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Groundwater statistics in the second-generation Eurocode 7

Statistiques des eaux souterraines dans l'Eurocode 7 de deuxième génération

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ABSTRACT: The second-generation Eurocodes, in particular EN 1990 and EN 1997, will rely more heavily on reliability and probability approaches for design (and verification) of geotechnical structures and for treating available data. The determination of groundwater levels will be based on concepts like annual probability of exceedance or fraction of time exceeded. When groundwater time series are available, the required groundwater levels can be determined using statistical analysis. In this paper we illustrate assessing the various groundwater levels values using extreme value statistics for real life data sets, highlighting pitfalls and providing practical recommendations for geotechnical practitioners. To that end, we address the selection of probability distributions, processing of the data to obtain annual extreme values and sanity checks of the results.

RÉSUMÉ: Les Eurocodes de deuxième génération, en particulier les EN 1990 et EN 1997, s'appuieront davantage sur des approches de fiabilité et de probabilité pour la conception (et l'évaluation) des structures géotechniques et également lors du traitement des données disponibles. L'évaluation des niveaux des eaux souterraines sera basée sur des concepts tels que la probabilité annuelle de dépassement ou la fraction de temps dépassée. Lorsque des séries chronologiques sur les eaux souterraines sont disponibles, les niveaux d'eau souterraines requis peuvent être déterminés à l'aide d'une analyse statistique. Dans cet article, nous illustrons l'évaluation des différentes valeurs des niveaux d'eau souterraine à l'aide de statistiques de valeurs extrêmes pour des ensembles de données réelles, en soulignant les pièges et en fournissant des recommandations pratiques aux praticiens géotechniques. À cette fin, nous abordons la sélection des distributions de probabilité, le traitement des données pour obtenir des valeurs extrêmes annuelles et les contrôles de cohérence des résultats.

Keywords: Groundwater; statistics; uncertainty; extreme values; design values.

1 INTRODUCTION

1.1 Second generation Eurocodes for geotechnical design

The second-generation Eurocodes will be published during the period 2023 to 2027 and will fully replace the current codes by 2028, when the first-generation Eurocodes are withdrawn. In the 2nd-Gen Eurocodes, the design of geotechnical structures is spread across four standards: EN 1990 for the *basis* of geotechnical design and three parts of EN 1997 for specific aspects of geotechnical design.

The scope of the 2nd-Gen EN 1990 (published in 2023) has been extended to include geotechnics (as reflected in its revised title *Basis of structural and geotechnical design*), which necessitated generalization of the core principles of EN 1990, particularly with respect to the verification of ultimate limit states (Bond et al., 2019).

The 2nd-Gen EN 1997 has been split into three parts, with general principles and rules in *Eurocode 7 – Geotechnical design* – Part 1: *General rules*; provisions for determining ground properties from ground investigation in Part 2: *Ground properties*; and specific rules for design and verification of common geotechnical structures in Part 3: *Geotechnical structures*.

1.2 Objectives and outline

According to a survey after the introduction of the first-generation Eurocodes, one of the main improvements that geotechnical engineers wanted to see in the 2nd-Gen Eurocode 7 was improved guidance on selection of water pressures (Bond, 2011). This has been addressed both in the 2nd-Gen EN 1997-1 and in EN 1990:2023.

The objective of this paper is to show how to determine various groundwater level values using a real data set.

The concepts related to groundwater in the 2nd-Gen Eurocodes are explained before presentation of the example. Data is fitted with different distribution functions to obtain the various groundwater levels that are required for geotechnical design.

2 WATER ACTION VALUES

2.1 Classification of water actions

In the same way as other actions are handled, the characterization of water actions in EN 1990:2023 depends on whether they are classified as permanent, variable, or accidental.

When the variation in magnitude of the water action is small or monotonic throughout the design service life, it should be classified as permanent. Its representative value (denoted $F_{w,rep}$ or $G_{w,rep}$) is then given by one of three possible values:

- a single characteristic value G_{wk} equal to the mean value of G_w (= $G_{wk,mean}$)
- either the upper or lower characteristic value, $G_{wk,sup}$ or $G_{wk,inf}$, whichever is more onerous
- a nominal value $G_{w,nom}$

These choices are illustrated in the top part of Figure 1. A nominal value is often used in geotechnical design when there is sparse information about groundwater levels (and hence pressures). This paper, however, concentrates on the case where there is sufficient data available to determine characteristic values of water levels and pressures.

