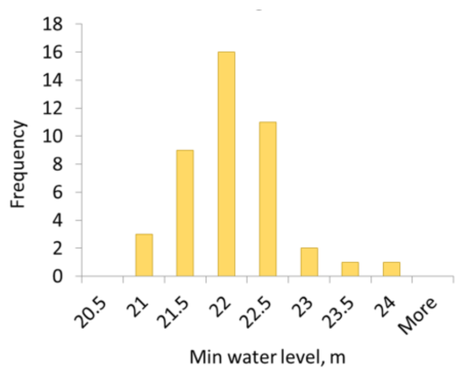

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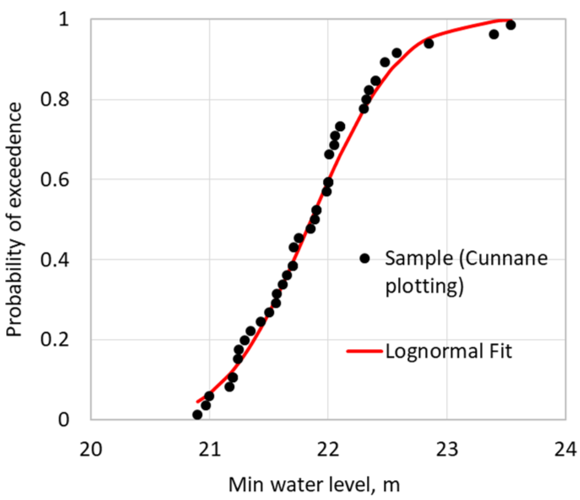
Figure 7. Set of observations for the minimum water level of the river for the period 1980-2023: a) discrete data b) histogram.



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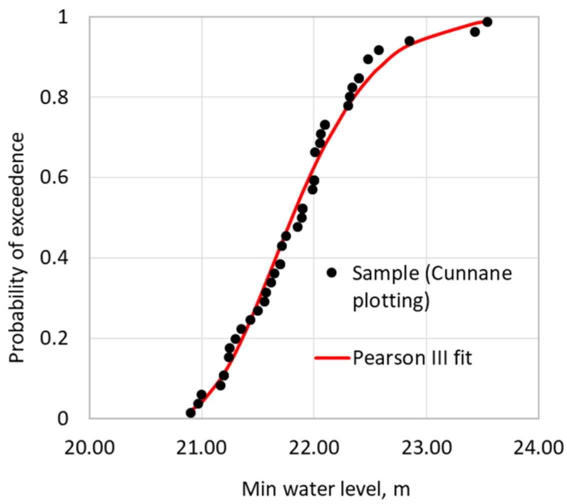

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Figure 8. Fitted observations to: a) Lognormal CDF, b) Pearson III CDF.

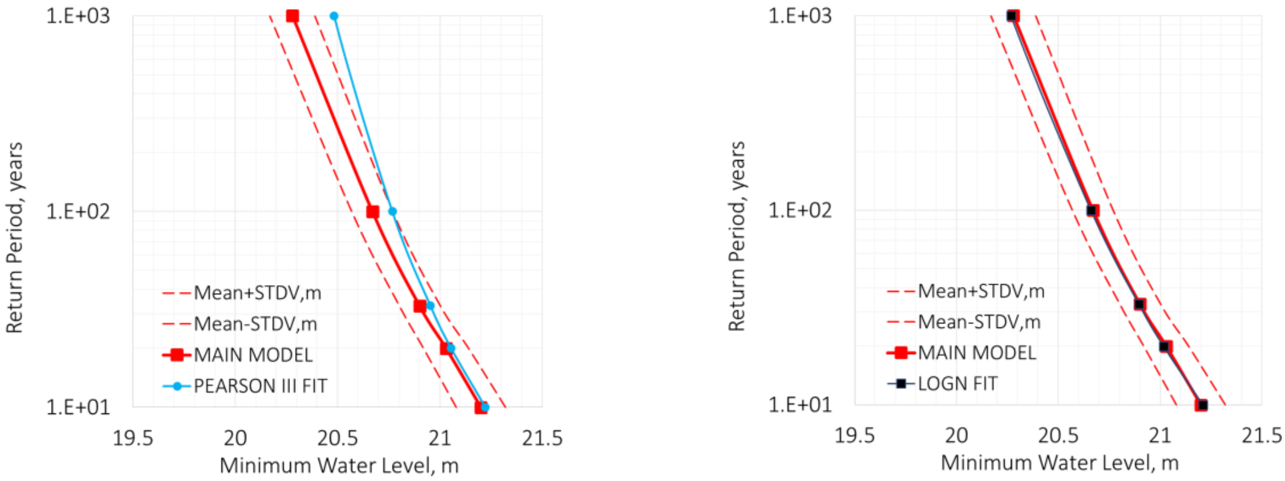

Figure 9. Comparison between the main model and the fitted observations (high-frequency range) for: a) Pearson III distribution, b) Log-normal distribution.

