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Statistical analysis of groundwater levels for the determination of design groundwater levels

Analyse statistique des niveaux d'eau souterraine pour la détermination des niveaux d'eau nominale

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ABSTRACT: According to the Eurocode 7 (2010), groundwater investigations shall provide information on possible extreme values and annual probabilities of exceedance of the groundwater levels, which is necessary, for example, for the planning of groundwater lowering during construction, or for the calculation of the expected hydrostatic pressure on a building. Several methods based on stationary extreme value analysis exist to determine the probability of exceedance, amongst others, Fank & Fuchs (1999), Vogt et al. (2006), Fürst et al. (2015) and Lalbat et al. (2015). However, the existing methods do not account for the difficulties in determining the probability of exceedance in urban areas or for non-stationary time series, with a non-zero trend. A new approach to determine the design groundwater level is proposed, which combines the advantages of the different existing methods and incorporates recent developments in non-stationary extreme value analysis. The method is in parts illustrated through an analysis of groundwater level data from the city of Munich, Germany. In addition, further statistical methodologies are applied to identify any anthropogenic influences, which are expected in urban areas, such as groundwater lowering due to the construction of underground infrastructure.

RÉSUMÉ: Selon l'Eurocode 7 (2010), les enquêtes sur les eaux souterraines doivent fournir des informations sur les valeurs extrêmes possibles et les probabilités annuelles de dépassement des niveaux des eaux souterraines, qui sont nécessaires par exemple pour planifier l'abaissement de celles-ci pendant une construction ou pour calculer la pression hydrostatique attendue sur un bâtiment. Plusieurs méthodes basées sur l'analyse de valeurs extrêmes stationnaires existent pour déterminer la probabilité de dépassement, parmi lesquelles Fank & Fuchs (1999), Vogt et al. (2006), Fürst et al. (2015) et Lalbat et al. (2015). Toutefois, les méthodes existantes ne tiennent pas compte des difficultés rencontrées pour déterminer la probabilité de dépassement dans les zones urbaines ou pour les séries chronologiques non stationnaires, avec une tendance non nulle. Une nouvelle approche pour indiquer le niveau de conception des eaux souterraines est proposée, combinant les avantages des différentes méthodes existantes et intégrant les développements récents en matière d'analyse de valeurs extrêmes non stationnaires. Cette méthode est en partie illustrée par une analyse des données sur le niveau des eaux souterraines de la ville de Munich, en Allemagne. En outre, d'autres méthodes statistiques sont appliquées pour identifier les influences anthropiques attendues dans les zones urbaines, telles que la diminution des eaux souterraines due à la construction d'infrastructures souterraines.

Keywords: Statistical analysis, design groundwater levels, extreme value analysis, anthropogenic influence

1 INTRODUCTION

According to the Eurocode 7 (2010), groundwater investigations shall provide information on possible extreme values and annual probabilities of exceedance of the groundwater levels, which is necessary, for example, for the planning of groundwater lowering during construction, or for the calculation of the expected hydrostatic pressure on a building.

Usually, two design groundwater levels need to be specified for any construction reaching down into the groundwater, the groundwater level GW_{Build} for the building phase of the construction and the groundwater level GW_{End} for the final state. GW_{Build} serves amongst others to dimension dewatering concepts, GW_{End} is applied for the specification up to which level joints have to be designed waterproof or for the calculation of the expected hydrostatic pressure on the building, for instance. Common practice in Munich is to presume a groundwater level with a 10-year return period for the groundwater level GW_{Build}. To determine this level the peaks of groundwater hydrographs are evaluated depending on the length of the time series. This approach resembles preparing an empirical distribution function of the data. To set the groundwater level GW_{End} usually maps are applied showing the reconstructed groundwater level of May 1940 (HW1940), which is the highest recorded groundwater level in Munich. These maps were initially created for the construction of the subway for the 1972 Olympic Games. A safety margin of 30 cm is then added to the reconstructed groundwater level from 1940. Due to the small number of observation wells in 1940, less high but still extreme groundwater levels in later years (especially 16960's to 1970's), which were better documented by more observation wells, were used to adjust the groundwater map to the conditions of 1940. The probability of recurrence for groundwater levels similar to the one from 1940 is mostly specified to be between 50 and 200 years.

