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Hydrological drought severity explained by climate and catchment characteristics

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SUMMARY

Impacts of a drought are generally dependent on the severity of the hydrological drought event, which can be expressed by streamflow drought duration or deficit volume. For prediction and the selection of drought sensitive regions, it is crucial to know how streamflow drought severity relates to climate and catchment characteristics. In this study we investigated controls on drought severity based on a comprehensive Austrian dataset consisting of 44 catchments with long time series of hydrometeorological data (on average around 50 year) and information on a large number of physiographic catchment characteristics. Drought analysis was performed with the variable threshold level method and various statistical tools were applied, i.e. bivariate correlation analysis, heatmaps, linear models based on multiple regression, varying slope models, and automatic stepwise regression. Results indicate that streamflow drought duration is primarily controlled by storage, quantified by the Base Flow Index or by a combination of catchment characteristics related to catchment storage and release, e.g. geology and land use. Additionally, the duration of dry spells in precipitation is important for streamflow drought duration. Hydrological drought deficit, however, is governed by average catchment wetness (represented by mean annual precipitation) and elevation (reflecting seasonal storage in the snow pack and glaciers). Our conclusion is that both drought duration and deficit are governed by a combination of climate and catchment control, but not in a similar way. Besides meteorological forcing, storage is important; storage in soils, aquifers, lakes, etc. influences drought duration and seasonal storage in snow and glaciers influences drought deficit. Consequently, the spatial variation of hydrological drought severity is highly dependent on terrestrial hydrological processes.

1. Introduction

Drought is considered one of the most damaging natural disasters in terms of economic costs (e.g. navigation and hydropower production, Wilhite, 2000; Carroll et al., 2009; Van Vliet et al., 2012), societal problems (e.g. increased mortality and conflict, Garcia-Herrera et al., 2010; Hsiang et al.) and ecological impacts (e.g. forest dieback and impacts on aquatic ecosystems, Lake, 2011; Lewis et al., 2011; Choat et al., 2012). Drought is commonly defined as a below-normal water availability (Wilhite and Glantz, 1985; Wilhite, 2000; Tallaksen and Van Lanen, 2004; Sheffield and Wood, 2011; Mishra and Singh, 2010), but there is no real consensus about the application of this definition (Hayes et al., 2010). In this study we assume that society and the ecosystem are adapted to the seasonal cycle and we regard drought as a deviation from this seasonal cycle, which means that droughts also occur in the high flow season. Drought is subdivided into different types of drought related to the variables of the hydrological cycle, precipitation (meteorological drought), soil moisture (soil moisture drought), and groundwater and streamflow (hydrological drought) (Tallaksen and Van Lanen, 2004). Almost all drought impacts are related to soil moisture drought or hydrological drought, since both the ecosystem and society depend upon water from the catchment stores (soil, aquifers, lakes, rivers) rather than from precipitation directly. Hydrological drought is determined by the propagation of meteorological drought through the terrestrial hydrological cycle and is therefore influenced by the properties of the hydrological cycle (Peters et al., 2006; Van Lanen, 2006; Vidal et al., 2010). For example, drought propagation is different in an semi-arid climate and a climate with snow accumulation in winter, and it differs between mountainous catchments, catchments with many lakes and wetlands, and catchments with mild slopes and large, porous aquifers (Van Loon, 2013).

Besides drought frequency (how often a drought occurs), drought severity (the strength of a drought) is an important characteristic of drought events since it is directly related to the

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impacts of drought (Hayes et al., 2010). Drought severity can be quantified in various ways. In standardised indices (e.g. Standardised Precipitation Index, SPI, McKee et al., 1993), and Standardised Groundwater level Index, SGI (Bloomfield and Marchant, 2013), which are increasingly used in scientific drought studies (e.g. Vicente-Serrano et al., 2009; Mishra et al., 2009; Joetzjer et al., 2013), drought severity is expressed by the number of standard deviations from the mean. For most impacts, however, more physical measures of severity are needed (Wong et al., 2013). For many aquatic ecosystems for example the duration of a drought in streamflow is crucial (Bond et al., 2008), whereas for hydropower production the missing volume of water compared to normal conditions (deficit volume) is more relevant (Jonsdottir et al., 2005; Rossi et al., 2012; Tsakiris et al., 2013).

Hydrological drought duration and deficit are related since the deficit accumulates over the duration of the drought event (e.g. Dracup et al., 1980; Woo and Tariiule, 1994; Shiau and Shen, 2001; Kim et al., 2003; Hisdal et al., 2004; Mishra et al., 2009; Wong et al., 2013). Van Lanen et al. (2013) and Van Loon et al. (2014) have shown that this relation is not linear. It is dependent on propagation of the drought (Van Loon et al., 2014) and relates strongly to climate and catchment characteristics (Van Lanen et al., 2013). Van Lanen et al. (2013) assessed the effect of climate (Köppen classes), soil and groundwater system on the bivariate probability distribution of drought duration and deficit. They found that the responsiveness of the groundwater system is as important for hydrological drought development as climate.

What is still unclear is how hydrological drought duration and deficit relate to climate and catchment characteristics and which factor is dominant. Tallaksen and Hisdal (1997) speculated that “The distribution of drought duration is primarily thought to be governed by climate. However deficit volume is expected to be more related to catchment characteristics” (Tallaksen and Hisdal, 1997). More recent studies however have shown convincingly that in a given climate hydrological drought duration is strongly related to the responsiveness of the groundwater system, both in a theoretical analysis and in a real world example (Peters et al., 2003; Peters et al., 2005). On the other hand, there are indications of an effect of climate on drought deficit, because in many studies the deficit volume of hydrological drought is standardised by dividing by mean discharge to be able to compare catchments with different wetness (Clausen and Pearson, 1995; Kjeldsen et al., 2000; Van Lanen et al., 2013). A quantitative analysis of the effects of climate and catchment control on drought duration and deficit has, to our knowledge, never been done.

We intend to fill that gap and investigate the relative effects of climate and catchment on hydrological drought duration and deficit volume. For this study we used an extensive Austrian dataset, that contains observations of precipitation, temperature and discharge for a high number of catchments and includes thematic information for each catchment, e.g. climate, elevation, geology, land use (Laaha and Blöschl, 2006; Gaál et al., 2012; Haslinger et al., 2014). By combining different types of analysis we hope to prove whether climate or catchment properties are more important in determining both drought duration and deficit. In Section 2, we will first describe the study area and data availability. Sections 3.1 and 4.1 deal with the drought analysis methods and its results and Sections 3.2 and 4.2 with the statistical analysis methods and its results. Finally, discussion and conclusions are given in Sections 5 and 6.

2. Study areas

The study has been conducted on a comprehensive Austrian dataset consisting of 44 catchments which are free from major disturbances. The study area is quite divers and the catchments

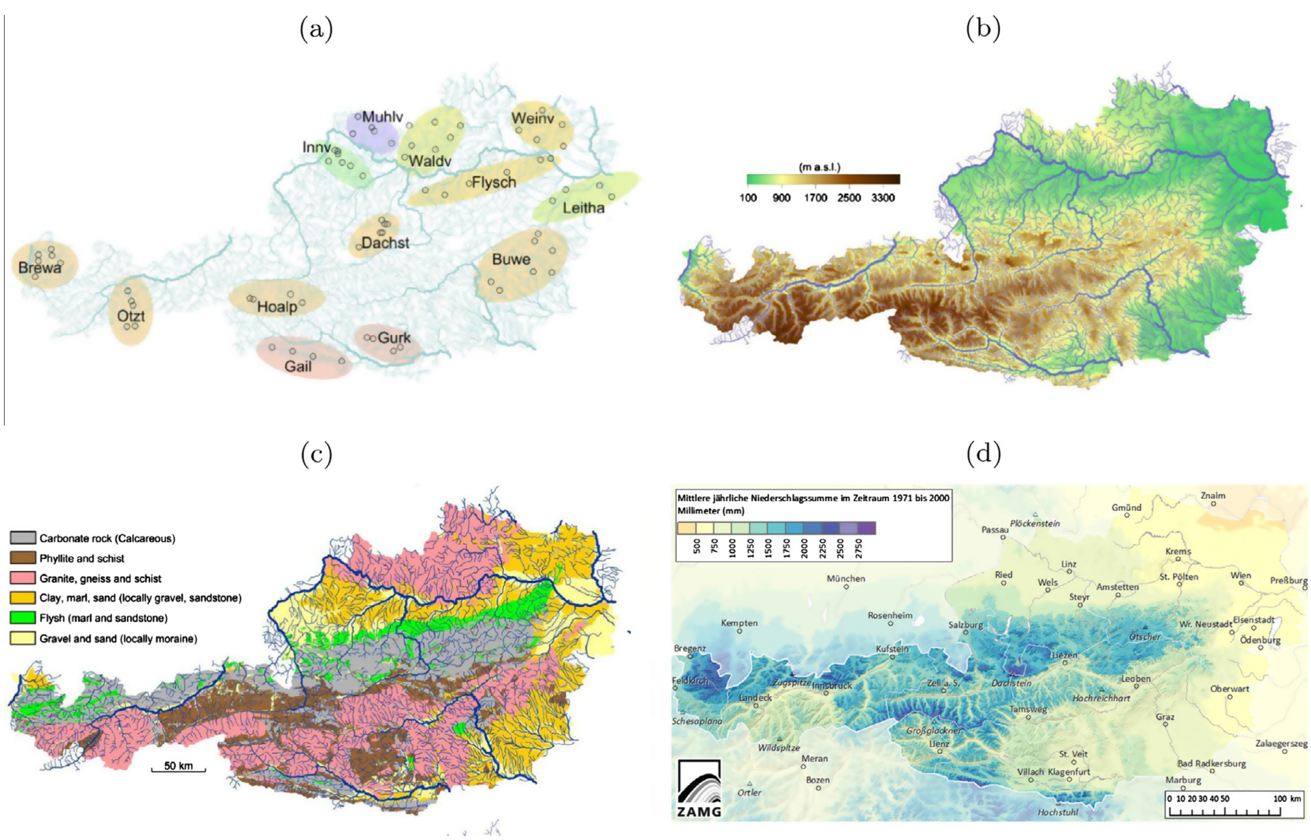

Fig. 1. Some characteristics of the study area: (a) clusters, (b) topography, (c) geology (all from Gaál et al. (2012), reprinted with permission from the publisher Wiley), and (d) mean annual precipitation (from ZAMG).

reflect a broad range of hydrological regimes. The catchments are pooled into 13 clusters which are homogeneous in terms of climate conditions and hydrological processes (Fig. 1a). The pooling is based on the work of Gaál et al. (2012) on flood time scales which have been shown to be a rich fingerprint of the hydrological processes in a catchment. In fact, the spatial pattern of the 'hotspots' (as they were termed in Gaál et al. (2012)) is very similar to that of the low-flow regions of Laaha and Blöschl (2006), discerned from seasonality analysis. The hotspots are on average smaller and, hence, likely more homogeneous. They obviously represent major climate and geological units of Austria (Fig. 1c and d) which are indeed also relevant for hydrological droughts (Haslinger et al., 2014).

