# The impacts of climate change on the groundwater system of the upper Danube catchment derived from piezometric head and groundwater quality time series data

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**Abstract**

This work presents the first results of an in-depth statistical analysis investigating the relationship between groundwater levels, chemistry, and regional and site specific factors such as land use and geology. The assumption is made that a GWB with similar regional and site specific factors should show a similar behavior of their groundwater levels and chemistry.

Different time series of the catchment are presented and discussed in terms of regional factors. For time series of 30 years length from the same period (1976-2006) the mean annual cycle was calculated for the whole period and than for each decade to visualize the change of the cycle over time. To quantify the results a sine function was fitted to the mean annual cycle. The parameters that determine the sine function can than used for classification of the time series using k-mean clustering.

Secondly the first results analysis of the available groundwater chemistry data is presented and discussed. A methodology that will aid in extending information about groundwater quality in time is also discussed.

**Keywords:** *Groundwater levels, groundwater quality, time series analysis*

## 1. Introduction

Understanding the interaction between climate and groundwater systems (GWS) has become increasingly important when considering the effects of climate change. The analysis of changing groundwater levels and groundwater chemistry over the last 30-100 years in the Upper Danube catchment has provided a wealth of information about the behavior of different GWS, their reaction to climate change, and possible future trends. Furthermore, influences due to land use, unsaturated zone thickness and surface water can be derived through time series analysis. Within the GLOWA-Danube project (Barthel et al., 2005) an extensive basis of time series data for both, chemistry and piezometric heads were collected for further investigation.

On the basis of the obtained study results, a concept for modeling changes in groundwater and chemistry coupled with regional climate change scenarios is to be developed. Such a concept must be able to include the relationships between both key processes and regional factors and in a manner which allows for the regionalization of transfer functions. An approach similar to the hydrologic study carried out in the well-known “Predictions in Ungauged Basins” initiative will be applied.

## 2. Research Site -The upper Danube catchment-

With a watershed-area of 817.000 km² shared by 15 countries, the Danube is the second largest river in Europe. GLOWA-Danube is restricted to the analysis of the Upper Danube (A~77.000 km²), which is defined by the discharge gauge Achleiten near Passau in Germany (Figure 1). The Upper Danube is a mountainous catchment with altitudes ranging from 287 to 4049 m.a.s.l. and a large foreland. This introduces strong geographical, meteorological and geological gradients (precipitation: 650 to >2.000 mm/a, evaporation: 450-550 mm/a, discharge: 150-1.600 mm/a, average annual temperature: -4.8 to +9 °C). The highly fragmented land cover and land-use is highly anthropogenic. Forestry and agricultural use of differing intensity (grassland, farmland) dominate, whereby climatic disadvantages due to high levels of precipitation and low temperatures limit the present agricultural potential in various parts of the catchment (Mauser and Barthel, 2004).

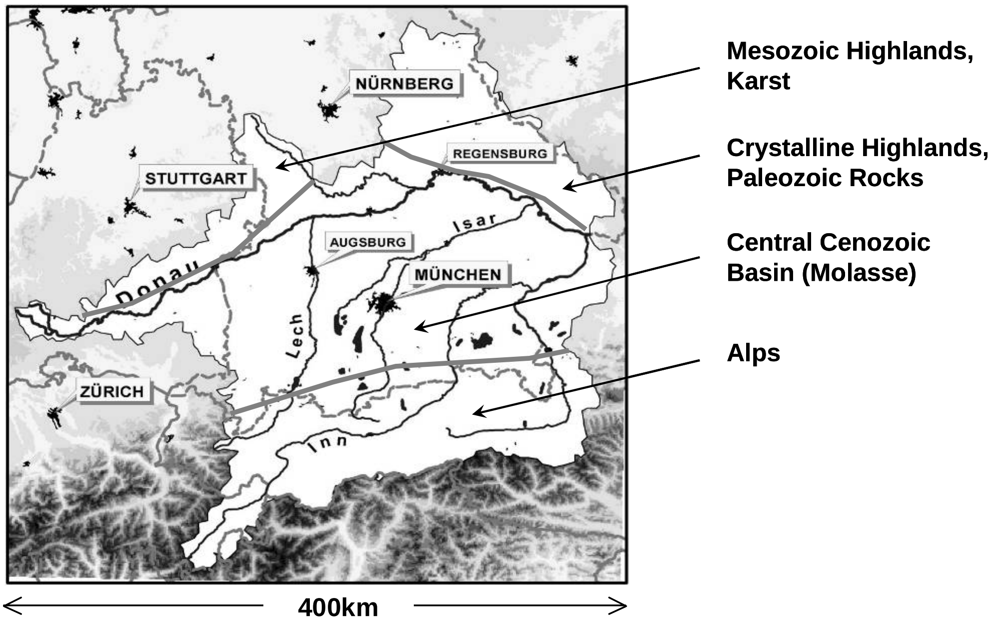

**Fig. 1:** The Upper Danube Catchment.

The Upper Danube is densely populated with approximately 8 million inhabitants. A large part of the water for the water supply of the larger cities and industry originates in the pre-alpine region and in the Alps. The most important industrial agglomeration areas are Munich (1.2 Mio inhabitants), Augsburg (260.000), Ingolstadt (115.000) and the "chemical triangle" of Burghausen.

