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The Propagation of Drought in Different Groundwater – Surface Water Systems in Germany

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Abstract

With rising water scarcity worldwide, and in the context of an increasing drought vulnerability of hydrological systems due to climate change, research on drought is getting more and more attention. Studying the propagation of drought through the different levels of the hydrological cycle is a crucial attempt to enhance knowledge about the underlying controls. Hereby a widely used approach is the Threshold Level Method, with which quantitative characterisation of droughts is possible. Commonly used thresholds are the constant and the variable threshold. In this thesis the method is modified to increase the significance of the droughts calculated for real impacts. The resulting Combined Threshold Level Method is then applied to precipitation, streamflow, spring discharge and groundwater data of six catchments across Germany. Without modelling, supported by observed data only, it is attempted to pin down catchment controls on drought propagation and how their influence varies in different hydrogeological settings. Specific focus is set to groundwater because it is believed that its role is underestimated. The study provides good examples how combinations of different controls can lead to unexpected outcomes. A small plateau aquifer was among the slowest responding variables. Groundwater gauges very close to the stream showed resilience against high drought severities. Yet no exact determination of specific controls is achieved due to the lack of supporting metadata. It is concluded that more elaborated methodological concepts for the analysis of groundwater droughts are needed to test and determine specific controls. Further research, especially on the role of streamflow connectedness, is recommended. Also, a specification of the drought concept for different groundwater storage ages is recommended.

Kurzzusammenfassung

Mit weltweit steigender Wasserknappheit und im Kontext der steigenden Vulnerabilität hydrologischer Systeme durch den Klimawandel bekommt die Dürreforschung immer mehr Aufmerksamkeit. Studien zur Fortpflanzung von Trockenwettersignalen im hydrologischen Kreislauf sind wichtige Beiträge zum Verständnis der kontrollierenden Faktoren von Dürren. Dabei ist die Schwellenwertmethode ein oft genutzter Ansatz der die quantitative Charakterisierung von Dürren ermöglicht. Üblicherweise werden dabei konstante oder variable Schwellwerte genutzt. In dieser Arbeit wird eine modifizierte Variante erarbeitet, mit der die Aussagekraft bezüglich der tatsächlichen Auswirkungen von Dürren erhöht wird: Die kombinierte Schwellenwertmethode. Sie wird auf Niederschlags-, Abfluss-, Quellschüttungs- und Grundwasserdaten aus sechs verschiedenen Einzugsgebieten angewendet. Unter Verzicht auf Modellierung, allein aufgrund realer Messwerte, wird versucht die terrestrischen Faktoren der Fortpflanzung von Trockenwettersignalen zu bestimmen, beziehungsweise wie sehr sich deren Einfluss bei variierenden hydrogeologischen Gegebenheiten unterscheidet. Dabei wird besonders Augenmerk auf das Verhalten des Grundwassers gelegt, da davon ausgegangen wird dass dessen Rolle unterschätzt wird. Die vorliegende Arbeit liefert gute Beispiele wie verschiedene Kombinationen von terrestrischen Faktoren zu unerwarteten Ergebnissen führen können. Ein kleiner, auf einem Plateau gelegener Aquifer war einer der am langsamsten reagierenden Variablen. Sehr nah an einem Fluss gelegene Grundwassermessstellen zeigten eine gewisse Resilienz gegen hohe Dürreintensitäten. Allerdings konnten die terrestrischen Faktoren aufgrund unzureichender hydrogeologischer Metadaten nicht genau genug spezifiziert werden. Weiterführende Forschung mit besonderem Augenmerk auf die Auswirkungen der Vernetztheit von Aquiferen und oberflächennahen Drainagenetzen werden nahegelegt. Des Weiteren wird eine genauere Spezifizierung des Konzepts von ‚Dürre' für verschiedene Grundwasserebenen nahegelegt.

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1 Introduction

1.1 Motivation and Objective

Drought can have massive impact on environment, economy and society. Without doubt, these impacts are most severe in arid or semiarid climates, where water resources are already scarce during non-drought years. But drought can as well be a big problem in the temperate zone. Germany, for example, has a predominantly humid climate (Köppen and Geiger, 1954). Its society is used to a much higher availability of water than societies in arid or semiarid climates. This in turn makes its society dependent on the maintenance of the high availability. Agriculture, for instance, is traditionally rain-fed. The overall proportion of terrestrial water used for irrigation is low (FAO, 2013). Rain-fed agriculture is particularly vulnerable to climatic conditions. Due to its absolute dependence on sufficient rainfall, lack of precipitation can cause agricultural droughts directly, thus causing direct impacts on economy and environment. In addition, even though water is theoretically abundant, only a limited part of the resources are tapped, not least because of water quality problems. Unusually low rainfall can therefore, depending on duration, lead to shortages in the actually developed resources. The draw to secondary reserves in times of drought may lead to a rapid decrease in water quality concerning e.g. tap water. In case of agriculture or river navigation, for example, manageable reserves are virtually non-existent. Therefore, drought is a matter of relativity. Even if superficially there are abundant water resources in humid climates, societies that are home to these climates fight their very own, distinct drought-related problems.

Motivation

In the light of the above, it is important to assess droughts, and the vulnerability to droughts appropriately in the face of local circumstances apart from climatic factors. The general basis for the assessment of vulnerabilities is a profound understanding of the development of hydrological droughts out of meteorological situations that ultimately cause them, or: The propagation of drought through the hydrological cycle. In this context, different levels of the hydrological cycle have already been assessed: Precipitation, soil moisture, river discharge and recharge, discharge and storage condition of groundwater (see chapter 1.2). Depending on which hydrological level one regards, its behaviour in the context of drought propagation is subject to different controls. The controls concerning groundwater are basically hydrogeological factors and are therefore in the category of catchment controls, which are local. On the contrary, meteorological conditions affecting the development and propagation of droughts are called climate controls, and are more global. Concerning groundwater, the role of catchment controls - and therefore local hydrogeological settings – during drought and its propagation aren't adequately understood yet (Wong et al., 2013). That is where this thesis comes into play.

Objective

The objective is to determine the role of catchment controls for groundwater in the context of drought propagation via the comparative approach. Thereby especially the aquifer connectedness to the channel grid is the subject to focus on. Method of choice is the Threshold Level Method. Because spring discharge, representing groundwater discharge, showed ambivalent behaviour in previous studies, additional focus is set on the differences between groundwater gauges and spring discharge. In summary, an examination of the propagation of drought in a variety of catchment across Germany with different hydrogeological setting will be conducted, with specific focus on stream connectedness of aquifers and other catchment controls, to evaluate how those affect the behaviour of groundwater in the context of drought propagation.

1.2 State of the Art

Focus in studies on drought propagation is on dependencies and processes leading to the development of a hydrological drought out of a meteorological drought (Mishra and Singh, 2010). A meteorological drought is referred to as a precipitation deficit in a specific time and place. A hydrological drought is a period of very low water resources on or below earth's surface, whereat Van Loon and Van Lanen (2013) narrowed down this term to droughts independent of anthropogenic influences. Science on the propagation of drought through the different hydrological levels precipitation, soil moisture, streamflow and groundwater (figure 1) is relatively young. First studies were conducted by Changnon (1987) and Eltahir and Yeh (1999), whereat Eltahir and Yeh (1999) coined the term drought propagation. Peters et al. (2003) continued the work and showed the dependency of drought characteristics (such as duration, severity and deficit volume) in groundwater from the storage coefficient by means of a linear storage model. Peters et al. (2003) introduced drought definition solely on grounds of a modified threshold level method (Yevjevich, 1967) which enables the straightforward quantification of drought characteristics (Mishra and Singh, 2010). Further studies on drought propagation were conducted by Peters et al. (2006), who took the concept of the threshold level method on catchment scale and analysed spatial variability of droughts, and Van Lanen (2006), who did a comparative study with several models. Tallaksen et al. (2009) included an area threshold for droughts. All of the latter studies, including Tallaksen et al. (2006), conducted research by calculating drought characteristics with the threshold level method, which then were analysed statistically. A useful overview over studies with the Threshold Level Method is given by Wada et al. (2013). Findings of these studies were summed up by Van Loon et al. (2012):

- Several consecutive meteorological droughts are combined into a prolonged hydrological drought (pooling);
- Meteorological droughts are attenuated in the stores (attenuation);
- A lag occurs between meteorological, soil moisture and hydrological drought (lag);
- Droughts become longer moving from meteorological to soil moisture to hydrological drought (lengthening).

Di Domenico et al. (2010) employed a different approach, using the Standardised Precipitation Index SPI, introduced by McKee et al. (1993), to study drought propagation on a catchment scale. Vidal et al. (2010) did the same on a global level and evaluated the SPI together with other standardized indices. A major disadvantage of this method is the lack of quantifiability of drought characteristics that would be needed for a more profound determination of controls. However all of these studies remained rather superficial, owing to the complex mechanisms controlling drought propagation(Wong et al., 2013). Latest work on the subject was done by Van Loon (Van Loon et al., 2012; Van Loon and Van Lanen, 2012; Van Loon, 2013; Van Loon and Van Lanen, 2013) by means of the threshold level method, touting the separation of natural and anthropogenic influences (Van Loon and Van Lanen, 2013) and profoundly determining some climate controls of the development and propagation of droughts (Van Loon and Van Lanen, 2012). Van Loon (2013) modified the hitherto existing concept of drought propagation under consideration of previous studies (Eltahir and Yeh, 1999; Peters et al., 2003; Peters et al., 2006; Van Lanen, 2006; Tallaksen et al., 2009; Di Domenico et al., 2010; Vidal et al., 2010). However, all of these studies, excluding Eltahir and Yeh (1999), were modelling studies.

1.3 Conceptual Approach

Basis of the study is a comparative approach in order to assess the role of groundwater-related catchment controls with special focus on the recovery of aquifers. In other words with focus on the persistence of drought signals in groundwater. This is done by comparing drought propagation in a set of hydro-meteorological variables - representing different levels in the hydrological cycle - in various catchments across Germany. Basic hydro-meteorological levels and associated drought categories are shown in figure 1. The selected variables in this study are precipitation, discharge, spring discharge and groundwater head. Soil moisture strongly influences the behaviour of stream discharge and groundwater recharge and is thus another important hydrological level that should be included in studies on drought propagation (Van Loon, 2013). However it is not considered here because no long-time data was available for any of the considered catchments. And since one principle of this thesis is to only use measured data, soil moisture was excluded. Measured data is used exclusively because the bulk of studies on drought propagation were based on modelled data (see chapter 1.2). The ambition is to avoid modelling in order to support possible results only with *hard* data and therefore to provide backup for previous results of modelling studies.

Concerning groundwater, without modelling it is necessary to follow the *key borehole approach*, where data from few or (as in this thesis) only one borehole is taken as a representative for the whole aquifer. This approach has major disadvantages, because drought characteristics are variable within an aquifer (Peters et al., 2006). Still it remains the only choice because the availability of groundwater gauges is scarce. To marginalize the disadvantages of the key borehole approach, a sufficient number of groundwater gauges can only be found in research catchments with dense gauging grids. Outside research catchments it is virtually impossible to find grids with adequate density, especially when limiting the selection of gauges to those under near-natural condition or other underlying data selection criteria as scheduled in this thesis (see chapter 2.1.1). As a compromise, one part of this thesis is to collect and evaluate hydrogeological metadata, e.g. (hydro-) geological maps, geo-stratigraphic sections, borehole profiles etc., to get the best possible idea of the aquifer in the location of the groundwater gauges. Herewith it is hoped to strengthen the validity of the results, i.e. the regarded links between hydrogeological catchment controls and groundwater behaviour during drought.

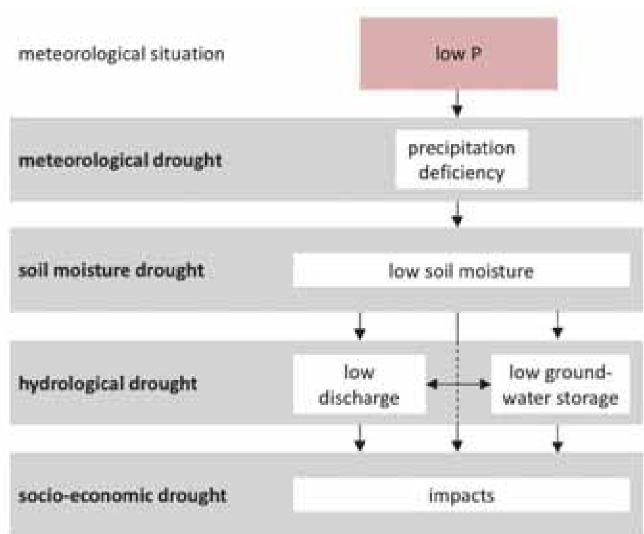

Figure 1: Different categories of drought and their development (Stahl, 2001; Peters et al., 2003).

This is because focus in this thesis is on catchment controls. The influence of climate controls is neglected. This is on grounds of the assumption that differences in climate controls are minimal because of the adjacency of the catchments. All catchments are in mid- to northern Germany (see figure 2). No major mountains are located in between them. Climate controls like topography and therefore the occurrence of orographic precipitation or windward exposure are still relevant but are considered minimal relative to the global range of climate controls. Also, macro weather situations are considered to happen essentially at the relatively same time and magnitude. On grounds of this assumption, different climate signals in precipitation in different catchments are taken as mere input signals on a terrestrial catchment system. It is therefore not necessary to normalise time series as to climate controls by e.g. deducting seasonality from precipitation.

To conduct the research, the threshold level method was chosen (chapter 1.2). It is particularly suitable for the comparative approach underlying this thesis, where different behaviour of hydrological variables in different hydrogeological settings allows conclusions on the controls dictating this behaviour (Sivapalan, 2009). To make conclusions robust and the comparison straightforward, it is essential that the characteristics, that are subject of the comparison, are derived from time series as uniformly as possible. The threshold level method is best to do so (chapter 1.2).

Qualitative definitions á la “drought is a period of scarce water resources” fall short of the scientific definition of droughts. Hence in this thesis no qualitative definition of drought is specified, instead only an operative drought definition for the quantitative determination of droughts is implemented, as performed by the threshold level method (Yevjevich, 1967; Peters et al., 2003; Fleig et al., 2006). In the Threshold Level Method, a specific quantile of the regarded hydrological variable is used as a threshold. When the variable drops under the threshold, it is defined as being in drought. Amongst a series of advantages and disadvantages (see chapter 1.2), the major disadvantage of the threshold level method is the altogether arbitrary choice of the threshold. It was not yet possible to coherently link drought vulnerabilities of real-life systems (environmental, societal and such) to droughts calculated with the threshold level method. Therefore it lacks significance concerning practical implication. Linking the threshold level method to real-impact significance is at issue in hydrological research. To tackle this issue, the combined threshold level approach is herewith introduced.

Essentially there are two different ways of using the threshold level method. First by using a constant threshold (Tallaksen et al., 1997; Hisdal et al., 2001; Corzo Perez et al., 2011), where a single quantile of the long-time cumulative frequency distribution is used as an all-time constant threshold. Commonly used quantiles for the threshold range from the 5%-quantile up to the 30%-quantile, with best practice being the 20%-quantile, as most recently used by (Van Loon, 2013). Second by using a variable threshold (Hisdal and Tallaksen, 2003; Fleig et al., 2006; Tallaksen et al., 2009; Fleig et al., 2011; Van Loon and Van Lanen, 2012), where the quantile is calculated from the long-time cumulative frequency distribution of every month separately. Afterwards a moving average is generally applied to create a smooth seasonal pattern (Van Loon, 2013). This smoothing of the threshold can also be seen as an indirect pooling method (Fleig et al., 2006). There are distinct advantages and disadvantages for both ways of using the threshold level method. The constant threshold is prohibitive concerning the occurrence of droughts during the wet season, especially for groundwater. The hydrological variable will tend to be above the threshold during this season, oftentimes even above the median. This may be different for climates with more uniformly distributed seasons, but it is certainly true for the climate of Germany with its distinct seasonality (see figures 13 to 19). Consequently, droughts as defined by the constant threshold will accumulate in the drier season of the year, which is, for Germany, the winter season. This is an advantage when we take into account the fact that in reality droughts take most effect in the dry season, when storages are running low anyway. In other words the timeframe in which the constant threshold is able to define droughts is more significant with regard to real impacts, than the timeframe in which the variable threshold will define droughts, which would be all year long, as it defines droughts relative to the normal storage condition during a particular season. But, as real effects are mostly observed when storage levels drop below the relatively normal condition of the storage during dry season (to which a societal or environmental system is adapted), within this more significant timeframe as defined by the constant threshold, droughts as defined by the variable threshold would be more significant regarding the severity of these droughts.

Or, stochastically speaking, the occurrence of droughts within the dry season as defined by the constant threshold is biased, since the occurrence of droughts is systematically highest at the time of the highest negative amplitude of the seasonal curve as defined by the variable threshold, which is the peak of the dry season. This is due to the calculation of the constant threshold from the cumulative frequency distribution of the whole time series, which contains information about the wet season as well. Therefore, within the dry season it would be better to use the variable threshold, which only contains information about the particular season or month it is applied for, in order to remove the bias. But the variable threshold is not able to emphasize the impact-significant timeframe (dry season), given that it defines drought during all times of the year. To solve this theoretical dilemma, the concept proposed in this thesis is a Combined Threshold Level Method as an attempt to bring the threshold level method closer to real drought impacts and therefore to cope with the practical applicability issue discussed in the paragraph above. Details on the calculation procedure are provided in chapter 2.3.1.

However, while the Combined Threshold Level Method can potentially tackle the problem of impact-significance from the methodological side, the more practical problem of the arbitrary choice of the height of the threshold level remains. Characteristics of droughts as defined with the Threshold Level Method are very sensitive to the level of threshold that is applied. In other words the choice of the quantile that is used as a threshold has major impact on the results. For example, choosing the 10% quantile will produce significantly fewer and less severe droughts than choosing the 20% or 30% quantile. One might argue that this issue is not that important in a comparative study. When variables of different catchment are calculated with a uniform method and uniform quantile, the actual choice of the quantile becomes secondary, because only differences of droughts in variables relative to each other matter. Using different levels of the threshold should still reveal more or less the same relations, following the argumentation of Sivapalan (2009). But the behaviour of natural, observed time series is not linear in different quantiles (figure 7). It is questionable if relative relations between variables are the same for different quantiles. Therefore the choice of the threshold level still has significance. The problem is, that in the end this choice remains arbitrary because, again, it was not yet possible to coherently link droughts as defined by the threshold level method to actual impacts. Different studies tried to cope with the problem of arbitrariness by conducting sensitivity analyses. However with the introduction of a new threshold level method, it seems necessary to conduct an independent sensitivity analysis. The basic idea was to illustrate changes in drought characteristics definition in order to determine where the threshold level method is most sensitive to a changing threshold level (i.e. quantile). The approach is rather complex and is further explained in chapter 2.3.4.

Concerning drought characteristics, both duration and number of droughts are taken as characteristics and will be used in the course of the thesis. But above that, deficit volume as a measure of drought severity is often referred to as the most important drought characteristic (Van Loon, 2013). It is the amount of deficient water that accumulates in a specific hydrological level or variable in the course of a drought. With knowledge about the deficit volume in groundwater, for example, it is possible to calculate the amount of precipitation that is needed to lift groundwater levels out of drought conditions, as for example done by Fleig et al. (2006). This is a handy, basic prediction tool on how persistent an occurring drought will be, depending on climate conditions (i.e. amount of rainfall) and has value for practical management application. However while precipitation, discharge and spring discharge are quantifiable flow variables, groundwater head is an unquantifiable state variable and therefore deficit volume was not computable from the available data. In order to calculate deficit volume from groundwater levels, the storage coefficient of the aquifer would be needed, which connects changes in head to drainage flow, which in turn is a quantifiable variable. But to determine the storage coefficient, knowledge of the extent, depth and stratigraphic composition of the aquifer is needed. This was not available in detail for most catchments. Therefore the deficit volume for the groundwater level was not calculable. For reasons of comparability and to keep analysis of the results straight-forward, I chose not to calculate two different characteristics, i.e. not to calculate deficit volume for precipitation, discharge and spring discharge, and a replacement characteristic for groundwater. Instead it was chosen to use a replacement variable for all hydrological variables: the maximum deviation from the threshold level, simply referred to as severity from now on, having a similar importance as the flood peak level of discharge in flood studies (Gaál et al., 2012).

Apart from drought characteristic analysis, another major part of this thesis is the visible assessment of the hydrographs of the regarded variables precipitation, stream discharge, spring discharge and groundwater head. This was done by means of the benchmark drought event of 1976, the early 1990s and 2003 (Sheffield and Wood, 2011). The approach here is classic and is simply a discussion of hydrograph plots under consideration of the combined threshold and the respective droughts. However these plots were modified in some way. For details please refer to chapter 3.4.

2 Methodology

2.1 Data

2.1.1 Hydrological Data

Data origin

Starting point was the data set that was the basis for Kohn et al. (in press). The data set contained data from about 280 groundwater gauges, 40 spring discharge gauges and 350 stream discharge gauges across Germany and was brought together by Kohn for the above-mentioned report. The groundwater, spring- and stream discharge data used in this thesis was picked from that data pool under data selection criteria as listed in the next paragraph. The data in the pool, and therefore the data used in this thesis, was provided by the administrative departments of the *Bundesländer* (German federal states) that operate the gauges within their territory. In particular, the data was provided by the departments of HLUG (2013), NLKWN (2013), LfULG (2013) and TLUG (TLUG, 2013). These *Landesämter* affirmed that the gauges provided are not anthropogenically altered, however no further details on applied criteria was provided. Therefore independent quality control was conducted (chapter 2.1.2).

Precipitation data was taken from the E-OBS data set (Haylock et al., 2008; KNMI, 2013) in the form of 0.25° grid cell averages and are freely available on the Internet. Because of the small size of the catchments, no further catchment-related interpolation of precipitation was applied, because grid cells mostly covered the catchments. In catchments where coverage was insufficient (e.g. Örtze), interpolation-corrected precipitation time series differed only marginally.

Stream discharge and precipitation data were provided on daily basis. Groundwater data and to a lesser extent spring discharge data was partly on a weekly or two-weekly basis or had a varying measurement frequency. In that case, the time series had to be interpolated in order to bring all variables down to daily basis (see chapter 2.1.2). Units are for all of the thesis are [m a.s.l.] for groundwater, [m^3/s] for stream discharge, [l/s] for spring discharge and [mm] for precipitation.

Data selection criteria

As already mentioned, the selection of data was based on several criteria.

These were:

1) **Location / adjacency of gauges.** To ensure high connectedness between gauges representing different hydrological level (precipitation, discharge, spring discharge, groundwater), they should be as adjacent as possible. This is where the catchment approach comes into play: The criteria that data of all variables has to be available within one catchment. The catchments are small to medium in size.
2) **Length of time series.** Von Amuth and Knotters (2004) postulated a minimum of 30 years of data for results to be statistically significant. This minimum is adopted here. Further goal is to maximise the time span, i.e. to prefer longer time series.
3) **Near-natural conditions.** Gauges should not be anthropogenically influenced in a major way in order to justify the assumption of natural conditions.
4) **Unconfined aquifers.** To study drought propagation, it is necessary to only consider unconfined aquifers because the recharge of confined aquifers and therefore the aquifer reaction to meteorological droughts is too complex for straightforward interpretation.

Criteria 1 and 4 was met by the selection of the gauges. The final selection included 6 catchments across Germany (figure 2), sizes ranging from ~50 to ~700 km^2, of which four included the sequence precipitation-discharge-groundwater, one included precipitation-discharge-spring discharge and one included precipitation-discharge-spring discharge-groundwater. They were divided into two clusters of five catchments with the sequence precipitation-discharge-groundwater and two catchments with the sequence precipitation-discharge-spring discharge, therefore one catchment being part of both clusters. These two clusters were then examined separately. Best practice would have been one single cluster with all catchments including all variables. However there weren't enough spring discharge gauges available in order to meet this goal. For further description of the individual catchments please refer to chapter 2.2.

Criterion 2 – a minimum of 30 years for time series - was barely met. The length of the time series for the groundwater-related cluster was 36 years (1975-2011), for the spring discharge related cluster it was 31 years (1980-2011). This (shortness) is because - despite the large data pool – the selection was limited because it proved to be difficult to meet all criteria. It is still considered lucky that at least in one cluster (groundwater) the 1976 benchmark event is still included. Unfortunately it could not be included for the spring discharge cluster because of various reasons, e.g. data availability).

For criterion 3, the principle of considering only natural or near-natural conditions, please refer to the following chapter *Data processing*.

2.1.2 Data Processing

Interpolation

Discharge and precipitation data was available on a daily basis, groundwater and to a lesser extent spring discharge was only partly available on a daily basis and partly on a weekly or two-weekly basis. Sometimes time series of the latter two variables had irregular measuring frequency, but not higher than two weeks. In order to equalise all time series down to daily basis, some time series had to be interpolated.

The original idea was to use some sort of spline for interpolation. Different methods were checked. These were the LOESS, an x-spline, a hermitic spline and as a control linear interpolation. They were inspected visually in consideration of how good the different methods of interpolation met observed data in points where observations were available and how large deviation in these points were. All methods except linear interpolation showed the typical problem of splines: Their curves “ran off” in the extremes, in minima and maxima. Since this is a study dealing with extremes – droughts – this has to be seen critical, because it seriously alternates the time series in the extremes and would therefore potentially distort results. Hence in the end linear interpolation was chosen, because it is the most straightforward method and does meet all measurement points.

Trends

Because of the assumption of near-natural conditions, trend tests were applied for all selected time series. Mann-Kendall trend tests were considered, but proved to be too computationally intensive. The linear regression method was chosen for trend analysis because of limited computing resources and also because both methods were tested for some time series and did not show major differences.

With this method, trends were detected in most time series. In two cases of groundwater and spring discharge time series that had been interpolated, significant differences were detected between trends of the interpolated and non-interpolated time series. Naturalisation via the subtraction of the trend was then tested for all time series. However time series did not show reasonable behaviour after naturalisation. European benchmark drought events (Sheffield and Wood, 2011) did not show expected drought conditions in the time series at the time these benchmark droughts occurred. The original, non-naturalised time series however showed a more reasonable occurrence of droughts in the time series. This led to the conclusion that detected trends were not caused by direct anthropogenic influences in terms of groundwater abstraction and such. Also, the administrational institutes of the *Bundesländer* that operate the gauges provided – in the course of data collection for the data pool for Kohn et al. (in press) - general statements that gauges are not or little anthropogenically altered, however they did not provide more detailed information other than this general statement, thus leaving room for mere speculation about the actual degree of anthropogenic alteration. Therefore it had to be decided to trust the statements. It is further assumed that climate change or other unknown causes are responsible for these long-term trends, and therefore that these trends cannot be tackled properly in this thesis. Instead the notion was that because it is likely that climate change has a major share in causing the trends, and that therefore they should be included in drought analysis, given that neglecting climate change may alter results in a way that they are not as relevant anymore for a future that is subject to climate change. Hence time series were not naturalised, trends were kept included.

Last but not least, a backward moving sum, calculated similar to formula (4) in chapter 2.3.1, was applied for precipitation. This is because original precipitation show zero values up to the ~60-80% quantile. Thus it would not have been possible to use the threshold level method used in this thesis (20%), which would be zero if time series are left unprocessed.

2.1.3 Hydrogeological Metadata

Metadata about the hydrogeological setting in the catchments was taken from different sources with different availability for different catchments. The HUEK200 and GUEK200 maps, which are freely available on the internet (BGR, 2013), and the HAD map (BMU, 2003) were available for all catchments. The HUEK200 and GUEK200 are joint projects of the German National Geological Services (*Staatliche Geologische Dienste*, SGD) under general management of the Federal Office for Geoscience and Resources (*Bundesanstalt for Geowissenschaften und* Rohstoffe, BGR). The HUEK200 is a compilation of maps depicting hydrogeological characteristics across Germany with a 1:200,000 scale. Amongst others, it contains a general map of conductivity. Conductivity maps for every catchments are included in the chapters on catchment characterisation.. The GUEK200 is a very detailed map of the geology in Germany with a 1:200,000 scale. The rock categorisation in chapter 2.2 is based on this map, and on the HAD. The HAD is the hydrological atlas of Germany and contains a variety of maps as well. Out of those, the map of the hydrogeological regions in Germany is used for catchment, geology and aquifer characterisation (figure 2).

Because HUEK200, GUEK200 and HAD are merely generalised maps, ambition was to acquire more detailed information about the specific aquifer conditions in the location of the groundwater gauges. The most detailed hydrogeological metadata that could be acquired were borehole profiles for the Lachte, Leine and Oertze catchments, and stratigraphic cross profiles of the Lachte and Oertze aquifer. These were provided by the *Landesämter* of TLUG and NLKWN (NLKWN, 2013). The other catchments were situated in other federal states of Germany, of which the *Landesämter* could not provide this information.

Furthermore, to take into account the topography situation and to build up river networks, calculate gradients or catchment areas, a digital elevation model (DEM) with 100x100 meter grid was employed. The DEM used is the mapping product HydroSHEDS by the USGS (2013) which is freely available on the internet.