Some clusters belong to regions where minimum flows typically occur in summer in consequence of low seasonal precipitation and high seasonal evaporation. These are Innviertel (Innv), Mühlviertel (Muhlv), Waldviertel (Waldv), Weinviertel (Weinv), Flysch, and Leitha. The catchments in the Alps, i.e. Öztal (Ozt), High Alps (Hoalp), and to some degree Bregenzerwald (Brewa) and Dachstein (Dachst), are situated at altitudes where snow storage processes have a major influence on the flow regime (Fig. 1b). They give rise to highly seasonal regimes with minimum flows in winter and high discharges in summer. Catchments in the south also belong to summer low flow type, but exhibit a particular climate as they are situated leeward of the Alps and are screened from moist Atlantic air masses. This yields lower amounts of precipitation then in the north, and often longer dry spells. As can be seen from Fig. 1d, clusters in the south (Gail, Gurk) and southeast (Buwe), but also in southern High Alps (Ozt) are affected by this particular climate. North of the Alps a precipitation gradient can be observed, reflecting increasing aridity towards Eastern Europe.

For each catchment, discharge time series were available from the Hydrographical Service of Austria (HZB) in daily resolution for different periods between 1951 and 2010. The length of the discharge series was on average 47 year with minimum 27 year and maximum 60 year. A linear interpolation was applied to fill a small number of gaps of a few days. We used the total length of the discharge time series to calculate hydrological drought characteristics duration and deficit (Section 3.1), which are the target variables of this study. For each cluster, one close-by meteorological station was selected which seems representative for its climatic conditions. In case multiple stations were present within or in the vicinity of the cluster, we chose the station that was most representative in terms of topographical factors such as elevation and exposition, since both precipitation and temperature are dependent on these factors. Considering exposition is notably important for Alpine catchments as there are major climatic differences between northern and southern slopes of the Alpine divide. For the selected stations daily temperature and precipitation data were available from the Central Institute for Meteorology and Geodynamics (ZAMG) for a period of on average 60 year (ranging from 46 to 62 year per station). Daily precipitation data of these stations were then used to calculate the meteorological drought characteristics per cluster.

For analysing the effect of catchment characteristics on hydrological drought we used the catchment dataset of Laaha and Blöschl (2006), consisting of 31 physiographic catchment characteristics (Table 1). They relate to catchment area (SUM.AREA), topographic elevation (H), topographic slope (SL), precipitation (N), geological classes (GEOL), land use classes (BONU), and stream network density (SDENS). In addition, the Base Flow Index (BFI) and Recession coefficient (Rec) were calculated by aid of the R-package 'lfstat' (Koffler and Laaha, 2013), based on the WMO Manual on Low-flow Estimation and Prediction (WMO, 2008). BFI and Rec have been shown to reflect storage and release properties of the catchments (e.g. Salinas et al., 2013) and are therefore used as catchment characteristics in this study.

Table 1
Catchment characteristics (based on Laaha and Blöschl (2006)).

Name	Variable	Unit
SUM.AREA	Subcatchment area	10^1 km^2
H.MIN	Altitude of stream gauge	10^2 m
H.MAX	Maximum altitude	10^2 m
H.DIFF	Range of altitude	10^2 m
H.MEAN	Mean altitude	10^2 m
M.NEIG	Mean slope	%
SL.FL	Slight slope	%
SL.MG	Moderate slope	%
SL.ST	Steep slope	%
N.GES	Average annual precipitation	10^2 mm
N.SOM	Average summer precipitation	10^2 mm
N.WIN	Average winter precipitation	10^2 mm
GEOL.BM	Bohemian Massif	%
GEOL.QUA	Quaternary sediments	%
GEOL.TER	Tertiary sediments	%
GEOL.FLY	Flysch	%
GEOL.KAL	Limestone	%
GEOL.KRI	Crystalline rock	%
GEOL.SHAL	Shallow groundwater table	%
GEOL.DEEP	Deep groundwater table	%
GEOL.QUELL	Source region	%
BONU.URB	Urban	%
BONU.ACK	Agriculture	%
BONU.DAU	Permanent crop	%
BONU.GRU	Grassland	%
BONU.WAL	Forest	%
BONU.FEU	Wetland	%
BONU.LOS	Wasteland (rocks)	%
BONU.WAS	Water surfaces	%
BONU.EIS	Glacier	%
SDENS	Stream network density	10^2 m km^{-1}
BFI	Baseflow index	–
Rec	Recession coefficient	day

3. Methodology

3.1. Drought analysis

Droughts were identified from the time series of precipitation and discharge with the widely-used threshold level approach (Zelenhasić and Salvai, 1987; Hisdal et al., 2004; Fleig et al., 2006; Van Loon, 2013), defining a drought when a variable falls below a pre-defined threshold. To reflect seasonality we used a variable threshold based on the 80th percentile of the flow duration curves of a 30 days moving window (Beyene et al., 2014). This means that every day in the year has a different threshold level based on the 80th percentile of the flow duration curve of the discharge/precipitation measured on that day, the 15 days before that day, and the 15 days after that day, for all years in the time series. This method has proven to be most robust in catchments with pronounced seasonality, for example catchments dominated by snow accumulation and melt (Beyene et al., 2014). We applied a pooling procedure to both time series of precipitation and discharge to pool dependent drought events, namely a 30-day moving average (Tallaksen and Hisdal, 1997; Hisdal et al., 2004; Fleig et al., 2006). The duration of a drought event was determined by calculating the total number of consecutive days that the variable was below the threshold and the deficit volume is the sum of the deviations from the threshold times the number of days (so the area between the two curves when the variable is below the threshold). Minor droughts with a duration of less than 3 days were removed. Subsequently, the statistics mean, maximum and standard deviation were calculated for both drought duration and deficit.

3.2. Statistical analysis

We investigated the effects of climate and catchment characteristics on discharge drought duration and deficit by statistical analysis. In the first part of the investigation we analysed the strength of the relationships between discharge drought and the individual climate and catchment characteristics using bivariate correlation analysis. We calculated the correlation matrix of pairwise combinations of all variables based on Pearson correlation coefficients. The correlation matrix allowed us to find important relationships between discharge drought characteristics and the various climate and catchment characteristics. As relationships could be non-linear, we also computed Spearman correlation coefficients and studied correlation plots to verify the results. Correlation analysis is limited by the fact that catchment characteristics are likely not independent, due to co-evolution of landscape, climate and geology. To explore intercorrelations of catchment characteristics, we analysed the correlation structure using heatmaps as implemented in the R software package 'stats'. Heatmaps employ an appropriate colour-coding to visualise sign and strength of relationships from the correlation matrix. Moreover, the algorithm performs a clustering of the pairwise correlations in order to find groups of variables which are dependent on each other. After rows and columns are arranged according to similarity, previously undetectable patterns can become obvious. The analysis is therefore useful for finding groups of climate and catchment characteristics which have a joint effect on drought characteristics. Based on hydrological reasoning, we aim to identify key variables of each group which appear as the most important physical factors in drought generation.

In the second step we extended the scope of analysis to interactions of key variables in drought generation. For this we applied linear models with multiple regression and interaction terms, which make the linear model more flexible to represent possible non-linear relationships. We also applied varying slope models to perform fitting individually for different climatological regions. We tested important combinations of predictor variables as suggested by correlation analysis and compared them with automatic stepwise (combined forward and backward) regression analysis based on the Akaike Information Criterion (Akaike, 1974). If the model appears well representative (from residual statistics and in terms of model assumptions) it can be used to analyse the effects of a predictor on the drought characteristic. By 'effect' we denote the change in a response variable produced by a change in one or more explanatory or factor variables, adjusted for the other variables in the model. In case of more than one predictor, the effect of one explanatory variable (regression line) is adjusted for the other variables in the model. This is similar to partial correlation analysis where the correlation between two variables is adjusted for the effect of a confounding variable. Linear model effects, however, are more general than partial correlations, since the method allows a simultaneous consideration of a number of predictors including possible interactions. The computation and visualisation of the effects of the regression terms is conducted using the R-package 'effects' (Fox, 2003).