## 3. Analysis of piezometric head time series

Within the GLOWA-Danube Project, data from about 4,500 observation wells was collected in order to provide an extensive basis for further investigation. Most of the time-series are based on daily or weekly measurements. Unfortunately, many observation wells were only measured once and only for short time intervals. To reliably assess the impact of climate change, time series of at least 30 years are needed. Around 650 observation wells have measured from 30 to 100 years. It has to be emphasized that the groundwater observation wells are not equally distributed over the research area, but are located in areas of special interest, such as major aquifers, and close to pumping wells of drinking water suppliers.

### *3.1. Time-Series of different groundwater systems*

Due to its size and heterogeneous geology, different groundwater systems are present within the Upper Danube catchment. The area contains a wide spectrum of geologic conditions, from deep aquifers of Jurassic carst to shallow alluvial aquifers closer to rivers.

This heterogeneity is reflected by the different groundwater head fluctuations over time (Figure 2). Different types of groundwater head time series can be observed. Time series vary, with linearly falling (Figure 2, Plot 2) heads over the last 30 years as well as time series with rising (Figure 2, Plot 5) heads over the same period. Not only the absolute values of the groundwater head time series show different behaviour, but the dynamics are also strongly location specific (see Figure 2, Plot 1 and 4). Time series of Figure 2, Plot 3 shows an obvious decline of the mean heads within the time period from 1980 to 1983 that do not recover afterwards, due to anthropogenic influences. The dry summer of 2003 shows a direct impact to some groundwater head time series, resulting in a minimum of groundwater heads (like Figure 2, Plot 6).