2.2 Study Areas

2.2.1 General

The six catchments discussed in this thesis are located in mid- and northern Germany (figure 2). The order of the subchapters in this chapter is according to mean height with account to hydrogeological conditions, location and size. Oertze and Lachte are directly adjacent lowland catchments with large-scale, sandy aquifers. There are a number of minor surface water storages (mostly fish ponds and quarry ponds) in these catchments, but they are rarely connected to the stream network and generally very small in size. They are therefore considered negligible and are not further discussed. Leine, Gründau and Salz catchments, of which the latter two are directly adjacent as well, are situated in different low mountain ranges with medium sized aquifers and varying hydrogeological conditions. Finally, Spree catchment is also located in a low mountain range and has a rather small aquifer. It has to be said that statements concerning aquifer size are qualitative estimates based on the metadata as mentioned in the previous chapter. This selection does contain a broad spectrum of hydrogeological settings that should enable valuable conclusions on catchment controls. Unfortunately the selection of catchments does not contain a more extreme, alpine example. This is because data availability in this region was scarce.

Lastly, catchment area and heights are displayed in table 1. Table 2 shows the gradient of the respective gauges in the catchments to the nearest stream. Since water levels are in varying depth beneath the ground surface, the gradients of water level to stream level are more significant and are included in the table. This should deliver an estimate on how interconnected aquifer and stream are. Stream heights are calculated from DEM, gauge height is taken from the metadata provided by the *Landesämter*.

Table 1: Area and heights of the catchments. h_{min} = lowest point of the respective catchment; h_{mean} = average height; h_{max} = maximum height; h_{range} = height difference in the catchment.

	Area [m^2]	h_{min} [m]	h_{mean} [m]	h_{max} [m]	h_{range} [m]
Örtze	714.8	38.0	83.1	151.0	113.0
Lachte	385.7	43.0	89.5	145.0	102.0
Gründau	56.4	141.0	310.0	423.0	282.0
Leine	272.4	198.0	354.7	524.0	326.0
Spree	274.0	188.0	360.0	616.0	428.0
Salz	87.7	150.0	382.3	705.0	555.0

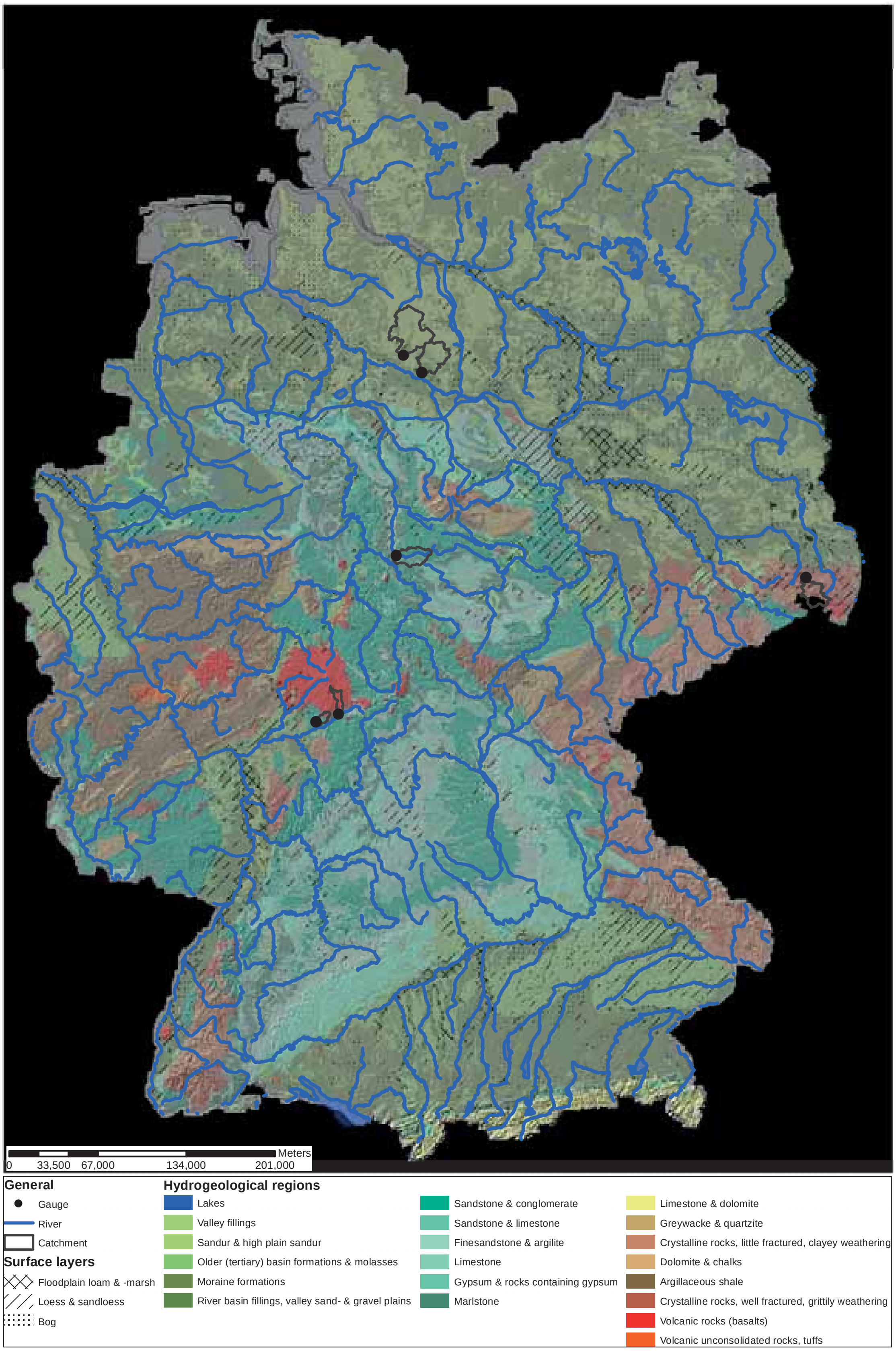

Figure 2: Map of the hydrogeological regions in Germany as explained in the legend, including the location of catchments regarded in this study. (1): Oertze, (2): Lachte, (3): Leine, (4): Gruendau, (5): Salz, (6): Spree. Black dots indicate the catchment outlet.

Table 2: Gradients of gauge height to stream level (for springs) and water levels to stream level (for groundwater gauges), respectively. h_{gauge} = height of the gauge; h_{min} = minimum water level of the groundwater time series; h_{max} = maximum water level; h_{range} = range of water levels; h_{stream} = stream level; D = distance from gauge to stream; I_{min} = gradient for the minimum groundwater level (and gradient for springs, respectively); I_{max} = gradient for the maximum groundwater level.

	Type	h_{gauge} [m]	h_{min} [m]	h_{max} [m]	h_{range} [m]	h_{stream} [m]	D [m]	I_{min} [-]	I_{max} [-]
Örtze	GW	50.8	46.28	47.79	1.51	41.0	876.0	0.006	0.008
Lachte	GW	84.5	81.10	82.45	1.35	78.0	1259.0	0.002	0.004
Leine	GW	220.9	204.60	206.25	1.65	205.0	297.0	-0.001	0.004
Leine	QU	321.0	-	-	-	304.0	117.0	0.145	-
Gründau	QU	180.0	-	-	-	179.0	106.0	0.009	-
Spree	GW	326.4	318.09	321.81	3.72	268.0	790.0	0.063	0.068
Salz	GW	306.9	294.64	297.84	3.20	182.0	1165.0	0.097	0.099

2.2.2 Oertze

Catchment

The Oertze catchment is the bigger one of the two northern lowland catchments (figure 3). The areal extent is roughly 715 km^2. The average height is 83 meters a.s.l., ranging 113 meters from 38 meters a.s.l. up to 151 meters a.s.l. (table 1). This makes it the biggest, lowest-lying and second flattest (only short of Lachte) sample catchment. It is rather broad and the stream alignment is nested. The groundwater gauge is located near the catchment outlet, about 876 meters from the main river. It lays within the wide and flat river valley, only about 10 meters above the river, on 50.8 meters a.s.l. (ground level). Water levels during the regarded period 1975-2011 ranged from 46.28 up to 47.79 a.s.l. (range: 1.51 meters), meaning that the lowest water level still was 8.3 meters above the water surface of the river. Therefore the perpendicular gradient of groundwater level to river level does not vary on magnitudes (it varies from 0.006 to 0.008). But 8.3 meters height difference is still little; river level some kilometres upstream is higher. Having this in mind, and regarding the overall flatness of the catchment, high connectedness between aquifer and river is probable. Groundwater and stream discharge hydrographs (figures 13 to 19) should prove to be somewhat similar, of course with a high grade of smoothing in groundwater, considering the large extent and high conductivity of the aquifer (see next paragraph).

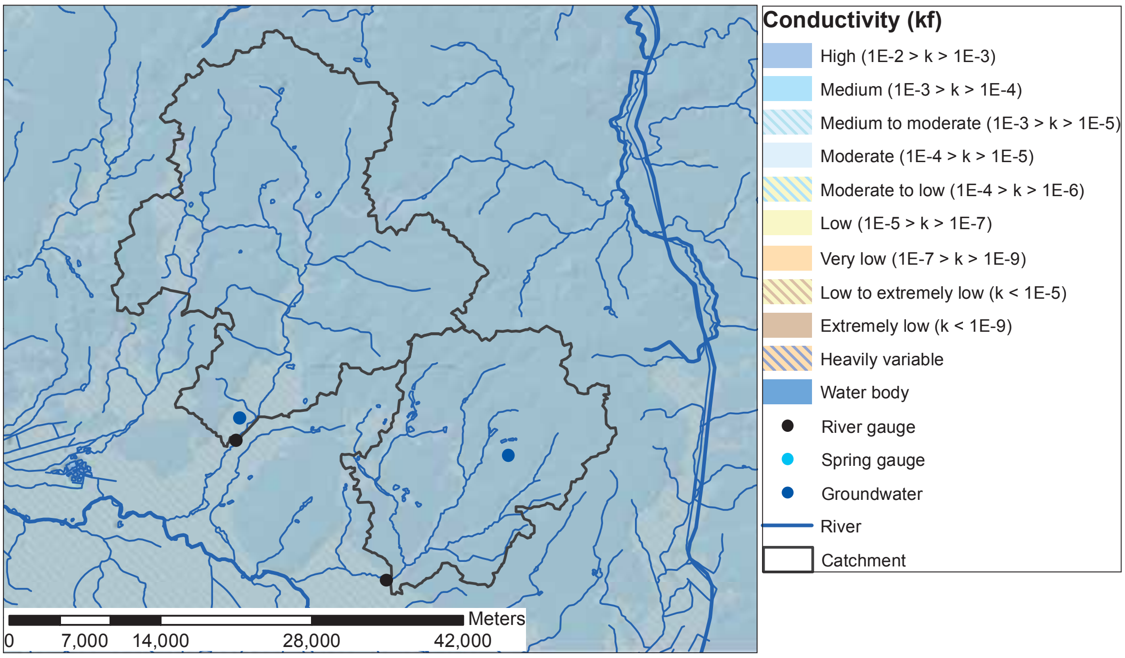

Figure 3: Form of and channel alignment in the two lowland catchments Oertze (northwest) and Lachte (southeast). Colours in the map refer to the conductivities of the unconfined top groundwater story according to HUEK (see legend). Black dots are stream discharge gauges, blue dots are groundwater gauges.

Aquifer

Looking at the stratigraphic cross profile (figure A3, appendix) and the borehole profile (figure A1, appendix), the aquifer that the borehole taps is a rather uniform sand aquifer, interlaid with some sandy-gravelly layer, both with relatively yielding conductivities in the magnitude of about 10^{-3} to 10^{-4} m/s, according to HUEK200. Because of the aquifer material, sand, and considering its recent age, isotropy of conductivities is likely to be high. In the river valley however, where the groundwater gauge is situated, (figure 3) shows a somewhat lower range of 10^{-3} to 10^{-5} m/s due to alluvial clay sedimentation. Here, horizontal conductivities are likely to be higher than vertical conductivities due to stratification. Although values according to HUEK200 are very rough and large-scaled estimates, this is consistent with the borehole profile (figure A1, appendix), showing mostly sand with some low portion of clay. The borehole does not tap the confining layer (marly till) underneath the sand aquifer. The aquifer depth can still be estimated from the stratigraphic cross profile (figure A3, appendix) to about 20 meters. The horizontal extent is extremely vast. The aquifer seems to be part of the big aquifer consisting of recent sand sediments along the Elbe River, to which the river Oertze is a direct tributary.

2.2.3 Lachte

Catchment

The Lachte catchment is the one southwest to the Oertze catchment (figure 3); it is directly adjacent and tributes to the Elbe River as well. It is about 385 km^2 in size with a mean height of 89.5 meters a.s.l., ranging from 43 meters a.s.l. up to 145 m a.s.l. (table 1), which makes it marginally flatter (10 meters less height difference), slightly higher and half as extensive as the Oertze catchment. Also, it is a little more stretched in form than the Oertze, but still wide and nested. So far, conditions in both catchments can be considered equal to a large degree. However one big difference is the location of the groundwater gauge. It is situated in the upper third of the catchment, in between two main branches of the Lachte River. Ground level in the location of the groundwater gauge is 84.5 meters a.s.l., river level is 78 meters a.s.l. (table 2). However water levels in the groundwater gauge are somewhat lower and range between 81.1 meters a.s.l. up to 82.45 meters a.s.l. (range: 1.35 meters), therefore groundwater levels are only between some 3 to 4.5 meters above river level some 1260 meters away. This results in a very low gradient of only 0.002 to 0.004, which indicates high connectedness between river and groundwater. Still, because the groundwater gauge is located close to the 'head' of the catchment and therefore close to the recharge area, it is likely that signals in groundwater influences signals in stream baseflow more than vice versa. Meaning that droughts should be visible in the groundwater hydrograph first.

Aquifer

According to the stratigraphic profile (figure A4, appendix) and the borehole profile (figure A2, appendix), aquifer composition is essentially the same as in the Oertze catchment, consisting mostly of sand with some portion of gravel in the depth. Conductivities according to HUEK200 are between 10^{-3} m / s and 10^{-4} m / s, which is a little higher than in the location of the groundwater gauge in the Oertze catchment. This is due to the location of the groundwater gauge offside the river valley in the Lachte catchment. The borehole profile shows no fractions of clayey river sediments whatsoever. Isotropy in conductivities is therefore likely to be high. The borehole taps the confining layer underneath the sand aquifer (clay), making exact determination of aquifer thickness possible. It is 19 meters in depth, indicating a fairly similar aquifer extent as in the Oertze catchment. However as can be seen from the stratigraphic cross profile (figure A4, appendix), the confining layer under the aquifer, a ground moraine of the Drenthe sub-stage of the Kansan Ice Age, taps the surface some 2 – 2.5 kilometers downstream the groundwater gauge. Firstly this limits the horizontal extent of the aquifer, secondly this might lead to a backwater-, or pondage effect, having an attenuating impact on the groundwater hydrograph.

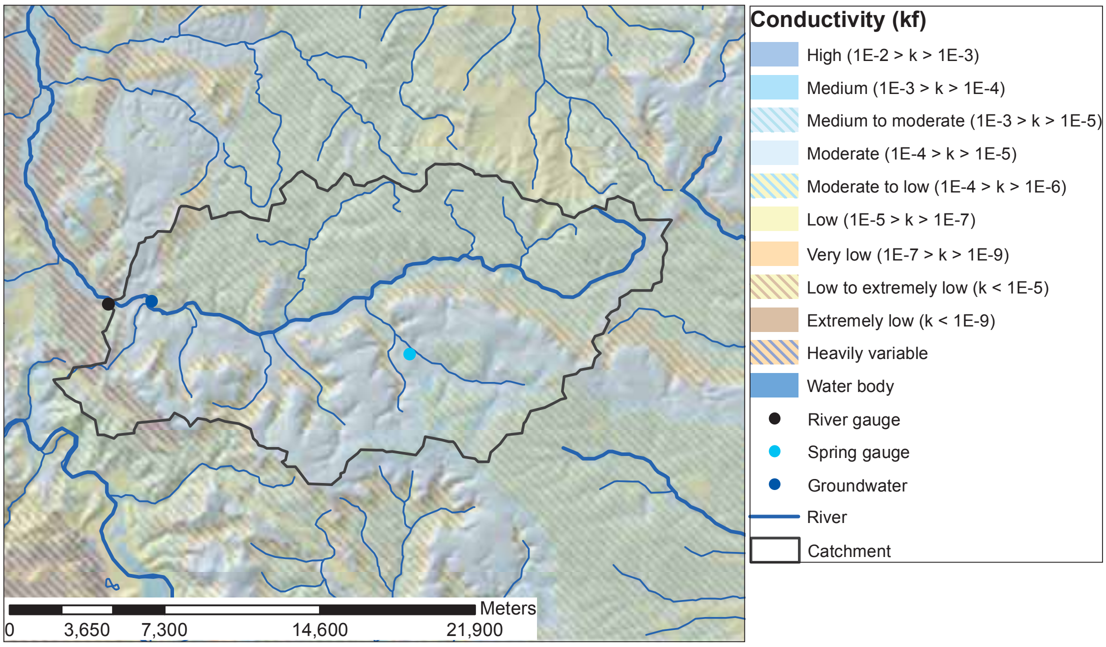

Figure 4: Form of and channel alignment in the Leine catchment. Colours in the map refer to the conductivities of the unconfined top groundwater story according to HUEK (see legend). The black dot is the stream discharge gauge, the dark blue dot is the groundwater gauge, the light blue dot is the spring discharge gauge.

2.2.4 Leine

Catchment

The Leine catchment is situated in mid-Germany, southwest of the Hartz massif (figure 2). It is within a low mountain range with a average height of about 354 meters a.s.l., ranging from 198 meters a.s.l. up to 524 meters a.s.l. (table 1). The catchment is about 272 km^2 in size and is rather stretched with one main channel with several tributaries of medium length along its course. There are two gauges in this catchment, one spring discharge gauge and one groundwater gauge. The spring discharge gauge is near the bottom of a slope above the valley of one of the tributaries (figure 4). The spring outlet is on 321 meters a.s.l., 17 meters above the stream, which is 117 meters away from the gauge and therefore very close. This results in a rather high gradient of spring gauge to stream level of 0.145. The spring drains a stretched hill with a top height of about 430 meters a.s.l., which is therefore quite high above the river valley. The hillside aquifer drained by the spring seems to be spatially confined from the alluvial aquifer in the valley. It is therefore assumed that spring discharge is not influenced by the river at all.

This is different for the groundwater gauge. It is close to the bottom of the main valley of the Leine River near the outlet of the catchment (figure 4). Ground level of the gauge is 220.9 meters a.s.l., 297 meters away from the stream, which is on about 205 meters a.s.l. . However water levels are much deeper, ranging from a minimum of 204.6 meters a.s.l. up to a maximum of 206.25 meters a.s.l. (range: 1.65 meters). During very dry times, groundwater levels are therefore beneath the river level, resulting in a reversal of the gradient from 0.004 for the maximum groundwater level to -0.001 for the minimum groundwater level (table 2). Even when considering some inaccuracy of the DEM, leading to a certain inaccuracy in determining stream level, groundwater levels are strikingly close to stream level. The gauge itself lies near the bottom of a rather broad erosive cut (not quite a gorge, but still drained by a small brook) in the hillside to the north of the narrow Leine River valley. The cut comes down a quite extensive plateau, which is about 300 to 330 meters a.s.l. . On grounds of the topographic situation one could suggest that the plateau potentially drains via this cut in the hillside and that therefore the groundwater gauge should be supplied with water constantly. But, although ground level of the groundwater gauge is about 16 meters above the stream, water levels in the borehole are on height of stream level, i.e. 14.6-16.3 meters below ground level. Therefore it is likely that the aquifer in location of the groundwater gauge is not connected with the plateau. Possibly some underground barrier in the cut confines the plateau from the valley, leaving only afflux from the river valley aquifer and a supposedly quite small hillside aquifer downside the confining barrier. However no stratigraphic cross section of the area is available, so this conclusion remains speculative.

Aquifer

The Leine River lies on the boundary of two different geological regions, divided by the Leine Graben, a graben named after the river as the Leine flows on its bottom. To the north of the river, bedrock is sandstone and various conglomerates, according to HAD and GUEK200. South of the river there is a small strip of gypsum and gypsum containing rocks. Further on, the south-eastern fringe of the catchment, bedrock is marly. To the southwest of the river, geology becomes more complex; the three above-mentioned bedrocks alternate strongly. Along the river there are small alluvial sediments. The sandstone aquifers north of the river, where the above-discussed plateau and hillside aquifer are located, have moderate to low conductivities ranging from 10^{-4} to 10^{-6} m/s (figure 4). The hill drained by the spring lies on the gypsum-containing bedrock and has somewhat higher conductivities of 10^{-4} to 10^{-5} m/s, according to HUEK200. The preliminary borehole profiles that were provided by the TLUG, however, draw a different picture. Bedrock in the location of the spring gauge is quaternary marl (figure A6, appendix), alternating with layers of gravel, without any fraction of gypsum. In the location of the groundwater gauge, alternating layers of sandstone and siltstone are forming the bedrock, with some gravel layer on top (figure A5, appendix). This is consistent with the GUEK/HAD information. But it should be mentioned that preliminary borehole profiles are not made on grounds of actual drilling on site, but are an estimated data product from a stratigraphic model based on surrounding boreholes. Depending on the size of the borehole grid, the outcome (preliminary borehole profiles) can be everything from exact to misleading.

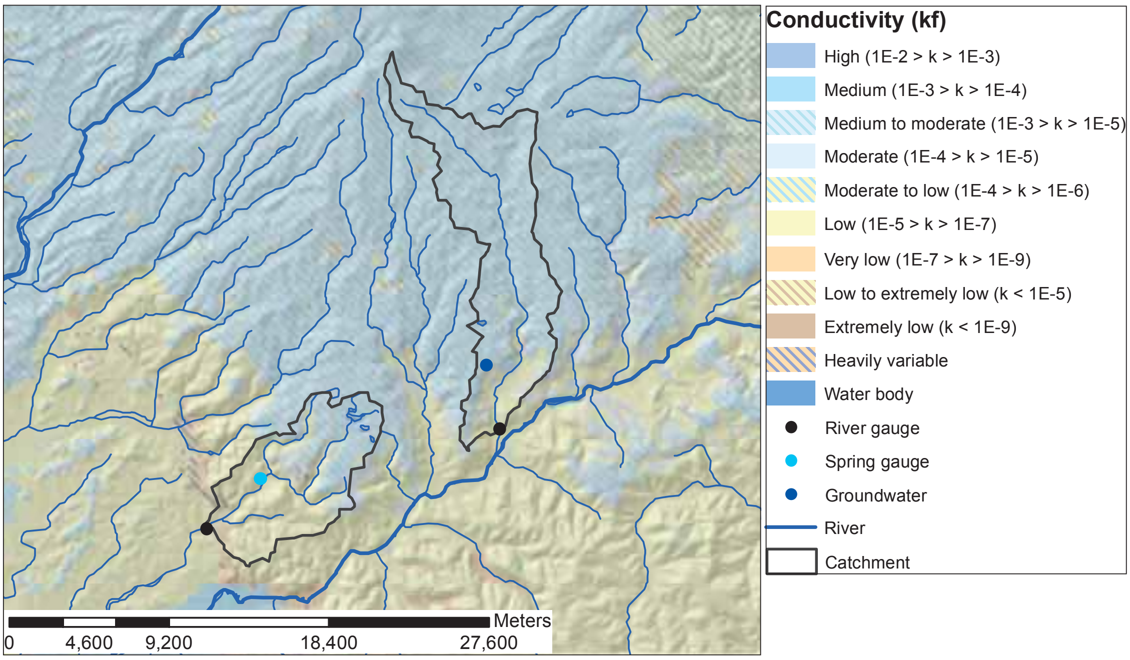

Figure 5: Form of and channel alignment in the Gruendau catchment (southwest) and the Salz catchment (northeast). Colours in the map refer to the conductivities of the unconfined top groundwater story according to HUEK (see legend). Black dots are stream discharge gauges, the dark blue dot is the groundwater gauge in the Salz catchment, the light blue dot is the spring discharge gauge in the Gruendau catchment.

2.2.5 Gruendau

Catchment

The Gruendau catchment is directly adjacent to the Salz catchment (figure 5). It lies to the west of the Salz and is with about 56 km^2 the smallest sample catchment in the selection. Mean height is 310 meters a.s.l., ranging from 141 meters a.s.l. up to 423 meters a.s.l. (range: 282 meters, table 1). The Gruendau is a confluence of streams from two sub-catchments. It can be therefore be classified as nested. The spring discharge gauge in this catchment lies near the conjunction of the two streams, at the foot of a small hill that goes up a rather gentle slope to the summit at about 180 meters above the river. However right above the gauge there is a small depression, which is drained by a small brook. It is assumed that in the brook most of the water coming from the hillside aquifer is concentrated, leaving only a spatially very small potential drainage area for the spring. The spring gauge itself is on about 180 meters a.s.l., only 1 meter above the river, and about 106 meters away from it, resulting in a gradient of 0.009 (table 2). Again the supposed inaccuracy of the DEM has to be taken into account. Still, the gauge is strikingly close to stream level. It is therefore likely, considering the small hillside drainage area of the spring as well, that the spring is part of the riverine aquifer network, where river and aquifer interchange constantly. Connectedness of spring gauge and river is assumed to be very high.

Aquifer

The Catchment lies directly on the boundary of two different geological formations. Topographically it is part of the Vogelsberg basalt massif, being one of its foothills that is partly disconnected from the massif by erosion cuts. Yet only roughly the upper third is classified as basaltic by the HAD. HUEK200 indicates conductivities of 10^{-3} up to 10^{-5} for this region (figure 5). The lower third is an outer branch of the Spessart bunter sandstone formation south of the catchment. Here conductivities are indicated to be much lower, in the range of 10^{-5} to 10^{-9}. In the middle of the catchment is the ‘collision zone’ of these two formations. Conductivities are highly variable here. However if the assumption from the paragraph above is correct and the spring is part of the river valley aquifer system, the aquifer conditions that are actually significant are the ones of the alluvial aquifer beneath the valley bottom. No statement can be made on that because no further information with higher detail than in HAD or HEUK200 is available for this catchment. It can be assumed that conductivities in the alluvial are somewhat higher (Hölting and Coldewey, 2013).

2.2.6 Salz

Catchment

The Salz catchment is located in mid-Germany (figure 2). It runs down the slope of the Vogelsberg, a flat basalt massif with its summit on 773 meters a.s.l. . The catchment is some 87 km^2 in size and is therefore the second smallest catchment in the selection. It starts just below the summit, on 705 meters a.s.l. and runs down the whole slope of the Vogelsberg into the Kinzig valley, with the lowest point at the stream discharge gauge on 150 meters a.s.l., near the inlet into the Kinzig. The range of height is therefore 555 meters, which, together with a mean height of 382 meters a.s.l., makes it the highest and steepest sample catchment (table 1). The form of the catchment is very long-stretched with no major tributaries.

The groundwater gauge is located in the lower third of the catchment on 307 meters a.s.l., on top of the western slope of the Salz valley, on the fringe of a small plateau. The bottom of the Salz valley is, at its nearest point 1165 meters from the gauge, on 182 meters a.s.l., some 125 meters below the groundwater gauge, which is a rather extreme slope. Groundwater levels range from 294.6 up to 297.8 meters a.s.l., a range of 3.2 meters. This is the second most extreme range in groundwater levels (after Spree gauge) observed in this thesis. However with the big distance from the stream and height difference, the gradient from groundwater levels to stream level fluctuates only marginally between 0.097 and 0.099 (table 2). Groundwater in the location of the gauge can be considered unaffected by the river with certainty.

Aquifer

Basically the entire catchment is underlain with basalt. The degree of fracturing is unknown but can be estimated. HUEK200 classifies the area with conductivities of 10^{-3} to 10^{-5} m/s, indicating that the basalt bedrock is well fractured (figure 5). After all the catchment is close to the Upper Rhine Rift, where light earthquakes occur on a regular basis. The constant mechanical stress renders rock highly fractured over time. Of course no general assumption can be made on the degree of isotropy of conductivities for fractured rock. In the lower Salz valley, just upstream the river gauge, a little basin formed with alluvial sediments (figure A7, appendix). Here the conductivities are estimated to be around 10^{-5} to 10^{-7} m/s, according to HUEK200.

As said before, the groundwater gauge is situated to the west of the river, on the fringe of a small plateau that spans some 100-150 meters above the river valley. Bedrock of the plateau is basalt. In the east of the plateau, shortly after the groundwater gauge, it drops steeply into the Salz valley. The gauge itself is located on the bottom of a shallow basin on the eastern end of the plateau. It can be assumed that the gauge is constantly supplied with water from the aquifer on the plateau, considering its topographically low position relative to the height of the plateau. However no further information like borehole profiles or stratigraphic cross sections were available, therefore no conclusions on aquifer depth, extent and actual composition can be made.

2.2.7 Spree

Catchment

The Spree headwater is located east of the Erzgebirge, on the border to the Czech Republic. Sadly, because maps were available for Germany only and the Spree is a trans-boundary catchment, figure 6 displays only part of the catchment. It is 274 km^2 in size with a mean height of 360 meters a.s.l., ranging from 188 meters a.s.l. up to 616 meters a.s.l. (range: 428, table 1). The topography can further be described as a hilly landscape with no highlighting summits. The catchment’s form is nested. The groundwater gauge is about 800 meters away from the stream, halfway down the river. Ground level of the gauge is on 326.4 meters a.s.l., 58.4 meters above the stream on 268 meters a.s.l. (table 2). Water levels in the borehole are 4.6 to 8.3 meters below ground level, ranging from 318.1 meters a.s.l. on its driest day up to 321.8 meters a.s.l., the maximum water level on record. This makes a range of 3.7 meters, which is the highest variability of all sample catchments. The range of the gradient is therefore 0.063 to 0.068. So to say despite the variability in groundwater levels, the gradient is relatively constant, due to the long distance and height difference.