- The deviation from the main model is in the range of (0.5-2) times the STDV of the main model;
- The influence of the last 10 years of data observations can be assessed as 0.65% (13 cm) for the log-normal fit and 0.8% (16 cm) for the Pearson III fit.

The observed results are explained with the completeness and sources of the set of observations as well the type of statistical function, selected for the generation of the main model. Nevertheless, the differences between the main model and the Lognormal and Pearson III fitted curves are not profound, which proves that the selected statistical distributions are representative for the annual minimum water level of the river.

The comparison between the fitted observations and the proposed approach for interpretation of the values from the main model for the very low-frequency of occurrence range (between once in 10^5 and once in 10^8 years) is performed in order to estimate the trend and conservativeness of the estimated values. Figure 10 illustrates the compared hazard curves for the very rare events. The comparison indicates that:

- The deviation from the interpreted main model increases with the decrease of frequency of occurence and its maximum values are of 0.5% or 9.5 cm for the Lognormal fit and of 3.5% or 65 cm for the Pearson III fit;
- For the database that includes the recent 10 years, the deviations from the main model increase to 1.5–6.5% or 29–125 cm;
- The larger deviation for the very low frequencies of occurrence corresponds to the larger uncertainty of the estimation;
- The estimated values by the Pearson III function results in values that are not conservative.

The observed results are expected and attributed to the high uncertainty of the estimations for the very low frequency of occurrence range. Nevertheless, for the purpose of the PSA, the more conservative but still relevant estimation is preferred, which is taken into consideration by the proposed approach for interpretation.

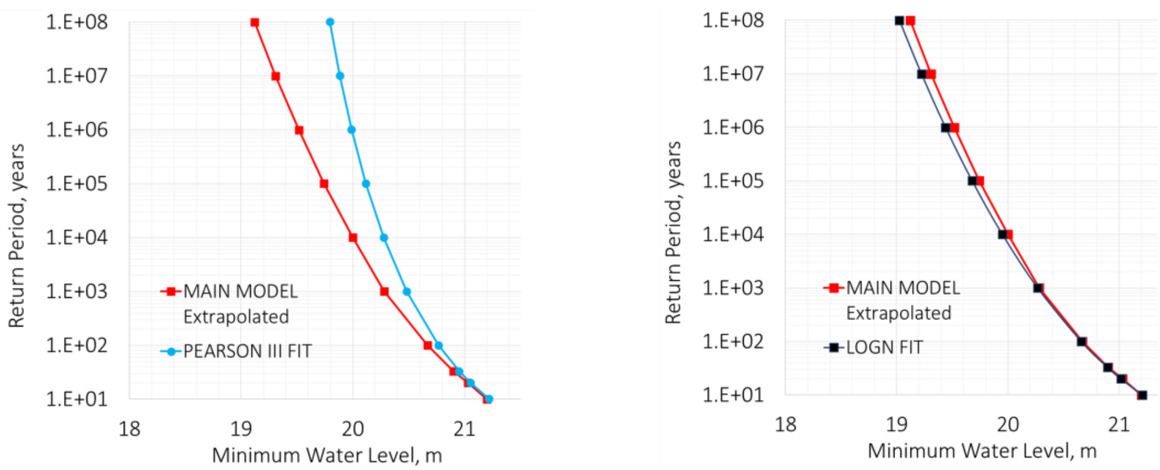

Figure 10. Proposed interpretation of the main model and extrapolated fitted data (low frequency range): a) Pearson III distribution, b) Log-normal distribution.

7 Conclusions

Based on the performed analysis and comparison of results, it is concluded that the proposed approach for interpretation of the natural hazards parameters is applicable for the purpose of the PSA elaboration, as it results in a conservative estimation of the mean values of the hazard parameters, includes an estimation of the large modelling uncertainty for the assessment of extremely rare natural events (occurrence frequency of 10^{-6}–10^{-8}) and concerns the natural physical bounds of the estimated parameters.

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