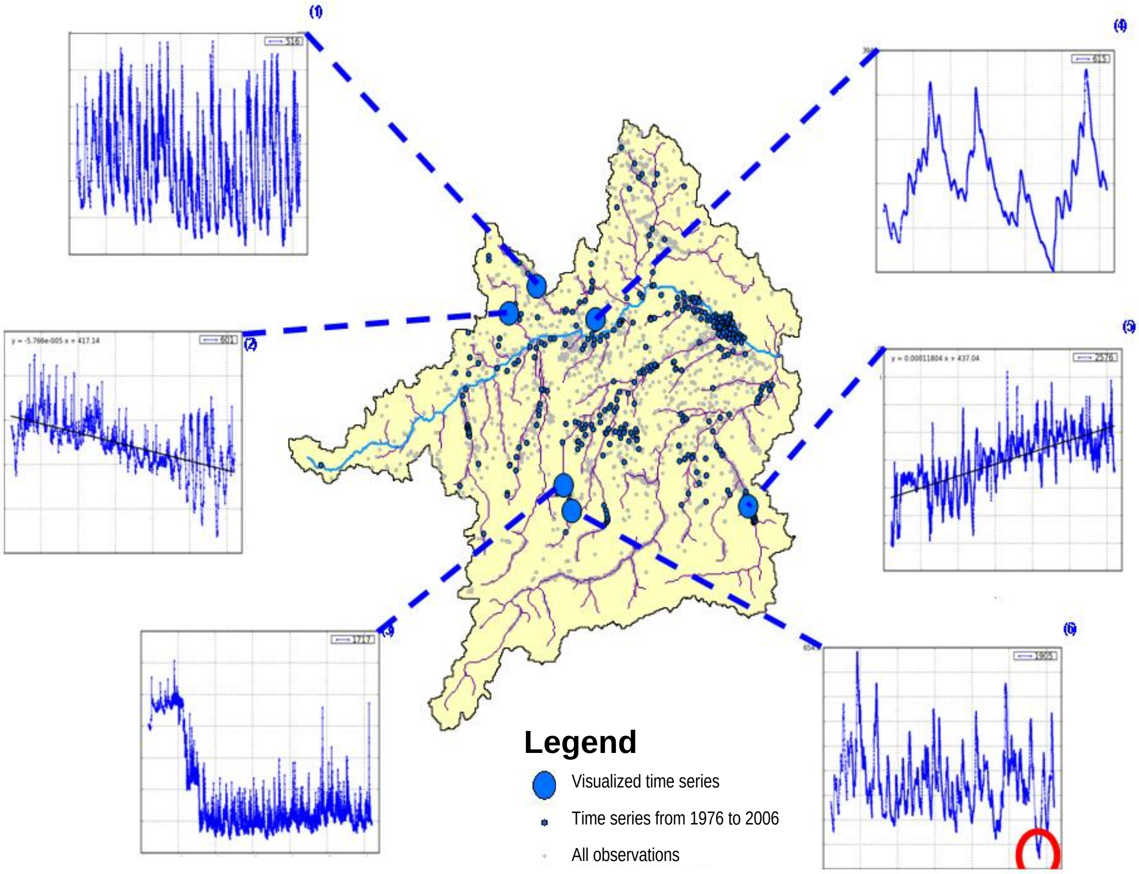

Fig. 2: Groundwater head time series from the period 1976-2006 of different groundwater systems in the Upper Danube catchment.

The aim of the ongoing research is to find methods to classify different groundwater head time series and to investigate the factors that determine the groundwater level dynamics.

### *3.2. Analysis of the seasonal behaviour*

Most of the groundwater systems are highly dependent on season. The highest groundwater recharge occurs in winter and spring when evapotranspiration is low, while during the summer less water reaches the groundwater table. This leads to a typical annual cycle with high groundwater heads in spring (around March) and low heads in autumn (October/November) for most of the aquifers (see Figure 3). In order to identify the annual cycle for all individual sites and to overcome the problem of different spaced data, the following procedure was applied (Bárdossy, 2004):

(1) For a selected day of the year, all data corresponding to a date within a given window, Δ, around the selected day were identified.
(2) The weighted mean of these data was calculated with weigths being inversely proportional to the time between observation and the day for which the mean had to be calculated.
(3) The procedure was performed for each individual day of the year resulting in a complete average anual cycle.

The width of the window Δ was chosen in dependency of the measurement interval. For daily measurements Δ was chosen as 5 days while for weekly measurements Δ was set to 31. This weighting ensured that a sufficient number of days were available for the calculations

The annual cycle of Figure 3 were all calculated for the same period of 30 years from 1976 to 2006. Most of the time series show a strong anual behaviour (like Figure 3(a) and 3(b)), while for a few time series no annual cycle can be observed (Figure 3(c)). Athough the first two anual cycles look similar, they belong to two complete different aquifer systems. While (a) belongs to a shallow (~3 m) quaternary aquifer. (b) belongs to a deep (~80 m) carstic aquifer. The quaternary aquifer reacts faster to climate impact having its maximum and minum about 25 to 50 days earlier than the deep carstic aquifer. The annual cycle of (c) belongs to a very deep (~230 m) unknown aquifer and shows no obvious seasonal influence.

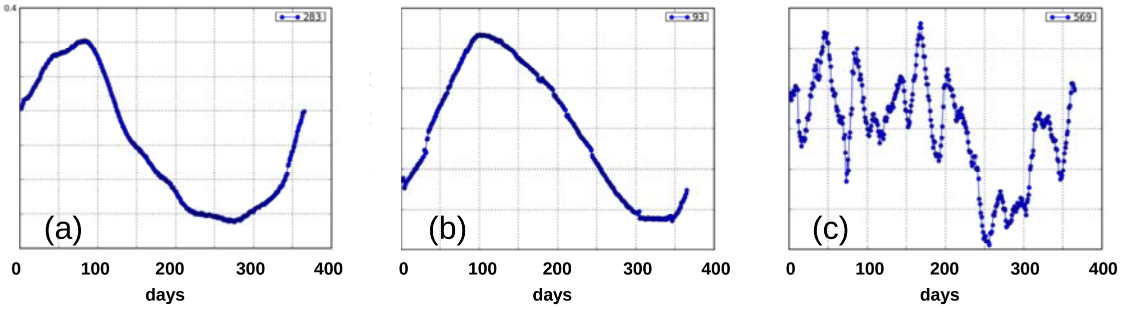

Fig. 3. Annual cycles of (a) a shallow (~3 m), quaternary aquifer,(b) a deep (~80 m), carstic aquifer and (c) an very deep (~230 m) aquifer, where it is not exactely known which aquifer is filtered.

To visualize the temporal behaviour of the seasonal cycle it was calculated for each decade (Figure 4. from green to yellow to red). For the shallow quaternary aquifer the seasonal cycle is mostly constant over time (a), although it seems as if the minimum tends to occur earlier in the last decade. For the carstic aquifer (b) something leads to an absolute difference in groundwater head between the first and the last two decades. Furthermore, it seems as if the minimum occurs earlier. The very deep, unknown aquifer (c) shows no systematic change or a seasonal behaviour for any decade. At a second glance, however, it seems as if the variability of the "seasonal cycle" is stronger in spring than in autumn. This indicates that even if there is no seasonal cycle in the means of the groundwater heads there might be a cycle for the variance and standard deviation, respectively. This is currently under investigation.

