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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.

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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

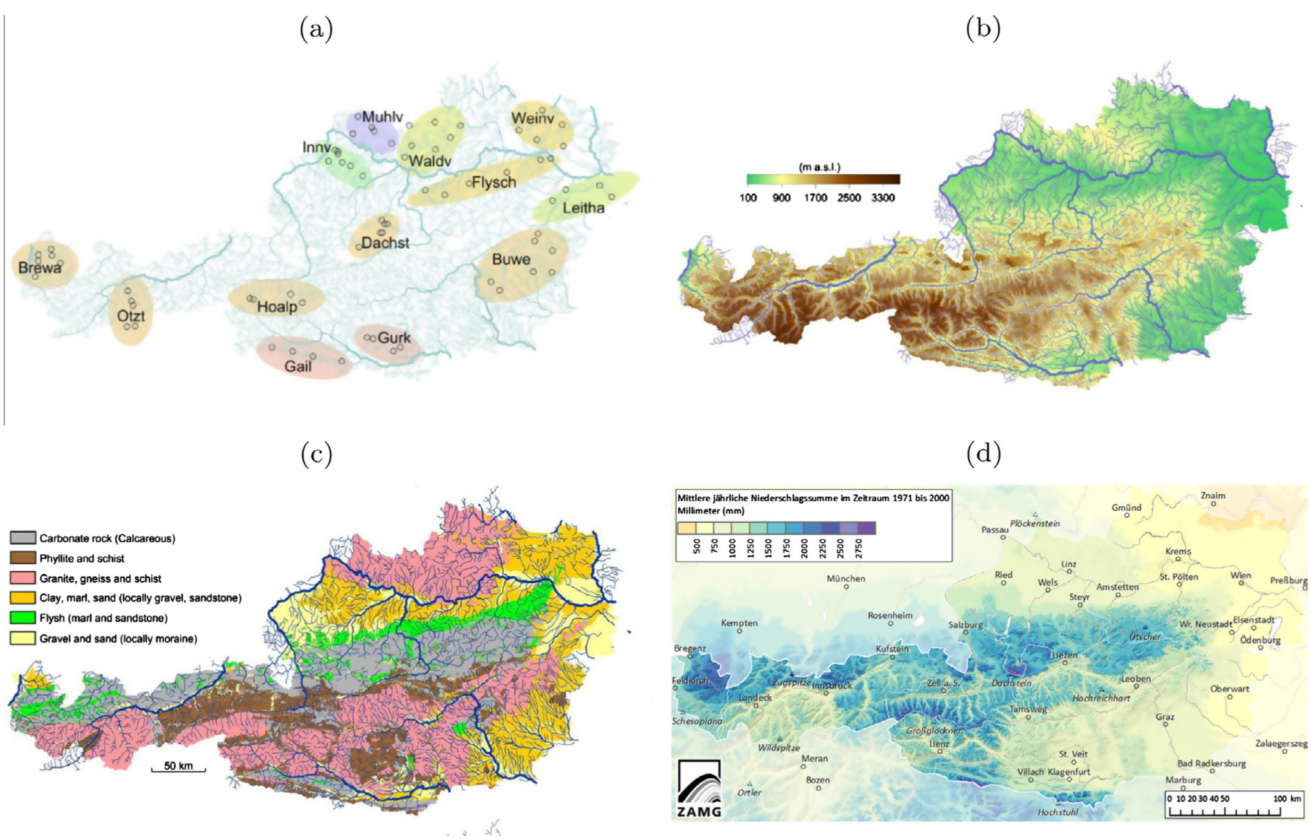

Fig. 1. Some characteristics of the study area: (a) clusters, (b) topography, (c) geology (all from Gaál et al. (2012), reprinted with permission from the publisher Wiley), and (d) mean annual precipitation (from ZAMG).

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