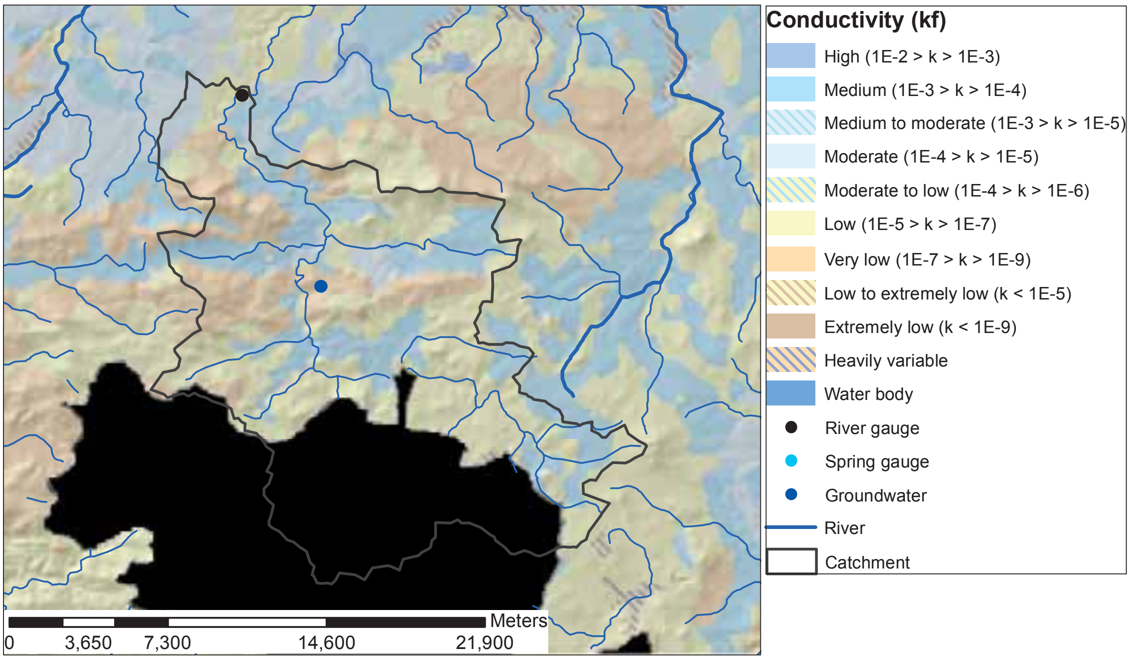

Figure 6: Form of and channel alignment in the Spree catchment. Colours in the map refer to the conductivities of the unconfined top groundwater story according to HUEK (see legend). The black dot is the stream discharge gauge, the dark blue dot is the groundwater gauge. The black area to the south is where German national territory ends. The HUEK map was only available for German territory.

Aquifer

Hydrogeological setting in the Spree catchment is very variable. Conductivities according to HUEK200 range from moderate (10^{-4} to 10^{-5}) in some basins to very low (10^{-7} to 10^{-9}) where the crystalline bedrock taps surface (figure 6). The groundwater gauge is located in the latter area. It is situated on a saddle in between several hills (which are around 400-480 meters in height) that surround the location from three sides. However in direction of the Spree mainstream, a rather deep eroded valley was formed, draining the saddle via a small stream. Bedrock is close to the surface on the hills, but the saddle in between the hills is filled with slope debris according to GUEK200, whose origin is most probably the surrounding hills. (figure 6) is just too rough to enable estimation of conductivities in the debris aquifer that is tapped by the groundwater gauge. No further maps or profiles are available. It is assumed that conductivities in the location of the gauge (on the saddle) are somewhat moderate, however the aquifer is estimated to be very small, considering topography and geological setting.

2.2.8 Preliminary Summary on Catchment Settings

Solely on grounds of the hydrogeological metadata that was available, the following hydrogeographical settings could be determined.

The Oertze is the biggest, lowest-lying catchment with 714 km^2 and a mean height of 83 meters a.s.l. . The groundwater gauge is located near the catchment outlet within the wide and flat river valley. Therefor the gradient of groundwater level to stream level is small (0.006 - 0.008) and water levels vary between 5-7 meters above stream level. Connectedness between river and aquifer in location of groundwater gauge is considered high. The aquifer in general consists of homogenous sandy sediments with high conductivities of 10^{-3} to 10^{-4} m/s. In location of groundwater gauge however conductivities are somewhat smaller due to some fraction of recent alluvial clayey deposits. The aquifer depth is about 20 meters and the horizontal extent is extremely vast, stretching across the topographical catchment boundaries.

The Lachte is directly adjacent to the Oertze and basically on the same height but only half as big (385 km^2). The groundwater gauge is in the upper third of the catchment, in the centre between two main branches of the Lachte. It is considered to be in the aquifer recharge area. The gradient is very small (0.002 - 0.004) because of the small height of groundwater levels above stream level (3 - 4.5 meters). A high connectedness between river and aquifer in location of groundwater gauge is assumed due to flat catchment conditions. The aquifer material is also sand but with some fraction of gravel. Conductivities are around 10^{-3} to 10^{-4} m/s, its depth is 19 meters. The confining layer beneath aquifer is a ground moraine that taps ground surface some 2 – 2.5 km downstream the groundwater gauge which might lead to a possible backwater- or pondage effect on the gauge.

The Leine catchment is similar in size as the Lachte, but lies significantly higher (272 km^2 on 354 meters a.s.l.). There is both a spring discharge and groundwater gauge in the catchment. The spring is located 17 meters above the closest stream, which is a tributary to the Leine, characterised by a narrow and steep valley. It lies at the foot of a hill that goes up to approximately 100 meters above the river. The spring drains said hill. No connectedness to the river is assumed. The groundwater gauge is near the outlet of the catchment in the narrow and steep Leine valley, close to the stream. It is located on a hillslope about 15 meters above the river, yet water levels in the borehole are deep and therefore close to the stream water level. A reversal of the gradient can be observed when groundwater levels drop low (0.004 -> -0.001). The gauge drains possibly the river aquifer and/or a small hillside slope debris aquifer. Drainage of a plateau aquifer above the groundwater gauge is considered unlikely. An extremely high connectedness to the river is assumed. There is differing information about aquifer composition that is discussed in more detail in the corresponding chapter (chapter 2.2.4).

The Gruendau catchment is very small (56 km^2) and lies rather high with a mean height of 310 meters a.s.l. . It is characterised by a distinct erosive valley as well, yet it is not as topographically pronounced as the Leine valley. There is only a spring gauge in this catchment, which lies very close (106 meters) to the stream and is only 1 meters above the stream, resulting in a small gradient (0.009). It is possibly part of the river valley aquifer or alternatively draining a small hillside aquifer. Trustworthy details about the aquifer composition or exact hydrogeological situation of the spring were not available.

The Salz catchment is very small as well (87 km^2). With 382 meters a.s.l. it is the highest catchment in the selection. It is the steepest as well with an rather deep valley. Also the alignment of the stream is very linear without any major sub-catchment nesting and only minor tributaries. The Groundwater gauge is located in the lower third of catchment on the fringe of a plateau about 125 meters above the stream. Also, the groundwater gauge is very close to the stream (180 meters), resulting in a high gradient (0.097 – 0.099). The small plateau is rather flat and stretches some 100 – 150 meters above the river. It drops steeply into the Salz river valley shortly behind the groundwater gauge. No details about aquifer composition in location of groundwater gauge were available. Connectedness to the river is non-existent.

Finally, the Spree catchment is similar in size as the Leine (274 km^2) and is the second highest (mean height: 360 meters a.s.l.) and steepest. The landscape is predominantly hilly, unlike the Salz, Leine or Gruendau catchments, which adhere more distinct erosive valleys. The groundwater gauge is about 60 meters above and 800 meters from the mainstream. Therefore the gradient is rather high with 0.063-068. The aquifer in location of the groundwater gauge is underneath a saddle in between three hills. The aquifers material is slope debris. Connectedness of aquifer to stream is considered negligible and the aquifer size is estimated to be very small. Also, it is possible that the aquifer is significantly sloped.

2.3 Drought analysis

For the argumentation and discussion leading to the choice of methods that are described in this chapter, please refer to (chapter 1.3).

2.3.1 Drought Definition

The identification of droughts is – for every hydrological variable in every catchment separately - performed with a binary variable δ.

$$\delta(t) = \begin{cases} 1 & if\ x(t) < \tau(t) \\ 0 & if\ x(t) \geq \tau(t) \end{cases} \tag{1}$$

Where 1 indicates that a hydrological variable x is below a threshold $\tau(t)$ at time t, i.e. that the variable is in drought.

In case of the **constant threshold**,

$$\tau(t) = \tau_c \tag{2}$$

With τ_c being a constant value. For this thesis it was chosen to be the 20%-quantile of the whole time series, following Van Loon (2013).

In case of the **variable threshold** $\tau_{v,i}(t)$, it is dependent on the monthly quantile at time t:

$$\tau_{v,i}(t) = \tau(i,t) \tag{3}$$

Where τ is the 20%-quantile of all values of $x(t)$ in the particular month i (in 1 to 12) at time t. Also,

$$m_i^{(n)}(t) = \frac{1}{n}\sum_{j=0}^{n-1} \tau_{v,i}(t - j + \frac{n}{2}) \tag{4}$$

Being the function of a centred moving average with a window of n = 30 days, resulting in:

$$\tau_v(t) = m_{MA}^{(n)}(t) \tag{5}$$

Being a function of seasonality for every year in the regarded period, i.e. the variable threshold. The width of the moving window of n = 30 days is used following Van Loon (2013). Different smoothing methods for the variable threshold other than the moving average were evaluated (e.g. LOESS, LOWESS), but proved to adhere crucial disadvantages not further discussed here. The moving average did prove to be the most unproblematic and straightforward.

Lastly, to get the **combined threshold**:

$$\tau(t) = \begin{cases} \tau_c & if\ \tau_c < \tau_v(t) \\ \tau_v(t) & if\ \tau_v(t) < \tau_c \end{cases} \tag{6}$$

Which is the threshold for (1) as used in this thesis.

2.3.2 Pooling Methods

The droughts as identified by the threshold level method are not always significant (Fleig et al., 2006). One example is droughts of very short duration. When a hydrological variable falls below the threshold for only one or two days, it cannot really be considered a drought, as it is likely that it is for example part of some short-term fluctuation. It can rather be seen as a small artefact of the calculation procedure of the threshold level method with no actual significance. Similarly, when a variable is under the threshold for quite some time and exceeds the threshold for a limited amount of days only to drop almost immediately below the threshold again, no actual recovery from drought occurred, instead the variable can rather be seen as under long-term drought condition with a short, fluctuative discontinuation. Both cases should be filtered out.

To eliminate minor droughts, all events with a duration of less than 3 days were excluded from calculation, following Van Loon (2013). This is a rather low and conservative exclusion criterion (Hisdal et al., 2004; Fleig et al., 2006; Van Loon, 2013). But, with reference to chapter 1.2, it is not recommendable to use a value much above the 3 days criterion, especially when precipitation ought to be considered, because a characteristic of precipitation is the almost exclusive occurrence of very short droughts.

To pool droughts that are interrupted by a short discontinuation, the inter-event time method (IT-method) was applied (Fleig et al., 2006). Droughts that are interrupted by a threshold exceedance period of less than 5 days were combined. The exceedance period is then considered as part of the drought. This leads to the subsequent problem that, if two rather short drought periods are interrupted by a relatively extreme exceedance period of less than 5 days, drought characteristics like the mean deviation from the threshold can become negative in average (i.e. above the threshold) for the combined drought. Droughts where this happened were excluded as well.

2.3.3 Drought Characteristics

In order to calculate the drought characteristics used in this thesis, separate drought events as defined in (1) are numerated to get the overall **number of droughts** n for each hydrological variable in each catchment. The **duration** Δ [days] of each drought is then determined.

$$\Delta_i = \sum_{t=1}^{T} \delta_i(t) * \Delta t \tag{7}$$

With $t = 1$ being the first, T the last day of drought i. For some applications in this thesis, Δ_i is then normalised in order to enable comparability across all catchments.

$$D_i = \frac{\Delta_i}{\frac{1}{n}\sum_{j=1}^{n} \Delta_j} \tag{8}$$

To get to the maximum deviation as a measure of severity, the individual deviation d for every day is calculated for the whole time series.

$$d(t) = \begin{cases} \tau(t) - x(t) & if\ x(t) < \tau(t) \\ 0 & if\ x(t) \geq \tau(t) \end{cases} \tag{9}$$

Deviation d is also used to display droughts in the hydrograph-plots (figures 13 to 19).

Then, the maximum deviation, or **severity** d_{max} is simply:

$$d_{max,i} = \max\left(d_{i,}(1), d_i(2), \ldots, d_i(T)\right) \tag{10}$$

With d being the deviation of individual days in drought i, which lasts from day $t = 1$ to day T.

2.3.4 Threshold Level Sensitivity Analysis

The drought characteristic that is subject to the sensitivity analysis is calculated for both the constant and variable threshold for the entire quantile-range from 1% to 50%. I order to carry this out, first step is to calculate all possible combinations of constant and variable threshold within this range similar to formula (6).

$$\tau_{i,j}(t) = \min\left(\tau_{c,i}, \tau_{v,j}(t)\right) \quad \forall\ i, j\text{: } 1,2, \ldots, 50 \tag{11}$$

With $\tau_{i,j}$ being the combined threshold of all combinations of the constant threshold with the quantile range of i, and the variable threshold level with the quantile range of j, resulting in 50*50 = 2500 combined thresholds $\tau_{i,j}$. For every one of these thresholds, the drought characteristic that is subject to the sensitivity analysis is calculated. The drought characteristic chosen to be discussed in the course of the sensitivity analysis is the mean duration of the droughts because duration is the most used characteristic in this thesis. Discussion of all drought characteristics would exceed the scope of this work, so focus was on mean duration $\overline{D}_{i,j}$, which is calculated similar to (7):

$$\overline{D}_{i,j} = \frac{1}{n}\sum_{k=1}^{n} \Delta_{i,j,k} \tag{12}$$

Afterwards the results are written into a matrix.

$$\begin{pmatrix} \overline{D}_{i=1,j=50} & \cdots & \overline{D}_{i=50,j=50} \\ \vdots & \ddots & \vdots \\ \overline{D}_{i=1,j=1} & \cdots & \overline{D}_{i=50,j=1} \end{pmatrix} \tag{13}$$

With, again, i referring to the constant threshold calculated with the quantile i and j referring to the variable threshold calculated with the quantile j.

After that, differences between the mean durations in (13) are calculated in x-direction (direction of variable threshold) and y-direction (direction of constant threshold) of the matrix separately.

$$\begin{pmatrix} 0 & y_{2,50} = (\overline{D}_{i=2,j=50} - \overline{D}_{i=1,j=50}) & \cdots & y_{50,50} = (\overline{D}_{i=50,j=50} - \overline{D}_{i=49,j=50}) \\ \vdots & \vdots & \ddots & \vdots \\ 0 & y_{2,1} = (\overline{D}_{i=2,j=1} - \overline{D}_{i=1,j=1}) & \cdots & y_{50,1} = (\overline{D}_{i=50,j=1} - \overline{D}_{i=49,j=1}) \end{pmatrix} \tag{14}$$

And

$$\begin{pmatrix} x_{1,50} = (\overline{D}_{i=1,j=50} - \overline{D}_{i=1,j=49}) & \cdots & x_{50,50} = (\overline{D}_{i=50,j=50} - \overline{D}_{i=50,j=49}) \\ \vdots & \ddots & \vdots \\ x_{1,2} = (\overline{D}_{i=1,j=2} - \overline{D}_{i=1,j=1}) & \cdots & x_{50,2} = (\overline{D}_{i=50,j=2} - \overline{D}_{i=50,j=1}) \\ 0 & \cdots & 0 \end{pmatrix} \tag{15}$$

Afterwards the entries of these two matrices are combined to form the **averaged bidirectional difference** $\beta_{i,j}$ of the mean duration between both thresholds, where $\beta_{i,j}$ is:

$$\beta_{i,j} = \begin{cases} \frac{x_{i,j+y_{i,j}}}{2} & if\ x_{i,j} \neq 0 \quad and \quad y_{i,j} \neq 0 \\ 0 & if\ x_{i,j} = 0 \quad or \quad y_{i,j} = 0 \end{cases} \tag{16}$$

And written in a matrix:

$$\begin{pmatrix} \beta_{1,50} & \cdots & \beta_{50,50} \\ \vdots & \ddots & \vdots \\ \beta_{1,1} & \cdots & \beta_{50,1} \end{pmatrix} \tag{17}$$

Formula (16) inherits an insensitivity assumption. If either $x_{i,j}$ or $y_{i,j}$ falls to zero, in other words if either the calculation in y-direction or the calculation in x-direction ceases to detect differences from the previous thresholds $\beta_{i-1,j}$ or $\beta_{i,j-1}$, $\beta_{i,j}$ is set to zero. Meaning if either one of the calculation dimensions are insensitive (no difference), the two-dimensional index $\beta_{i,j}$ is assumed to be insensitive as well. In other words if there is a 1D-insensitivity, a 2D-insensitivity is concluded. This is on grounds that, if one dimension is insensitive, it cannot be considered a combined threshold anymore. Outside the fringes where the insensitivity occurs, the threshold is either a constant or a variable threshold only, as displayed in figures A8 (appendix), which are the straightforward plot of matrix (17). Note that $\beta_{i,j}$ is not a physically interpretable index as such. It is an index of changes in drought characteristic definition and can only be interpreted relative to other $\beta_{i,j}$.

3 Results

3.1 Threshold Level Sensitivity Analysis

The Threshold Level Sensitivity Analysis was conducted in order to find a best value for the Threshold Level. Some vague assumptions can be made on ground of the produced graphics. They show some ranges, outside of which the combined threshold is insensitive. Also, certain horizontal strips indicate especially sensitive quantile ranges, where some minor seasonal patterns might be detected. However they were different for every variable. The averaged bidirectional differences that were basis of these graphics proved to be too abstract for a useful, straightforward analysis. No coherent conclusions could be made, therefore the sensitivity analysis is left out, not least because time was limited so the intensity with which it should have been dealt with in order to deliver robust results was limited as well. However the method is potentially yielding within a more detailed study. Produced graphics can be found in the appendix (figures A8, appendix). A discussion about the influence of the combined threshold on results in general is included in chapter 4.

3.2 General

To characterise the hydrological systems, the duration curves are presented. Figures 7 a) to c) shows the duration curves of stream discharge, spring discharge and groundwater levels for all catchments. Precipitation is not displayed because it did not show any differences in the form or angle of the curves. The only difference is a marginal parallel translation of the curves. The similarity of the precipitation curves supports the assumption of equal climate controls for all catchments.

The range of crossing points, where the duration curves are crossing the mean (y=1) is different for every hydrological variable. The crossing point represents the quantile that coincides with the mean. This “crossing point quantile” is the maximum of the associated probability distribution. The closer the crossing point quantile is to the 50%-quantile, the closer the median to the mean. Coinciding mean and median would then imply a uniform distribution of values. Analogous, a variable has a lower confidence level when the crossing point quantile is farther away from the median. Stream discharge curves have a crossing point quantile between 68% and 78%. The two spring gauges are at 52% and 63%, respectively. Groundwater is between 49% and 58%. Therefore groundwater shows the

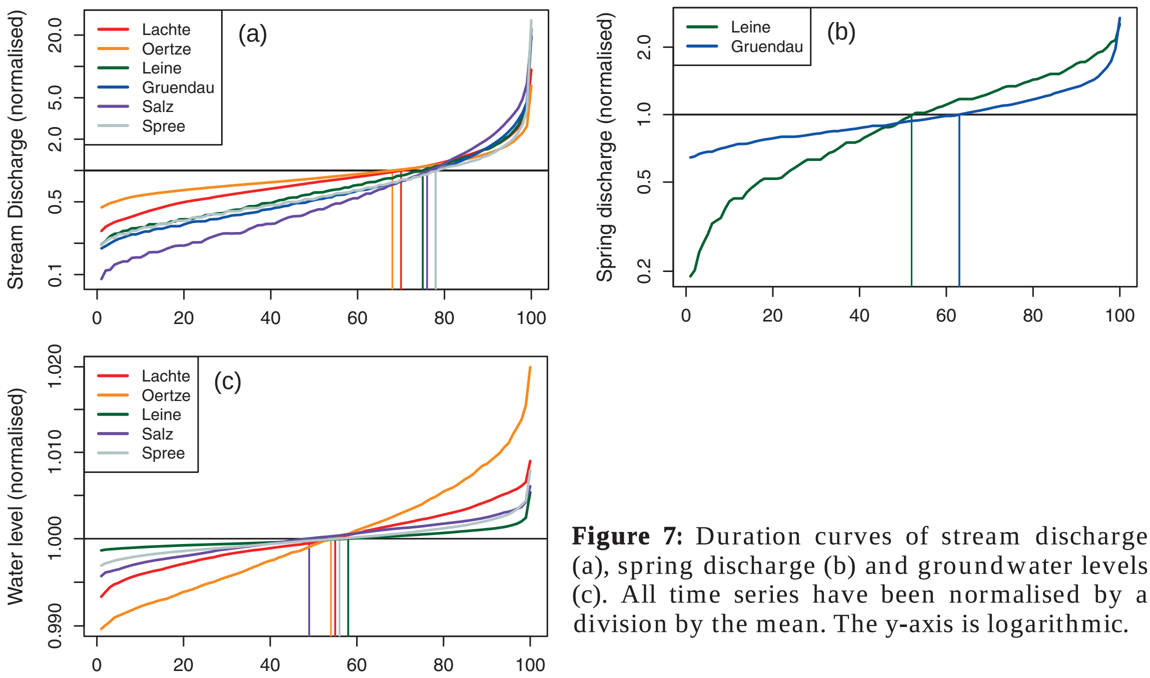

Figure 7: Duration curves of stream discharge (a), spring discharge (b) and groundwater levels (c). All time series have been normalised by a division by the mean. The y-axis is logarithmic.

lowest confidence level, stream discharge the highest and spring discharge is in between. This is also visible by the bare eye (figures 7 a, b, c). Stream discharge shows a far more extreme behaviour in the top quantiles. The long tailing under the crossing point represents the well-known regression behaviour of stream discharge and b aseflow. The form of the groundwater curve above and below the crossing point are far more alike, although they are still far from being normal distributed.

Concerning stream discharge, the Lachte and Oertze gauges have the flattest duration curves (figure 7a). This seems to be obvious because they are lowland catchments with high retention storage. Precipitation is temporarily stored and released over a longer period, leading to a more uniform flow curve. Analogously, the Salz gauge - having the steepest catchment (table 1) - shows the most extreme duration curve. A much bigger share of precipitation is immediately lost and not stored in temporary retention. The Leine, Gruendau and Spree gauges do not differ much from each other, showing mostly similar duration curves. Topographically they are in between Lachte/Oertze and Salz. They are topographically diverse, but not extreme. In other words they are intermediate. Altogether this represents the well-known catchment mechanisms. The steeper a catchment, the more extreme its discharge response and therefore its discharge curve. Thereby steepness coincides with lower subsurface storage and retention potential, because slopes cannot hold big soil layers and therefore soil storage is limited. Also, big subsurface storages like aquifers need surface depressions to some extend in order to develop.

Regarding groundwater, the Lachte and Oertze gauges have the most extreme, meaning steepest duration curves (figure 7c). This can be attributed to the high conductivities and depth of the sandy aquifers that are tapped by the groundwater gauges. Therefore the groundwater discharge of such an aquifer tends to be more uniform over all quantiles. Nevertheless the Oertze gauge has some specialities. Apart from the steep slope in the higher quantiles, which is characteristic to all time series, the duration curve is rather linear and especially low in the lower quantiles. It does not flatten like all the other groundwater duration curves. This characteristic is an evidence for high drought vulnerability, because groundwater levels do not truncate when reaching a low state. The flattest curve is the one of the Leine gauge, which is also pretty linear and in that respect similar to Oertze, but much flatter. This means water levels do not vary much and in drought condition, i.e. in the lowest quantiles, the aquifer holds water levels more or less constant. The Leine gauge is the one that is considered to reflect a riparian aquifer when groundwater levels drop low (chapter 2.2.4). It is assumed that it then gets a constant stream of water that flows through the aquifer in the river valley. The Salz and Spree are rather unspectacular, they lie somewhere in between Leine and Lachte / Oertze.

Concerning spring discharge (figure 7b), the behaviour of the Gruendau spring is somewhere in between the stream discharge and the groundwater curves. But the Leine spring discharge duration curve is outstanding. It is nearly linear from about 100% down to about 20%. Only below those 20% it slides off. I.e. the discharge drops over proportionally fast in drought conditions. One possible explanation is, that there is some threshold of disconnection. At a certain water level in the aquifer, which is drained by this spring, a major part of afflux to the spring gets disconnected. Another possibility is, that the Leine spring actually drains a confined aquifer. This would explain the high grade of linearity of the duration curve.

3.3 Drought Characteristics

3.3.1 Drought Duration Frequency Distribution

The standard approach to evaluate drought characteristics is to look at the distribution of drought durations in precipitation, stream discharge, spring discharge and groundwater (Peters et al., 2006; Van Lanen, 2006; Tallaksen et al., 2009; Van Loon, 2013). The presented graphs and tables in this chapter show the number of droughts dependent on their duration in particular catchments. They are evaluated for the groundwater cluster (figure 8, table 3) and the spring discharge cluster (fig 10 and table 4) separately.

3.3.1.1 The groundwater cluster

Precipitation

In figure 8 it is shown that in precipitation the major share of droughts - around 60% - are shorter than 15 days. About 80% of droughts in precipitation are not longer than a month. Consequently only few droughts occur with durations of up to 2 months, whereas 98% of the droughts are shorter than 45 days. Only a few droughts are 45-60 days in length (table 3). This distribution is similar for all catchments. Droughts in precipitation are rather uniform, there are only very small differences in the absolute number of droughts from one catchment to the next. Only precipitation in the Oertze catchment differs slightly. There are a little more short droughts and less “long” droughts, i.e. with up to 2 months duration, in this catchment (table 3).

Stream discharge

For stream discharge, the percentage of very short droughts with durations of not more than 15 days is – as in precipitation - also in the area of about 60% (figure 8). But there is a somewhat higher variation between the different catchments. For example the percentage of very short droughts in Salz discharge is outstandingly high at about 75%, which is an even higher percentage of short droughts than in precipitation. Alike, the Salz catchment also has the highest absolute number of streamflow droughts compared to the number of streamflow droughts in other catchments. It is to be emphasised that in absolute terms (table 3), the number of streamflow droughts is in general still much smaller than in precipitation. The Salz catchment is the steepest catchment with the most linear response, i.e. it is stretched and not nested at all. This results in a flashy response pattern, interrupting drought periods frequently.

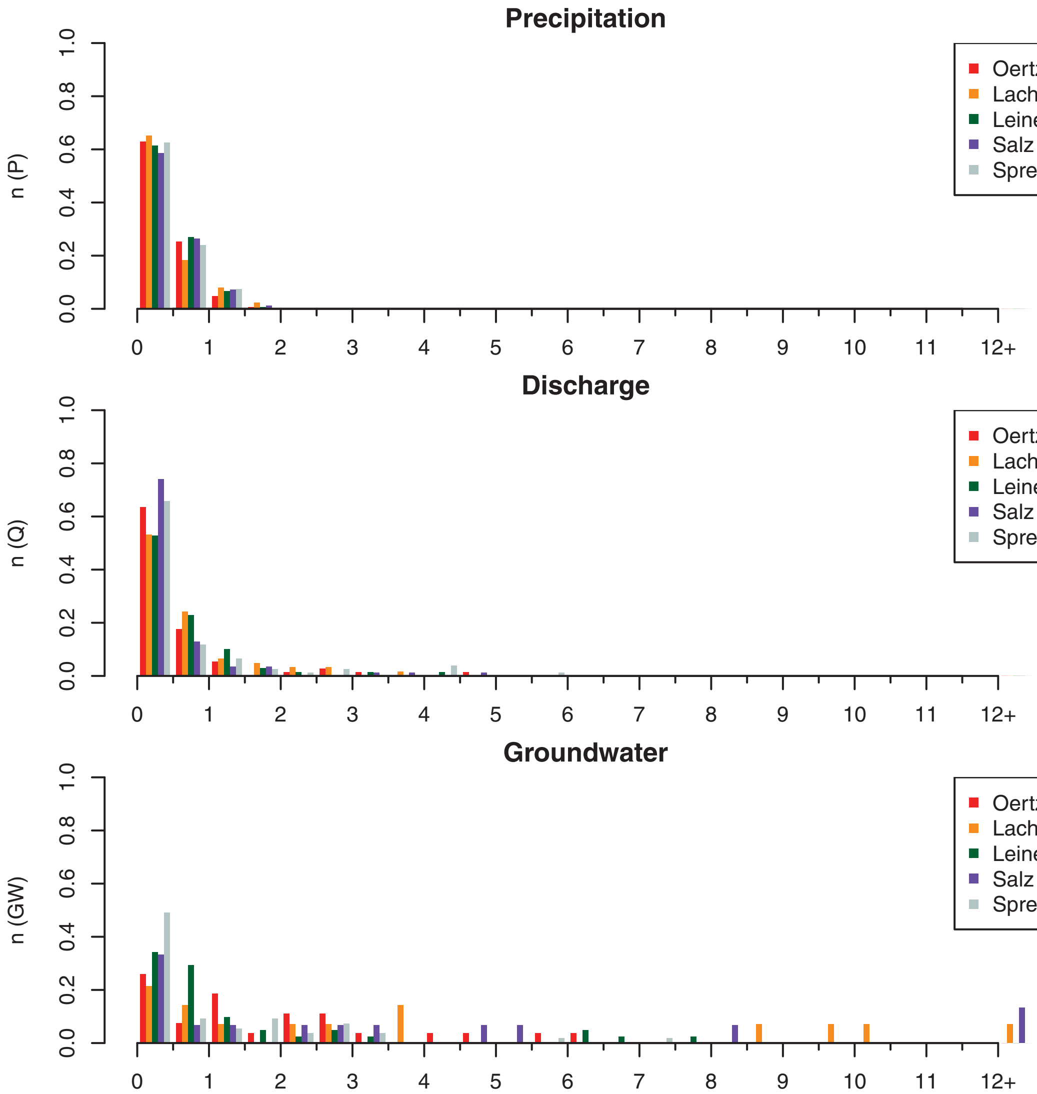

Figure 8: The relative frequency distributions of drought durations for precipitation, stream discharge and groundwater for all catchments. On the x-axis is the duration of droughts in steps of 15 days. The y-axis shows the percentage of droughts with a specific duration.