4. Results

4.1. Drought analysis

Drought analysis on the precipitation data (Tables 2 and 3) shows that there is little difference between clusters in the number (around 4.8 per year) and average duration (around 15 days) of meteorological droughts. The largest difference is found between Gail and Inn (Gail: 4.5 droughts per year with an average duration of 16.2 days and Inn: 5.2 droughts per year with an average duration of 13.4 days). This difference is related to the variability in precipitation described in Section 2. In Gail there are less, but longer dry spells, whereas in Inn the higher number of short dry spells points to a larger variability in precipitation. The deficit volume of droughts in precipitation is more variable with 3.9 mm for Weinv and 13.3 mm for Brewa. This difference is due to differences in mean annual precipitation, which amounts to 500 mm per year for Weinv and 1900 mm per year for Brewa. A higher mean annual precipitation results in a higher threshold, which produces higher deficit volumes.

In all catchments we see a clear propagation of the drought signal from meteorological to hydrological drought (Tables 2 and 3): there are fewer but longer droughts in discharge than in precipitation (on average 2.2 droughts per year with an average duration of 35 days in discharge vs. 4.8 droughts per year with an average duration of 15 days in precipitation). There is much more variability between the clusters in hydrological drought characteristics than in meteorological drought characteristics. The number of discharge droughts varies between 1.4 and 3.2 and average duration ranges from 23 to 54 days. Gurk has fewest and longest droughts and Brewa has most and shortest droughts. The average deficit volume of droughts in discharge is comparable with that of droughts in precipitation, but the ranges are even larger (0.5–18 mm per cluster and 0.3–22 mm per catchment). Some clusters are homogeneous in terms of discharge drought

Table 2
General drought characteristics using a 80% variable threshold (based on a moving window of 30 days), the moving average method for pooling, and a minimum duration of 3 days for the hydrometeorological variables of all clusters.

	Station	No. of droughts [per year]	Mean duration [day]	Max duration [day]	Mean deficit [mm]	Max deficit [mm]
Brewa	Precipitation	4.8	15.1	85	13.3	133
	200154	3.1	24	144	17	284
	200204	3.5	21	130	16	226
	200287	3.1	23	128	22	398
	Average Q	3.2	23	134	18	303
Buwe	Precipitation	4.8	15.0	95	6.8	57
	208827	1.4	53	409	5.2	51
	208835	1.5	48	321	4.9	47
	210245	1.4	53	437	3.0	48
	208835	1.6	45	311	3.2	42
	208827	1.9	40	426	3.8	92
	Average Q	1.6	48	381	4.0	56
Dachst	Precipitation	4.7	14.8	73	12.5	99
	205799	2.8	26	143	14	186
	205831	2.6	28	143	13	138
	205856	2.7	27	122	8.2	89
	210583	2.8	26	142	17	223
	Average Q	2.7	27	138	13	159
Gail	Precipitation	4.5	16.2	150	10.7	113
	212613	1.8	42	301	14	166
	212647	1.4	53	293	18	123
	212670	1.6	46	213	15	117
	212753	1.7	42	216	13	115
	Average Q	1.6	46	256	15	130
Gurk	Precipitation	4.9	14.7	76	9.1	78
	212860	1.7	43	254	8.9	70
	212951	1.1	66	379	6.4	42
	Average Q	1.4	54	317	7.6	56
Hoalp	Precipitation	4.9	14.1	92	7.4	81
	212068	2.9	25	147	19	174
	212076	2.9	25	141	16	175
	Average Q	2.9	25	144	17	175

Table 3
Continuation - General drought characteristics using a 80% variable threshold (based on a moving window of 30 days), the moving average method for pooling, and a minimum duration of 3 days for the hydrometeorological variables of all clusters.

	Station	No. of droughts [per year]	Mean duration [day]	Max duration [day]	Mean deficit [mm]	Max deficit [mm]
Innviertel	Precipitation	5.2	13.4	79	5.6	57
	204768	2.8	26	202	3.8	47
	204784	2.5	29	285	4.9	66
	204834	2.7	27	180	3.5	27
	204859	2.7	26	181	3.7	31
	204958	2.4	31	158	3.2	32
	205047	2.4	30	149	3.5	34
	Average Q	2.6	28	193	3.8	40
Leitha	Precipitation	5.0	14.4	90	4.6	40.9
	208413	1.6	46	286	4.7	32
	209007	2.0	38	256	1.9	20
	210013	1.9	42	245	1.6	20
	Average Q	1.8	42	262	2.8	24
Muhlviertel	Precipitation	4.6	15.2	91	6.7	60
	204875	2.2	34	234	6.7	78
	204891	2.1	35	242	8.3	66
	204917	2.1	34	186	7.1	70
	204925	1.8	40	205	5.7	40
	Average Q	2.0	36	217	7.0	64
Ozt	Precipitation	5.0	13.9	161	6.0	94
	201350	2.3	28	222	14.0	203
	201376	2.4	26	161	14.3	205
	201392	2.5	25	205	9.3	120
	201418	2.4	24	193	7.0	99
	201434	2.7	24	192	6.5	92
	Average Q	2.4	25	195	10.2	144
Waldviertel	Precipitation	4.9	14.8	80	4.6	64
	205997	2.1	31.2	246	4.5	44.2
	207944	2.2	27.5	256	2.6	35.1
	Average Q	2.1	29	251	4	40
Weinviertel	Precipitation	4.8	15.1	76	3.9	28
	208041	1.8	42	352	0.59	6.7
	208058	1.5	48	391	0.53	7.4
	208447	2.5	29	133	0.37	2.5
	208637	2.0	36	348	0.36	5.0
	208678	2.0	39	295	0.71	11.2
	209189	2.2	33	198	0.32	2.6
	Average Q	2.0	38	286	0.5	6

characteristics, others are quite heterogeneous. Most variability is visible in the Weinv cluster. The longest drought occurs in Buwe (437 days, more than 14 months) and the maximum deficit occurs in Brewa (398 mm). The different values for average drought duration and deficit in Tables 2 and 3 are a first indication that drought duration and deficit might have different governing factors.

This is even more apparent from the spatial distribution of mean duration and deficit of both precipitation and discharge droughts (Fig. 2). We can see that:

- the average duration of precipitation droughts (P_meandur) is high in the East and South;
- the average deficit volume of precipitation droughts (P_meandef) is highest in the northern Alps;
- the average duration of discharge droughts (Q_meandur) is high in the East and South, but more scattered than P_meandur;
- the average deficit volume of discharge droughts (Q_meandef) is high in the southern Alps.

When comparing Fig. 2 with Fig. 1, some of the patterns can be explained. The general patterns of both P_meandur and Q_meandur reflect the influence of climate: in the Alps, precipitation events are more frequent than in the lowlands, so droughts in the Alpine region have the lowest duration. In the region north of the Alps, the patterns reflect increasing drought duration from west to east which is obviously related to decline in annual precipitation and increasing aridity (Fig. 1d). South and southeast of the Alps longer dry spells are observed, because the catchments there are screened by the Alps (Section 2). Overall, Q_meandur has longer time scales than P_meandur, reflecting drought propagation, i.e. pooling of shorter meteorological drought events into longer streamflow droughts as a result of catchment storage processes. Differences between catchments in the same cluster are likely the effect of geology (storage, Fig. 1c), which is most pronounced in the eastern (Weinv) and southern clusters (Gail and Gurk). This would indicate a combined effect of climate and catchment control on hydrological drought duration.

It is interesting to see that the patterns of drought deficit in precipitation and discharge (P_meandef and Q_meandef) are very different from the patterns of drought duration (Fig. 2). Highest deficit volumes are found in the Alpine region. High deficit volumes in the northern Alps are expected because of the high catchment wetness (Fig. 1d) resulting in higher threshold values, but the high deficit volumes in discharge (Q_meandef) seem to reflect more the spatial distribution of altitude (Fig. 1b) than that of precipitation (Fig. 1d). So, the question arises whether there is an additional effect of catchment properties related to elevation on deficit volume of hydrological droughts.

For a selection of clusters, we studied some catchment characteristics that were assumed to influence drought duration and deficit (i.e. area, elevation, BFI and recession constant) in more detail (Table 4). Some conclusions can be drawn:

- All Brewa catchments have many droughts with short duration and high deficit (Table 2), they also have a small area, high elevation, low BFIs and low recession constants. The geology of the Brewa catchments is characterised as Flysch. According to Gaál et al. (2012) "Flysch tends to produce very flashy response as the flow paths are at the surface or very near the surface with little infiltration." This has important implications for floods (short flood time scales, Gaál et al. (2012)), but also for drought.
- All Muhlv catchments have few droughts with long duration and average deficit (Table 3), they also have a large area, low elevation, high BFIs and high recession constants.
- The Innv and Weinv catchments show high variation in area, BFI and recession constant, whereas elevation is comparable. This offers the possibility to separate the effect of storage from climate and elevation effects. For Innv, catchments with a high BFI, also have longer drought events and lower deficit volume (Table 3). For Weinv the relation is less clear.

4.2. Statistical analysis

Statistical analysis allows for a quantitative investigation of relations between hydrological drought duration and deficit and possible governing factors (climate and catchment characteristics). The heatmap in Fig. 3 shows the correlation structure between average duration and deficit of droughts in discharge (Q_meandur and Q_meandef), average duration and deficit of droughts in precipitation (P_meandur and P_meandef) and a selection of climate and catchment characteristics from Table 1. We did not include all variables because some are interchangeable in the sense that they correlate the same way with other variables, for example the variables related to altitude (H.MIN, H.MAX, H.MEAN) and precipitation (N.GES, N.SOM, N.WIN).