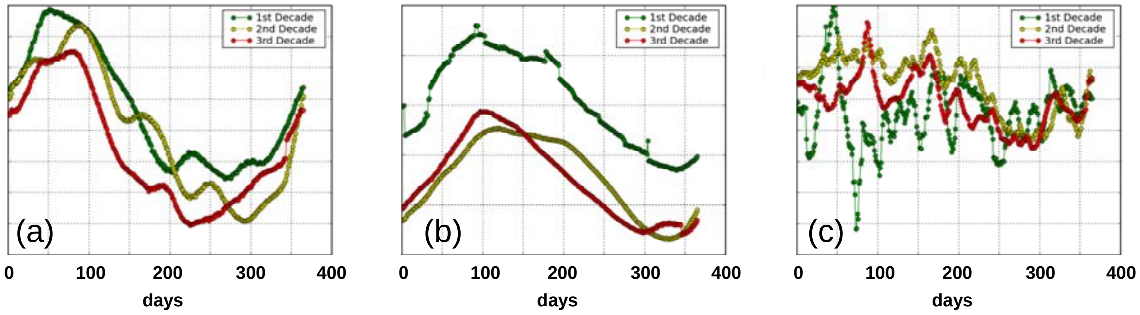

Fig. 4. Annual cycles for all three decades of (a) a shallow (~3 m), quaternary aquifer, (b) a deep (~80 m), carstic aquifer and (c) an unknown very deep (~230 m) aquifer.

To quantify changes of the annual cycles a simplified sine function with two parameters α and β was fitted to the annual cycles using the least square method (Figure 5):

$$\bar{y} = \alpha * \sin\left(\frac{2}{365} * \pi * (t+\beta)\right) \qquad \text{Equation 1}$$

with α being the Amplitude of the sine function in meters and β being the time shift of the sine function in days. For our example of the two annual cycles of the quaternary and the carstic aquifer the sine function can be seen in Figure 5. The parameters are:

Tab. 1. Parameters of the sin function.

| | Parameter α Amplitude (m) | Parameter β Time shift (d) | Coefficient of determination $R^2$ (-) |
|---|---|---|---|
| Quaternary aquifer (a) | 0.26 | 20.38 | 0.96 |
| Carstic aquifer (b) | 1.12 | -39.68 | 0.98 |

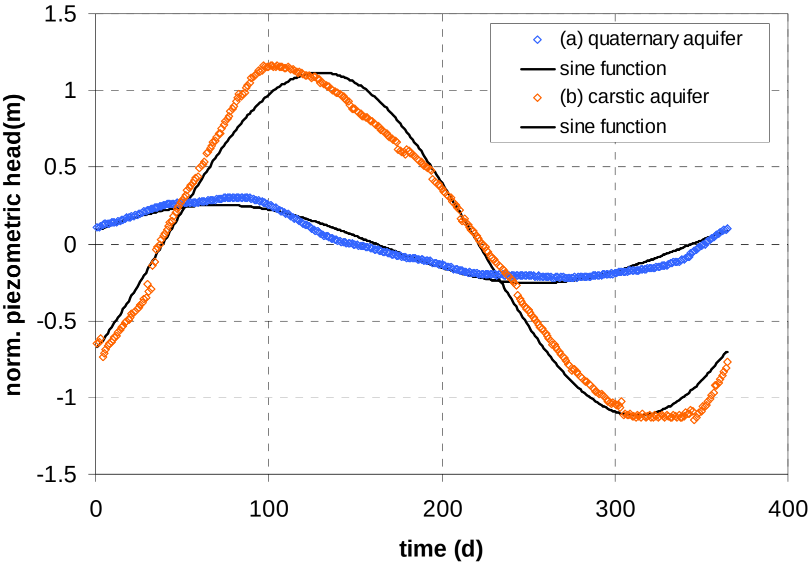

Fig. 5. Annual cycles for a shallow (~3 m), quaternary aquifer(a) and a deep (~80 m), carstic aquifer with fitted sine functions.

According to the high coefficient of determination for both cases the seasonal behaviour is described appropriate by the sin function.

The approach indicates a time lag between the deep, carstic groundwater system and the shallow, quaternary system of 60 days. Also the intensity of the average groundwater head fluctuations is different. For the carstic system the fluctuations are around four times higher than for the quaternary system.