Discharge in Spree has a notably high percentage of very short droughts (smaller 15 days) as well, but the Spree also has a more pronounced tail, i.e. it does have several long droughts of about 5 months duration (table 3). It is therefore quite ambivalent, showing relatively many short and long droughts but few intermediate droughts. The Spree catchment is a hilly, nested catchment of medium size. It is actually not ought to have big aquifer systems with big memory that would cause long droughts. It is possible though that disharmonic response of sub-catchments cause the cumulative discharge at the catchment outlet to be low over extended periods of time. But after all, the difference in the drought duration frequency distribution of the Spree is rather similar other catchments.

Table 3: Numbers of droughts depending on duration (in months) for every variable in the groundwater cluster. Colouring is done with HSV. Thereby the saturation is the percentage of total droughts in a specific timestep to help identify patterns.

		Duration [months]													
Catchment	Variable	1	2	3	4	5	6	7	8	9	10	11	12	12+	Total
Lachte	P	137	17												154
	Q	48	7	4	1										60
	GW	5	1	2	2					1	1	1		1	14
Oertze	P	150	9												159
	Q	60	4	3	1	1									69
	GW	9	6	6	1	2	1	1							26
Leine	P	144	12												156
	Q	53	9	1	1	1									65
	GW	26	6	4	1			3	1						41
Salz	P	142	14												156
	Q	74	6		2	1									83
	GW	6	1	2	1	1	1			1				2	15
Spree	P	141	12												153
	Q	59	7	3		3	1								73
	GW	32	8	6	2		1		1						50

Another interesting feature is the difference between the two lowland catchments. Lachte is in relative and in absolute terms slower responding than its sister catchment, the Oertze. In other words the Oertze has more short droughts and is therefore faster responding and develops droughts faster. This is noteworthy despite the fact that it is the bigger catchment with otherwise equal catchment properties and should therefore in theory be not as quick responding as it obviously is. A possible explanation might be that a somewhat less nested alignment of channels (figure 3) in the Oertze catchment may favour a more direct runoff response.

Altogether, all catchments show a still relatively uniform distribution in stream discharge drought durations, although there is some degree of variation. Also, droughts longer than 2 months are rather scattered on the plot. Additionally, droughts longer than 2 months make up only low percentages. In summary the overall picture is, that in principle the relative frequency distribution of stream discharge is similar to the relative frequency distribution of precipitation, while the absolute number of stream discharge droughts is only about half to one third the amount of precipitation droughts (table 3). Also, stream discharge does show a much longer tailing. Longer tailing meaning more droughts with high durations, which surprisingly occur especially in topographically more extreme catchments like the Salz. A fact that might have a plausible explanation, but that is generally not consistent with drought theory.

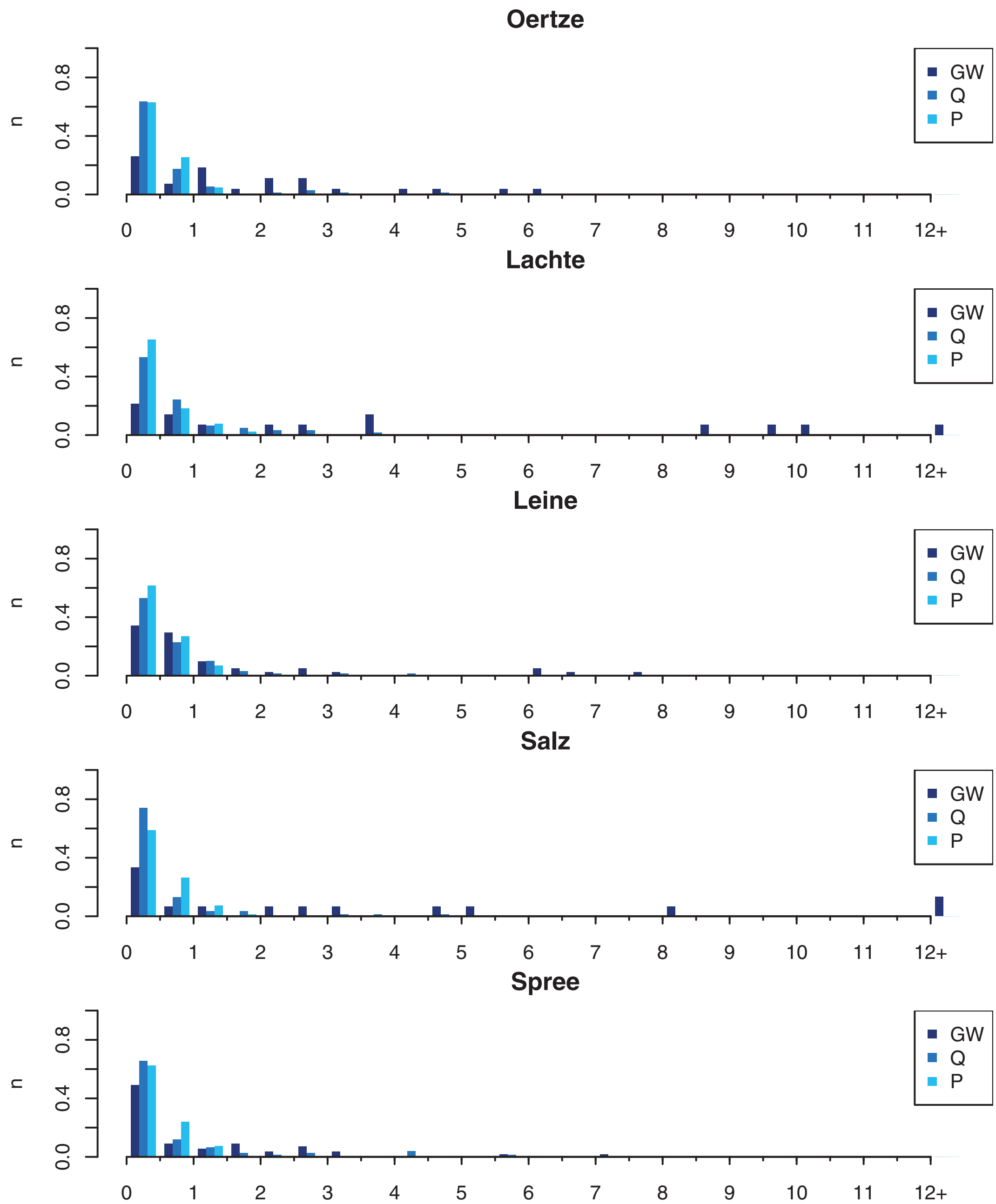

Figure 9: Relative frequency distributions of duration; same as figure 8, but grouped catchment-wise.

Groundwater

For groundwater, figure 8 generally shows a much more tailed and scattered relative frequency distribution. It also shows a much smaller percentage of short droughts (21-34%) with the exception of the Spree aquifer, which has a share of 54% in small droughts (shorter 15 days), which is more like the magnitude of discharge. Thereby the lower absolute number of droughts in groundwater has to be considered (table 3). In general it can be said that in groundwater there are still more short droughts than long droughts. Yet the relative distribution is much more scattered with a high share of extremely long droughts.

Lachte and Salz are the gauges with the biggest share of most extreme durations. They also have the smallest absolute number of droughts (table 3). The Salz aquifer has a total of 15 droughts, of which two are multi-year droughts. One is 424 days, the other 847 days or 2.3 years, which is the longest drought of all variables. To remember, the Salz groundwater gauge is located on a plateau above the catchment, whose aquifer is supposed to be rather small in size (chapter 2.2.6). Lachte on the other hand, one of the catchments in the lowlands, is supported by a vast aquifer. It has a total of 14 droughts and is therefore in total number similar to the Salz. 10 of 14 droughts are shorter than 4 months, and 4 are longer than 8 months, showing a gap between 4 and 8 months. It also has the second longest drought on record with 678 days (1.85 years). It is emphasised, that the two aquifers with the by far most extreme drought durations have completely different aquifer characteristics (compare chapters 2.2.3 and 2.2.6).

Interestingly, the Oertze groundwater gauge, the sister catchment of the Lachte in the lowlands, does not show such an extreme behaviour. Looking at (figure 9) we see a big difference: Droughts in groundwater with duration of more than 6.5 months do not occur in the Oertze aquifer. Therefore it can be said that it is much quicker responding than the Lachte aquifer. With 26 droughts in total, the Oertze groundwater gauge is in the middle field: Salz and Lachte have fewer and longer droughts, Leine and Spree shorter and more droughts.

Like the Salz gauge, the Leine gauge as well shows a gap in durations, between 3.5 and 6 months, which is however smaller than in Lachte. Also, the Leine groundwater gauge has a much higher absolute number of droughts and a much higher percentage of short droughts (table 3, fig 9). To remember, the Leine groundwater gauge is suspected to be influenced by the river. It taps the alluvial aquifer that is responsible for the baseflow in the Leine discharge hydrograph. However a small hillside aquifer contributes to the gauge (compare chapter 2.2.4). Its relative frequency distribution should therefore resemble the relative frequency distribution of stream discharge, which is true for droughts before the gap. Droughts above the gap are therefore out of context. Their occurrence points to a possible two-storage groundwater system.

Finally, the Spree groundwater gauge has the highest percentage of very short drought. Also, it has very few long droughts, none of them with durations above 8 months. The Spree aquifer therefore seems to be the quickest responding aquifer. This is consistent with the findings of chapter 2.2.7, where it is concluded that the Spree aquifer is the smallest in extent.

3.3.1.2 The spring discharge cluster

Precipitation

Concerning the two catchments in the spring discharge cluster, the relative frequency distributions of drought durations for precipitation are also very uniform in both catchments in both relative and absolute terms (figure 10, table 4). They look rather similar to the ones in the groundwater cluster, with the only exception that the absolute number of droughts is a little lower. This is due to the fact that time series in this cluster are a little shorter (1980-2011 instead of 1976-2011 in the groundwater cluster).

Stream discharge

For discharge, just like in the groundwater cluster, the relative frequency distribution is relatively uniform as well, especially for very short droughts (figure 10). But the absolute number of droughts in the Leine catchment is about 25% lower than in the Gruendau catchment. Also, the difference in tailing is only minor. The Leine catchment is about five times the size of the Gruendau catchment. Despite this fact, one cannot say on grounds of the displayed data, that this leads to a more slowly responding behaviour, i.e. fewer and longer droughts, as it would be expected. One possible explanation might be, that the Gruendau catchment is more nested than the Leine catchment (compare figure 3 and 4), leading to a more direct runoff response in the Leine catchment. Also, the Leine catchment is a bit more topographically pronounced (table 4), so that might counteract as well and lead to a more rapid response pattern.

Spring discharge

Regarding spring discharge, the first eye-catcher is, that droughts in the springs are not that extreme. There are no droughts that are longer than 5 months. All groundwater gauges had droughts longer than this. The second noteworthy thing is, that differences between the two springs are rather significant. The Leine spring has all in all only 23 droughts in the related period, Gruendau on the other hand has 60, almost 3 times as many. And while the length of the tail is equally long, and for both springs droughts occur in about the same timespans, the Leine spring has a much more pronounced tendency towards long durations. There is a much smaller percentage of very short droughts in the Leine spring. Plus the percentage as well as absolute number of long droughts is higher for the Leine spring as well. It can be concluded that the Leine spring resembles the behaviour of groundwater gauges much more, and the Gruendau spring more the stream discharge behaviour, although droughts are a little longer than in stream discharge.

Table 4: Numbers of droughts depending on duration (in months) for every variable in the spring cluster. Colouring is done with HSV. Thereby the saturation is the percentage of total droughts in a specific timestep to help identify patterns.

Catchment	Variable	Duration [months]											Total
			1		2		3		4		5		
Gruendau	P	90	45	6	2								143
	Q	53	23	4	2	2	1	2					87
	QU	30	14	6	2	3	2			1	1	1	60
Leine	P	92	42	8									142
	Q	39	14	6	2	1	1			1			64
	QU	6	6	2	2	1		1	2		1	2	23

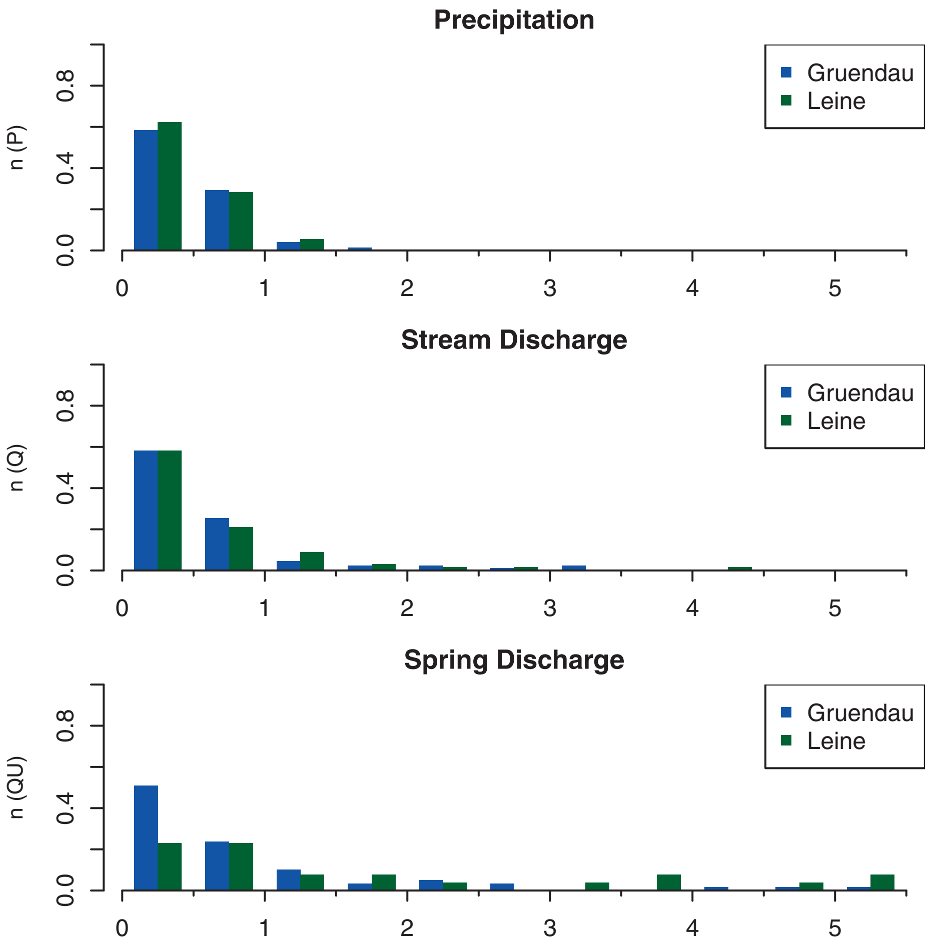

Figure 10: The relative frequency distributions of drought durations for precipitation, stream discharge and spring discharge for all catchments. On the x-axis is the duration of droughts in steps of 15 days. The y-axis shows the percentage of droughts with a specific duration.

3.3.2 Correlation between Drought Duration and Severity

While the duration of a drought is an important characteristic and its analysis leads to important conclusions, the overall notion of the intensity of a drought can be improved by including severity, i.e. the maximum deviation from the threshold during drought, in the analysis. Therefore in figure 11 and 12, the relationship between severity and duration is presented in order to answer the question what effect duration has on the severity of a drought in different hydrological levels. Before going into detail, it should be mentioned that in Leine groundwater (figure 11 i), there was an outlier with extreme severity. It can be seen in the hydrographs as well (figure 15). This outlier was excluded in order to make figure 11 i) readable. This was done under the assumption that this outlier with extreme severity is due to a temporary groundwater abstraction, measurement error or other, non-natural cause.

Precipitation

Figure 11 a) to o) depicts the correlation between normalised drought duration (x-axis) and drought severity (y-axis). For precipitation, the correlation is similar for all catchments (figure 11, left column). They are steep with a relatively uniform spread, meaning they are short and extreme. Droughts with extreme severity can occur in very short droughts and long droughts alike. There is a limit visible at the top, at the end of the y-axis, becoming apparent in all precipitation scatterplots. Characteristics – duration and maximum deviation, i.e. severity - are calculated for the moving sum of precipitation. Unlike discharge and groundwater head, this variable can drop to zero when there is a period of 30 days or more without rainfall (window of the moving sum is 30 days). When this happens, the absolute maximum deviation from the threshold is reached, thus severity is limited in precipitation. This does naturally not occur in groundwater at all. Groundwater basically cannot dry up under natural conditions because there is always some share of groundwater that is immobile or has such a low flow rate that it can be considered immobile. Also, rivers in the humid German climate are perennial. Therefore they do not dry up; an absolute limit for the maximum deviation cannot occur in stream discharge as well.

Stream Discharge

However in stream discharge a similar effect can be observed. Here it is not a sharp limit, rather a range where severities level off. Most obvious examples are the Salz River (figure 11 k) and to some extend also the Spree (figure 11 n), where some level of limit can be vaguely suspected at the top of the scatterplots. This is due to the fact that in general stream discharge in perennial streams does asymptotically converge to zero. In dry times, baseflow from groundwater is the only streamflow component since there are no glaciers in the

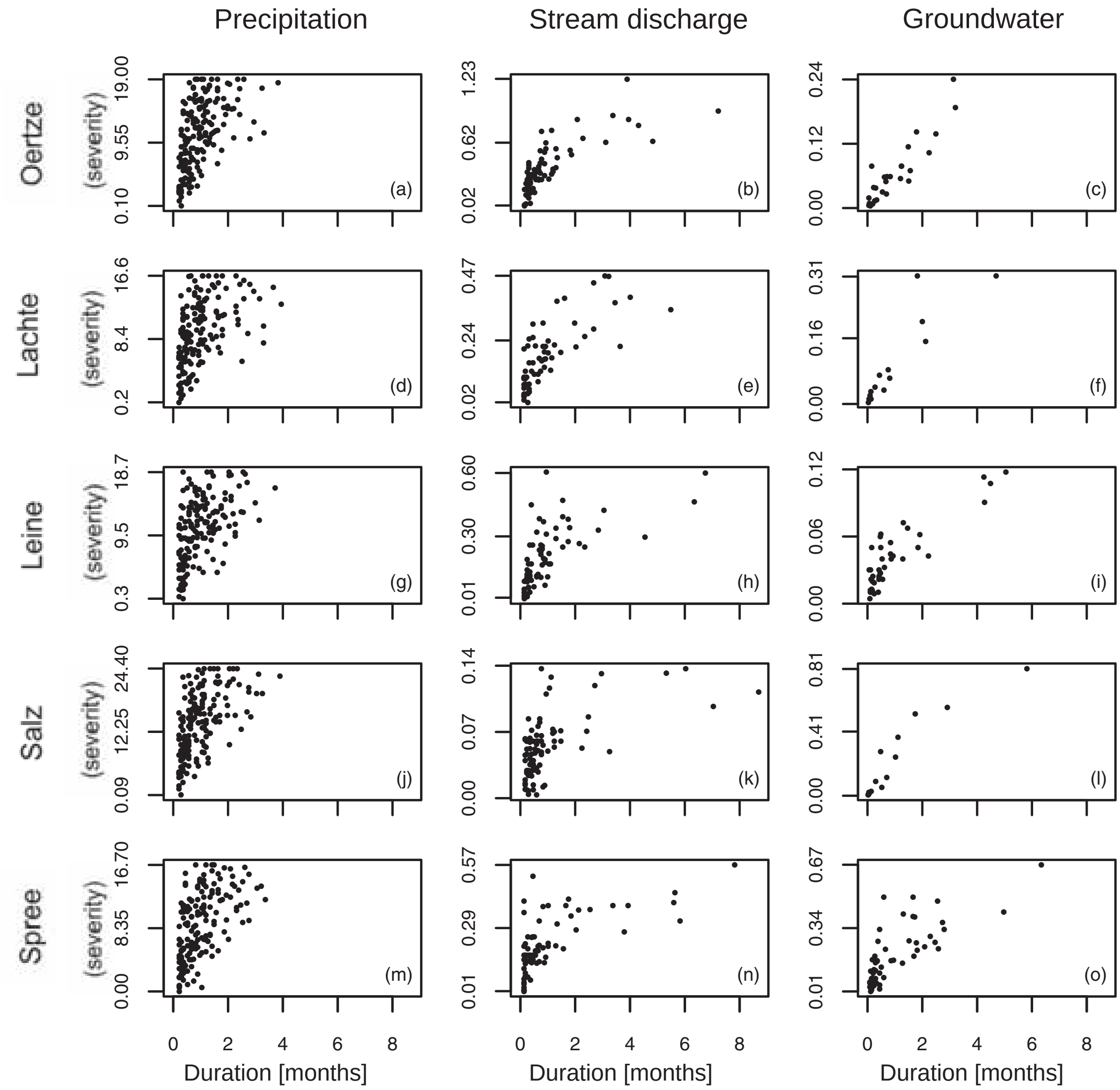

Figure 11: Scatterplots of normalised duration of droughts (x-axis) versus severity (y-axis), also known as the maximum deviation from the threshold. Scatterplots are shown for droughts in all variables and catchments of the groundwater cluster.

regarded catchments and surface water storage negligible. Therefore groundwater discharge is mainly responsible for the rivers behaviour during drought. Characteristic for groundwater is a slow release of storage. Giving an endless period of drought, increasingly less water will be released until storage will eventually diminish, thus correlations between stream discharge duration and severity converges to zero. This can be seen nicely in the scatterplots. Correlations for Lachte and especially Oertze stream discharge (figure 11 b, e) show a more narrow range than precipitation. It is crooking when durations increase. This indicates that only very long droughts tend to produce high severities, which can be attributed to a high baseflow share in stream discharge, which affects behaviour during drought. This is consistent with the catchment properties drawn up in chapter 2.2.2 and 2.2.3. Oertze and Lachte are lowland catchments with spatially very extended aquifers, indicating a high baseflow influence as well. This is different for Salz, Spree and Leine. They show a much wider range of correlations (figure 11 h, k, n) that is more similar to the precipitation spread. Stream discharge for these catchments seem to adhere two components: One crooked, flattening component representing baseflow i.e. groundwater influence and a rather vertical component that resembles more the precipitation plots, therefore representing a fast responding behaviour. For the quick component, severe droughts with high severities do not ultimately require long drought durations, very short droughts can breed high severities as well. This bipolarity is presumably owed to storage conditions prior to a specific drought. When catchment storages (and therefore baseflow) are already low in advance, discharge will drop relatively rapidly. When storages are sufficiently filled before a drought, it will take longer for high severities to occur. Another explanation may be, that interim rainfall during drought may prevent the development of very severe droughts. Following this logic, short, intense droughts without interim rainfall would actually be more hazardous concerning stream discharge, because they produce high severities much faster. In this respect, for stream discharge, maximum deviation is a suboptimal severity measure, because it is not able to give information about the dynamics of storage recharge and discharge that leads to the wide spread in high severities. After all, there is a higher spread in the upper severities than in precipitation. Also, storage, especially groundwater storage preconditions should be considered due to the role of baseflow during drought.

Groundwater

In general, the range of the scatterplot is much different for groundwater. Taking Lachte and Oertze, for example (figure c, f), the two vast, sandy lowland aquifers, the form of the correlation is narrow and seems to be almost linear. This is evidence for a close relationship between severity and duration. The longer the drought is, the more severe it gets. Instant drops into high severities are not possible in short droughts. This is not true for all aquifers in the selection. For Spree, the correlation between duration and severity in groundwater resembles more the characteristics of stream discharge (compare figure 11 n and o), showing a spread of durations for high severities. This is consistent with the assumption of chapter 2.2.7, that the aquifer of the Spree groundwater gauge is very small, if not the smallest aquifer in the selection of gauges in this thesis, being a slope debris aquifer located on a saddle between several hills. Also, as table 3 shows, figure 11 o) is yet another evidence that the Spree groundwater gauge is indeed the fastest responding aquifer. Yet bipolarity (high severities can be caused by long and short droughts equally) is given, indicating that under certain circumstances, it can act relatively slow responding as well. Reason for this bipolarity is most likely either varying storage preconditions prior to the drought or varying recharge patterns during the drought, analogous to the argumentation of regular interim rainfall events preventing extreme severities in stream discharge.

Like Spree, the Leine groundwater gauge as well shows a spread of correlations that is similar to the stream discharge spread (compare figure 11 i and o). After all, the groundwater gauge is very near to the stream and highly influenced by it (table 2). Yet the scatterplot shows a small cluster of four droughts with high duration and severity, occurring after a gap between the duration of 2 and 4. This gap equals the gap visible in figure 9. One possible explanation for the occurrence of the cluster in the Leine groundwater scatterplot might be that it is caused by the existence of a different, much slower responding storage system. Possibly from a certain threshold on, the aquifer in location of the gauge is getting disconnected from a second storage system, which usually provides constant water supply to the gauge and prevents droughts to become very severe. The hypothesis of a dual storage system is backed up when looking at the scatterplots of Lachte (figure 11 f), the other catchment that shows a gap in the durations of droughts (figure 9). Scatterplots for this catchment shows a narrow range and nearly linear correlation. Although this catchment does show gaps in the durations, this gap does not show in the relationship between duration and severity. Lachte has a very homogenous, sandy aquifer. Drainage from this aquifers should be – unaffected by the overall duration - linear, i.e. representing only one single storage system. Therefore it is logical that the correlation of severity to duration is linear as well, which is true for both lowland aquifers Lachte and Oertze. It is concluded that a discontinuation is taking place only when two or more systems are present, as it is assumed for the Leine aquifer.

Correlations for Salz groundwater are rather narrow and linear with only little crooking (figure 11 l), indicating a rather extended, slow responding storage system. This is although Salz being the topographically most extreme catchment in the selection, which normally coincides with smaller subsurface storage. However, we need to remember that the Salz gauge is located at the fringe of a plateau right above the Salz river valley, which led to the assumption of a behaviour that should be absolutely independent from the stream behaviour (chapter 2.2.6). It is very interesting, however, that, despite tapping a rather small plateau aquifer, the form of the scatterplot for Salz very much resembles the one of Lachte and Oertze, the two lowland aquifers with vast extent.

It has to be said again, that the depth or composition of the Salz gauge aquifer is unknown. The HUEK maps indicate conductivities of about 10^{-3} to 10^{-5} for the Salz aquifer, being only slightly less permeable than in the lowlands. It is possible that the actual composition of the aquifer might differ from the HUEK information. Apart from the HUEK data, the only solid fact about the Salz aquifer is, that it is significantly smaller than the Lachte and Oertze aquifers. Of course, in general it is a combination of factors such as local conductivities, aquifer depth, slope, extent and flow pattern, that determine the response behaviour of an aquifer. It may be that one of the unknown factors are especially diverging from the expected, leading to the unexpectedly slow behaviour of the Salz aquifer. But it does seem like the aquifer extent alone does not seem to play a dominant role. Aquifer size still does matter. The Spree for example, which is supposedly the smallest aquifer in the selection, behaves quick responding as expected. Yet maybe from a certain size upwards, size does not play a role anymore and other factor become dominating, as it is possible for the Salz.

Connectedness

Concerning connectedness, the catchments with highest connectedness between stream and aquifer are Leine, Lachte and Oertze. For Lachte and Oertze, it was pointed out that the streams are highly influenced by groundwater, being lowland catchments with huge storage system and major baseflow influence. For them, correlations between duration and severity in stream discharge are less spread than in other catchments, resembling more the groundwater correlation than the precipitation correlation. For Leine, it is the other way round. Here, groundwater correlations show a higher spread, resembling more the stream discharge spread. Due to the depth of the water table (about 15 meters beneath ground surface (table 2), direct rainfall response is unlikely. Therefore drainage from the river is the remaining explanation. This means that for the Leine, groundwater is highly influenced by stream discharge. After all, the groundwater gauge presumably taps the riparian aquifer in the narrow Leine valley. The Oertze groundwater gauge is located in the river valley as well, but laying in the lowland plains, the river valley is not confined from surrounding aquifers here, but rather part of one big aquifer, whereas the Leine valley aquifer is tightly confined by bedrock hillslopes with presumably very small soil or even aquifer cover providing storage. For the Spree there is also a high resemblance between groundwater and stream discharge, but it can be said with certainty on grounds of the topographic situation that the aquifer is not influenced by the stream. Here it is another explanation that is most likely; that the Spree aquifer is simply a very small aquifer that is fast responding.