In Fig. 3 red squares indicate high positive correlation, blue squares indicate high negative correlation. These correlations are based on Pearson correlation. The heatmap based on Spearman correlation coefficients to test for non-linearity showed a similar

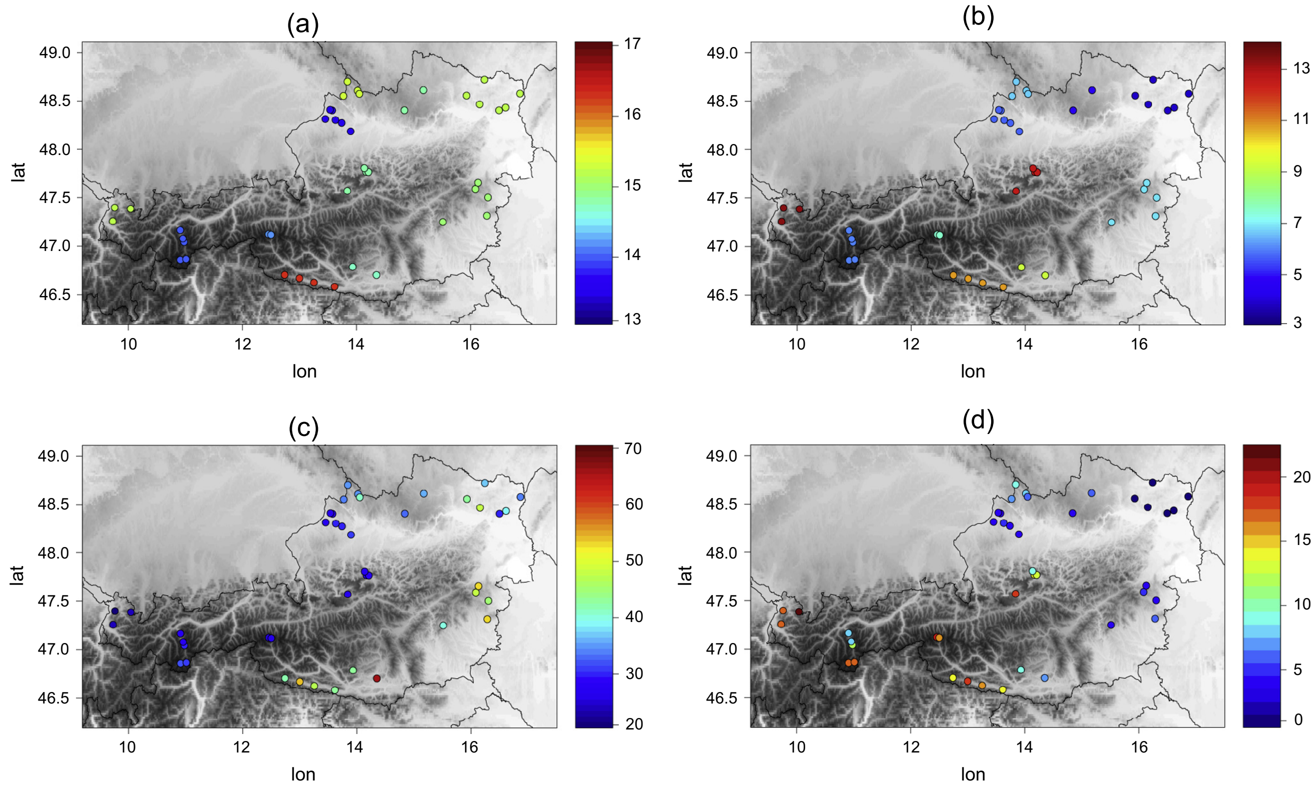

Fig. 2. Drought duration and deficit in precipitation and discharge. (a) P_meandur [days], (b) P_meandef [mm], (c) Q_meandur [days], (d) Q_meandef [mm]. Note the different colour scales.

Table 4
Selected catchment characteristics per catchment for a subset of clusters (variable names see Table 1).

		SUM.AREA [10^1 km^2]	H.MEAN [10^2 m]	BFI [–]	Rec [–]
Brewa	200154	33	1472	0.54	10
	200204	54	1159	0.30	6.7
	200287	31	1510	0.43	11
Innviertel	204768	70	456	0.45	20
	204784	60	460	0.42	13
	204834	81	486	0.67	16
	204859	303	443	0.52	11
	204958	66	460	0.74	17
	205047	29	420	0.49	16
Muhlviertel	204875	135	693	0.69	19
	204891	123	790	0.67	19
	204917	255	763	0.68	18
	204925	139	759	0.68	19
Weinviertel	208041	213	337	0.72	16
	208058	380	285	0.77	19
	208447	130	273	0.69	18
	208637	370	321	0.60	10
	208678	69	232	0.79	–
	209189	515	260	0.77	–

pattern. This indicates that we can assume that in our case linear models are also suited to represent monotonic relationships even if they are not perfectly linear. The ordering of variables is the result of hierarchical cluster analysis using Euclidean distance. This yields that variables with similar correlation patterns are grouped together. An example is the high correlation and close clustering between SL.FL, BONU.ACK, GEOL.TER and BONU.URB, which indicates that urban area and agriculture are present in regions with a slight slope and tertiary sediments. This is not surprising and does not give any information explaining drought characteristics. In the following paragraphs we only focus on factors that relate to the duration and deficit volume of discharge droughts.

4.2.1. Drought duration

The average duration of droughts in discharge (Q_meandur) shows highest correlation (Fig. 3) with the baseflow index (BFI). From the scatterplot (Fig. 4a) this relation is obvious. BFI itself is not a catchment characteristic but it integrates the effect of storage and response times of a catchment (Section 2). The same is true for the recession constant (Rec), but Rec has a lower correlation with Q_meandur.

It is also interesting that Q_meandur has a much lower correlation with catchment characteristics indicative of catchment storage, such as area percentages of geological classes (GEOL.QUA, GEOL.KRI), aquifers (GEOL.SHAL, GEOL.DEEP), lakes and wetlands (BONU.WAS, BONU.FEU), and catchment area (SUM.AREA), than with BFI (Fig. 3). Although all these correlations are plausible regarding their sign (characteristics reflecting high storage are positively correlated), not one of them seems dominant. One of the reasons for that is that not all catchments have data for all variables. In Fig. 4a, for example, all catchments with some degree of GEOL.DEEP and GEOL.SHAL are indicated. These correspond to high BFI, but the low number of catchments with GEOL.DEEP or GEOL.SHAL makes finding a quantitative relation difficult.

After BFI, the highest correlation of Q_meandur is with P_meandur, and there is also a strong negative correlation with mean annual precipitation (N.GES) (Fig. 3). This points at an effect of climate on the duration of droughts in discharge. In the drier catchments with longer dry spells the duration of discharge droughts is longer (Fig. 4b), but the relation is less clear than with BFI.

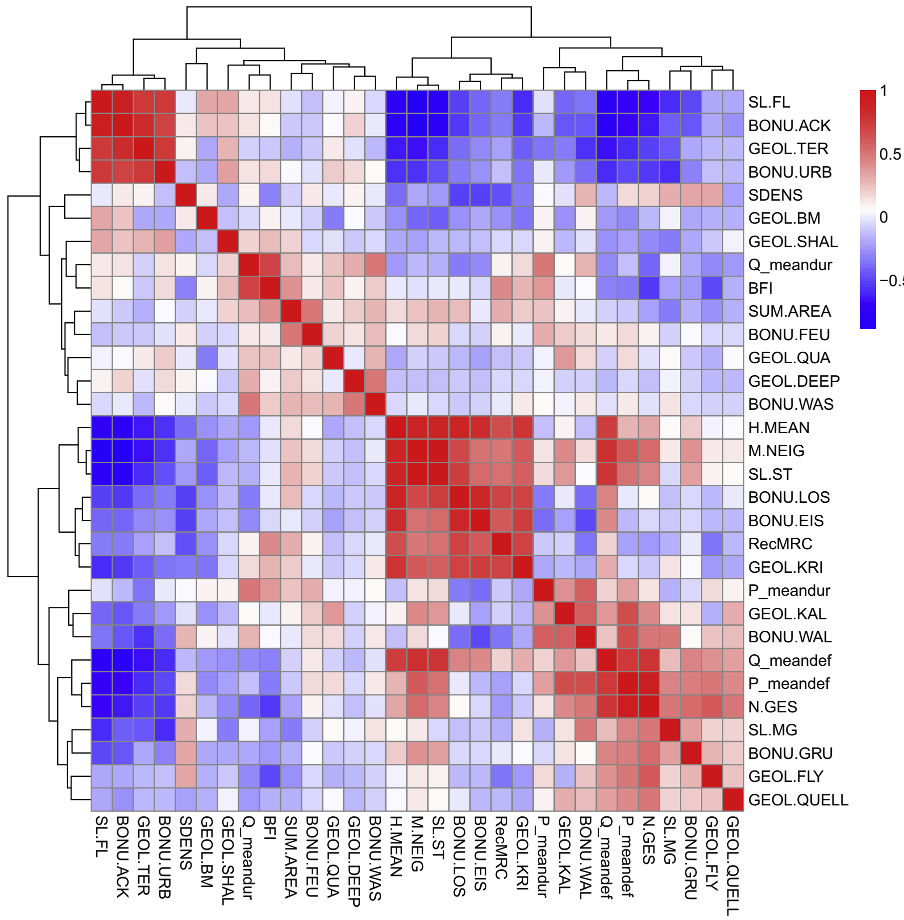

Fig. 3. Heatmap of correlations between drought severity indices, climate and catchment characteristics. Euclidean distances used for clustering.