In near future this quantification of seasonal long-term behaviour will be used to categorize groundwater head time series of similar groundwater systems by using k-mean clustering.

## 4. Analysis of groundwater chemistry dataset

Groundwater quality aspects are of various interests within the GLOWA-Danube catchment. Throughout the catchment the water-supply is dependent on the different groundwater systems and at the same time large areas are of intense agricultural use and highly populated with more than 4 million inhabitants living within the greater Munich (1.3 Mio) area. Though of great public interest within this region, little is known about the changes in groundwater quality that might be realized through analysis of a catchment wide dataset. Even less is known about potential future changes and their possible impacts.

Groundwater quality changes in time are of key interest to the EU Groundwater Directive (EU, 2005) and aspects such as the detection of trends and the demonstration of trend reversal become necessary but are rarely published or are available only for specific locations (e.g.: Visser et al., 2007). Large datasets of groundwater quality were more often used for the derivation of natural background levels or threshold values (Hinsby, 2008; Wendland, 2008). The main interests with respect to groundwater quality and climate change is how and to what extend a changing climate will result in a different groundwater chemistry expressed as changing background levels or as a change in the general change in the time-patterns of groundwater chemistry data, and to what extend this changing groundwater chemistry can for instance be linked to changing groundwater levels, land use or climatic variables.

### *4.1. Available Data*

The GLOWA-Danube dataset on groundwater chemistry contains measurements of more than 8,600 different groundwater observation wells, water supply wells and springs. The dataset holds information for 124 different groundwater quality parameters and contains more than 1.2 Mio single groundwater quality measurements. The dataset itself is heterogeneous in space and time, since the various states and national environmental agencies which had collected the data had differing priorities and data collection methods. Thus the dataset shows regions with a high measurement density in space and other regions with measurement locations that are equipped with long-term time series for certain water quality parameters. The left part of Figure 6 shows the general distribution of measurement locations in space and the frequency Plot (Figure 7) displays how the numbers of available groundwater chemistry measurements evolve in time. The first continuous samplings start around 1930 at selected locations and taking the log-scale of Figure 7 into consideration it can be seen that catchment-wide sampling did not start until the 1970s. Nowadays a relatively dense monitoring network is established providing samples on an annual or semi annual basis for the various water quality parameters and micro pollutants. Among the various parameters nitrate may be considered as the best observed one with over 50,000 single measurements. The right map of Figure 6 shows how more frequently sampled nitrate measurement locations are distributed throughout the catchment. It has to be pointed out that most measurement locations are located within the quaternary aquifers as those are of major concern to the water-supply and therefore most frequently sampled. Apart from nitrate, reasonable numbers of measurements are available for the other nitrogen species, pH, temperature, electric conductivity (EC), dissolved oxygen and the major cations and anions. Considering compounds such as herbicides, a large number of measurements are for other pollutants as well e.g.; atrazine (>27,000 samples), bromacil (> 10.000 samples) or DCMU (Diuron) (>8,000 samples).

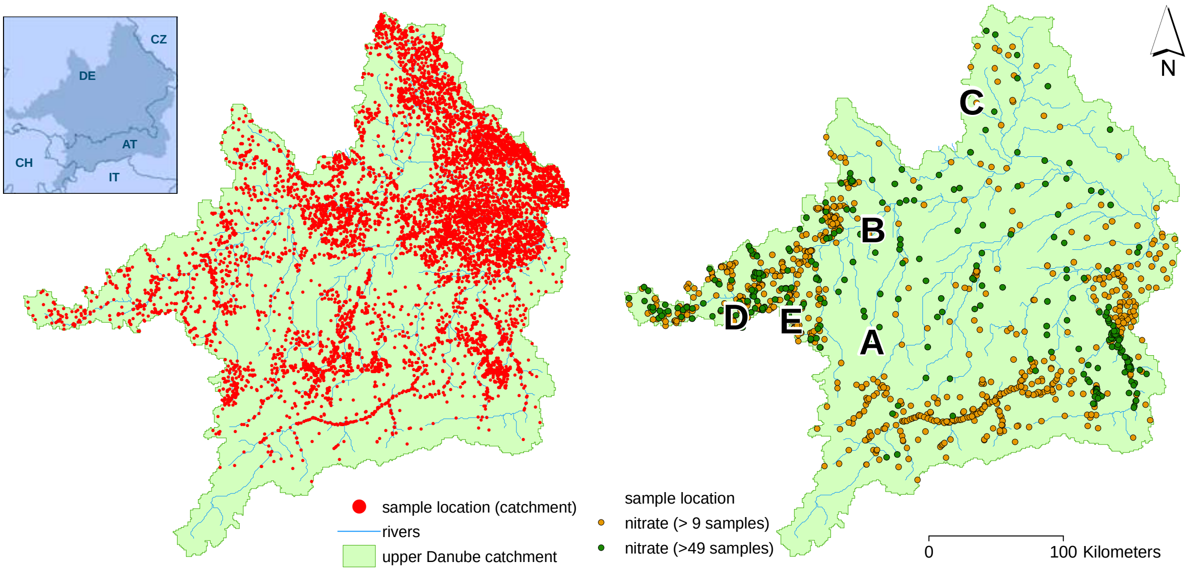

Fig. 6. Overview of measurement locations and nitrate measurements.