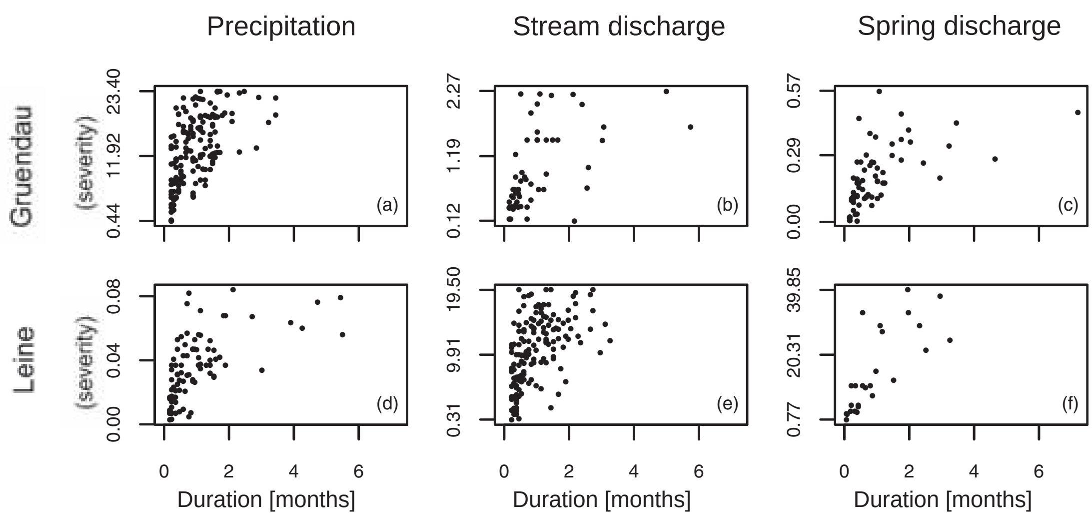

Figure 12: Scatterplots of normalised duration of droughts (x-axis) versus severity (y-axis), also known as the maximum deviation from the threshold. Scatterplots are shown for droughts in all variables and catchments of the spring discharge cluster.

The Spring discharge cluster

Coming to the spring discharge cluster (figure 12 a to f), we can see that precipitation and stream discharge are not different from what was discussed about precipitation and discharge in the previous paragraphs. This is especially true for Leine, since it is essentially the same time series for precipitation and stream discharge, only 5 years shorter. Scatterplots for spring discharge are more interesting. The correlations of duration and severity in Leine spring discharge are similar to the ones of Spree groundwater, although Leine does have only roughly half as many droughts (table 4). Coincidently, both Spree groundwater gauge and Leine spring discharge gauge drain small hillside aquifers (compare chapter 2.2.4 and 2.2.7). After all, springs are located at the relative location of an aquifer where groundwater discharge occurs. Having that in mind, one possible conclusion is, that the Spree groundwater gauge is located at relatively the same location to its aquifer as the Leine spring discharge gauge is located relative to its aquifer.

The second spring discharge gauge in the selection, the Gruendau gauge (figure 12 c), is different from the plots of all other variables and catchments. Unlike all others, it does not have a specific starting point, or zero point, from which the scatterplot spreads. Instead the lowest severities already occur over a range of durations from zero to two. This is proof for the extreme ambivalence of this spring gauge. While for other variables some assumptions can be made on grounds of the direction and spread of the scatterplot, this is not possible for the Gruendau spring. The form of the scatterplot is rather a cloud without clear direction, in other words random. Speculation about possible reasons on grounds of figure 12 c) is otiose, more insight can be provided by means of the hydrograph discussion chapter 3.4.

3.3.3 Preliminary Summary

In general, when moving from precipitation over stream discharge to groundwater, droughts get longer and fewer. For precipitation, the relative as well as absolute distribution of drought durations is basically the same in all catchments (figure 9). This, again, supports the assumption of uniform climate controls previously made. For stream discharge, the relative frequency distribution of drought durations is basically similar to the one of precipitation. Yet it is flatter and has a longer “tail” that is quite scattered, meaning there is a trend toward longer droughts without losing the overall form of the frequency distribution. Also, in stream discharge some differences from catchment to catchment are visible. Concerning groundwater, this is much different. The overall form of the frequency distribution is completely different, droughts are scattered over all durations. Differences between catchments/groundwater gauges are significant. Springs show an ambivalent behaviour and can resemble either groundwater patterns or stream discharge pattern, depending on their location.

To summarise the findings of chapter 3.3.1 regarding individual catchments, we can say that for the Spree, stream discharge behaves ambivalent. There is a high percentage of very short droughts but also some long droughts of about 5 months. Concerning groundwater, it is the fastest responding aquifer with highest absolute number of droughts and highest percentage of short droughts. Leine stream discharge on the other hand is quite fast responding, having many short droughts and very few long droughts. Yet it is somewhat slower responding than the Salz catchment, which is most extreme in absolute numbers and shortness of droughts. For groundwater, the Leine groundwater gauge shows the second most droughts in general and is therefore the second fastest responding aquifer after Spree. It shows an intermediate behaviour in general. As mentioned, Salz is the fastest responding catchment concerning stream discharge. For groundwater it is the exact opposite. Together with the Lachte aquifer, the Salz aquifer is the most extreme. It has the longest droughts on record and also the fewest. Then, Lachte and Oertze is an interesting comparison. Stream discharge of the Lachte catchment is slower responding, i.e. there are more long droughts than in the Oertze stream discharge. But the Oertze catchment is actually bigger in size. Therefore its stream discharge should in theory be slower responding. However it does not behave like that. Concerning groundwater, the Lachte gauge is also slow responding, in fact it is the slowest responding groundwater gauge in the whole selection. The Oertze groundwater gauge is in the middle field of all catchments, with an intermediate absolute numbers of droughts, and intermediate groundwater drought duration frequency distribution, meaning some short, some long, but not extremely long, relatively steady distribution among durations (no gap). The behaviour of spring discharges are, as expected, ambivalent. While the Leine spring resembles more the behaviour of groundwater gauges, and the Gruendau spring more the stream discharge behaviour, although droughts are a little longer than in stream discharge.

Concerning the correlation between drought duration and severity, in precipitation the main characteristic for droughts is that they are short and severe. Although long droughts with high severities occur, short droughts can produce high severities as well. In fact, there are more short droughts with high severities than there are long ones that do so. However severity is limited in precipitation. This limit shows, when rainfall ceases for over 30 days (which is the width of the window of the moving sum that was applied on precipitation time series). Such a limit is only partly visible in stream discharge and spring discharge because they convergence to zero due to baseflow influence during drought. In slow responding catchments with high baseflow influence (e.g. Lachte & Oertze), correlations between duration and severity are higher. I.e. high severities tend to require long durations. Topographically more pronounced, faster responding catchments (e.g. Spree, Leine, Salz) are more bipolar. Here, both short and long droughts can induce high severities. This ambivalent behaviour can be attributed to catchment storage preconditions prior to the drought or interim precipitation input during drought, affecting drought characteristics of fast responding catchments, but not slow responding catchments like Lachte and Oertze. The same bipolarity can be seen in the Spree groundwater gauge (having a very small aquifer) and to some extent in the Leine groundwater gauge. For the Leine aquifer, a two-storage system is assumed, one with a similar behaviour as stream discharge, one with a more linear behaviour as it would be expected for an aquifer. Best example of a linear aquifer behaviour can be seen in the two vast lowland aquifers Lachte and Oertze, where correlations between duration and severity show narrow ranges and clear directions. Surprisingly this is the same for the Salz groundwater gauge, although its aquifer is a rather small plateau aquifer. Consequently it is assumed that the aquifer extent is not the dominant factor to determine if an aquifer is slow or fast responding.

Concerning connectedness, the Lachte and Oertze stream discharges are highly influenced by groundwater. In contrast, the Leine groundwater gauge is highly influenced by the river. Due to their location, Salz and Spree groundwater a priori cannot be influenced by stream. However Spree does show high similarity to general stream discharge behaviour, leading to the conclusion that the behaviour of groundwater is controlled by a whole range of factors, and that two aquifers with completely different settings can behave similar. Consistent conclusions on how influential certain factors are cannot be made since they are highly dependant on local conditions. Good examples are the springs. Correlations of the Gruendau spring, located within the river valley, show – as expected – a high similarity to stream discharge correlations, whereas the Leine spring, draining a hillside aquifer, acts more like a classical groundwater gauge

3.4 Visual Assessment of Hydrographs

In the following subchapters, a qualitative description of the behaviour of hydrological variables is provided for every catchment separately. Thereby drought characteristics are not discussed in detail again since this has been done in chapter 3.3 already. To harmonize hydrograph interpretation in all catchments, their behaviour is characterised by means of three European benchmark drought events. These are the droughts in 1976, in the early 1990s and in 2003 (figure 13 to 19). Detailed information about these events is provided in Sheffield and Wood (2011), for example. Focus was set on the differences in the behaviour of streamflow, groundwater and spring discharge. Precipitation is not covered in detail, because visual interpretation is only vaguely possible. Precipitation was modified with a moving sum of 30 days, which on the one hand sometimes leads to a nicely visible concision of precipitation peaks and peaks in stream discharge or groundwater. On the other hand, however, droughts seem to be distributed quite randomly, making interpretation difficult. For example, “droughts” in precipitation as determined by the threshold level method occur basically in every year, even in times when there is an extreme rainfall surplus. Although precipitation droughts show an effect on streamflow and groundwater hydrographs, it rather seems to be the long-term sub-average precipitation supply that leads to severe impacts on streamflow or groundwater, ultimately resulting in hydrological drought. However periods with long-term sub-average precipitation supply do not necessarily inherit high numbers, high durations or high severities of droughts as calculated by the threshold level method from the moving sum of precipitation. This is because these precipitation droughts are only a measure of short-term fluctuations with a small memory of only 30 days, which is the length of the moving window. Because of these disadvantages, main focus in this chapter is on the interpretation of streamflow, groundwater and spring discharge hydrographs.

3.4.1 Oertze

Stream discharge and groundwater hydrographs in general show a high seasonality with a high baseflow rate, whereat seasonality for groundwater is much more distinct (figure 13). Thereby quantiles in groundwater are relatively far apart. Major rainfall events can temporarily modify the overall seasonal curve, as best seen in summer 2002 for stream discharge and autumn 1978 or autumn 2002 for groundwater. But altogether this does not sustainably alter the seasonal pattern. Consequently, droughts in both stream discharge and

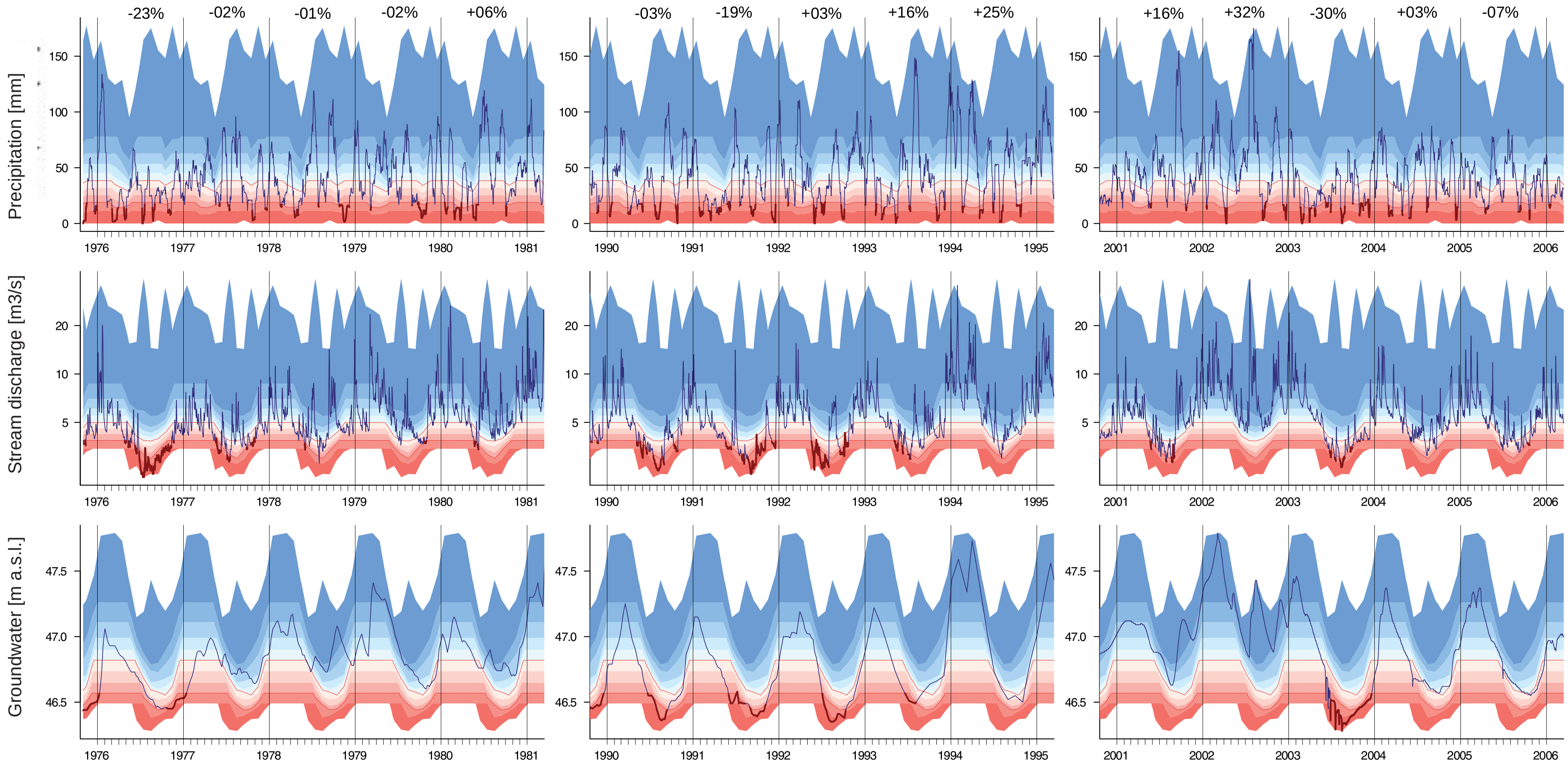

Figure 13: Hydrographs of precipitation, stream discharge and groundwater (rows) in the **Oertze** catchment for the three benchmark drought events 1976, early 1990s and 2003 (columns). The blue line is the respective hydrograph. It turns red when defined to be in drought according to the threshold level method. The ranges from red over white to blue depict all percentiles of the respective variable. Note that the top and lowest ranges are the absolute extremes that occurred in the respective variable, and not a percentile. The two thin red lines depict the combined 20% -threshold (lower) and the median (upper). On the very top the precipitation anomalies are given as a percentage of the average annual amount of precipitation. Stream discharge is logarithmic on the y-axis.

groundwater occur almost exclusively during the “dry season”, i.e. in the period of the year when the variable threshold falls below the constant threshold. In stream discharge, drought conditions occur when baseflow drops low. Short discharge peaks can discontinue droughts, but as soon as the hydrograph returns to baseflow levels, drought conditions continue as long as baseflow stays low. In groundwater, most of the time the highest severities are detected around the time of the minimum of the seasonal amplitude. Due to high amplitudes, multi-year droughts do not occur; In general groundwater levels rise very high above the threshold in the wet season, which is winter and spring. Still major dry periods can cause sustainably critical conditions, as can be seen in the period of 1990-1995. Obviously the overall groundwater and stream discharge levels are below average due to dry preconditions and further aggravated by the exceptionally dry year of 1991, causing the occurrence of droughts in the dry periods of several consecutive years. Only an excessive rainfall surplus in the years of 1993 and 1994 leads to sustainable recovery.

The overall form of the groundwater hydrograph is very smooth. Sharp peaks can be seen, but do exclusively occur when the hydrograph is moving in the higher quantiles. They are not a sign of short-term fluctuation, but rather a response to major rainfall events. Although direct reaction of groundwater is in general slow to non-existent, these major rainfall events can propagate to groundwater with little delay, given that the hydrograph is in a high quantile during said event. Stream discharge is obviously much quicker responding. Almost every rainfall event is detectable in the stream discharge hydrograph. The height of the peak, in other words the intensity of response, is varying. It can be observed, however, that during the dry period, when baseflow drops low annually, response to rainfall events is in general much smaller. A good example can be seen in summer 1976, when stream discharge develops a major drought. During this drought, only one rainfall event is able to trigger a small peak, which is however too small to break drought conditions. Still sometimes major peaks during the dry season, or even during drought, can be observes, as for example in summer 1991 and 1992.

3.4.2 Lachte

Just like the Oertze, the Lachte stream discharge hydrograph shows a distinct seasonality with a high rate of baseflow (figure 14). The overall height of the seasonal curve can be in different states. In 1977 to 1980, for example, the stream discharge hydrograph is overall high, being above the median most of the time. In contrast, the hydrograph from mid-2003 onwards is in a generally low state. Seasonality, however, is maintained at all times. Groundwater as well shows a seasonal pattern, but here it is not as dominant as in the

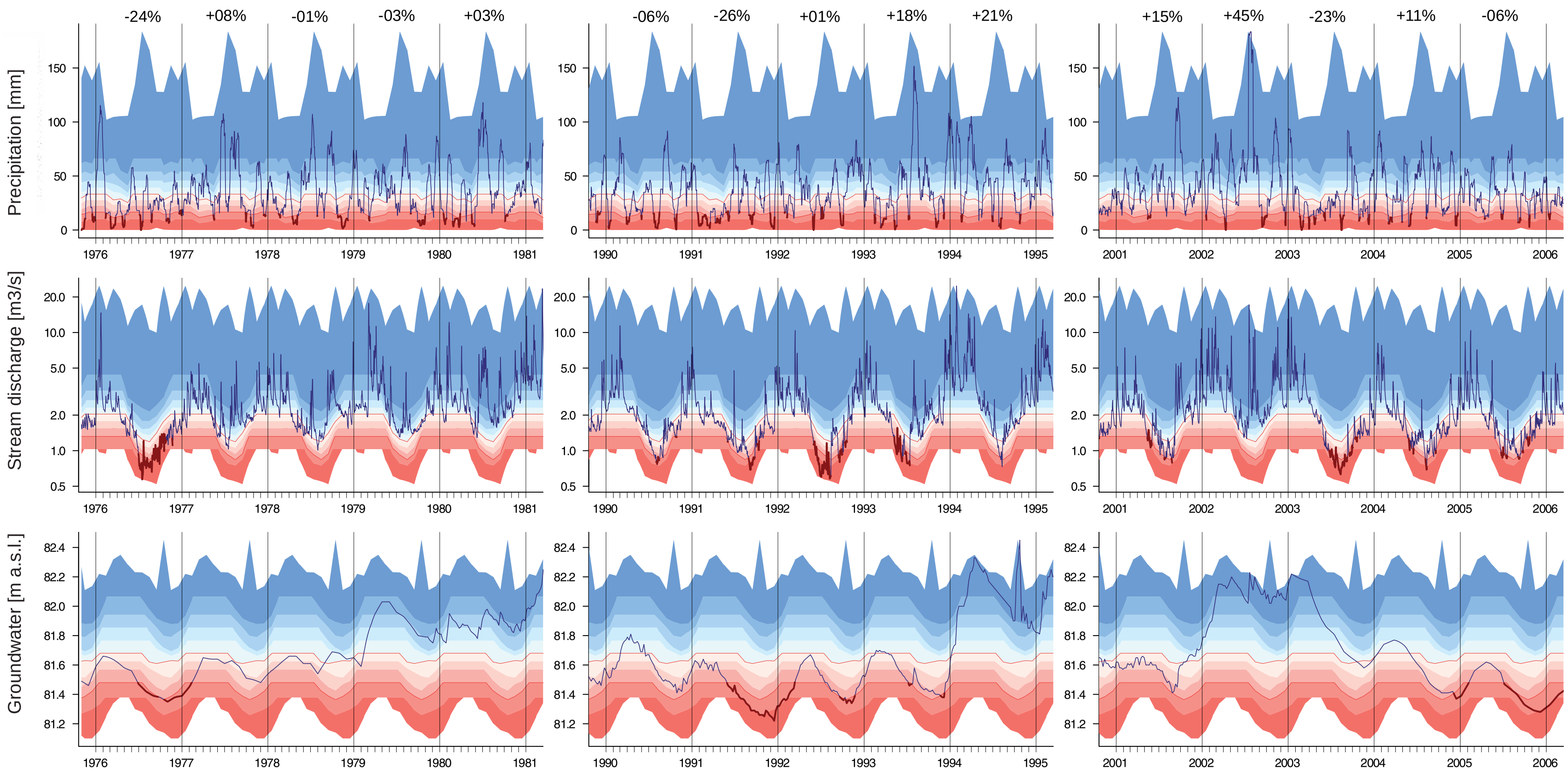

Figure 14: Hydrographs of precipitation, stream discharge and groundwater (rows) in the **Lachte** catchment for the three benchmark drought events 1976, early 1990s and 2003 (columns). The blue line is the respective hydrograph. It turns red when defined to be in drought according to the threshold level method. The ranges from red over white to blue depict all percentiles of the respective variable. Note that the top and lowest ranges are the absolute extremes that occurred in the respective variable, and not a percentile. The two thin red lines depict the combined 20% - threshold (lower) and the median (upper). On the very top the precipitation anomalies are given as a percentage of the average annual amount of precipitation. Stream discharge is logarithmic on the y-axis.

Oertze groundwater gauge. The relative height of the seasonal curve can differ significantly. From 1976 onwards, groundwater levels constantly rise and reaches very high levels in 1979, on which it remains for almost 7 years (not displayed). While seasonality is maintained when the hydrograph moves in the lower quantiles, it is partly lost in the highest quantiles.

As in the Oertze, droughts in the Lachte groundwater gauge tend to occur exclusively during the dry season, with highest severities around the time of the lowest point of the seasonal amplitude. Because a relatively strong seasonal pattern is present in the lower quantiles, multi-year droughts normally do not occur. However there is one exception from 1996 onwards (not displayed). Coming from a two-year high in the 80- to 90%-quantile, the groundwater hydrograph suddenly drops into the 10%-quantile within a year. It then stays in drought for two years. This happens under less severe meteorological conditions than any of the displayed benchmark events. Reasons are unknown.

For stream discharge, droughts as well occur exclusively within the dry periods, because baseflow rises well above the median during the wet period. Critical states do still occur, as can be seen for example in 1991 to 1993, where relatively long and severe droughts occur in three consecutive years. Interestingly, the longest and most severe drought out of these three occurs in the year after the exceptionally dry year of 1991, at a time when rainfall is average in sum. This can be attributed to a delayed baseflow response. This delay is not visible in the groundwater gauge in 1992, probably because the flow system in location of the groundwater gauge is a different one.

Recovery in streamflow is generally relatively fast, although it sometimes cannot be explained by rainfall surplus alone. After the 1976 streamflow drought, for example, recovery is fast and sustainable, although the overall amount of rainfall in the consecutive years is merely average. A sustainable upwards trend can be seen in groundwater during the same period. Therefore influence of temperature on both stream discharge and groundwater recharge is likely.

Floods, i.e. peaks in stream discharge have a tendency to occur predominantly in the wet season, which is winter and spring. During dry season, streamflow response on rainfall events is minor, as was pointed out for the Oertze as well. However occasionally flashfloods occur in the dry season as well, as can be seen in late summer 2002. But in general direct streamflow response is negligible during drought, real recovery is taking place only when the seasonal amplitude goes up. For groundwater, response times are generally slow, the groundwater hydrograph is overall smooth. Delay can be strong, as can be seen from 2003 onwards, when groundwater goes into a severe and prolonged drought only two years after the meteorological drought of 2003. But then again, in times of excessive rainfall surplus, sharp rises can occur as well, for example at the turn of the years 2001/2002. Therefore behaviour of groundwater is quite ambivalent.

But the most striking thing happens when following the groundwater hydrograph from 1980 onwards. After water levels remained exceptionally high for about a year, at the start of 1980 a fast, fluctuative noise pattern starts to overlay on the otherwise smooth hydrograph. This fluctuation is visible all the way to 1991, when groundwater goes into a major drought. The noise signal starts to diminish, however it does not vanish completely. With the sharp rise in 1994, it starts to show more dominantly again, causing one sharp peak in October 1994 that is very unique for this time series, resembling more a small, fast responding aquifer and not the vast lowland aquifer of Lachte. The noise is present until 2003, when it abruptly stops and the very smooth pattern from prior to 1980 continues. The 2003 drought is known for breaking temperature records in addition to the rainfall deficit. It is possible, that in wet periods, some fast responding percolation channels were activated and stayed active during several droughts until extreme temperatures disconnected these channels again in 2003. After the meteorological drought of 2003, it takes two years until a major drought occurs in groundwater. This drought lasts for 10 months, “recovers” shorty or about one month due to the season rise, and then drops into drought for another 9 months. When disregarding the minor recovery, this drought is a 20-month multi-year drought. The hypothesis here is that this major drought could only occur due to the percolation channel disconnection in 2003, which triggered a sustainable decline in water levels. This might be proof that the 2003 drought was system changing for the Lachte aquifer, although no drought could be detected with the threshold level method in the year 2003 itself, which would be a strong argument against this method since it does not catch such dynamics in any way.

3.4.3 Leine

The Leine is the catchment with both spring discharge and groundwater gauge. Both will be discussed together, without separation into groundwater cluster and spring discharge cluster as in chapter 3.3. Anyway, the seasonal amplitude of stream discharge is present, yet not as strong as in Lachte or Oertze streamflow (figure 15). Severe drops during the wet season are possible, as can be seen for example in spring 1976, 1980 or 1991. Still the seasonal amplitude is strong enough to prevent droughts during wet season. Droughts predominantly occur during the dry season, when baseflow levels are low anyway. However, direct rainfall responses during drought, i.e. flashy peaks, are more common during drought. In groundwater, response behaviour is dependent on the state the aquifer is in. When groundwater levels are very low, direct response to rainfall events is negligible. Water levels during drought stay rather constant. They level off horizontally and do not show any major decline or increase (with one exception on the turn of 1979/1980, but this one is considered an outlier and is neglected) and it takes major rainfall events to lift

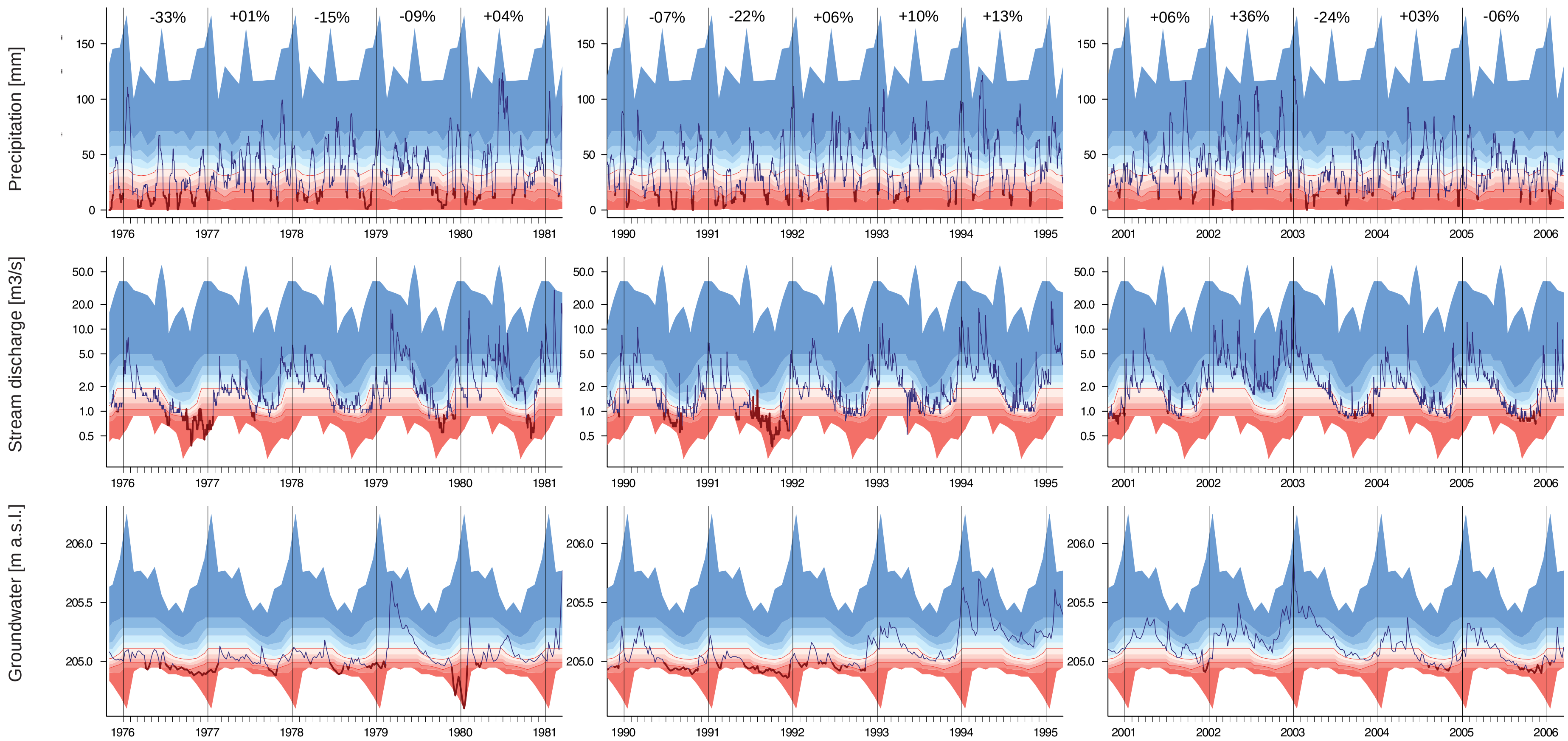

Figure 15: Hydrographs of precipitation, stream discharge and groundwater (rows) in the **Leine** catchment for the three benchmark drought events 1976, early 1990s and 2003 (columns). The blue line is the respective hydrograph. It turns red when defined to be in drought according to the threshold level method. The ranges from red over white to blue depict all percentiles of the respective variable. Note that the top and lowest ranges are the absolute extremes that occurred in the respective variable, and not a percentile. The two thin red lines depict the combined 20% - threshold (lower) and the median (upper). On the very top the precipitation anomalies are given as a percentage of the average annual amount of precipitation. Stream discharge is logarithmic on the y-axis.