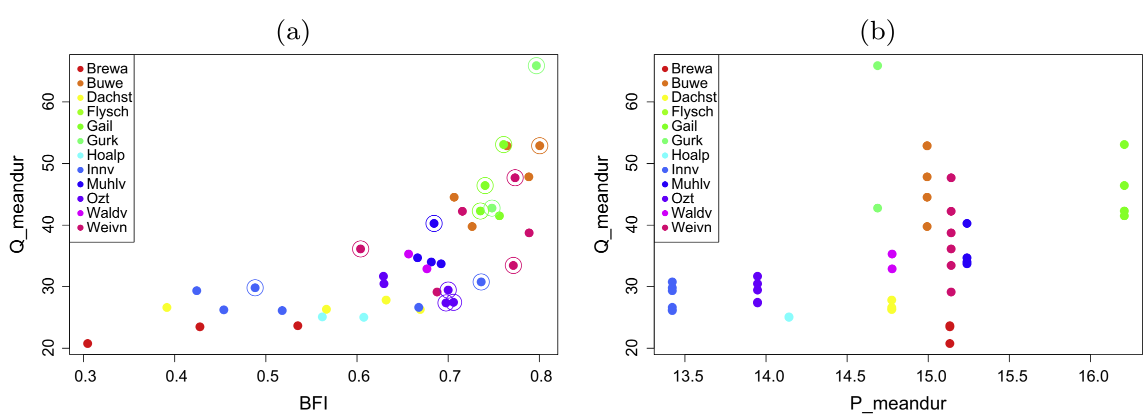

Fig. 4. Relation between the average duration of droughts in discharge (Q_meandur) and (a) the baseflow index (BFI), colour coded per cluster. Catchments with deep or shallow groundwater (GEOL.SHAL and GEOL.DEEP) are indicated with circles and (b) the average duration of droughts in precipitation (P_meandur).

To investigate the effects of climate and catchment characteristics on drought duration in more detail, we studied a number of linear regression models. In Table 5 the three best models are described. The model with only BFI is highly significant (model 1) and the model with only P_meandur is also significant (model 2). P_meandur also adds information to the model with BFI (model 3) and so much that this combined model is the best model to explain Q_meandur. Adding more complex interactions or adding other variables did not improve the model.

With the same analysis we can find out if any combination of catchment characteristics can replace BFI to explain Q_meandur. In Table 5 we see that only using catchment characteristics does not yield a significant model (model 4). Adding P_meandur to model 4 does yield a significant model (model 5). There are differences in significance between the different catchment characteristics, but again no factor seems dominant. All variables are needed to yield a model that is comparable to the model with BFI and P_meandur (model 3), excluding one of the variables from model

Table 5
Linear models tested to explain the average duration of discharge droughts (Q_meandur), with multiple regression and interaction terms, including their statistical significance.

	Model 1	Model 2	Model 3
BFI	1.33e−07 (***)	–	5.27e−08 (***)
P_meandur	–	0.00103 (**)	0.0277 (*)
Comparing models	–	–	1.001e−06 (***)
	Model 3	**Model 4**	**Model 5**
BFI	5.27e−08 (***)	–	–
P_meandur	0.0277 (*)	–	7.14e−05 (***)
GEOL.SHAL	–	0.1618	0.20327
GEOL.DEEP	–	0.0172 (*)	0.00629 (**)
GEOL.QUA	–	0.0857 (.)	0.04168 (*)
GEOL.KRI	–	0.0926 (.)	0.00613 (**)
BONU.WAL	–	0.0152 (*)	0.66517
BONU.WAS	–	0.0813 (.)	0.02959 (*)
BONU.FEU	–	0.6750	0.12049
SDENS	–	0.3715	0.03521 (*)
SUM.AREA	–	0.6193	0.79736
Comparing models	7.281e−06 (***)	–	0.0001672 (***)

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

5 did not yield a significant model (not shown). In the stepwise regression analysis adding the variables of model 5 one-by-one resulted in a decreasing Akaike Information Criterion, so increasing model performance. We can conclude that in our study area BFI is made up of a combination of catchment characteristics related to geology, land use and area. However, the information content of each of these characteristics alone is rather low as compared to BFI, which is highly informative for streamflow drought duration.

4.2.2. Drought deficit

The average deficit of droughts in discharge (Q_meandef) shows high correlation (Fig. 3) with variables related to climate (N.GES and P_meandef) and catchment characteristics (H.MEAN, M.NEIG, SL.ST, BONU.EIS, BONU.LOS, GEOL.KAL). These variables are not independent: precipitation generally increases with altitude, slopes are higher in the Alps, glaciers are present only above 2500 m, and calcareous rocks are found in the northern Alps (Fig. 1). All these characteristics are finally related to catchment altitude. To disentangle the effects of climate and altitude we studied the relation of Q_meandef with mean annual precipitation (N.GES) and mean elevation (H.MEAN). Both show a positive relation (Fig. 5a and b). The relation with N.GES was expected; high average precipitation results in high average discharge and therefore a high threshold. Fluctuations around the threshold then result in high deficit volumes, as can be seen in Fig. 6a, in which the hydrographs of two catchments in the same cluster are compared. The catchments show similar drought periods but deficit volumes are different, i.e. the upper (208413) and lower (209007) catchment have an average discharge of 1.4 and 0.5 mm/d and an average deficit of 4.7 and 1.9 mm, respectively (Table 3). Hence, catchments with higher mean discharge have higher deficit volumes. This wetness effect was also concluded in Section 4.1 and hypothesised in Section 1.

In Section 4.1 the ambiguous relation between N.GES and H.MEAN was already noted, but with statistical analysis we can

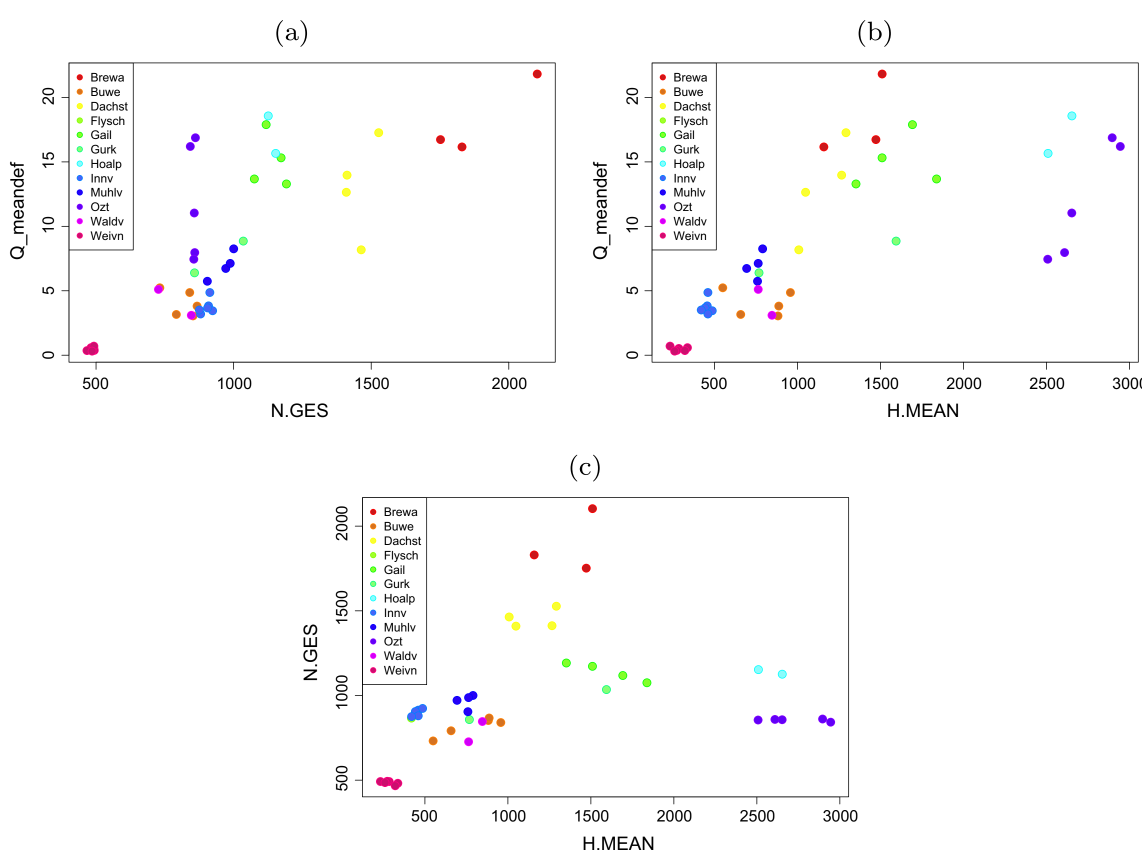

Fig. 5. Relation between the average deficit of droughts in discharge (Q_meandef) and (a) mean annual precipitation (N.GES), and (b) average elevation (H.MEAN), and (c) the relation between N.GES and H.MEAN; colour coded per cluster.