Problems with the common way to determine the design groundwater levels are the following:

1. GW_{Build} doesn't take into account the duration of works. Especially for short durations this is assumed to be quite conservative.
2. The method is not robust.
3. The HW1940 map has not been revised for more than 25 years, thus it does not account for any effect since then due to construction or changes in infiltration.
4. Groundwater measurements show that in some parts of the city of Munich the HW1940 groundwater levels have been exceeded several times.

In the last few years, the Chair of Soil Mechanics and Foundation Engineering, Rock Mechanics and Tunneling of the TUM applied statistical analyses of groundwater level data for determining the design groundwater levels in Munich for several construction projects. These analyses were carried out based on the work by Vogt et al. (2006). However, results have shown that the application of a statistical analysis in urban areas tends to pose certain problems.

2 GEOLOGICAL AND HYDROGEOLOGICAL SETTING IN MUNICH

Munich is located in the south of Germany within the so-called Munich gravel plain. This plain is predominantly made up of sandy gravels, which were deposited during and after the ice ages. In the south of the gravel plain the quaternary sediments are up to 100 m thick, in the north their thickness diminishes to only a few meters. The groundwater level is also inclined from south to north, but at a lower angle than the ground surface. Consequently, the depth to groundwater gets smaller from south to north. In Munich, the groundwater level is situated about 20 m below the ground surface in the south and only a few meters in the north.

The groundwater level is mainly depending on the amount of water coming from the Alps and on the amount of rainfall. Close to the river Isar, the water level of the river also has an impact on the groundwater levels, as it either infiltrates water (especially south of Munich city center) or receives groundwater (especially north of Munich city center).

3 STATISTICAL ANALYSIS OF EXTREME VALUES

Typically, two approaches for the statistical analysis of extreme events can be distinguished, the block maxima method and threshold exceedance models (peaks-over-threshold method).

The block maxima method splits a time series in parts of the same length, typically periods of one year. From these intervals the highest value is taken (Figure 1, part A) and a new series of the highest values per period is created. Different distribution functions are then fitted to these data, from which then the annuality of an event can be calculated. The method can be adjusted to consider not only the highest value per interval, but the r largest values. Accordingly, it's then called r-largest order statistic model (Coles 2001).

Instead of only the highest value(s) of each interval, the peaks-over-threshold method (POT) considers all values above a certain threshold (Figure 1, part B). The advantage of this approach is that only extreme values are evaluated and that the amount of data for the analysis may be larger. However, its implementation is more challenging.

4 PROBLEMS FOR EXTREME VALUE STATISTICS IN GENERAL AND IN URBAN AREAS

Problems in determining design groundwater levels arise from several reasons, especially when groundwater level data from urban areas are examined. The available groundwater measurements often times comprise a relatively short time period, typically less than thirty years. Additionally, due to anthropogenic interventions data from these periods may have to be rejected reducing the usable data. Furthermore, the requirements regarding stationarity of the data may not be fulfilled due to changes in the climate leading to a trend. Another challenge is how to deal with measurement intervals. The longer the time is between two measurements, the higher is the probability of not catching the extreme value.

5 EXISTING METHODS FOR THE DETERMINATION OF DESIGN GROUNDWATER LEVELS

5.1 Method by Fank & Fuchs (1999)

The method by Fank & Fuchs (1999) adjusts extreme value distributions, namely Gumbel, Weibull, and Fréchet distribution, to annual maximum groundwater levels. For the determination of design groundwater levels, a confidence interval is added. Fank & Fuchs also show how to regionalize the results.

5.2 Method by Vogt et al. (2006)

The work by Vogt et al. (2006) is based on the technical bulletin DVWK 251/1999 for the analysis of water levels of rivers and streamflow. Like Fank & Fuchs (1999), Vogt et al. fit distribution functions to annual maximum groundwater levels. Differences to Fank & Fuchs arise from the distribution functions being analyzed, parameter estimation methods, and goodness-of-fit tests. In contrast to Fank & Fuchs, Vogt et al. incorporate a way to account for non-daily measurements.