Alternatively, when the variation in magnitude of the water action is neither negligible nor monotonic, it should be classified as a variable action whose representative value $F_{w,rep}$ is made up of two components:

- a permanent component $G_{w,rep}$ taken as the mean value of G_w ($G_{wk,mean}$), i.e. the first option above
- a variable component $Q_{w,rep}$ that represents the variation in water action from the mean

These choices are illustrated in the middle part of Figure 1. The magnitude of the variable component $Q_{w,rep}$ depends on which combination of actions is appropriate for the design situation being considered and can be any of the alternatives given in Table 1.

Finally, when the water action is of significant magnitude and typically of short duration but unlikely to occur during the design service life, it should be classified as an accidental action whose representative value $F_{w,rep}$ (denoted $A_{w,wep}$) is as specified in bottom part of Table 1.

Table 1. Specification of water actions according to EN 1990:2023.

Variable or accidental water action	**Symbol**	**Probability of exceedance**
Characteristic	Q_{wk}	2% per annum (return period 50 years)
Combination	$Q_{w,comb}$	10% per annum (return period 10 years)
Frequent	$Q_{w,freq}$	Fraction of time exceeded = 1%
Quasi-permanent	$Q_{w,qper}$	Fraction of time exceeded = 50%
Accidental	$A_{w,rep}$	0.1% per annum (return period 1000 years)

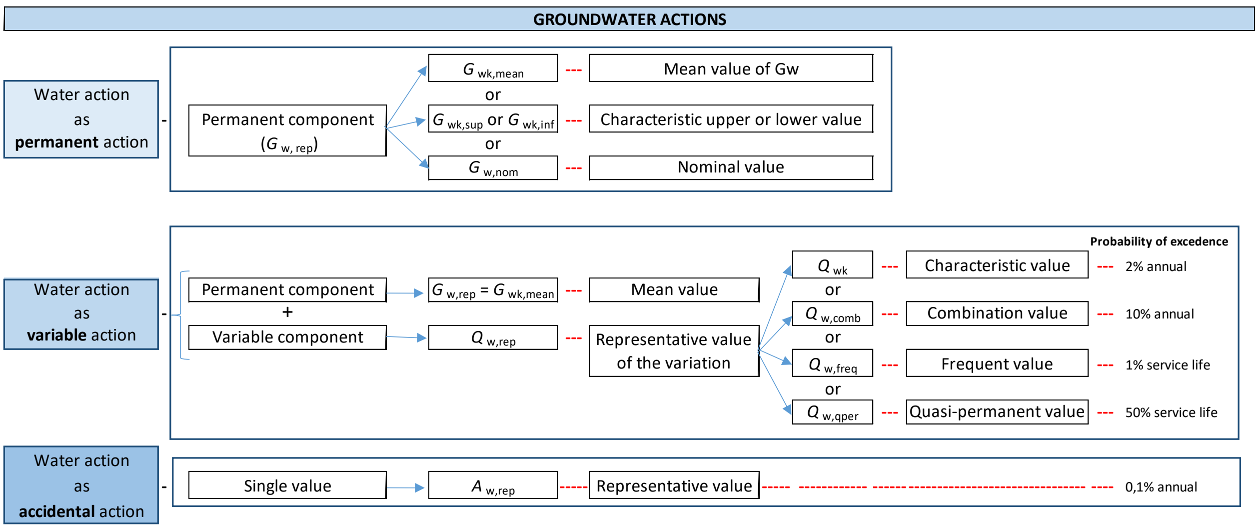

Figure 1. Determination of the representative value of water actions.

2.2 Statistical analysis

For basic theory, we refer the reader to standard textbooks on the topic; here we provide pointers to the approaches relevant to the determination of water action values.

For the quasi-permanent and frequent values, we simply assess the 50% quantile (median) and the 1% quantile of the entire data set (time series in Figure 2), respectively. This determination requires the data to be equally spaced in time, otherwise the data points have to be weighted according to the time period they represent.