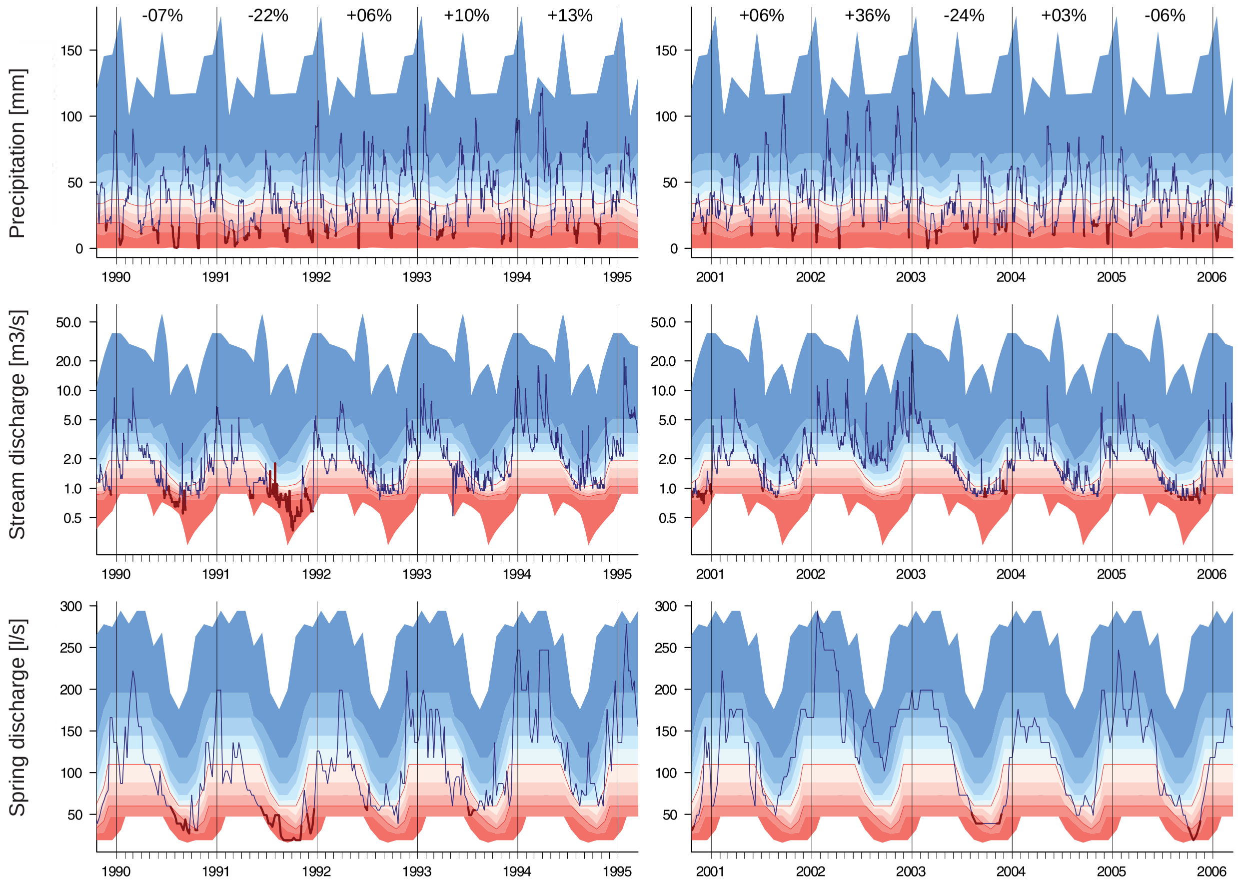

Figure 16: Hydrographs of precipitation, stream discharge and spring discharge (rows) in the **Leine** catchment for the two benchmark events in the early 1990s and in 2003 (columns). The blue line is the respective hydrograph. It turns red when defined to be in drought according to the threshold level method. The ranges from red over white to blue depict all percentiles of the respective variable. Note that the top and lowest ranges are the absolute extremes that occurred in the respective variable, and not a percentile. The two thin red lines depict the combined 20% - threshold (lower) and the median (upper). On the very top the precipitation anomalies are given as a percentage of the average annual amount of precipitation. Stream discharge is logarithmic on the y-axis.

groundwater levels out of this non-respondent drought condition (e.g. 1976 or 1990 / 1991, figure 15). In the intermediate state, roughly characterisable as being between the 20% and 50% quantile, some tentative smaller peaks start to show, i.e. response becomes quicker (see period 1976-1978). However it is only when the groundwater hydrograph moves well above the median that more extreme, flashy peaks occur on a regular basis. For example, after 1993 the groundwater hydrograph begins to rise into the highest quantiles due to particularly wet meteorological conditions. Once water levels are in the range of the top quantiles, more extreme peaks occur that highly resemble a somewhat smoothed stream discharge curve (see for example 1994 or 2002 / 2003). Obviously the groundwater gauges behaviour in drought is very different from the behaviour when groundwater storage is well replenished. Considering the hydrogeographical setting (chapter 2.2.4), it is therefore assumed that a two-storage system is present in the Leine aquifer, characterised by the disconnection from a second, faster responding storage during drought.

The hydrograph of the spring discharge gauge in the Leine catchment (figure 16) generally shows equal signal responses as the stream discharge hydrograph. Both curves are relatively similar, however with spring discharge being more smoothed. Also, the measurement resolution is much worse in spring discharge, leading to a very jagged hydrograph in parts. Data for this gauge was provided on weekly- to two-weekly basis, however this data obviously was partly interpolated already and actual measurement frequency was presumably lower. Also, drops and rises during droughts do not attenuate as in other variables, response patterns stay equally fast. This is also visible in the duration curve of Leine spring discharge (figure 7). However, the previous made assumption made on the duration curve was that this spring is possibly confined. Looking at the ostentatious hydrograph, this assumption has to be refused.

3.4.4 Gruendau

The Gruendau is the catchment with a spring discharge gauge only and no groundwater gauge. Here, the stream discharge hydrograph shows an even weaker seasonal baseflow signal than in the Leine catchment (figure 17). Droughts sometimes extend well into the wet season or start in the wet season prior to the dry season. Streamflow in the Gruendau catchment is altogether much flashier concerning floods. Peaks during drought can pretty significantly discontinue droughts, yet normally it is still the seasonal baseflow recovery that is the dominant criteria in terms of sustainable drought recovery.

In general the spring discharge hydrograph in the Gruendau catchment shows kind of a similar behaviour as the Leine groundwater gauge. It is very slow responding or almost non-responding as well as flat during drought. In contrast, in the higher quantiles it becomes

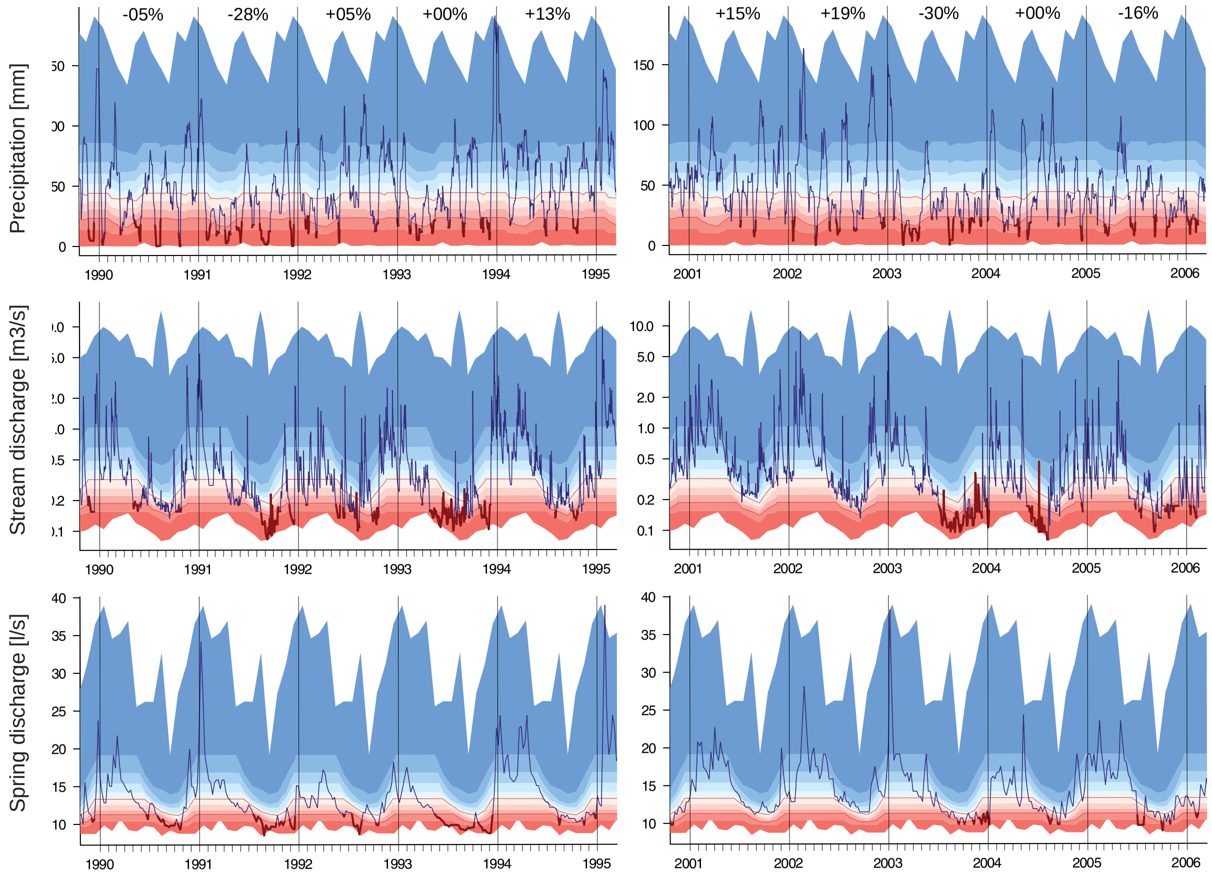

Figure 17: Hydrographs of precipitation, stream discharge and spring discharge (rows) in the **Gruendau** catchment for the two benchmark events in the early 1990s and in 2003 (columns). The blue line is the respective hydrograph. It turns red when defined to be in drought according to the threshold level method. The ranges from red over white to blue depict all percentiles of the respective variable. Note that the top and lowest ranges are the absolute extremes that occurred in the respective variable, and not a percentile. The two thin red lines depict the combined 20% - threshold (lower) and the median (upper). On the very top the precipitation anomalies are given as a percentage of the average annual amount of precipitation. Stream discharge is logarithmic on the y-axis.

very flashy to a similar extent as streamflow, although with a higher degree of smoothing. And just like in the Leine groundwater gauge, it takes a high precipitation surplus to lift the overall spring discharge hydrograph out of critical condition. This can be seen for example in 1990 to 1994, where droughts during summer recur annually until a positive precipitation anomaly in 1994 manages to trigger a more sustainable recovery of both stream and spring discharge in 1994. Yet unlike in Leine groundwater, the streamflow-like, flashy behaviour recurs annually during the wet season whereas in the Leine there are only seldomly years where groundwater switches its behaviour in a similar way. The annually recurring flashiness during winter and non-responsiveness during summer may be attributed to the fact that in general soils are well saturated during winter, when temperature is low, and tend to be rather dry in summer, when temperature and therefore evapotranspiration is high. This might lead to the conclusion that during summer, when soils dry up, connection to recharge channels is lost temporarily and therefore rainfall does not percolate or propagate from the river as easily, thus restricting response of the springs aquifer whereas peaks in stream discharge occur relatively frequently during summer.

Concerning the flat, almost horizontal regression curve of spring discharge during drought, the hydrogeographical settings described in chapter 2.2.5 are recalled. The spring is only about 100 meter from the stream and only about 1 meter above (assuming correct values from the DEM). It is likely that the spring gets afflux from the river when falling low. Therefore high severities cannot develop during drought, as it is observed. To recall, the gradient is very small and is calculated perpendicular to the stream. The slope of valley bottom is high enough that influx from the river aquifer above the spring occurs. The spring should therefore be considered as part of the river aquifer system.

3.4.5 Salz

The first thing to be mentioned for the Salz catchment is the extremely low scale of stream discharge (figure 18). There is not much absolute difference between the lower quantiles. This becomes apparent when comparing the constant median, which is about 0.6 m^2/s, and the constant threshold, which is at about 0.25 m^2/s. Simultaneously, the stream discharge hydrograph is very flashy. This is consistent with the topographical setting described in chapter 2.2.6. The Salz is the steepest and least nested catchment in the selection, resulting in said flashy runoff response patterns and very little baseflow. This might be the reason why Salz streamflow does not inherit many major droughts. Because the threshold is extremely low, minimal discharge variation results in frequent drought discontinuation.

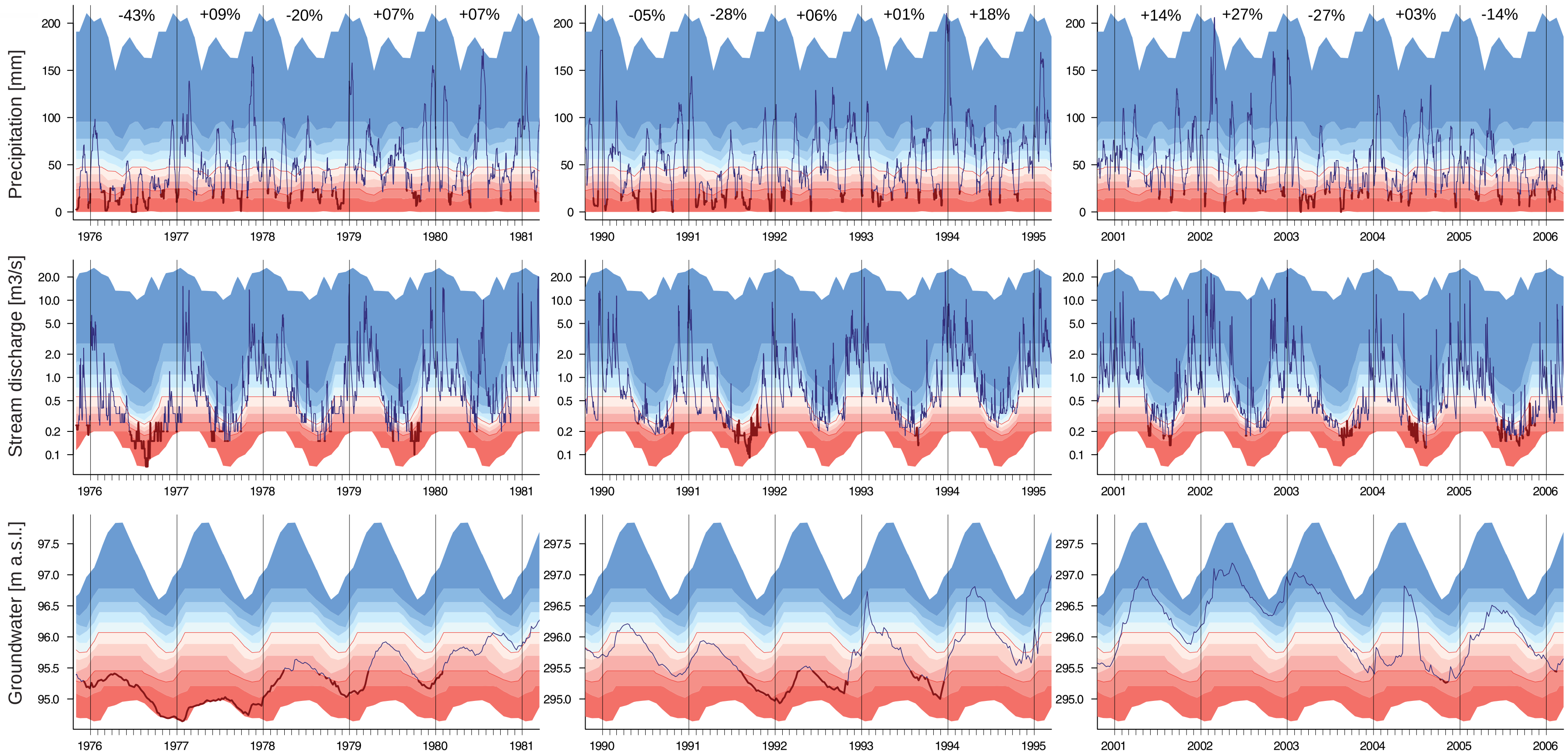

Figure 18: Hydrographs of precipitation, stream discharge and groundwater (rows) in the **Salz** catchment for the three benchmark drought events 1976, early 1990s and 2003 (columns). The blue line is the respective hydrograph. It turns red when defined to be in drought according to the threshold level method. The ranges from red over white to blue depict all percentiles of the respective variable. Note that the top and lowest ranges are the absolute extremes that occurred in the respective variable, and not a percentile. The two thin red lines depict the combined 20% - threshold (lower) and the median (upper). On the very top the precipitation anomalies are given as a percentage of the average annual amount of precipitation. Stream discharge is logarithmic on the y-axis.

In contrast to that, the groundwater hydrograph has a very smooth shape and is very slow responding (figure 18). Due to this slow respondse, multi-year droughts occur. One of those can be seen from December 1975 onwards. This drought takes 28 month, or 2.3 years, until groundwater levels exceed the threshold again. However this exceedance is only a temporary recovery triggered by the seasonal amplitude. Groundwater levels go into drought in the dry seasons of the following two years again. Sustainable recovery only takes place from 1980 onwards. The aquifer takes therefore more than four years to fully recover from the 1976 drought, implying a very long memory of the system. Also, the peak of the “dry season” in this groundwater gauge is surprisingly in late early winter, which is later than in in all the other aquifers of the selection. This – compared to other aquifers of the selection – higher delay of seasons in groundwater is another evidence for a long memory effect in the Salz aquifer. Also, as mentioned before, there are hardly any flashy peaks visible in the groundwater hydrograph, although they do occur sometimes when water levels are very high, but this happens very seldom. It is supposed that these peaks occur when some minor, quick percolating flowpaths, that are evident from the small fluctuation signal on top of the otherwise very smooth hydrograph, are getting temporarily excessively more permeable in particularly wet times.

3.4.6 Spree

The last catchment of the selection is the Spree. Here, although stream discharge is similar fast responding as other catchments, it does seem to be a system that can be disturbed sustainably. The years 1990 and 1991 for example are two consecutive years with severe negative precipitation anomalies of -23% and -27% of total precipitation compared to the average (figure 19). This situation leads to a nearly complete disappearance of the positive seasonal amplitude and droughts appear throughout the wet season. Then, although temporary recovery takes place in winter 1991/1992, streamflow drops back into drought during the following summer as well as in the year after that. In contrast, after the 1976 drought, which turns out to be only minor for the Spree, positive precipitation anomalies lift the streamflow hydrograph well above the median. It stays on high levels above the median for several years and the seasonality largely disappears. Therefore it is concluded that the Spree stream shows a particularly high memory while at the same time the seasonal signal is very weak. This is an interesting combination, because usually the seasonal pattern showed to be an indication of high memory.

In the Spree groundwater gauge as well, a seasonal pattern is visible yet it is not very distinct (figure 19) and seems to be easily discontinued. High peaks (e.g. 1977 and 1978) or droughts (1990 and 1991) are able to interrupt the seasonal pattern. Drought can even occur

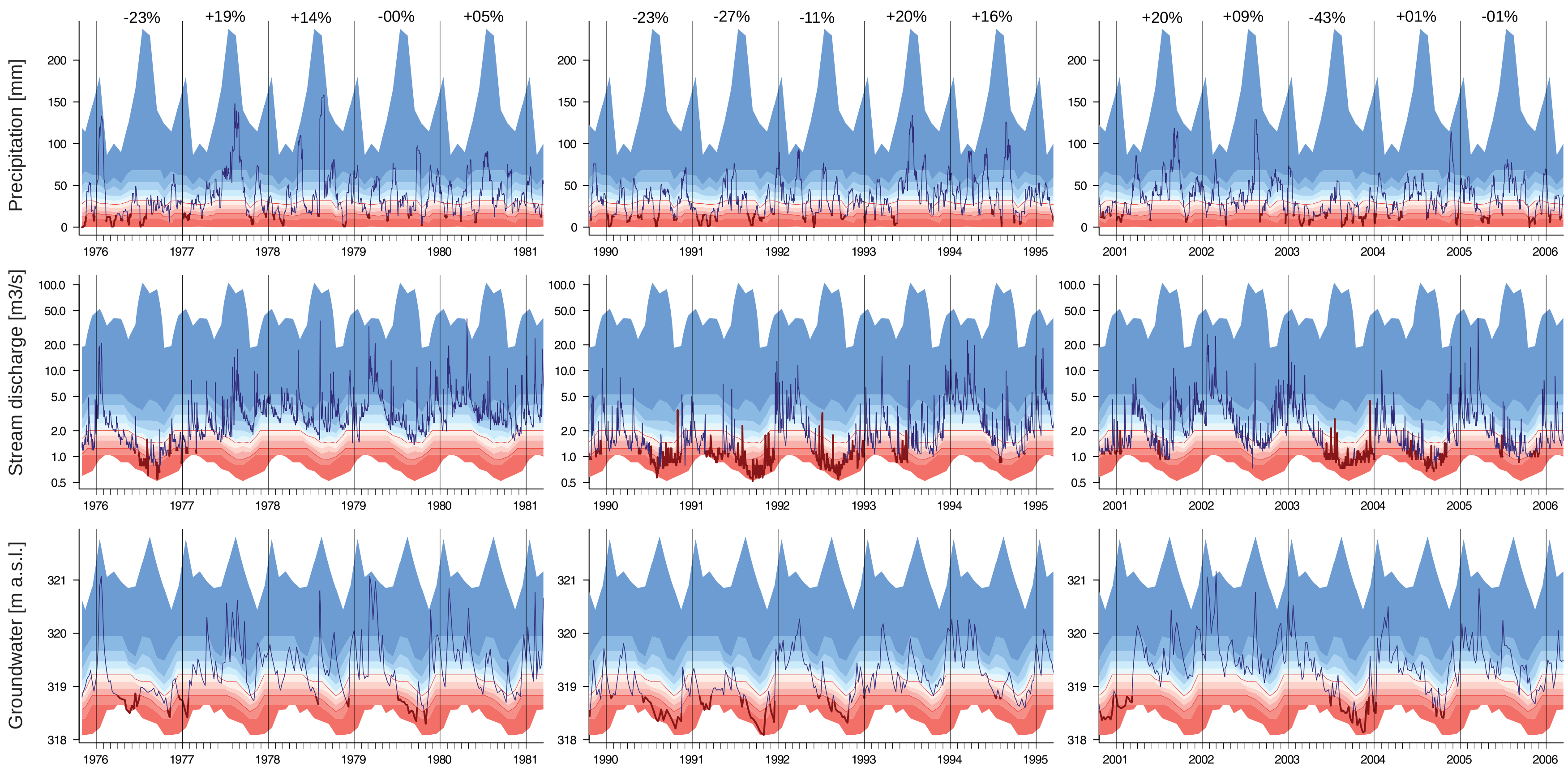

Figure 19: Hydrographs of precipitation, stream discharge and groundwater (rows) in the **Spree** catchment for the three benchmark drought events 1976, early 1990s and 2003 (columns). The blue line is the respective hydrograph. It turns red when defined to be in drought according to the threshold level method. The ranges from red over white to blue depict all percentiles of the respective variable. Note that the top and lowest ranges are the absolute extremes that occurred in the respective variable, and not a percentile. The two thin red lines depict the combined 20% - threshold (lower) and the median (upper). On the very top the precipitation anomalies are given as a percentage of the average annual amount of precipitation. Stream discharge is logarithmic on the y-axis.

in the wet season. Also, compared to other groundwater gauges, the Spree gauge is extremely direct responding to precipitation events (i.e. flashy) and shows the highest variability of groundwater levels for all aquifers in the selection. However it does show a reduced responsiveness during drought. Thereby it does not level off on a certain height. Instead groundwater levels tend to keep dropping further during drought. This might be attributed to the presumably high slope of the aquifer. Together, the lessened responsiveness and the proceeding drop during drought can lead to especially high severities and surprisingly long durations, considering the otherwise extreme flashiness of the aquifer. Yet, as expected, frequent drought discontinuation by steep rises in the groundwater levels is somewhat more common. Distinct states of depression where only major rainfall events of specifically wet periods can alleviate drought conditions, as it was observed in other aquifers, do not develop. Overall the Spree aquifer is a classic fast-responding aquifer.

3.4.7 Preliminary Summary

Lachte and Oertze, the two lowland catchments, have several characteristics in common. Stream discharge in both the Lachte and much more in the Oertze catchment is very baseflow pronounced. In the dry season, stream discharge hydrographs often consist of baseflow only, especially during drought. Response to rainfall events is negligible during drought, although it does occur occasionally. These flashy peaks may discontinue the droughts intermediately, thus altering drought characteristics (see chapter 3.3), however they are no sign of real recovery. It can be seen that, when - like in these two catchments - baseflow contribution is high, real drought recovery is only possible when the baseflow rises again. This happens annually in the course of seasonal recovery of baseflow. Because baseflow is – at least in these catchments – supplied by subsurface storages like groundwater only, the consequence is a high drought memory. Droughts tend to occur in consecutive years until baseflow and therefore subsurface storages are recovering more sustainably and exceed the threshold during the dry season again.

The behaviour of groundwater in the Lachte and Oertze differ in certain ways. In the Oertze aquifer, droughts almost exclusively occur in the dry season although it is overall slowly responding. Yet a very high seasonal amplitude leads to annual recovery and prevents multiyear droughts. Also, sharp peaks occur but generally do not alter the seasonal amplitude in a major way. Seasonality in the Lachte aquifer is not as pronounced. The overall water level relative to the seasonal amplitude can vary significantly, implying a longer storage memory that can result in multi-year droughts. A striking observation in the Lachte aquifer is the fluctuation pattern on top of the otherwise smooth groundwater hydrograph that starts to occur during high water levels in 1980 and cease during the high-temperature drought of 2003. A multi-year groundwater drought occurs with a delay of two years. This might be evidence for an occurring connection of percolation channels during a relative wet time in 1980 and a consecutive discontinuation some 20 years later in 2003, which leads to a sustainable change in system dynamics followed by a severe decline of water levels due to lower recharge rates.

In the Leine catchment, streamflow is less baseflow driven. Its hydrograph is therefore more susceptible to steep drops during the wet season, making it potentially more susceptible to drought. Yet droughts do still occur exclusively in the dry season. In groundwater, there is evidence for a two-storage system. The groundwater hydrograph is flashy and fast responding during high water levels, when an assumed second, fast responding storage is connected to the gauge. In contrast it is slow to non-respondent in drought condition. In order to lift groundwater levels out of drought, or even switch response states, major rainfall surplus is needed, implying inertness. The threshold level height, the 20%quantile, proved to be appropriate here, marking the boundary between the two different response states pretty well. Furthermore, water levels do not drop or rise significantly during drought, they rather stay on a more or less horizontal level. This is consistent with the findings of chapter 2.2.4, where a reversal of the gradient of water levels to stream level could be shown, suggesting that influx from the stream during drought prevents a drop in groundwater levels once it is on height with the streamflow level. In contrast, the spring discharge curve is very close to the stream discharge curve at all times. It responds equally fast in all quantiles, however being more smoothed than the stream discharge hydrograph.

In the Gruendau catchent, stream discharge is much flashier with a weaker baseflow signal. Droughts are not confined to the dry period exclusively and at times extend well into the wet period or start in the wet period prior to dry period. The Gruendau spring gauge shows a similar behaviour during drought as the Leine groundwater gauge, stagnating on a level only little below the threshold and not showing major response any more until a major rainfall event lifts groundwater on a higher level again. Water levels in the Gruendau spring are non-responsive during summer in general. Yet in contrast to Leine groundwater, the Gruendau spring annually switches to a fast responding behaviour during winter, the wet season. This is because the Gruendau spring reflects supposedly one storage system as opposed to the multi-storage system of the Leine aquifer. On grounds of mere visual hydrograph interpretation it is not distinguishable whether stream discharge affects spring discharge or vice versa. Recalling hydrogeological settings, however, it is likely that the Gruendau spring can be ascribed to the riparian aquifer system.