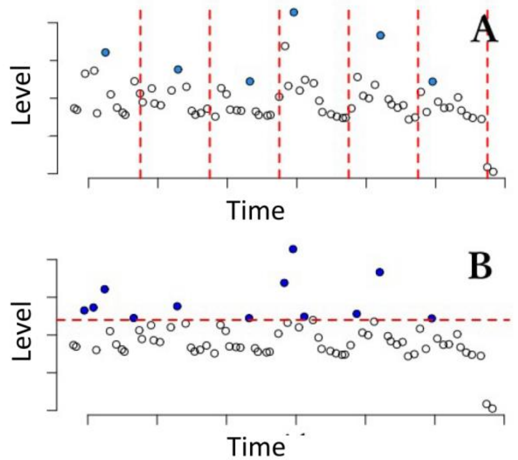

Figure 1. Block Maxima method (A) and Peaks-over-Threshold (B), modified from Haaf (2015).

5.3 Methods by Fürst et al. (2011)

Fürst et al. (2011) examine several ways of how to analyze groundwater data regarding extreme values:

The local analysis based on the block maxima method resembles the works by Fank & Fuchs (1999) and Vogt et al. (2006), but fits more distribution functions to the data. To a greater extent emphasis is put on the suitability of the methods, e.g. goodness-of-fit tests, for extreme values.

Fürst et al. also implement a POT approach for the local analysis of groundwater data based on Coles (2001) and Reiss & Thomas (1997). A methodology on how to select independent extreme values is presented.

Beside the two methods for local analysis of groundwater data, Fürst et al. (2011) and Fürst et al. (2015) present a regional analysis of groundwater data considering several observation wells at a time. This approach is based on the regional frequency analysis proposed by Hosking & Wallis (1997). However, the accuracy of this method is smaller compared to local analyses if sufficient data is available.

5.4 Methods by Haaf (2015)

Similar to Fürst et al. (2011), Haaf (2015) applies both the block maxima method as well as the POT method to assess groundwater level data. The methods differ in detail from the ones by Fürst et al.

5.5 Method by Lalbat et al. (2015)

Lalbat et al. (2015) present a way of determining extreme groundwater levels when only short time series are available. The approach is based on the implementation of a numeric groundwater model, whose influencing factors are well known. The GEV distribution is applied for the determination of extreme values.

5.6 Further considerations

The method by Svensson (1984), which suggests ranges of groundwater levels for observation wells with only short groundwater level time series by the comparison to available longer time series and which is mentioned in Eurocode 7 (DIN EN 1997-2:2010-10), was not further investigated since the accuracy of ± 0.5 m as stated by Svensson is regarded as not acceptable for the intended application.

Additionally to the overall problems regarding extreme value analysis in urban areas summarized in chapter 4, the existing methods for determining design groundwater levels as presented in this chapter all have certain advantages and disadvantages. However, amongst the existing methods two approaches shall be emphasized considering their properties.

With respect to the general attributes of extreme value analysis, Fürst et al. (2011) can be regarded as the most advanced of all the methods. It comprises the block maxima method as well as the POT approach, many different probability distributions known to be suitable for extreme values, and uses the Anderson-Darling test as goodness-of-fit test, which is best when it comes to check at the tales of a distribution.

Regarding the effects of non-daily measurements, the approach by Vogt et al. (2006) is the only method trying to account for errors due to the measuring interval. For times with daily measurements, the actually measured maximum value is compared to maximum values resulting from artificially reduced data sets with bigger measuring intervals. A regression curve is then fit to the average differences (Figure 4). For times of non-daily measurements, a supplement based on the regression is added to the measured maximum value depending on the measurement interval at the time when the maximum value was observed.

6 NEW APPROACHES TOWARDS THE DETERMINATION OF DESIGN GROUNDWATER LEVELS

For the determination of design groundwater levels, a new method is presented in this paper. The overall approach does not differ from the existing methods, but takes advantage of the positive characteristics of the existing ones and reduces their disadvantages.

The method comprises the following steps:

1. Plotting the data to visually identify outliers and trends
2. Identification of periods of time without data and, if possible, generation of synthetic data for these periods as well as identification of anthropogenic influence
3. Trend analysis, decision between stationary and non-stationary analysis

For the stationary analysis the analysis continues with the following steps:

4. Block maxima approach (BM):
   a) Definition of the blocks (calendar year of hydrological year)
   b) Generation of a time series of annual highs
   c) Examination regarding the independence of the data
   d) Addition of a surcharge for non-daily measurements dependent on the measuring interval according to Vogt et al. (2006)
   e) Display of the sample distribution function
   f) Adjustment of different distribution functions using various parameter estimation methods
   g) Review of the adjustments using quantile-quantile plots and application of goodness-of-fit tests, rejection of inappropriate distribution functions
   h) Construction of confidence levels for selected annualities
   i) Determination of groundwater levels with certain return periods
5. Peaks-over-threshold method (POT):
   a) Specification of the threshold value u
   b) Identification of independent values above threshold u and generation of the exceedance dataset
   c) Surcharge for non-daily measurements
   d) Display of the sample exceedance distribution function
   e) Adjustment of a Generalized Pareto distribution and estimation of the parameters using various methods
   f) Review of the adjustment using quantile-quantile plots and application of goodness-of-fit tests
   g) Construction of confidence levels for selected annualities
   h) Determination of groundwater levels with certain return periods
6. Comparison of the results (BM vs. POT, different distributions functions, different parameter estimation methods, ...)
7. Specification of a design groundwater level based on the comparison

To 2.) One problem in urban environments is the human impact on groundwater levels. This can further reduce the often time anyhow low number of available data to examine. A way to enlarge the available dataset is the application of a multichannel Wiener filter. Bucher (1999) applies this method to identify anthropogenic influence, although not in an urban area, but in the surrounding of an opencast mine with extensive groundwater lowering measures.

The method offers three possibilities: As examined by Bucher, anthropogenic influence on the data can be identified and quantified. In addition these methods also give the chance to fill gaps, where data is not available because groundwater levels were not recorded at an observation well, or thirdly to add/subtract anthropogenic influence to older data to enlarge the available dataset, if the starting time of this impact is known.

In the following results of the application of a multichannel Wiener filter on groundwater data in Munich are presented for illustration. Figure 2 shows the comparison of the groundwater level data of an observation well in Munich and a synthetic replication of it.

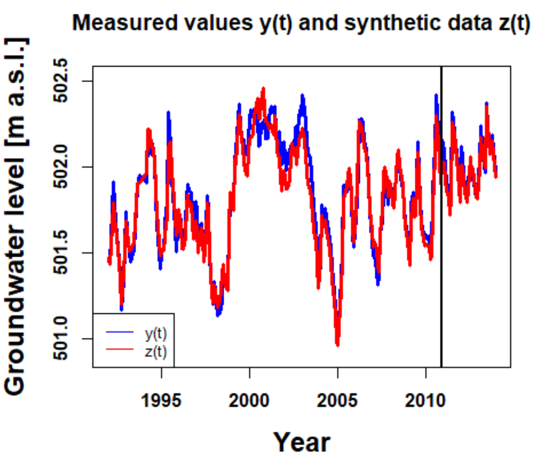

Figure 2. Comparison of synthetic data z(t) and measured groundwater levels y(t) of wells in Munich.

The measured time series shown in blue is recreated using the groundwater levels of three surrounding observation wells leading to the red line. The calibration period ends at the vertical black line. The mean error during the simulation period right of the vertical black line is approximately 0,04 m, maximum and minimum errors are 0,16 m and -0,07 m (Figure 3), meaning that that the Wiener filter in this case is able to replicate the groundwater time series y(t) very well.

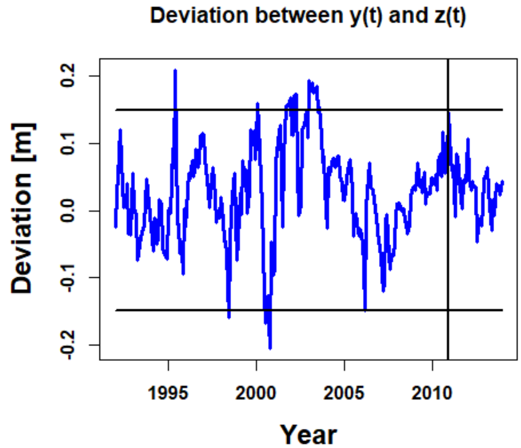

Figure 3. Difference between measured (y(t)) and synthetic (z(t)) groundwater level data.

Alternatively to the multichannel Wiener filter, transfer function models, e.g. according to Gehrels (1999), or methods from machine learning like artificial neural networks may be applied.

To 3.) Trend detection is achieved using the Mann-Kendall trend test and unit-root tests or tests on stationarity, amongst others the Augmented Dickey-Fuller test as well as the examination of the autocorrelation and the partial autocorrelation function. In the case that no trend is detected, the analysis can be continued. If there is a trend, the reasons for this trend have to be identified and it has to be decided, whether this trend is on-going or not. In the case of an on-going trend the application of non-stationary methods may be supported (see below). Alternatively, if the non-stationary analysis is rejected, it may be reasonable to detrend the data. According to Vogt et al. (2006), this is admissible if the trend is known to be due to anthropogenic influence.