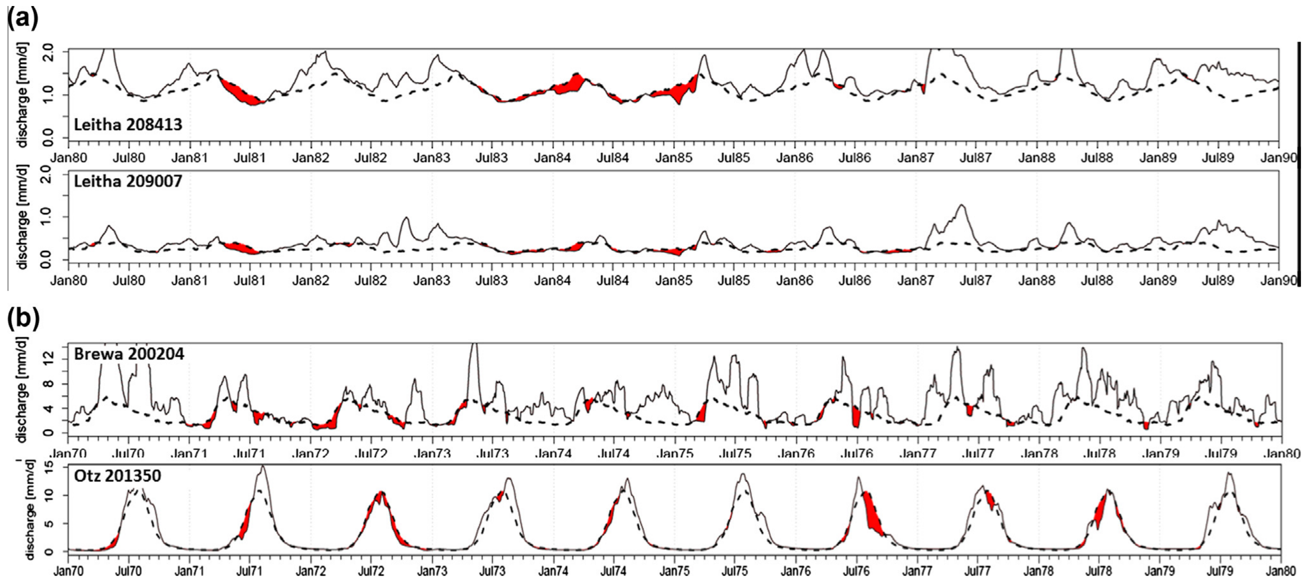

Fig. 6. Example of the effect of a higher mean discharge on drought deficit volume, (a) comparing two catchments in the Leitha cluster, and (b) comparing a catchment in the Brewa and one in the Otz cluster.

Table 6
Linear models tested to explain the average deficit volume of discharge droughts (Q_meandef), with multiple regression and interaction terms, including their statistical significance.

	Model 1	Model 2	Model 3	Model 4
N.GES	5.54e−10 (***)	–	< 2e−16 (***)	<2e−16 (***)
H.MEAN	–	2.72e−08 (***)	3.64e−11 (***)	1.08e−11 (***)
Interaction (N.GES, H.MEAN)	–	–	–	0.0243 (*)
Comparing models	–	–	1.904e−12 (***)	0.028516 (*)

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

study if there is any additional information in H.MEAN. Linear regressions models (Table 6) prove that both N.GES and H.MEAN are important in modelling Q_meandef (models 1–3). The interaction between both is also significant (model 4), but it does not result in a better model ($p = 0.029$ instead of 1.9e−12). Since a bimodal distribution is visible between N.GES and H.MEAN (Fig. 5c), i.e. in some clusters precipitation does not increase with altitude, we need a varying slope model to account for the confounding effects of altitude and precipitation. We grouped the catchments in the southern Alps region that have a deviating relation of precipitation with altitude (Ozt, Hoalp, Gail and Gurk; Figs. 1 and 5c) and fitted a different relation between Q_meandef and N.GES for this selection and for the remaining catchments. In Fig. 7 we see a clear effect of H.MEAN on Q_meandef (after adjusting for precipitation effects). We also tried a model that differentiates between the southern Alpine catchments and the rest in terms of H.MEAN, but that did not give satisfactory results (not shown).

From this analysis we can conclude that, additional to the precipitation effect mentioned above, the elevation of a catchment plays a large role in determining the average drought deficit. The higher the catchment, the larger is the deficit volume. This can be explained by the stronger seasonality of flows in higher altitudes, i.e. alpine areas have stronger seasonal regimes compared to lowland areas (Weingartner et al., 2013). Due to snow accumulation in winter and snow melt and glacier melt in summer, streamflow is concentrated in a short season. This results in seasonally high thresholds and hence high deficit volumes. In the example in Fig. 6b, the hydrographs of two catchments with similar deficit volume (on average 16 and 14 mm; see Tables 2 and 3) show very different drought behaviour. In Brewa severe droughts can occur in any season and deficit volumes are high because of the overall high threshold (caused by high precipitation on the north side of the Alps), whereas in Otz severe droughts only occur in the summer half year because of zero flows in winter and deficit volumes are high because of the seasonally high threshold (caused by concentration of streamflow in a short season in the highest part of the Alps, Weingartner et al., 2013). According to the hydrological drought typology, the most severe droughts in Brewa are *classical rainfall deficit droughts* (Van Loon and Van Lanen, 2012) and the most severe droughts in Otz are *rain-to-snow-season droughts*, *snowmelt droughts* and *glaciermelt droughts* (Van Loon and Van Lanen, 2012; Van Loon et al., 2014). This example underlines the fact that precipitation and altitude are different effects in generating high deficit volumes. The higher the precipitation, the larger the possible deviations from normal, and therefore the higher the deficit volumes. And the higher the elevation, the more the flow is concentrated in a short season and the higher the deficit volumes.

From this statistical analysis we can conclude that for hydrological drought duration catchment storage (various catchment variables with a combined effect represented by BFI) is dominant and climate plays a role through the duration of dry spells. For hydrological drought deficit we found that catchment wetness (depending on mean annual precipitation) and seasonality of the regime (depending on elevation) are of equal importance. We did the same analysis on the maximum and standard deviation of drought duration and deficit, but that did not change our conclusions.

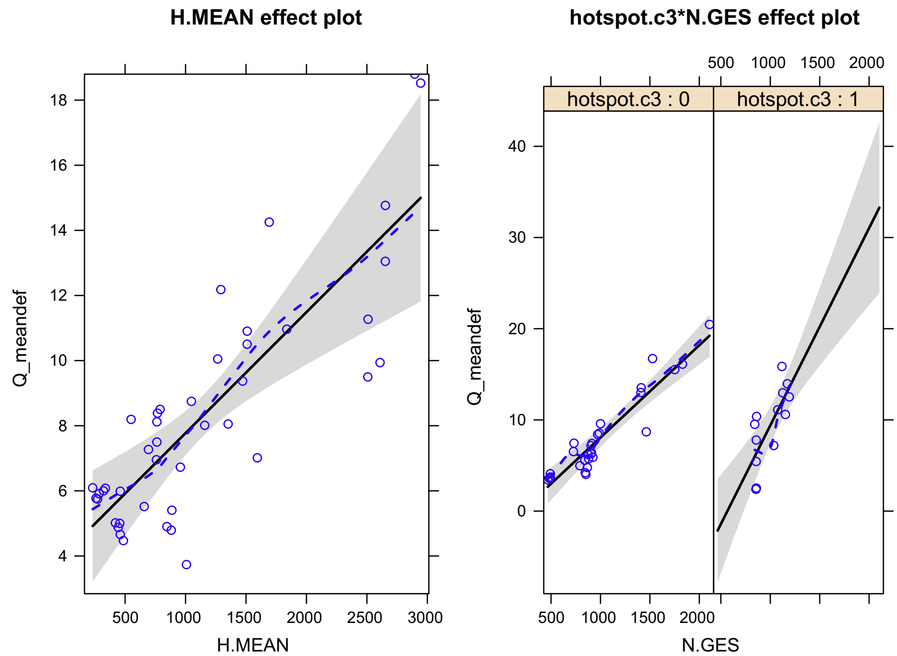

Fig. 7. Varying slope model of Q_meandef vs. H.MEAN and N.GES (subdivided between Southern Alps catchments and the rest); contribution of each regression term to the prediction.

5. Discussion

5.1. Data and methods

In this study, the variable threshold level method was used for drought analysis. As mentioned before (Section 1) standardised indices like SPI were not applied because they cannot provide information on drought deficit volumes. Instead of using a variable threshold we could also have chosen a fixed threshold, but the yearly recurring winter low flows in the Alpine catchments (Section 2) should not be reported as drought because they are not a deviation from normal conditions (Van Loon and Van Lanen, 2012; Van Loon, 2013). Anomalies in the high flow season can be important in water resources management (hydropower production), so therefore we decided to use a variable threshold level, as was done previously in many other studies (e.g. Stahl, 2001; Nyabeze, 2004; Hirabayashi et al., 2008; Vidal et al., 2010; Hannaford et al., 2011; Prudhomme et al., 2011; Van Huijgevoort et al., 2013; Parry et al., 2012).

Pooling with a 30-days moving average was done to merge dependent drought events. This pooling allowed us to focus on the longer-term water shortages. We estimate the effect of the pooling method on our conclusions to be negligible, because we performed the same correlation analysis on drought events without pooling and obtained the same results. Also for the non-pooled drought events catchment storage was most important for drought duration, whereas mean annual precipitation and elevation played a major role for drought deficit. The statistical relations were only slightly weaker.

5.2. Drought duration and deficit

The relation between hydrological drought duration and BFI (baseflow index) is confirmed in earlier studies (Clausen and Pearson, 1995; Zaidman et al., 2002; Fendeková and Fendek, 2012; Van Huijgevoort, 2014). In our study we found BFI to be a proxy for the combination of a number of catchment characteristics indicative of storage. This is in accordance with Peters et al. (2003), Peters et al. (2005), Bloomfield et al. (2009) and Salinas et al. (2013). Bloomfield et al. (2009) showed that geology is a key determinant of BFI. Although other factors play a role as well (Tetzlaff et al., 2008), it is not possible to say that one parameter (e.g. a soil index or the catchment area) is responsible for all the variation in BFI (Bloomfield et al., 2009). The statistical analysis presented in this paper confirmed that a combination of a high number of catchment characteristics is needed to obtain the same effect on drought duration as BFI.

The governing factors of drought deficit are investigated in some studies (Clausen and Pearson, 1995; Kjeldsen et al., 2000; Van Lanen et al., 2013) and in all of those the deficit was standardised to remove the effect of differences in catchment wetness. So, although the relationship between drought deficit and mean annual precipitation was never investigated explicitly, the standardisation is an indication that mean annual precipitation does play an important role. We also tested the relation between standardised deficit and climate and catchment characteristics and found that the effect of climate was completely removed by the standardisation and only catchment control (BFI) remained.