The combination, characteristic and accidental values are defined with annual probabilities of exceedance. To obtain these values, the most straightforward option is to determine a probability distribution for the annual maxima (or minima), and then assess the respective quantiles according to Table 1. Since we deal with maxima or minima, the most common extreme value distributions to be considered for this task are:

- Generalized Extreme Value (GEV)
- Weibull
- Gumbel (e.g. Gumbel, 2013)

An alternative to analysing annual maximum or minimum values directly, which we illustrate in the example below, is the 'peaks-over-threshold' method (Lechner et al., 1993).

3 EXAMPLE

To illustrate the application of extreme value statistics for the various values of groundwater action as described above, we analyse a real-life data set and discuss the findings, possibilities and pitfalls.

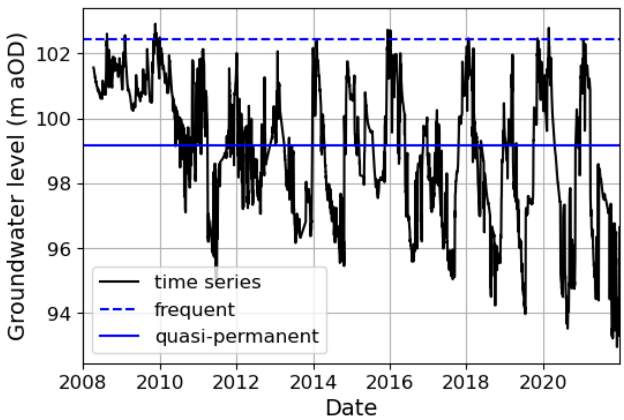

Figure 2. Groundwater level time series including quasi-permanent and frequent values.

3.1 Data set

The data set (from Dunshaughlin in Ireland) contains daily readings of groundwater levels between April 2008 and December 2021, so almost 14 years of data. Figure 2 also shows the quasi-permanent and frequent values, which were obtained from the data as explained in 2.2.

For our particular geotechnical design example, we are looking for exceedance of high groundwater levels. For simplicity in this example, we assume that low groundwater levels do not cause a limit state to be exceeded. We will use the annual maxima to assess the extreme value statistics. The data set exhibits an apparent downward trend in the low water levels, which we ignore here because the high groundwater levels, particularly the annual maxima, do not show such a trend.

3.2 Fitting extreme value distributions

Fitting the distributions mentioned in 2.2 using the maximum likelihood approach leads to the visual fit compared to the empirical cumulative distribution function (ECDF) in Figure 3. Visual comparison does not give a conclusive answer as to which distribution fits the data best, even though the Weibull distribution approximates the right tail (high values) best, as highlighted in Figure 3.

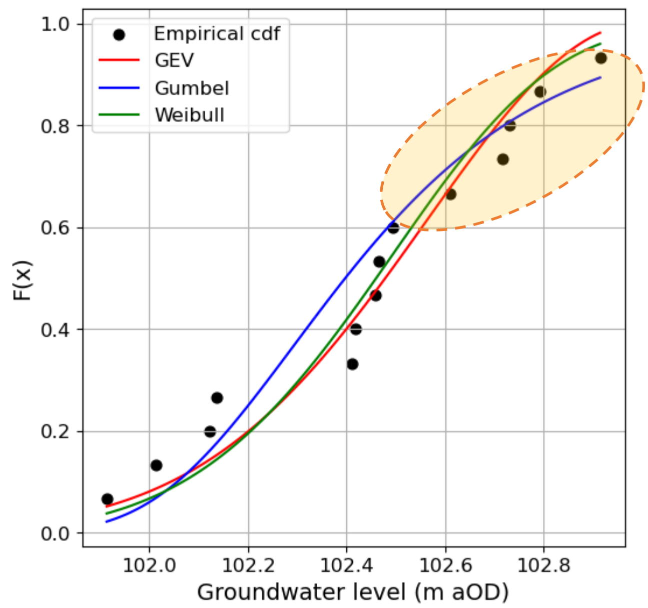

Figure 3. Extreme value distributions compared to Empirical Cumulative Distribution Function (ECDF).

Using the fitted extreme value distributions and the other definitions of water action values discussed in 2.2, the results are presented visually in Figure 4 and numerically in Table 2.