The Salz catchment is the steepest and least nested catchment. Therefore the stream discharge hydrograph is particularly flashy with little baseflow fraction, which can be seen from the particularly low scale. Consequently the threshold is on a very low level as well, at about 0.25 m3/s. This leads to a situation where small discharge variability can easily discontinue, which is why major droughts do not occur in this catchments streamflow hydrograph. The groundwater gauge acts quite contrary. It is very slow responding and behaves similar to the Lachte aquifer. Possibly the storage memory is even higher in the Salz aquifer. This is rather surprising because it is a rather small plateau aquifer. As a reminder, due to its topographic exposedness it is completely unaffected by the stream and may even be considered nearly confined from any significant stream networks since on plateau (chapter 2.2.6). On the other hand the Lachte gauge is part of a vast lowland aquifer that is drained by a nested channel network. The conclusion here would be that the degree of drainage via a channel network is a stronger control than aquifer extent.

In the last catchment, the Spree, streamflow hydrographs are overall flashy, yet a high memory effect can be observed, when for example discharge levels get severely depressed during drought to such an extent that even the seasonal pattern is largely discontinued. This can happen the other way round as well, when discharge rises to high levels during particularly wet periods and stays there for several years with, again, seasonal pattern being largely not distinctly visible anymore. The groundwater hydrograph shows a weak seasonal signal as well. It furthermore proves to be the flashiest aquifer in the selection. The hydrograph does get less responsive, yet does not flatten when dropping low, i.e. when in drought. Instead it keeps falling. This might be attributed to a presumably high slope of the aquifer. However the most striking observation is that at times the seasonal pattern diminishes. This can be observed for both streamflow and groundwater and is an outstanding behaviour compared to all other catchments in the selection.

4 Discussion

Drought characteristics

Known facts about drought propagation are that a lag occurs between the meteorological and hydrological drought (lag), that meteorological droughts are combined into a prolonged hydrological drought (pooling), that meteorological droughts are attenuated in the stores (attenuation) and that droughts get longer when moving from meteorological to hydrological drought () (Van Loon and Van Lanen, 2012). These facts can be tested by means of drought characteristics.

Concerning lag and pooling, these processes did not necessarily become evident in this thesis because droughts in precipitation occurred at all times, even during rather wet periods; the development of hydrological droughts out of meteorological droughts therefore seemed rather random, at least when looking at precipitation, stream- or spring discharge and groundwater levels only. One reason for this might be the influence of evapotranspiration and other climate controls on drought development, which were not regarded in this thesis. However the main cause can more likely be found in the data processing procedure of precipitation (chapter 2.1.2). The appliance of a moving sum on precipitation might not be suitable for drought propagation studies, but more on that later in the paragraph on the *evaluation of applied methods for precipitation and streamflow*. Also, drought attenuation in “lower” hydrological levels was not possible to determine, because this would require all hydrological levels to be available as a flux variable in order to calculate drought deficit volume which is needed for the determination of attenuation effects. The calculation of deficit volume was not possible because of various reasons (chapter 1.3).

Lengthening, however, could be confirmed. It was shown that droughts get longer when moving from meteorological to hydrological drought in general. For every “lower” hydrological level, variation in drought characteristics (like duration) between different catchments increases. While for precipitation the distribution of drought durations is basically the same in every catchment, more significant differences between the catchments start to show in streamflow (chapter 3.3). In groundwater, the distribution of drought durations does barely show any similarity between different catchments anymore. Hereby storage properties and streamflow connectedness are indicated as two major controls, but more on that later in the paragraph *groundwater during drought*.

Stream discharge during drought

The same applies for stream discharge. Flashier catchments have high numbers of droughts with little duration, although severities can't get that high because droughts generally occur during baseflow conditions and deviations from the threshold are in general low then. This is true for all catchments in the selection. Therefore in stream discharge, the main control of deficit volume is duration, because deficit volume equals deviation times duration. Thus it would be the less flashier, slower responding catchments that breeds higher deficit volumes despite severities not differing in magnitudes. Catchments with slower responding streamflow are therefore more vulnerable to droughts. Thereby, as expected, topography proved to be the major catchment control on the behaviour of stream discharge during drought because it controls the sort of discharge processes that are dominant in the respective catchment. In steep and high-lying catchments, quick runoff components like overland flow, throughflow or quick groundwater discharge from thin and heavily sloped hillside aquifer layers are dominant. Flat and low-lying catchments are more prone for slow runoff processes that contribute heavily to baseflow. Therefore steeper catchments show more and shorter droughts and flat catchments longer and fewer droughts.

Also, catchment size is important. Bigger catchments are slower responding in general. However one striking observation can be made when looking at the two big lowland catchments Lachte and Oertze. The Oertze catchment is twice the size of the Lachte catchment and should therefore be slower responding. Yet the opposite behaviour takes place. There are significantly more and shorter droughts in the Oertze streamflow records, indicating a shorter response for the bigger catchment. Reasons are unidentified, but can maybe be found in different channel alignments.

Furthermore, for all catchments except one (Gruendau), the influence of baseflow was big enough that prolonged and severe droughts predominantly occurred during the dry season (summer) when baseflow was low. Also, it was shown that droughts continued to occur in consecutive years as long as baseflow did not recover from drought. This means that droughts in streamflow are dependent on baseflow. When baseflow is dominated mostly by groundwater discharge, which is the case for the catchments in this thesis, this implies that droughts in streamflow are controlled by groundwater discharge. Which in turn means that prolonged and severe droughts in streamflow only occur when the corresponding aquifer responsible for baseflow is in drought. This leads to the conclusion that droughts propagate through groundwater first and to streamflow afterwards. Exceptions should be topographically extreme catchments, very small catchments (roughly < 100 km^2) or catchments that are disconnected from sufficient aquifer discharge because of some reason, i.e. with very little baseflow.

Groundwater during drought

The results show that connectedness is a major control of an aquifer’s behaviour during drought. Also, groundwater storage properties strongly control how fast water levels drop. Therefore, severities and durations of droughts are controlled by storage properties. This is also visible from the results of this thesis. Small, fast responding aquifers induce shorter droughts, but not necessarily less severe droughts, because water levels can drop quickly and therefore breed high severities fast (e.g. Spree). In contrast, the drop of water levels in classical slow responding aquifers (e.g. Lachte & Oertze) are more enduring, resulting in high severities as well, yet by trend only with increasing duration. Thereby obviously recovery is harder as well, leading to higher drought vulnerability for slow responding aquifers because high severities are enduring.

However for the two classical slow responding aquifer in the selection, having a vast spatial extent and lying in the lowlands, there are significant differences in the behaviour that are due to river connectedness. The Oertze groundwater gauge is located close to the stream, which leads to a strong seasonal amplitude in water levels. This is because it receives groundwater from remote recharge areas that integrate into a seasonal recharge pattern (Van Lanen et al., 2004). Because of the strong seasonal amplitude, temporary recovery from drought is observed annual with the rising amplitude. Multi-year droughts do not occur. Sustainable recovery is only possible when extended wet periods lift the overall seasonal amplitude. Without this, droughts continue to occur in consecutive years. The groundwater gauge in the Lachte is much different. Located in an aquifer recharge area itself, it does not receive much influx from other parts of the aquifer, resulting in a much less pronounced seasonal amplitude. Water levels are more dependent on direct percolation in location of the gauge. This is supported by the observation of the onset of a minor percolation pattern, visible by means of a fluctuation pattern on top of the otherwise rather smooth hydrograph. It starts to appear around 1980 in a rather wet period and persists for more than twenty years, “surviving” several severe droughts, until it ceases again in the 2003 drought (figure 14). From 2003 on, the Lachte groundwater hydrograph experiences a severe and persistent drop, ultimately resulting in an extreme 23-month drought some two years later. Because 2003 is a drought linked with extreme heat in Germany (Sheffield and Wood, 2011), the conclusion is that the outstanding soil moisture drought in 2003 leads to the sustainable discontinuation of recharge patterns which then massively affects groundwater storage with a two year delay, supporting the susceptibility of the Lachte groundwater gauge to direct recharge alteration, rendering it more vulnerable to drought than the Oertze gauge which is stabilised by constant influx from surrounding aquifer areas. Thereby streamflow connectedness can be taken as a proxy control indicating drought vulnerability.

The Oertze groundwater gauge is about 900 meters from the river with water levels about 5-7 meters above stream level. When moving closer to the stream, another striking observation can be made. The Leine groundwater gauge and Gruendau spring gauge are both located very near to their respective streams (300 and 100 meters, respectively) with water level heights respectively gauge height very close to the stream level (< two meters). Being therefore part of the river aquifer system, where aquifer discharge and recharge easily interchange, a certain resilience against high severities is evident. When water levels respectively spring discharge drops low and go into drought, it was shown that the hydrographs level off and go into a kind of indifferent state. They do not drop deep below the threshold and excessive rainfall events are needed to lift them out of drought again. This is because on low levels both Leine groundwater gauge and Gruendau spring gauge start to receive influx from the river. For water levels / spring discharge to drop further, presumably the whole river aquifer above the gauge, and therefore the river itself, has to dry up, leading to a high resilience to severe drought. Thereby it is indicated that spring behaviour is equal to the behaviour of groundwater gauges that are located in the same relative location of an aquifer.

Another interesting observation can be made when looking at the Salz groundwater gauge. It is located on the fringe of a small plateau aquifer, yet it acts similar slow as one of the gauges in the vast lowland aquifer, the Lachte groundwater gauge. Moreover, the Salz gauge actually proves to be slower than the second lowland groundwater gauge, the Oertze gauge, which differs significantly in its behaviour from the Lachte, as already discussed. In theory however, small aquifers should be quick responding. This is true when looking at the Spree groundwater gauge, which is a very small aquifer located on the saddle between several hills and acts as fast responding as expected. The Salz aquifer is somewhat bigger than the Spree aquifer, however not by much. Both Salz and Spree are topographically exposed. Differences between the Salz gauge and the Spree gauge are first much lower conductivities in the Spree according to HUEK, whereby the reliability of HUEK information is doubted because conductivities indicated contradict information about the aquifer material according to GUEK. Second the aquifer slope, with the Salz gauge being located on a rather flat plateau aquifer and the Spree on a sloped saddle aquifer. Slope is therefore concluded to be one dominant control.

However the Salz plateau itself is similar flat as the lowland catchments, indicating no major slope in both aquifers systems. When comparing the properties of the Salz aquifer and the lowland aquifers, conductivities according to HUEK indicate similar ranges, however doubted this information may be. If the information is correct and conductivities are somewhat similar, then the similarity of Lachte and Salz groundwater behaviour is a good example on how strong secondary controls can be. Although no single control can be pinned down as the dominant factor, several controls can be attributed. First, aquifer extent alone maybe not a major control, at least from a certain aquifer extent onwards. Second, cliffs, as occurring on the fringes of the Salz aquifer plateau, are normally impermeable bedrock. If they weren't, they would have been eroded into more gentle slopes. Therefore the plateau aquifer of the Salz can be considered to be similar to a basin aquifer, being surrounded by confining bedrock barriers. Possibly basin confinement has to be included into the set of catchment controls on aquifer behaviour. Third, the plateau aquifer has a thin drainage channel grid with only very minor brooks, as opposed to the Lachte and Oertze with many larger rivers, indicating drainage density as another major catchment control. Further research on the influence of drainage grids on aquifer behaviour is needed.

Finally, to evaluate drought vulnerability of groundwater, one has to set severity into context with the overall storage capacity of a groundwater storage. In general groundwater storage mostly cannot run empty, at least in human time periods, because in most cases a certain share of the storage is "immobile", i.e. does not discharge under natural circumstances. However, the shorter the flowpaths of groundwater, the more likely it is that groundwater discharge supported by these flowpaths cease in times of temporary negative precipitation anomalies, i.e. droughts. Therefore in order to assess the vulnerability of an aquifer to drought, or even to answer the question if drought is a concept applicable to groundwater, one has to differentiate between different "storage levels", or groundwater ages. It is suspected that for old groundwater, having long flowpaths, drought in the conventional sense is not applicable because they are not affected by short-term meteorological fluctuations, while for young groundwater, having short flowpaths, the concept of drought is presumably applicable. The overall storage capacity of an aquifer might be a good first proxy for that, indicating that high overall storage content speaks for a relatively low percentage of young groundwater, i.e. small drought vulnerability. However this is only when looking at the aquifer only in terms of storage vulnerability. Interlinked systems, like environmental or riparian systems, are dependent on the height of water levels or groundwater discharge, which are controlled by young groundwater only. A specification of the drought concept for different groundwater ages is therefore recommended.

Seasonality/ climate controls

Generally winter is considered the dry season in Germany, because precipitation is higher in summer. However, the timing of the 'dry' season or better said the low flow season is dependent on which hydrological level one regards. Seasonality in streamflow and groundwater is highly controlled by evapotranspiration, altering the shape and timing of seasons (Eltahir and Yeh, 1999). In Germany the rainfall surplus in summer coincides with the low flow, or 'dry' season in streamflow and groundwater. But while seasonality in humid regions like Germany is controlled by evaporation, drought development is in theory controlled by anomalies in precipitation mostly, with some unclear additional influence of evaporation (Van Loon and Van Lanen, 2012). However in some instances in this thesis, variables show a disproportional good recovery without any major rainfall surplus (e.g. Lachte groundwater in 1979/1980 or Oertze 1977-1980, figures 13 and 14). Vice versa, excessively wet periods do are not guarantee to trigger drought recovery in e.g. stream discharge or groundwater. It is striking that drought development or recovery is not always controlled by rainfall alone. This observation is most distinct in especially slow responding aquifers (Salz & Lachte). As has been shown, slow responding aquifers are dominated by seasonal patterns, which are controlled by evapotranspiration. The hypothesis is therefore, that evapotranspiration might be a major, although possibly indirect control in the development and recovery of droughts. Evapotranspiration was not considered in this thesis, which is a disadvantage. Quantification of the influence of evaporation is needed to further evaluate its role. After all, temperature and especially solar radiation, the main controls of evapotranspiration, are spatially highly variable. They may be at times significantly different for every catchment, thus invalidating the initial assumption of constant climate controls for all catchments on grounds of their relative adjacency.

Evaluation of applied methods for precipitation and streamflow

One characteristic of streamflow hydrographs is the long regression tail after rainfall and/or flood events. This is why duration curves for streamflow time series are very flat for lower quantiles (figure 7), which in turn implies that scale differences for low quantiles are small. While this might be different for major rivers, it is true for small catchments as regarded in this thesis. This means that only minor discharge variation is needed to lift the hydrograph in significantly higher quantiles. Because the threshold is generally set to a low quantile, this means that droughts as defined with the Threshold Level Method are frequently discontinued by relatively minor flash peaks although no real recovery took place because, at is was shown in this thesis (chapter 3.4), in most cases streamflow recovery is dependent on baseflow recovery. This leads to a distortion of drought characteristics as calculated with the Threshold Level Method. Conclusions made on grounds of these drought characteristics are misleading. They only point to the fact that flashy peaks do occur in stream discharge time series. When the results of this thesis are correct and baseflow proves to be the main control for the occurrence of and recovery from droughts in streamflow, the best way to get rid of said distortion effect would be to apply the threshold to baseflow only. However this would ultimately mean that the threshold is applied on the cumulative groundwater discharge of the catchment, which would require the acceptance of the hypothesis that drought propagates through groundwater first and triggers streamflow drought later, considering that streamflow drought is controlled by baseflow. This argumentation applies for small catchments as regarded in this thesis and might be false for big river basins with higher scale range in the lower quantiles, i.e. higher variability during low flow. Also, the results this argumentation is based on might be distorted themselves by the use of the combined threshold.

Furthermore, concerning precipitation, the appliance of a moving sum might not be suitable for drought propagation studies. This is because the moving sum procedure does not reduce the flashiness of precipitation significantly, thus leading to an overabundance of meteorological droughts even during wet periods with high precipitation surplus. These droughts often do not show any major effect on streamflow and groundwater whereat droughts in the streamflow and groundwater are often produced without any major preceding meteorological drought. Procedures with a higher grade of inherent pooling, like the moving average (Fleig et al., 2006), might be more suitable than the moving sum.

Influence of the threshold level method applied

Now the question of how different threshold methods influence drought characteristics is an important one. In other words how the application of a constant, variable or combined threshold would change the results based on drought characteristics. The Combined Threshold Level Method cuts out the part of the variable threshold that is in the wet season, thus suppressing the determination of droughts in the wet season for most variables except extremely fast responding ones like precipitation or some rare streamflow time series. When taking a constant threshold, these droughts are still suppressed. The main alteration of drought characteristics would be that higher severities would occur, affecting the correlation between duration and severity (chapter 3.3.2). Notions on how the correlations would be altered are speculative and should be tested before making anticipatory conclusions. However this was not done in this thesis due to time limitations. When using a variable threshold instead, this would alter drought characteristics in different ways. For slow responding variables, droughts would extent further into the wet period, thus increasing their durations. For fast responding variables, droughts would still get frequently discontinued, however additionally determined droughts in the wet period would lead to higher number of droughts with very short duration. Thus drought characteristics for slow and fast responding variables would drift apart. It is therefore suspected that the duration distributions in figures 8 to 10 would depict much more distinct differences between the variables. Qualitative conclusions on the basis of these graphs would probably be more robust.

Concerning the visual hydrograph assessment, the application of a variable threshold would be more useful, since the qualitative discussion would be easier against the background of the variable threshold, for it gives useful information about seasonality, which is highly influential on drought development and recovery as it was shown. Also, and this is maybe the most crucial critique, conclusions made on the extreme baseflow dependency of streamflow droughts might be different when applying a variable threshold, for example, since it can be expected that droughts will then occur during the wet season as well, when baseflow is relatively less influential on the quantile distribution. However when including the principle of real impact significance into the definition of droughts, as done by the Combined Threshold Level Method, these conclusions might still be valid.

Remarks on the key borehole approach

The groundwater time series used in this thesis are data from single observation well. Thus the findings cannot be interpolated on the whole aquifer. Also, the used data were water table heights only and do not resemble the groundwater system in general (Van Lanen et al., 2004). Yet the results of this thesis are valid for the aquifer settings in the location of the groundwater gauge and do therefore enable the conclusions made. Still, the main principle that should underlay every study that is conducted with observed data cannot be repeated enough: The more data, the more robust the study. Every bit of metadata collected provides tremendous advantages for interpretation. Maybe the most crucial meta-information for groundwater data proved to be the borehole profile. With it, it is possible to estimate the actual conductivities or even storage coefficients for the location of the gauge. Another possibility to obtain storage coefficients is pumping tests (Banton and Bangoy, 1996; Singh, 2003). No effort should be spared to further determine aquifer settings, especially when trying to pin down catchment controls.

5 Conclusion

In this thesis, previous findings of modelling studies on drought propagation could be confirmed. It was further demonstrated how different catchment controls affect the behaviour of streamflow and groundwater during drought. Different combinations of controls like basin confinement, drainage channel density, aquifer slope, extent and conductivities can lead to an unexpected behaviour of aquifers, referring to the case of the Salz aquifer. Also it was found that connectedness to streams can be a good proxy control for drought vulnerability, because closeness to a stream prevents deep drops in water levels during drought. Thereby the visual assessment of hydrographs was very yielding.

Indications were found that in small catchments drought propagates through groundwater first and streamflow afterwards. This is because baseflow majorly controls the occurrence and recovery of streamflow droughts in these catchments. The role of groundwater for streamflow drought should be more thoroughly studied. Also, the question is posed if it would be useful to specify the concept of drought for different groundwater flow paths. In other words to look at groundwater in terms of a system of different storage levels having varying susceptibilities to drought in order to further specify the applicability of the drought concept to groundwater.

Furthermore, evapotranspiration should be more thorroughly studied as a control for drought development and recovery. This is because indications were found that evapotranspiration might be, next to precipitation, a second trigger for drought development and recovery.

Although findings for groundwater cannot be interpolated on the whole aquifer due to the limitations of the key borehole approach, limited conclusions on the influence of aquifer settings in the location of the groundwater gauge are possible, thus helping to determine catchment control. The key borehole approach is therefore considered useful, although a higher number of gauges for an aquifer is desirable. Furthermore, especially the collection of hydrogeological metadata should be focused on as much as possible.

Finally, the methodology used in this thesis was suboptimal. A moving sum was applied on precipitation and turned out to be not as yielding as expected. Also, the sort of threshold level that was applied (combined threshold instead of constant or variable threshold) has presumably a big effect on the outcome of the study. The Combined Threshold Level Method is not further recommended because it is not straightforward for interpretation.

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Appendix

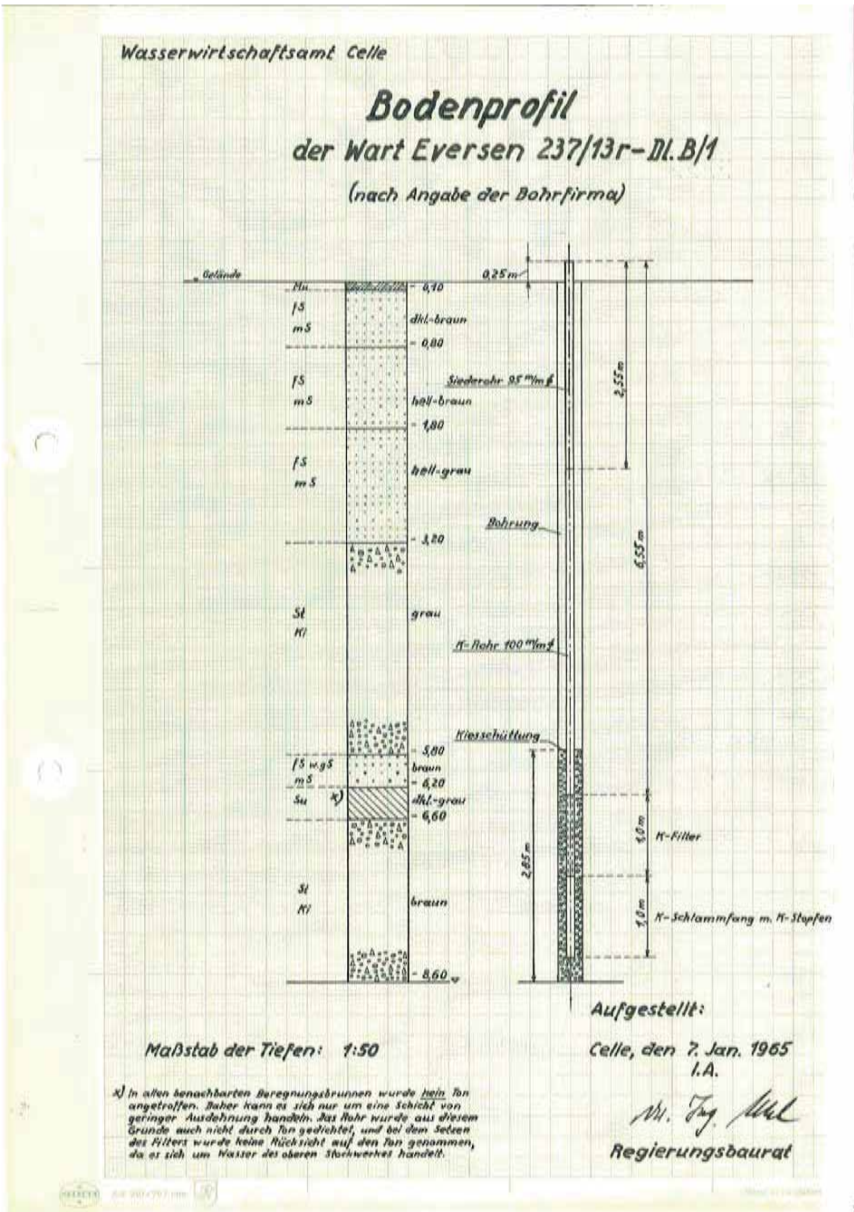


Figure A1: Borehole profile of the Oertze groundwater gauge.

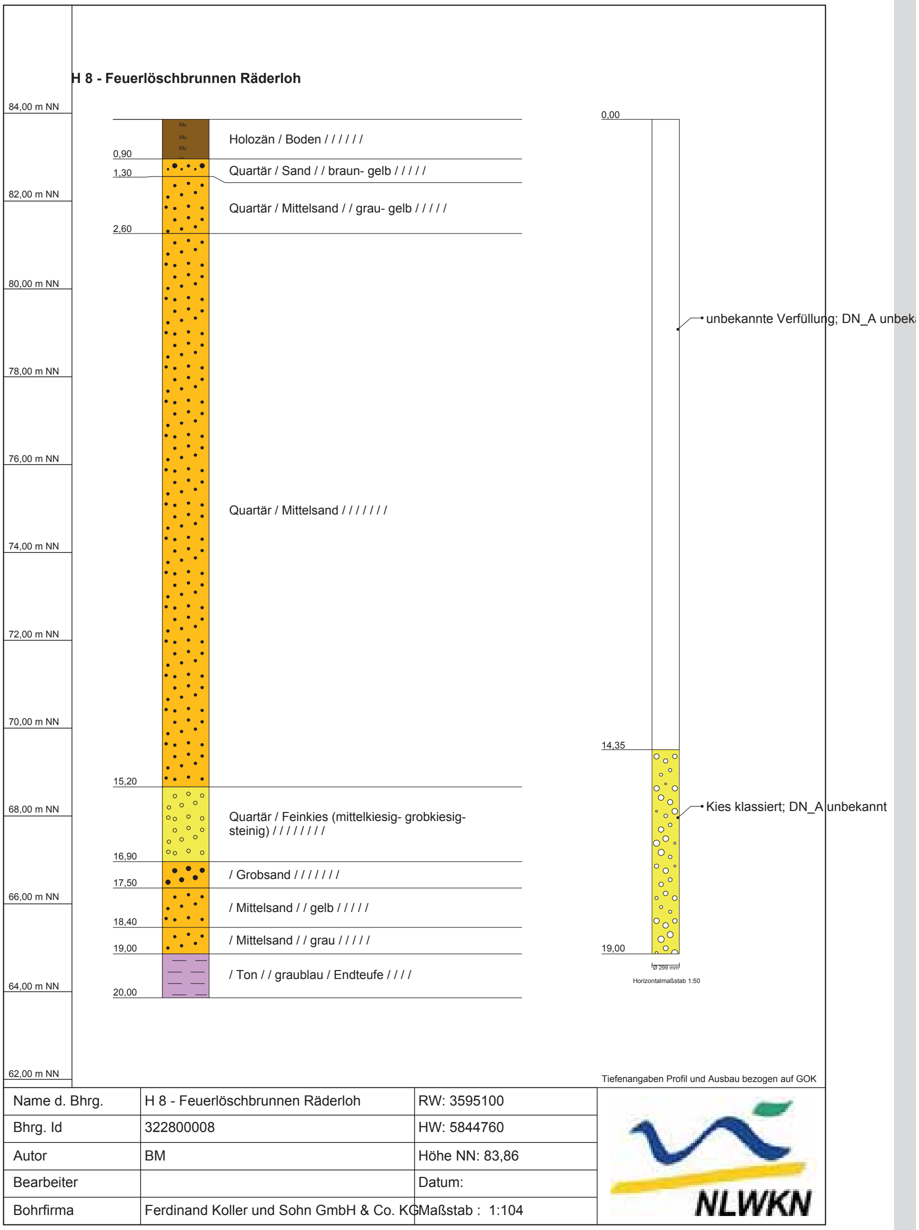


Figure A2: Borehole profile of the Lachte groundwater gauge.

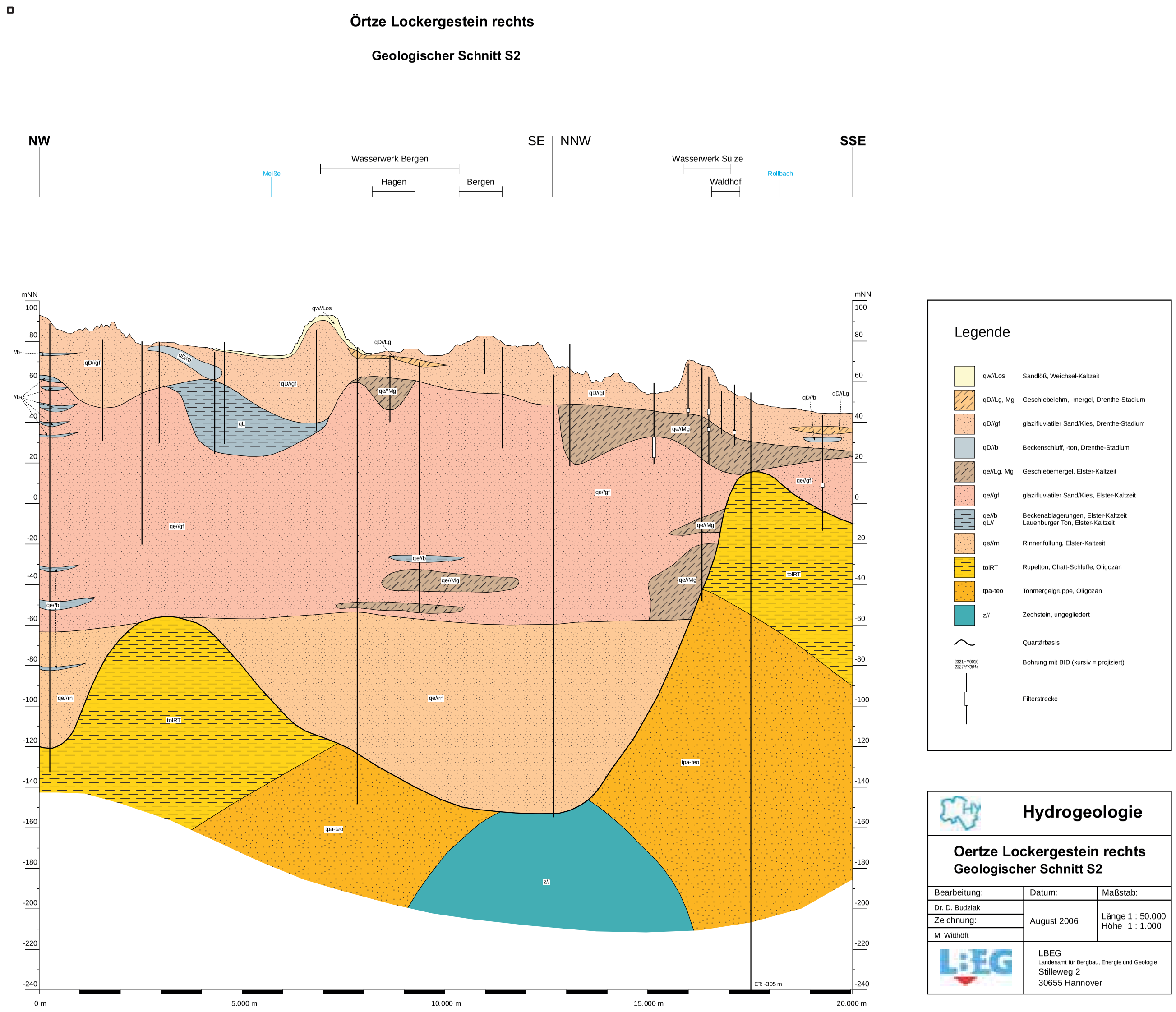


Figure A3: geo-stratigraphic cross profile of the Oertze aquifer.