5.3. General applicability of the results

Since this research is based on a specific study area, its conclusions might not be valid for other regions. The Greater Alpine Region was chosen because of, on the one hand, the wealth of hydrometeorological data and catchment descriptors available and, on the other hand, the large variability in climate and catchment characteristics.

Within our study region differences in temperature and precipitation can be found related to the presence of mountains (decreasing temperature with altitude, increasing precipitation with altitude except in the rain shadow, and increasing aridity towards the east), influencing also the accumulation of snow. However, these differences are relatively minor as almost the entire study region has a continental climate type and is governed by the same weather pattern with large scale depressions moving in from the north-west creating comparable meteorological drought conditions. If we would compare this region to a region with a completely different climate, for example much drier and governed by multi-year weather patterns like in Australia, then we would expect differences in drought duration to be more determined by these differences in climate. However, when comparing catchments within that drier climate region again catchment characteristics will be dominant in determining hydrological drought duration. Hence, our results are assumed to be applicable to regions that are relatively uniform in climate. This reconciles our results with the hypothesis of Tallaksen and Hisdal (1997) mentioned in Section 1, because in that paper the authors are probably referring to the effects of climate at a larger scale.

The effect of elevation is not purely catchment control, because it is actually related to mean annual temperature, i.e. the lower the temperature, the higher the glacier cover and snow accumulation, the higher the seasonality, the higher the deficit volume. Because it is related to temperature, the effect of altitude is different in different climates. For example, in warmer climates (e.g. in the tropics) the relation with altitude is different since snow and glaciers generally occur at higher altitudes than in temperate and continental climates. In regions without snow and glaciers this effect of altitude might be totally absent, because the concentration of streamflow in a short season does not occur (Weingartner et al., 2013). The effect of temperature also means that on a cross-section from south to north on the Northern Hemisphere there might be a relation between drought deficit and latitude.

Consequently, the conclusion of what is the dominant factor in determining hydrological drought duration and deficit is highly dependent on scale. On a global scale, drought duration might be more related to climate than to catchment control and the effect of altitude on drought deficit might not be obvious. However, on the scale that water resources management takes place, namely a regional to national scale, the climate is assumed to be governed by the same weather generating mechanism and therefore relatively uniform, while geology, soil, land use and other catchment characteristics vary more on these smaller scales.

Climate change may lead to non-stationary relationships between hydrological variables. In this paper, we analysed average relationships over a standard period as is common for low flow regionalisation studies. This allows comparison between stations even in case of weak non-stationarity. An analysis of possible future changes in the found relationships would be a logical next step after this research. This would, however, require much longer records than usually available.

6. Conclusions

Drought analysis and statistical analysis on an extensive Austrian dataset, combining hydrometeorological data from a high number of catchments with thematic data on climate and catchment characteristics, prove that hydrological drought duration and deficit do not have the same governing factors. Hydrological drought duration is determined by BFI (combining information on storage in the catchment related to a number of different catchment characteristics) and the duration of dry spells in precipitation (that increases with increasing aridity). BFI is most important, so catchment control on drought duration is dominant. Hydrological drought deficit is determined by mean annual precipitation and elevation, which both are related to climate control. The additional effect of elevation is attributed to the concentration of discharge in a short season (summer) with rainfall, snow melt and glacier melt in highly seasonal regimes.

This information is relevant for sectors that experience different drought impacts. Based on their climate and catchment characteristics catchments can be selected that are more sensitive to severe drought in terms of drought duration and catchments that are more sensitive to severe drought in terms of drought deficit.

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References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Automatic Control 19 (6), 716–723. http://dx.doi.org/10.1109/TAC.1974.1100705.

Beyene, B.S., Van Loon, A.F., Van Lanen, H.A.J., Torfs, P.J.J.F., 2014. Investigation of variable threshold level approaches for hydrological drought identification. Hydrol. Earth Syst. Sci. Discuss. 11, 12765–12797. http://dx.doi.org/10.5194/hessd-11-12765-2014.

Bloomfield, J.P., Marchant, B.P., 2013. Analysis of groundwater drought building on the standardised precipitation index approach. Hydrol. Earth Syst. Sci. 17 (12), 4769–4787. http://dx.doi.org/10.5194/hess-17-4769-2013.

Bloomfield, J.P., Allen, D.J., Griffiths, K.J., 2009. Examining geological controls on baseflow index (bfi) using regression analysis: an illustration from the thames basin, UK. J. Hydrol. 373 (1–2), 164–176. http://dx.doi.org/10.1016/j.jhydrol.2009.04.025.

Bond, N., Lake, P., Arthington, A., 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia 600 (1), 3–16. http://dx.doi.org/10.1007/s10750-008-9326-z.

Carroll, N., Frijters, P., Shields, M.A., 2009. Quantifying the costs of drought: new evidence from life satisfaction data. J. Population Econ. 22 (2), 445–461. http://dx.doi.org/10.1007/s00148-007-0174-3.

Choat, B., Jansen, S., Brodribb, T.J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Feild, T.S., Gleason, S.M., Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martinez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., Zanne, A.E., 2012. Global convergence in the vulnerability of forests to drought. Nature 491 (7426), 752–755. http://dx.doi.org/10.1038/nature11688.

Clausen, B., Pearson, C., 1995. Regional frequency analysis of annual maximum streamflow drought. J. Hydrol. 173 (1–4), 111–130, doi:http://dx.doi.org/10.1016/0022-1694(95)02713-Y.

Dracup, J.A., Kil Seong, L., Paulson Jr, E.G., 1980. On the statistical characteristics of drought events. Water Resour. Res. 16 (2), 289–296.

Fendeková, M., Fendek, M., 2012. Groundwater drought in the Nitra River Basin – identification and classification. J. Hydrol. Hydromech. 60, 185.

Fleig, A.K., Tallaksen, L.M., Hisdal, H., Demuth, S., 2006. A global evaluation of streamflow drought characteristics. Hydrol. Earth Syst. Sci. 10 (4), 535–552. http://dx.doi.org/10.5194/hess-10-535-2006.

Fox, J., 2003. Effect displays in r for generalised linear models. J. Stat. Softw. 8 (15), 1–27.

Gaál, L., Szolgay, J., Kohnová, S., Parajka, J., Merz, R., Viglione, A., Blöschl, G., 2012. Flood timescales: understanding the interplay of climate and catchment processes through comparative hydrology. Water Resour. Res. 48 (4). http://dx.doi.org/10.1029/2011WR011509.

Garcia-Herrera, R., Daz, J., Trigo, R.M., Luterbacher, J., Fischer, E.M., 2010. A review of the european summer heat wave of 2003. Crit. Rev. Environ. Sci. Technol. 40 (4), 267–306.

Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., Prudhomme, C., 2011. Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit. Hydrol. Process. 25 (7), 1146–1162. http://dx.doi.org/10.1002/hyp.7725.

Haslinger, K., Koffler, D., Schöner, W., Laaha, G., 2014. Exploring the link between meteorological drought and streamflow: effects of climate-catchment interaction. Water Resour. Res. 50 (3), 2468–2487. http://dx.doi.org/10.1002/2013WR015051.

Hayes, M., Svoboda, M., Wall, N., Widhalm, M., 2010. The lincoln declaration on drought indices: universal meteorological drought index recommended. Bull. Am. Meteor. Soc. 92 (4), 485–488. http://dx.doi.org/10.1175/2010BAMS3103.1.

Hirabayashi, Y., Kanaae, S., Emori, S., Oki, T., Kimoto, M., 2008. Global projections of changing risks of floods and droughts in a changing climate. Hydrol. Sci. J. 53 (4), 754–772. http://dx.doi.org/10.1623/hysj.53.4.754.

Hisdal, H., Tallaksen, L.M., Clausen, B., Peters, E., Gustard, A., 2004. Hydrological Drought Characteristics. Elsevier Science B.V., Amsterdam, the Netherlands, Developments in Water Science, 48, 2004, Chapter 5, pp. 139–198.

Hsiang, S.M., Burke, M., Miguel, E. Quantifying the influence of climate on human conflict, Science 341 (6151). arXiv:http://www.sciencemag.org/content/341/6151/1235367.full.pdf, http://dx.doi.org/10.1126/science.1235367.

Joetzjer, E., Douville, H., Delire, C., Ciais, P., Decharme, B., Tyteca, S., 2013. Hydrologic benchmarking of meteorological drought indices at interannual to climate change timescales: a case study over the amazon and mississippi river basins. Hydrol. Earth Syst. Sci. 17 (12), 4885–4895. http://dx.doi.org/10.5194/hess-17-4885-2013.

Jonsdottir, H., Eliasson, J., Madsen, H., 2005. Assessment of serious water shortage in the icelandic water resource system. Phys. Chemis. Earth, Parts A/B/C 30 (6–7), 420–425. http://dx.doi.org/10.1016/j.pce.2005.06.007, integrated Water Resource Assessment.

Kim, T., Valdés, J., Yoo, C., 2003. Nonparametric approach for estimating return periods of droughts in arid regions. J. Hydrol. Eng. 8 (5), 237–246. http://dx.doi.org/10.1061/(ASCE)1084-0699(2003)8:5(237).

Kjeldsen, T.R., Lundorf, A., Rosbjerg, D., 2000. Use of a two-component exponential distribution in partial duration modelling of hydrological droughts in zimbabwean rivers. Hydrol. Sci. J. – J. Sci. Hydrol. 45 (2), 285–298.

Koffler, D., Laaha, G. Lfstat-low-flow analysis in r. EGU General Assembly Conference Abstracts 15, 2013

Laaha, G., Blöschl, G., 2006. Seasonality indices for regionalizing low flows. Hydrol. Process. 20 (18), 3851–3878.

Lake, P.S., 2011. Drought and Aquatic Ecosystems: Effects and Responses. John Wiley & Sons.