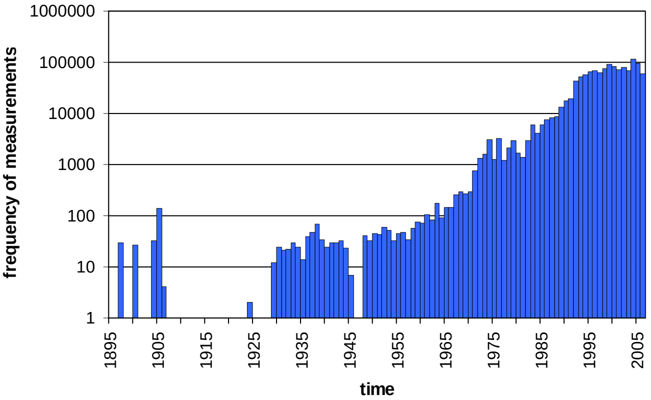

Fig. 7. Frequency of groundwater quality measurements per year within the catchment.

### *4.2. The first analysis of the available dataset.*

The first analysis of the GLOWA-Danube groundwater quality dataset shows that compounds such as nitrate can show a clear cyclic behaviour. This cyclic behaviour is clearly not of seasonal origin and hints at long-term processes influencing groundwater quality as well as slower response times to changing inputs of the system. Figure 8 shows nitrogen time series of four selected locations within the catchment available from 1987 to 2007. For purposes of clarity the measurement values where normalized by subtraction of their median values. The frequency and amplitude of the four different time-series vary as the groundwater system for each observation well is unique.

Strongly depending on the hydrogeological setting and the specification of the measurement location itself, such as overall borehole depth and screening intervals, water quality time-series show typical behaviours similar to the four examples displayed in Figure 8. Further analysis throughout the catchment is needed to find links between the general behaviour of compounds such as nitrate and for instance groundwater levels. Figure 9 shows that for selected measurement locations a clear link between groundwater level and nitrate may be established. An extended analysis of the existing groundwater chemistry dataset will help to contribute to the understanding of the general behaviour of selected groundwater quality compounds such as nitrogen with respect to groundwater levels, land use changes, changes in groundwater recharge and climatic changes.

