LETTER

Drought propagation in space and time: the role of groundwater flows

J Hellwig\(^{1,\ast}\), Y Liu\(^{2,\ast}\), K Stahl\(^{3}\) and A Hartmann\(^{1,3}\)

\(^{1}\) Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, 79085, Germany
\(^{2}\) Chair of Hydrological Modeling and Water Resources, University of Freiburg, Freiburg, 79085, Germany
\(^{3}\) Institute of Groundwater Management, Technical University of Dresden, 01069 Dresden, Germany

\(^\ast\) Authors to whom any correspondence should be addressed.

E-mail: jost.hellwig@hydrology.uni-freiburg.de and yan.liu@hydmod.uni-freiburg.de

Keywords: drought, groundwater, drought propagation, intercatchment groundwater flows

Abstract

Droughts cause large economic and social impacts all over the world. During drought, groundwater maintains streamflow and can help to mitigate impacts. It governs how drought propagates through the hydrological cycle. Groundwater flows between topographic catchments may modify groundwater dynamics considerably and also influence groundwater's drought mitigation potential. In this study, we relate drought propagation times to quantitative estimates of groundwater gains or losses for a global set of catchments. For the majority of catchments there is no link found, however, for 16.5% of both groundwater gaining and groundwater losing catchments groundwater flow processes affect drought propagation. Influences of intercatchment groundwater flows (IGFs) on drought propagation are significantly related to catchment characteristics and abundant in North America, South America and Australia. As IGF mostly slow down drought propagation they may increase the potential of the system to buffer meteorological droughts. Reliable drought forecasting and proactive drought governance will benefit from better understanding major influences on drought propagation including IGFs.

1. Introduction

Droughts are recurring extreme events causing major impacts on environment, economy and society all over the world. During droughts, the fast components of river discharge (e.g. generated by direct runoff or interflow) diminish until streamflow is solely maintained by the delayed flow component. Groundwater storage can buffer the hydroclimatic variations of water availability to maintain streamflow during such dry times and help to mitigate drought impacts. Groundwater outflow, i.e. baseflow, is the most important source of delayed streamflow. Accordingly, a plethora of studies have demonstrated the significant influence of baseflow on streamflow dynamics including variability, flashiness and drought response (van Lanen et al 2013, van Loon and Laaha 2015, Konapala and Mishra 2020, Apurv and Cai 2021). However, groundwater exhibits large heterogeneity over short distances resulting in e.g. highly variable groundwater–surface water interactions, preferential subsurface flow paths or horizontal and vertical aquifer interactions within a catchment and beyond. A more profound understanding on the specific groundwater characteristics is promising to help better understanding the observed surface water dynamics during drought.

Meteorological drought events (i.e. precipitation deficits) usually cover large regions. Subsequently, the water deficit propagates through the hydrological cycle leading to streamflow droughts (Yevjevich 1967). Contrary to the common assumption of a closed water balance within the topographically defined catchment, topographic catchments are rather groundwater importers or exporters (Schaller and Fan 2009, Fan 2019). Hence, intercatchment groundwater flows (IGFs), i.e. groundwater flows crossing topographic surface catchment boundaries,
will influence streamflow and drought development as well.

Across the globe, catchments with substantial IGF influences are abundant (Liu et al. 2020). In particular, the influence of IGF is important for headwater catchments (Bouaziz et al. 2018). Further, catchments in arid regions frequently lose water via regional groundwater flows, thus this groundwater does not discharge at the catchment outlet (Fan 2019, Liu et al. 2020). Especially for karstic aquifers, discharge areas often not coextend with the topographic catchments, due to the complex connectivity of their groundwater systems (Hartmann et al. 2014, Fan 2019, Liu et al. 2021). Bouaziz et al. (2018) and Le Mesnil et al. (2020) demonstrated the importance of considering IGF and their temporal variability for analyses of catchments’ water balances.