Lewis, S.L., Brando, P.M., Phillips, O.L., van der Heijden, G.M.F., Nepstad, D., 2011. The 2010 Amazon drought. Science 331 (6017), 554. http://dx.doi.org/10.1126/science.1200807.

McKee, T., Doesken, N., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: Eight Conference on Applied Climatology, 17–22 January 1993, Anaheim, California, Amer. Meteor. Soc., pp. 179–184. <http://ccc.atmos.colostate.edu/relationshipofdroughtfrequency.pdf> (last accessed 16.07.12).

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391 (1-2), 202–216. http://dx.doi.org/10.1016/j.jhydrol.2010.07.012.

Mishra, A., Singh, V., Desai, V., 2009. Drought characterization: a probabilistic approach. Stochastic Environ. Res. Risk Assessm. 23 (1), 41–55.

Nyabeze, W.R., 2004. Estimating and interpreting hydrological drought indices using a selected catchment in Zimbabwe. Phys. Chem. Earth 29 (15–18), 1173–1180.

Parry, S., Hannaford, J., Lloyd-Hughes, B., Prudhomme, C., 2012. Multi-year droughts in Europe: analysis of development and causes. Hydrol. Res. 43 (5), 689–706. http://dx.doi.org/10.2166/nh.2012.024.

Peters, E., Torfs, P.J.J.F., van Lanen, H.A.J., Bier, G., 2003. Propagation of drought through groundwater – a new approach using linear reservoir theory. Hydrol. Process. 17 (15), 3023–3040. http://dx.doi.org/10.1002/hyp.1274.

Peters, E., van Lanen, H.A.J., Torfs, P.J.J.F., Bier, G., 2005. Drought in groundwater – drought distribution and performance indicators. J. Hydrol. 306 (1–4), 302–317.

Peters, E., Bier, G., van Lanen, H.A.J., Torfs, P.J.J.F., 2006. Propagation and spatial distribution of drought in a groundwater catchment. J. Hydrol. 321 (1/4), 257–275. http://dx.doi.org/10.1016/j.jhydrol.2005.08.004.

Prudhomme, C., Parry, S., Hannaford, J., Clark, D.B., Hagemann, S., Voss, F., 2011. How well do large-scale models reproduce regional hydrological extremes in Europe? J. Hydrometeorol. 12 (0), 1181–1204. http://dx.doi.org/10.1175/2011JHM1387.1.

Rossi, G., Caporali, E., Garrote, L., 2012. Definition of risk indicators for reservoirs management optimization. Water Resour. Manage. 26 (4), 981–996. http://dx.doi.org/10.1007/s11269-011-9842-x.

Salinas, J.L., Laaha, G., Rogger, M., Parajka, J., Viglione, A., Sivapalan, M., Blöschl, G., 2013. Comparative assessment of predictions in ungauged basins – part 2: flood and low flow studies. Hydrol. Earth Syst. Sci. 17 (7), 2637–2652. http://dx.doi.org/10.5194/hess-17-2637-2013.

Sheffield, J., Wood, E., 2011. Drought; Past Problems and Future Scenarios. Earthscan, London, Washington DC.

Shiau, J., Shen, H., 2001. Recurrence analysis of hydrologic droughts of differing severity. J. Water Resour. Plann. Manage. 127 (1), 30–40. http://dx.doi.org/10.1061/(ASCE)0733-9496(2001)127:1(30).

Stagge, J., Tallaksen, L., Gudmundsson, L., Van Loon, A.F., Stahl, K., submitted for publication. Candidate distributions for climatological drought indices (SPI and SPEI). Int. J. Climatol.

Stahl, K., 2001. Hydrological Drought – a Study across Europe. Ph.D. thesis, Albert-Ludwigs-Universität, Freiburg, Germany.

Tallaksen, L.M., Hisdal, H., 1997. Regional analysis of extreme streamflow drought duration and deficit volume, FRIEND '97 – regional hydrology: concepts and models for sustainable water resource management. In: Proc. International Conference, Postojna, vol. 246, pp. 141–150.

Tallaksen, L.M., Van Lanen, H.A.J. (Eds.), 2004. Hydrological drought: processes and estimation methods for streamflow and groundwater. In: Developments in Water Science; 48, The Netherlands, Elsevier Science B.V., Amsterdam, The Netherlands.

Tetzlaff, D., McDonnell, J.J., Uhlenbrook, S., McGuire, K.J., Bogaart, P.W., Naef, F., Baird, A.J., Dunn, S.M., Soulsby, C., 2008. Conceptualizing catchment processes: simply too complex? Hydrol. Process. 22 (11), 1727–1730. http://dx.doi.org/10.1002/hyp.7069.

Tsakiris, G., Nalbantis, I., Vangelis, H., Verbeiren, B., Huysmans, M., Tychon, B., Jacquemin, I., Canters, F., Vanderhaegen, S., Engelen, G., Poelmans, L., Becker, P., Batelaan, O., 2013. A system-based paradigm of drought analysis for operational management. Water Resour. Manage. 27 (15), 5281–5297. http://dx.doi.org/10.1007/s11269-013-0471-4.

Van Huijgevoort, M., 2014. Hydrological drought: characterisation and representation in large-scale models. Ph.D. thesis, Wageningen University, the Netherlands.

Van Huijgevoort, M.H.J., Hazenberg, P., van Lanen, H.A.J., Teuling, A.J., Clark, D.B., Folwell, S., Gosling, S.N., Hanasaki, N., Heinke, J., Koirala, S., Stacke, T., Voss, F., Sheffield, J., Uijlenhoet, R., 2013. Global multimodel analysis of drought in runoff for the second half of the twentieth century. J. Hydrometeor 14, 1535–1552. http://dx.doi.org/10.1175/JHM-D-12-0186.1.

Van Lanen, H.A.J., 2006. Drought propagation through the hydrological cycle. In: Demuth, S., Gustard, A., Planos, E., Scatena, F., Servat, E. (Eds.), Climate Variability and Change Hydrological Inpacts, vol. 308. IAHS-AISH Publication, IAHS Press, Wallingford, UK, pp. 122–127.

Van Lanen, H.A.J., Wanders, N., Tallaksen, L.M., Van Loon, A.F., 2013. Hydrological drought across the world: impact of climate and physical catchment structure. Hydrol. Earth Syst. Sci. 17, 1715–1732. http://dx.doi.org/10.5194/hess-17-1715-2013.

Van Loon, A.F., 2013. On the propagation of drought. How climate and catchment characteristics influence hydrological drought development and recovery. Ph.D. thesis, Wageningen University. <http://edepot.wur.nl/249786> (last accessed 28.05.13).

Van Loon, A.F., Van Lanen, H.A.J., 2012. A process-based typology of hydrological drought. Hydrol. Earth Syst. Sci. 16 (7), 1915–1946. http://dx.doi.org/10.5194/hess-16-1915-2012.

Van Loon, A.F., Tijdeman, E., Wanders, N., Van Lanen, H., Teuling, A., Uijlenhoet, R., 2014. How climate seasonality modifies drought duration and deficit. J. Geophys. Res.: Atmos. 119 (8), 4640–4656. http://dx.doi.org/10.1002/2013JD020383.

Van Loon, A.F., Ploum, S.W., Parajka, J., Fleig, A.K., Garnier, E., Laaha, G., Van Lanen, H.A.J., 2014. Hydrological drought typology: cold climate drought types and associated societal impacts. Hydr. Earth Syst. Sci. Discuss. 11, 10465–10514. http://dx.doi.org/10.5194/hessd-11-10465-2014.

Van Vliet, M.T.H., Yearsley, J.R., Ludwig, F., Vogele, S., Lettenmaier, D.P., Kabat, P., 2012. Vulnerability of US and European electricity supply to climate change. Nature Clim. Change 2 (9), 676–681. http://dx.doi.org/10.1038/nclimate1546.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2009. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Climate 23 (7), 1696–1718. http://dx.doi.org/10.1175/2009JCLI2909.1.

Vidal, J.-P., Martin, E., Franchistéguy, L., Habets, F., Soubeyroux, J.-M., Blanchard, M., Baillon, M., 2010. Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite. Hydrol. Earth Syst. Sci. 14 (3), 459–478. http://dx.doi.org/10.5194/hess-14-459-2010.

Weingartner, R., Blöschl, G., Hannah, D., Marks, D., Parajka, J., Pearson, C., Rogger, M., Salinas, J.L., Sauquet, E., Srikanthan, R., Thompson, S., Viglione, A., 2013. Prediction of Seasonal Runoff in Ungauged Basins, Cambridge, pp. 102–134 (Chapter 6).

Wilhite, D. (Ed.), 2000. Drought: A Global Assessment, vols. I &II. Routledge Hazards and Disasters Series, Routledge, London.

Wilhite, D.A., Glantz, M.H., 1985. Understanding the drought phenomenon: the role of definitions. Water Int. 10 (3), 111–120.

WMO, 2008. Manual on low flow estimation and prediction. Operational Hydrology Report No.50 WMO-No. 1029. p. 136.

Wong, G., Van Lanen, H.A.J., Torfs, P.J.J.F., 2013. Probabilistic analysis of hydrological drought characteristics using meteorological drought. Hydrol. Sci. J. 58 (2), 253–270.

Woo, M.-K., Tariiule, A., 1994. Streamflow droughts of northern Nigerian rivers. Hydrol. Sci. J. 39 (1), 19–34.

Zaidman, M.D., Rees, H.G., Young, A.R., 2002. Spatio-temporal development of streamflow droughts in northwest Europe. Hydrol. Earth Syst. Sci. 6 (4), 733–751.

Zelenhasić, E., Salvai, A., 1987. A method of streamflow drought analysis. Water Resour. Res. 23 (1), 156–168. http://dx.doi.org/10.1029/WR023i001p00156.