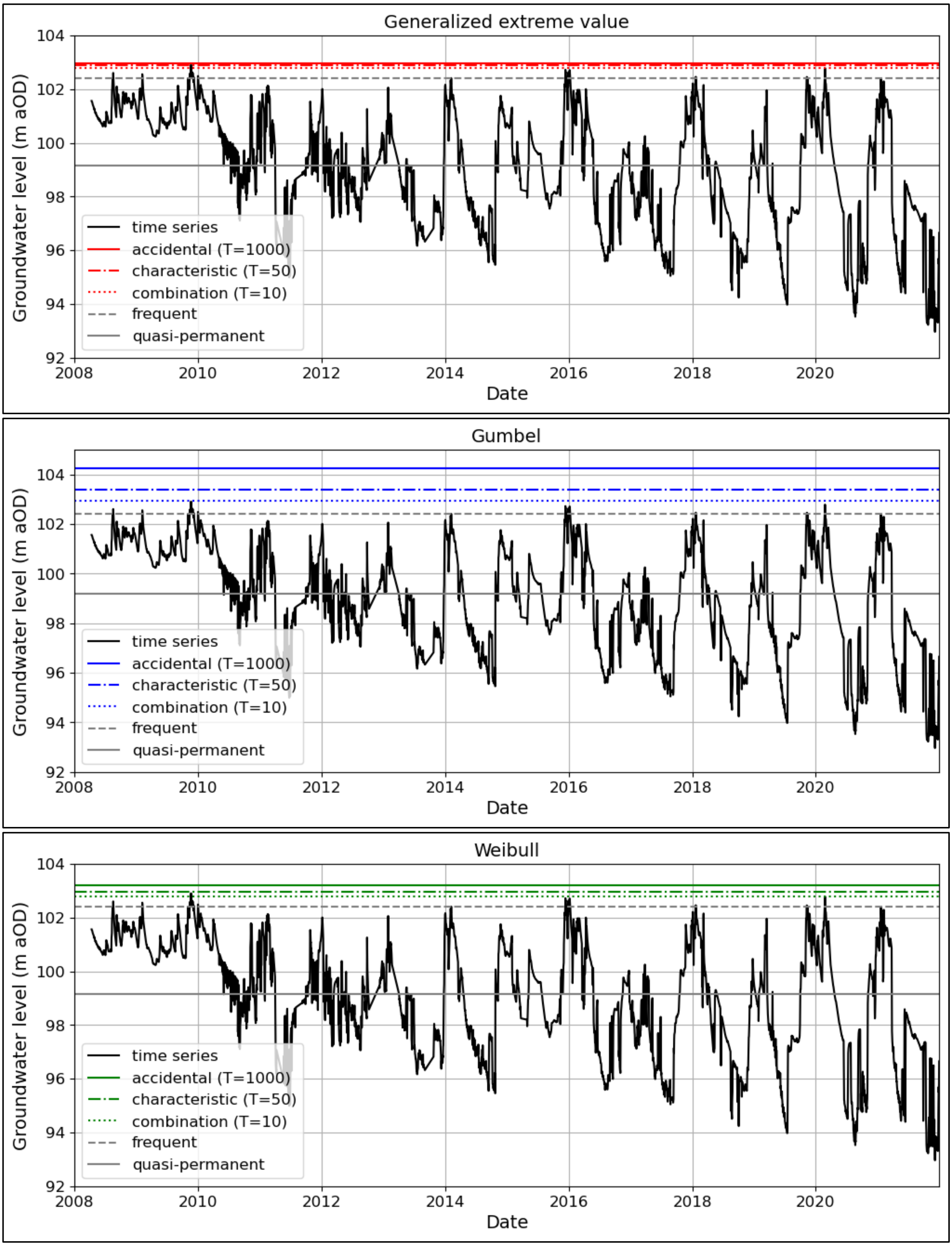

Figure 3. Comparison of extreme value distributions fitted to annual maxima of the time series (top: GEV; middle: Gumbel; bottom: Weibull).

Table 2. Groundwater levels, according to EN 1990 definitions, per distribution fit (in m aOD).

Value	Data set	Gumbel	GEV	Weibull
Characteristic	Annual maxima	103.40	102.91	102.98
Combination		102.93	102.80	102.80
Frequent	Time series	102.43 (independent)		
Quasi-permanent		99.18 (independent)		
Accidental	Annual maxima	104.26	102.98	103.20

3.3 Discussion

To begin with, we observe that the time series exhibits a considerable seasonal variation of roughly 7 to 8 m, while the variation in the extremes (maxima) falls within a relatively small bandwidth of approximately 1 m.