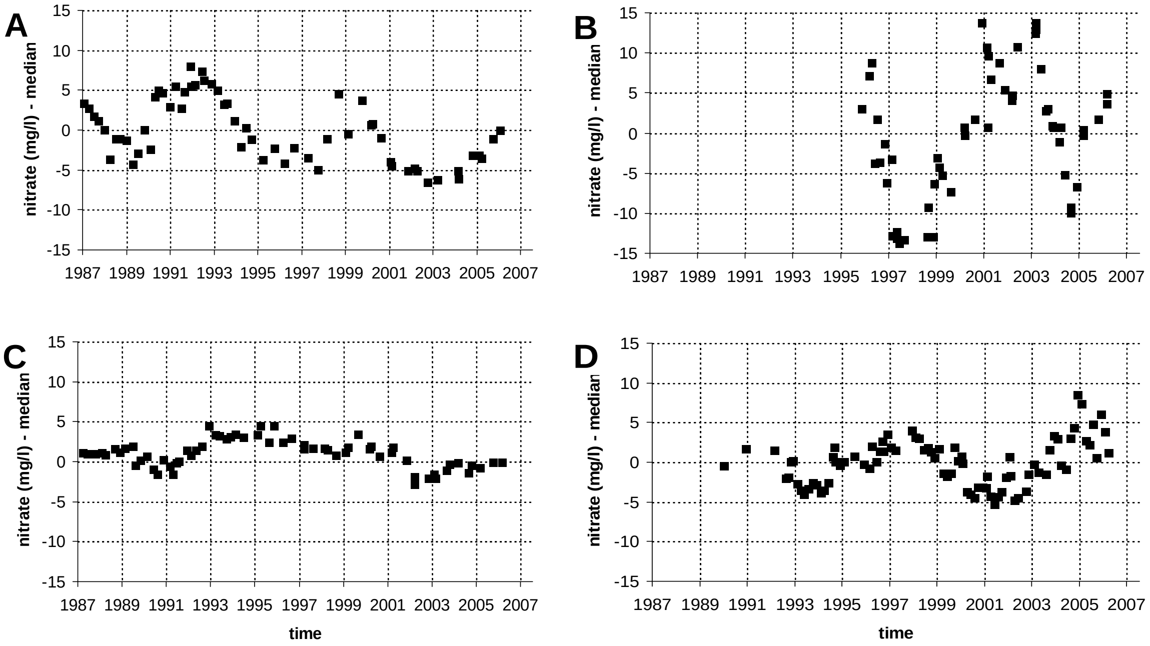

Fig. 8. Nitrate time-series with different final borehole depth, the location of the observation wells is marked in Fig. 6. (A: 41 m, B: 14 m, C: 37 m, D: 11 m).

## 4.2. Extending groundwater chemistry time-series

Due to the sparse availability of groundwater chemistry data, regional water quality investigations often do not take the temporal dimension into account, but work with median values in the case that more than one measurement is available for a single measurement location. Spatial interpolation of water quality parameters has been performed by the use of various statistical methods and leads to reasonable results on the regional scale (e.g. Bárdossy et al., 1998; Bárdossy, 2006). Regional studies either consider a certain time period taken to get a general idea of the spatial distribution of water quality parameters, or water quality trends are investigated for a selected number of measurement locations. Investigations considering groundwater quality in time mostly consider linear trends (e.g.: Grath; 2001 Loftis, 1996) which are highly dependent on the length of the available time-series. Parameters such as well-screening-intervals, overall borehole depths, groundwater levels, the general hydrogeological stetting or land use are rarely taken into account. Changes in the cyclic behaviour of groundwater quality parameters such as shifts in time, damping or enhancement of amplitudes are not considered.

The first analysis of the GLOWA-Danube dataset shows parameter combinations where a strong linkage between groundwater quality parameters and other parameters such as groundwater level may be established. As for Figure 9 with an overall borehole depth of 12 m, the groundwater level seems to result in almost immediate change in nitrate concentrations. Due to the relatively shallow depth of the measurement well located in a quaternary hydrogeological setting, this rapid change in nitrate concentrations seems reasonable, but an offset in time and a different pattern of interaction is expected once the hydrogeological setting is different and/or the well-depth is increased. For a different setting this link between groundwater level and groundwater chemistry may not hold at all and different factors will have to be considered. In Figure 9 few measurements in the late 1980s do not follow this scheme and show unreasonably high values. This unlikely behaviour may be a sign of a different factor influencing nitrate concentrations during that time-period and lead to further considerations. Once the interaction of groundwater levels and other factors within this setting is understood, such discrepancies can be used to identify sudden changes within the system and made use of in groundwater monitoring or trend assessment.

Clear cyclic behaviour as displayed in Figure 8 and dependences as shown in Figure 9 can be taken into account in extending the existing groundwater quality time-series. The extended ongoing analysis of the existing GLOWA-Danube groundwater chemistry dataset will help to establish or outline specific dependencies for selected water quality parameters such as nitrate to different factors e.g. groundwater levels. Different hydrogeological settings display a unique combination of factors and result in a typical behaviour of not only groundwater levels but also groundwater chemistry. As a first step linking the extended analysis of groundwater levels and groundwater chemistry will help to set up a methodology that allows us extending water quality time-series for selected parameters.

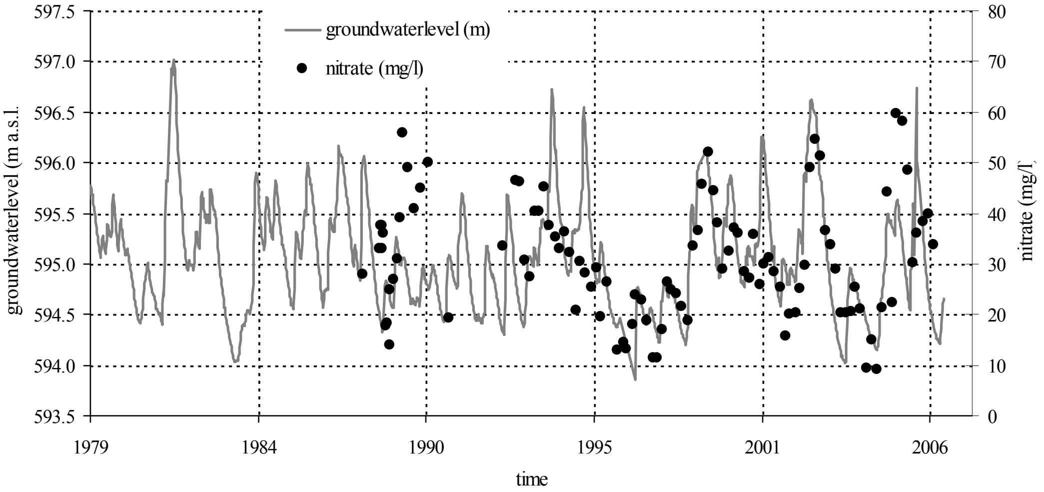

Fig. 9. Development of groundwater level and nitrate concentrations in time; the location of the well is marked in Fig. 6. as E; the final borehole depth is 12 m.