To 4.a-b,d) For the Block maxima method the calendar year was chosen instead of the hydrological year as in Vogt et al. and Haaf, because the highest groundwater levels in Munich usually occur in early summer. To account for non-daily measurements, a surcharge according to Vogt et al. (2006) is added to the yearly maxima. Figure 4 shows the regression curves for two observation wells in Munich. It can be seen that an observation interval of 7 days leads to a mean error of about 3 cm and 12 cm for observation well 1 and 2, respectively.

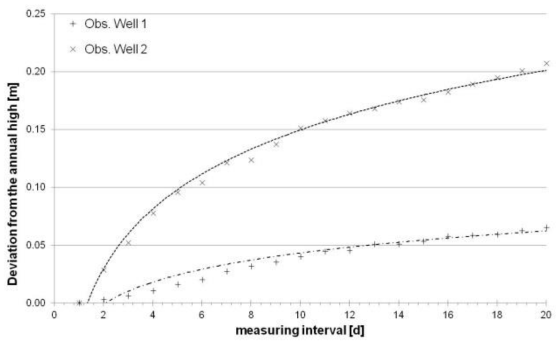

Figure 4. Logarithmic regression for non-daily measurements for two observation wells.

To 4.c,e) The independence of the data is examined using autocorrelation and partial autocorrelation functions. However, dependence of the data to a certain extent has proven not to influence the results of extreme value analysis. For visual comparison of the adjusted distribution functions the sample distribution function is constructed.

To 4.f-h) Several distribution functions (df) are adjusted to the data: (log)normal df, Gumbel df, Weibull df, Generalized Extreme Value df, (log)Pearson-III df using different parameter estimation methods like method of moments, probability weighted moments, l-moments, maximum likelihood estimation, and maximum product of spacing. The choice of the distribution function is then based on the results of different goodness-of-fit tests, of which the Anderson-Darling test is preferred. A visual control of the adjustment to the data using quantile-quantile plots is recommended as well. Confidence intervals are added. Asymptotic confidence intervals and bootstrapping confidence intervals are examined and compared. The confidence level may be chosen in coordination with the builder for GW_{Build} depending on the requested safety needs. For GW_{End} a 95 % confidence level is proposed.

To 4.i) Groundwater levels for certain return periods are calculated in the end. Additionally, a diagram showing groundwater levels vs. annuality is constructed.

To 5.a-d) The peaks-over-threshold approach starts with the determination of the threshold u. The widely used mean residual life plot is applied therefore as well as the suggestion by Fürst et al. (2011) to use 1-, 1.5- and 2-times the number of years as number of exceedances. Analogous to the block maxima method a surcharge for non-daily measurements is added. The data are then compared to the sample exceedance distribution function.

To 5.e-h) In the following the Generalized Pareto distribution is adjusted to the data using different methods of parameter estimation and goodness-of-fit tests are used to verify the suitability of the GPA distribution. A visual examination is also conducted. Again, confidence levels are added and groundwater levels for different annualities are calculated.

To 6.-7.) In the end the results of the block maxima method and the peaks-over-threshold method are compared. It has to be decided, which method provides the more trustworthy results and in case of the block maxima method which distribution function is to be chosen.

In the case of non-stationary analysis an approach suggested by Mudersbach & Bender (2017) for surface water is adapted for groundwater. First, the groundwater level for a certain exceedance probability is calculated using the block maxima approach. Subsequently, this exceedance probability is equated to the exceedance probability calculated with a GEV distribution with a known time-variable location parameter. Using the time-dependent formulation of the exceedance probability and the expected service life of the building the respective groundwater level can be calculated.

7 CONCLUSIONS

For the construction of buildings reaching into the groundwater two design groundwater levels are required in Munich. A new method for the determination of design groundwater levels is proposed that brings together the advantages of the existing methods and adds further possibilities to account for anthropogenic. This methodology allows for the determination of design groundwater levels in urban areas. However, due to the ongoing changes in the groundwater regime in urban areas, existing groundwater data has to be carefully reviewed. Future changes in the groundwater regime may also have to be respected.

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