Furthermore, we observe that the quasi-permanent and frequent values are equal and independent of the choice of distribution (by definition), while the characteristic, combination and accidental values differ. Below we discuss observations and sanity checks of the fits to make the most appropriate choice.

Firstly, the combination values from the different distributions are practically identical, so we do not need to select a preferred distribution. For the characteristic and accidental values, we see bigger differences (around 0,5 m as maximum) between the distributions.

The GEV produces very similar values for the combination, characteristic and accidental cases, which is not credible. Therefore, we make a visual check by inspecting the probability density and cumulative distribution functions (PDF and CDF), as depicted in Figure 4.

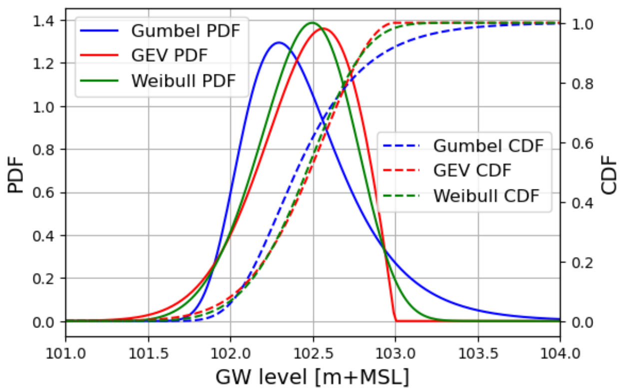

Figure 4. Extreme value distributions (PDF and CDF) fitted to the annual maxima using maximum likelihood.

We immediately observe that fitting the GEV distribution has actually led to a distribution of minima with a fat tail to the left. The sharp bend in the right tail, resulting in a right tail with zero thickness, is the reasonfor the little to no difference between the combination, characteristic and accidental values. Hence, the GEV is not suited to this case. The Gumbel distribution has the fattest right tail, while the Weibull distribution has a less fat right tail. As observed earlier from Figure 3, these latter distributions give a reasonable match to the data.

The Gumbel distribution produces values far higher than the observed range, with the highest value observed in 14 years still somewhat below the combination value (return period: 10 years).

The Weibull distribution exhibits clear separation of the combination, characteristic and accidental values. The combination value is exceeded exactly once in 14 years, while the maximum observed is still somewhat below the characteristic value.

Additionally, we may consider goodness-of-fit measures like chi-square or Kolmogorov-Smirnov tests. However, with such small data sets of 14 annual maxima, these have limited value and instead we prefer to decide on the distribution to use based on visual inspection. The conservative choice in this case is the Gumbel distribution with the associated values in Table 2, while choosing the Weibull distribution leads to more favourable but equally defendable values considering the information that is available. Of course, if more information (for example regarding a physical upper limit to the data) was available, this should be taken into account in the decision.

A final remark on the use of annual maxima is that maxima may stem from the same 'event', depending on the year limit used. Also, the peak-over-threshold method is prone to multiple peaks in the same event and not necessarily a remedy for this issue. The issue can be solved mostly, though, by choosing the year limit in summer, if high values are attained in autumn/winter.

4 CONCLUSIONS

In the 2nd-Generation Eurocodes (specifically EN 1990:2023), characteristic values of water actions are defined in terms of probability and frequency, requring statistical analysis. The alternative is to assess nominal values using judgment and experience.

Statistical analysis is rather straightforward and requires just a couple of lines of code (e.g. using SciPy in Python or R). Of course, reasonable data sets of sufficient length in time need to be available for statistical analysis to be beneficial.

As demonstrated in the example, there is no unique solution and judgment is also required for assumptions and choices in the statistical analysis, such as the type of (extreme value) probability distribution. Sometimes also outliers have to be removed. At the same time, we have shown that reasonable choices can be made based on relatively simple sanity checks and visual inspection of the results. In that sense, the current exercise is no different to other experience-based assumptions in geotechnical engineering.

We recommend providing further guidance to practitioners for assessing water action values, also covering issues not addressed in this paper, such as dealing with very short time series of measurements or scaling extreme value distributions to different reference periods.

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