In general a link between a specific groundwater quality parameter of interest and another more frequently observed parameter is searched for. This link has to be coupled with secondary information on the hydrogeological setting that influences the baseline concentrations of the parameter of interest. Joining both types of information will lead to additional information about the parameter of interest at the specific location or in general at for a given combination of certain parameters derived from hydrogeology, land use, climate, etc.

This methodology will not result in a defined time series of water quality parameters such as nitrate but will give typical parameter ranges and behavioural patters that take hydrogeological factors, well characteristics or other parameters such as climate or land use into account and will help to interpret single available measurements in time.

Any outcomes that will help to understand long-term behavioural changes in groundwater chemistry that are induced or at least influenced by a changing system are most valuable. As far as climate change and time-scales of 30 years and more go, little or no information is available for groundwater chemistry to-date. Deriving dependencies, reaction patterns and estimating typical reaction times or time-lags for changes in different hydrogeological systems will be most valuable additional information for stakeholders, governmental agencies and water-supply companies. Timescales for groundwater monitoring can be adjusted and trend reversals can be evaluated more easily.

## 5. Conclusions

As stated in the beginning, the work presented here has just started. The available data were acquired, homogenised and prepared for detailed evaluation. A methodological framework was developed and first results analysed. At this stage it is therefore too early to present substantial conclusions.

## References

Bárdossy, A, Molnár, Z (2004) Statistical and geostatistical investigations into the effects of the gabcikovo hydropower plant on the groundwater resources of northwest Hungary. Hydrological Sciences-Journal-des Sciences Hydrologiques, 49(4).

Bárdossy, A (2006) Copula-based geostatistical models for groundwater quality parameters. Water Resources Research 42 (W11416).

Bárdossy, A, Giese, H, Grimm-Strele, J (1998) Interpolation of groundwater quality parameters using geological and land use classification. IN: Gómez-Hernandez, J., Soares, A., Froidevaux, R. (Eds.), geoENV II - Geostatistics for Environmental Applications Proceedings of the Second European Conference on Geoststistics for Environmental Applications held in Valencia (Spain) from November 18-20 1998. Vol. 10 of Quantitative Geology and Geostatistics. Springer.

Barthel, R, Rojanschi, V, Wolf, J, Braun, J (2005) Large-scale water resources management within the framework of GLOWA-Danube. Part A: The groundwater model. Physics and Chemistry of the Earth 30 (6-7):372-382

EU (2005) Common position Adopted by the Council with a View to the Adoption of a Directive of the European Parliament and of the Council on the Protection of Groundwater Against Pollution. Interinstitutional file 2003/0210 (COD), n. 12062/05, 9 November 2005.

Grath, J, Scheidleder, A, Uhlig, S, Weber, K, Kralik, M, Keimel, T, Gruber, D (2001) The EU water framework directive: Statistical aspects of the identification of groundwater pollution trend, and aggregation of monitoring results - final report.

Hinsby, K, Condesso de Melo, M T, Dahl, M (2008) European case studies supporting the derivation of natural background levels and groundwater threshold values for the protection of dependent ecosystems and human health. Science of The Total Environment 401 (1-3):1-20.

Loftis, J C (1996) Trends in groundwater quality. Hydrological Processes 10 (2):335–355.

Mauser W, Barthel R (2004) Integrative Hydrologic Modelling Techniques for Sustainable Water Management Regarding Global Environmental Change in the Upper Danube River Basin. Research Basins and Hydrological Planning (Ed., Xi, R.-Z., Gu, W.-Z., Seiler, K.-P.):53-61

Visser, A, Broers, H P, van der Grift, B, Bierkens, M F (2007) Demonstrating trend reversal of groundwater quality in relation to time of recharge determined by 3h/3he. Environmental pollution. 148 (3):797–807.

Wendland, F, Berthold, G, Blum, A, Elsass, P, Fritsche, J-G, Kunkel, R, Wolter, R, (2008) Derivation of natural background levels and threshold values for groundwater bodies in the upper rhine valley (France, Switzerland and Germany). Desalination 226 (1-3):160–168.