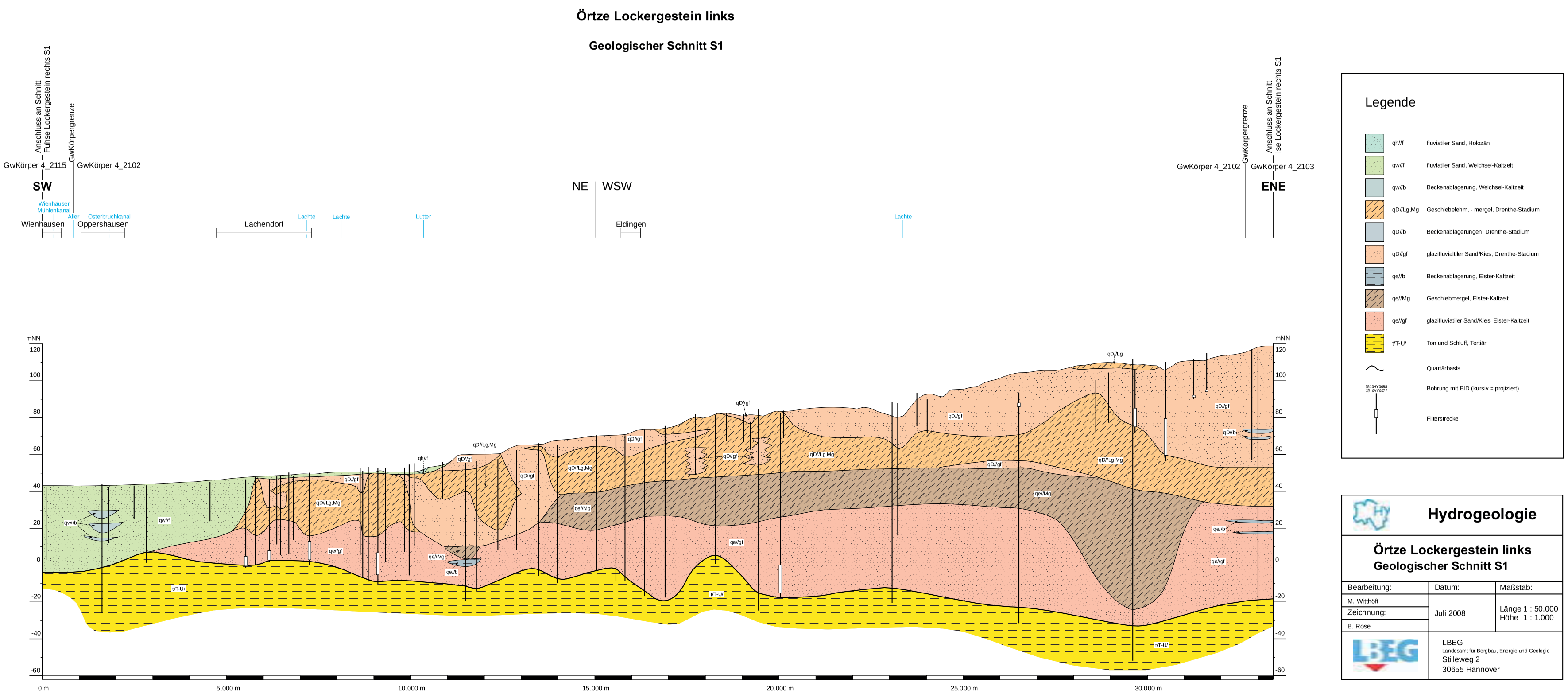


Figure A4: Geo-stratigraphic cross profile of the Lachte aquifer.

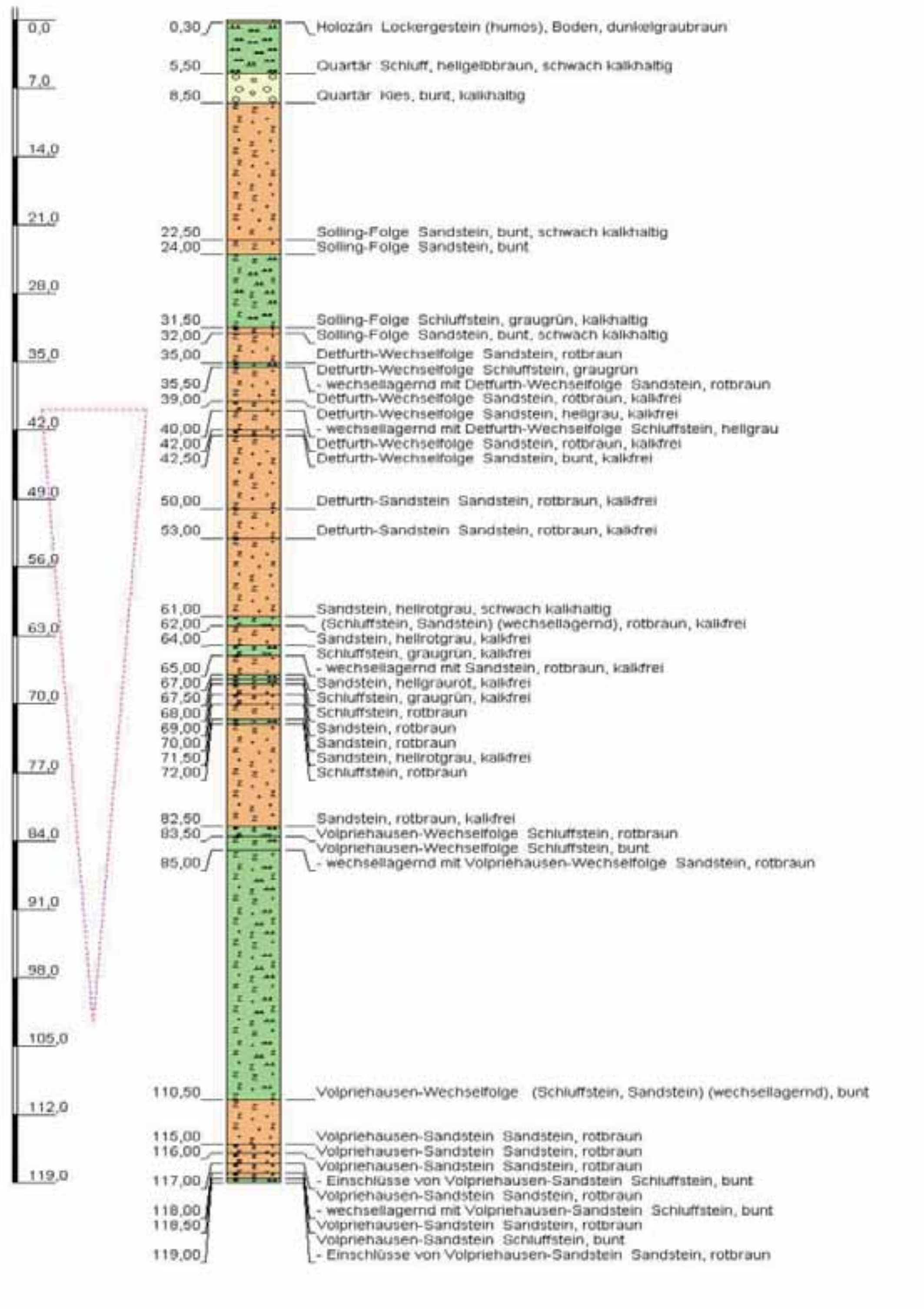


Figure A5: preliminary borehole profile of the Leine groundwater gauge. A preliminary profile is estimated from surrounding borehole profiles via a stratigraphic model.

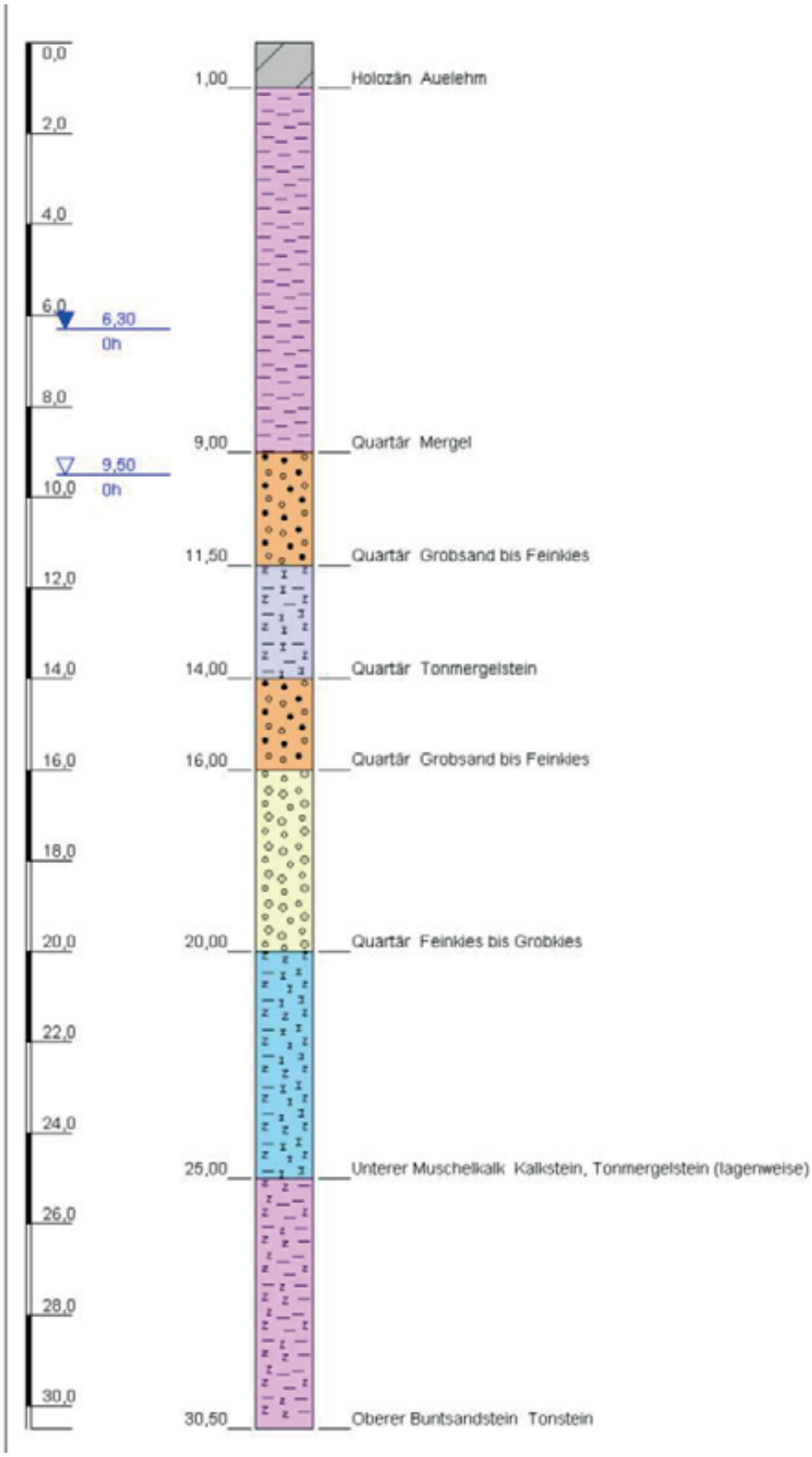


Figure A6: Preliminary borehole profile of the Leine spring discharge gauge. A preliminary profile is estimated from surrounding borehole profiles via a stratigraphic model.

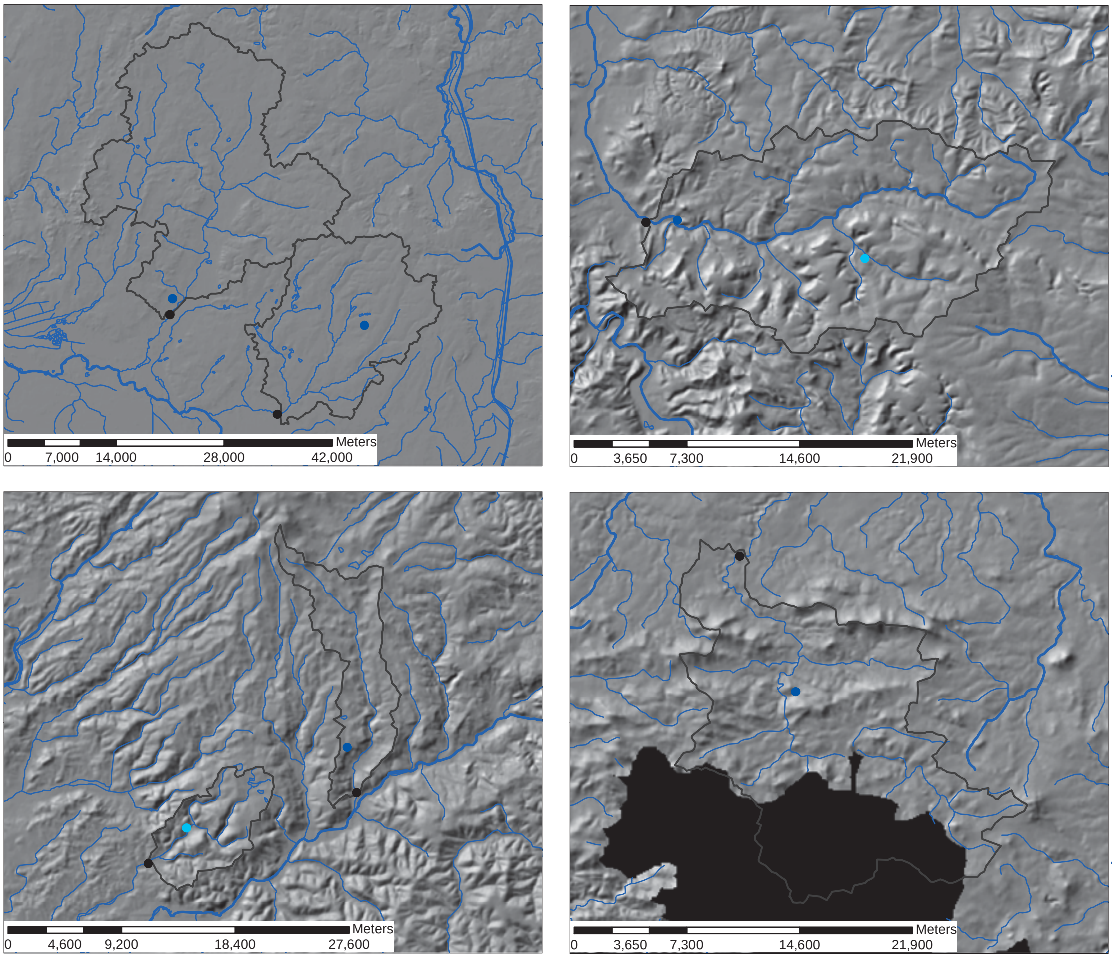


Figure A7: Hill shading of the catchments topography. Top left is the Lachte / Oertze couple, top right the Leine catchment, bottom left the Gruendau / Salz couple and bottom right the Spree catchment.

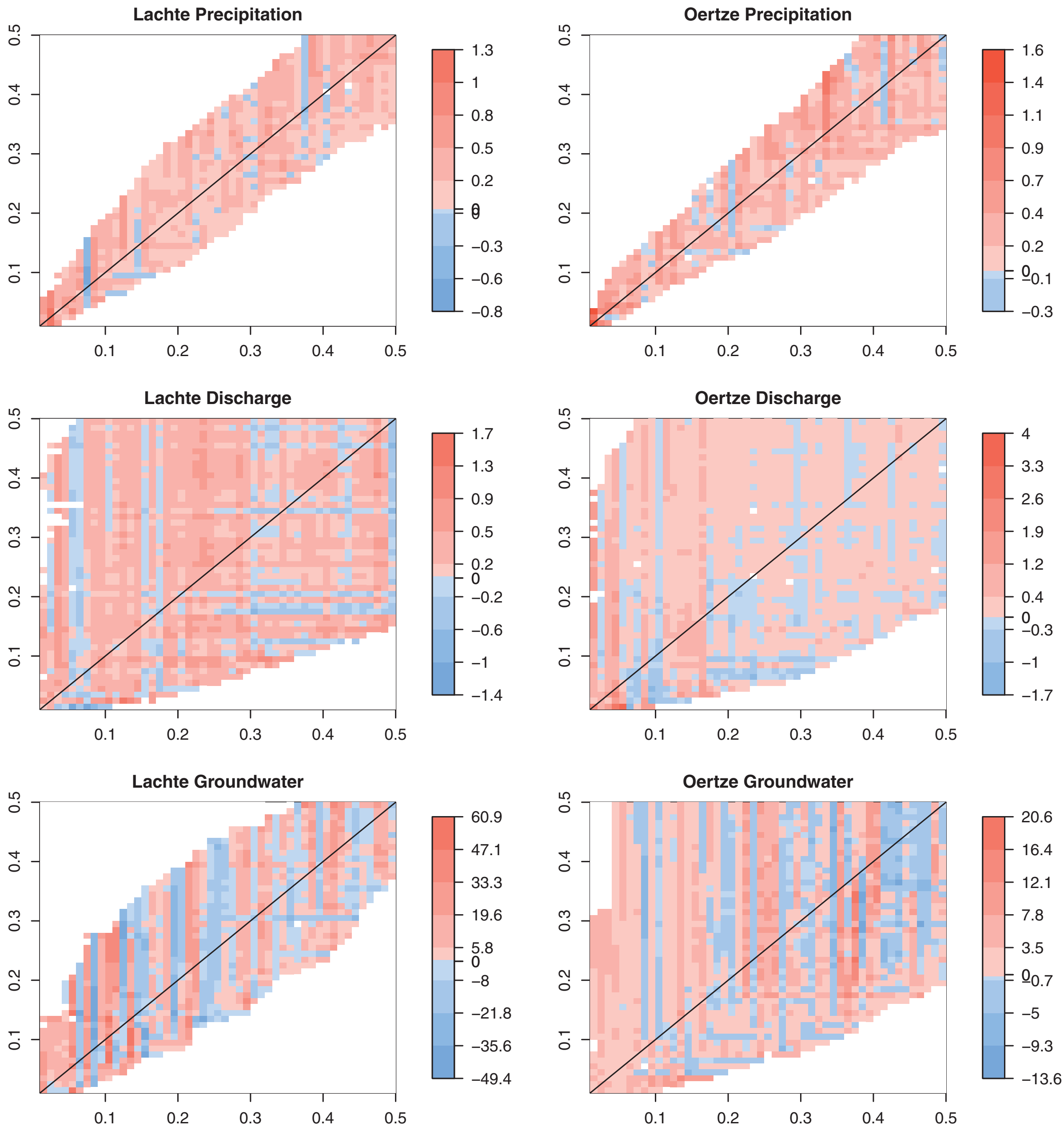


Figure A8 a) to f): Sensitivity plots on grounds of the methodology of chapter 2.3.4. The x-axis is the constant threshold, the y-axis is the variable threshold. Colouring as defined by the legend refers to the height of the averaged bidirectional differences under a respective combination of constant and variable threshold. Insensitivity ranges can be clearly identified. Strips within the sensitive ranges indicate a somewhat higher, respectively lesser sensitivity of a certain constant (vertical strips) or variable (horizontal) threshold level. However interpretation is difficult because of the high degree of abstraction in the averaged bidirectional differences index. Only speculations can be made, thus analysis was left out of this thesis.

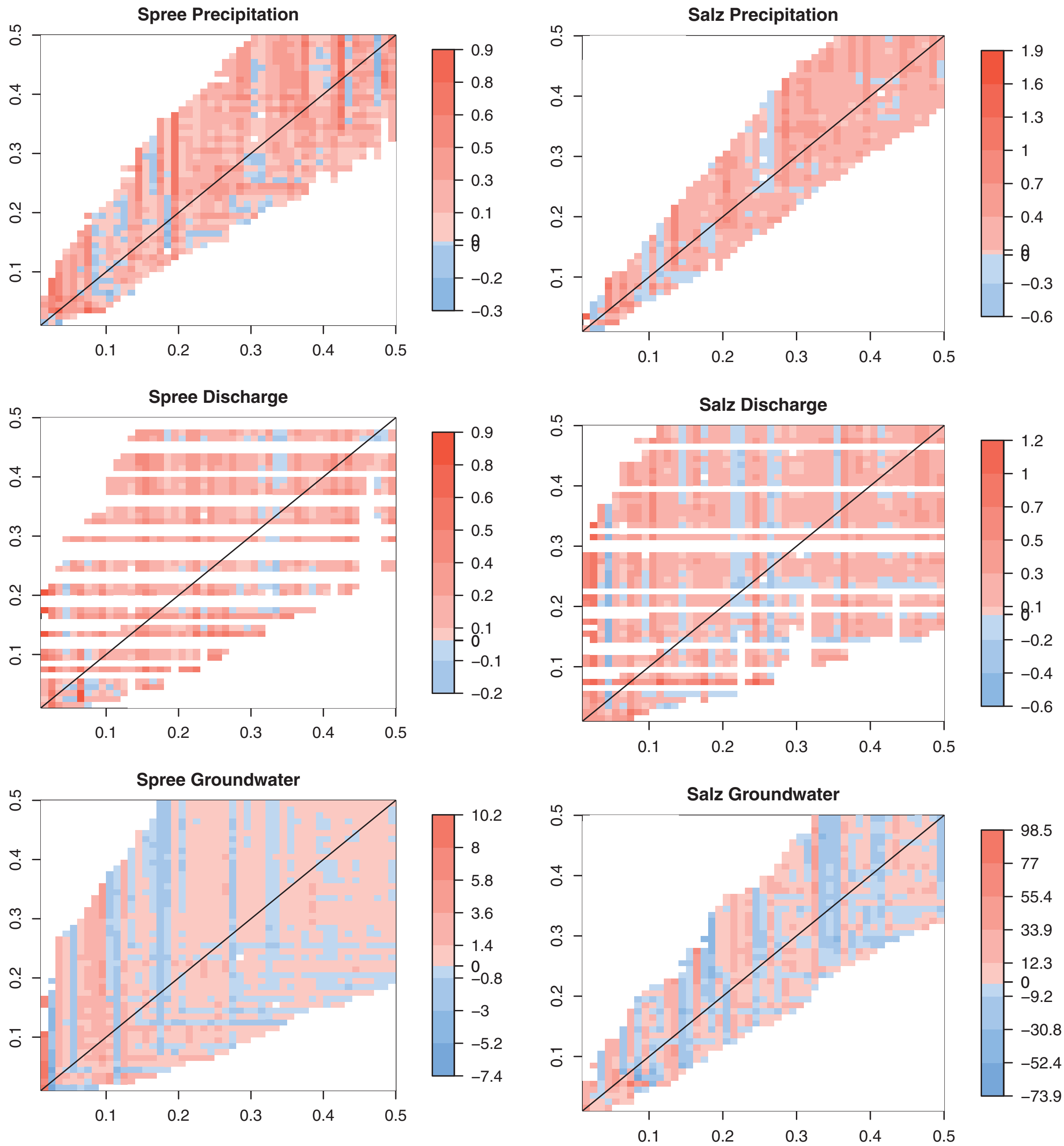
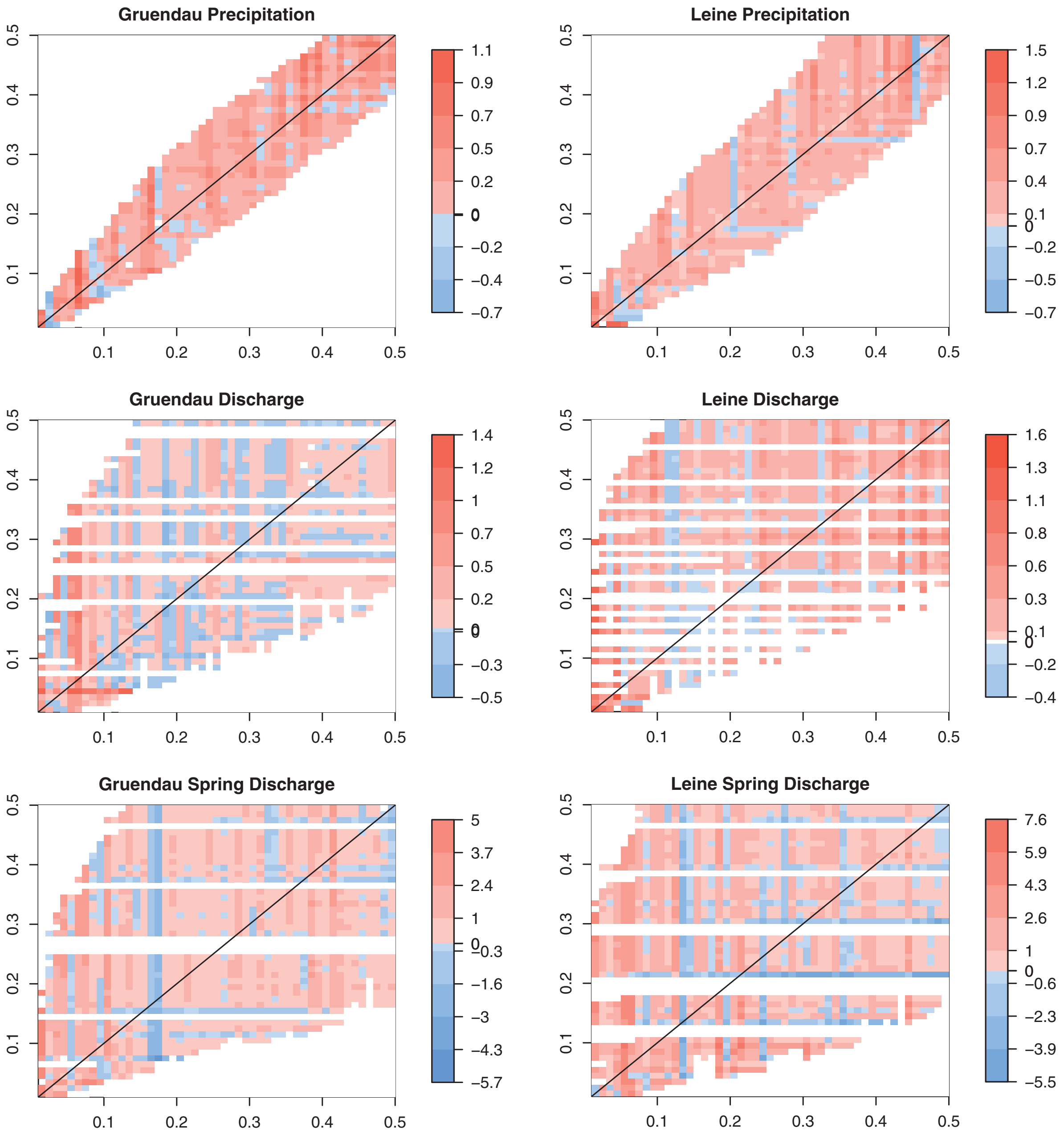


Figure A8 g) to l), continued.



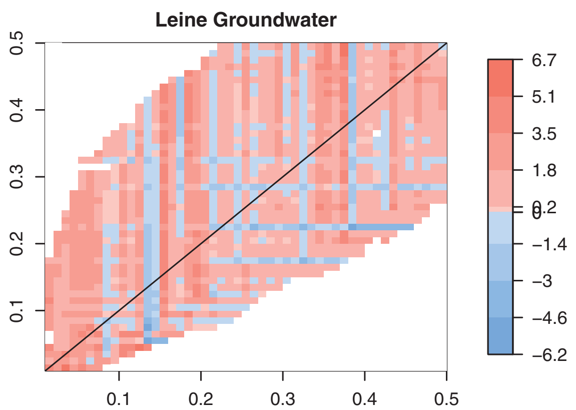


Figure A8 m) to s), continued.

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Ehrenwörtliche Erklärung:

Hiermit erkläre ich, dass die Arbeit selbstständig und unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

(Benedikt Severin Heudorfer)

Freiburg im Breisgau, den 29. November 2013