IGF are not necessarily constant over time and will usually be most important during drought. Firstly, the fast flow components diminish faster than groundwater outflows, hence, the groundwater dynamics become in general more important for streamflow in periods without rainfall (Käser and Hunkeler 2016, Staudinger et al. 2019). Secondly, during times of dry weather water transfers shift to deeper processes which are more independent from surface topography and facilitate IGF (Fan 2019). Despite this particular relevance of IGF during drought and the well-known relevance of groundwater processes for drought propagation (e.g. van Lanen et al. 2013), IGF has not been considered in studies on streamflow drought and on the temporal and spatial aspects of drought propagation so far. However, given the important role of groundwater for drought mitigation and streamflow dynamics in dry periods, influences of the IGF on streamflow drought characteristics can be expected.

In this letter, we first develop hypotheses on potential influences of IGF on drought propagation into streamflow. Then, we statistically analyse a global ensemble of catchments to test whether considering IGF improves the quantification of drought propagation and, supporting the hypotheses, may help to understand the temporal and spatial patterns of drought propagation.

2. Influences of IGF on drought propagation

IGF may have a relevant influence on drought propagation both in groundwater gaining and losing catchments. Based on the drought propagation times and types of IGF, four different classes of catchments can be distinguished (table 1). For each of the classes different processes can be hypothesised. As these processes relate to specific environmental conditions in the catchments, we expect the classes to occur under different settings and in different parts of the world. Specifically, we hypothesise the linkages of IGF and drought propagation given in table 1.

Apart from the four classes regarding IGF’s temporal effects on drought propagation, an effect on spatial drought propagation can also be expected where droughts propagate from a losing catchment into a gaining catchment. A streamflow drought in the gaining catchment will not only be driven by a precipitation/recharge deficit in this catchment but also be triggered by recharge deficits in the much larger subsurface catchment. While meteorological droughts mostly occur over large regions (including in most cases both the gaining and the losing catchments), this intercatchment drought propagation will become particularly relevant in the context of snowmelt- or human-induced droughts.

3. Materials and methods

For our analysis, we combine two measures characterizing drought propagation (propagation time, $T_{\text{prop}}$) and IGF (quantified with the effective catchment index, ECI). The streamflow observations and catchment properties stem from a global catchment database, which consists of 21,953 catchments in daily or monthly resolution and is originally described in Beck et al. (2019a). They were refined to 8,701 catchments with longer than 10 year daily records and insignificant irrigation influence to meet the requirement for ECI analysis (Liu et al. 2020). For each catchment, a number of climate and catchment property indices were available representing (a) climate, aridity index (AI = PET/P, PET and P signify potential evapotranspiration and precipitation, respectively); (b) surface characteristics, topographic area ($A$), distance to coast (L), mean slope (S), and mean elevation (H); and (c) subsurface characteristics, permeability ($k$), baseflow index (BFI, calculated according to WMO 2008). The Multi-Source Weighted-Ensemble Precipitation MSWEP v2.2 (Beck et al. 2019b) was used to obtain monthly precipitation for the quantification of the quickness of anomaly (drought but also flood) propagation.

The ECI served as an IGF indicator. It describes the difference between the topographic and effective catchment areas via calculating the water balance using long-term average streamflow observations ($Q$), total precipitation ($P$) and estimates of actual evapotranspiration ($AET$). To consider the uncertainty in $P$ and $AET$, three independent $P$ and three independent AET datasets were used to derive nine ECI estimates for each catchment, where the data sources of $P$ and AET are described in table 1 of Liu et al. (2020). ECI is defined as follows:

$$ECI = \log \left( \frac{Q}{P - AET} \right).$$

(1)

Positive ECI values indicate a discharge surplus, negative values point to a deficit relative to climatic
Table 1. Processes and catchment characteristics for four classes of catchments with different combinations of groundwater gains/losses by IGF and related slow/fast drought propagation.

| Catchment type | Losses by IGF | Gains by IGF |
|----------------|--------------|--------------|
| Drought propagation to streamflow | Slow | Class 1 |
| Potential processes | For rivers with a high transmissivity beneath the channel a significant part of discharge may be exported from the catchment by IGF parallel to the river. The same hydrogeological structure will usually also form a large dynamic storage buffering streamflow depletion and leading to slow drought propagation. |
| Related catchment features | Rivers in a wide valley containing alluvium with groundwater flows parallel to the river |
| Fast | Class 2 |
| Potential processes | A substantial part of recharge can be diverted from the catchment given that groundwater is exported via deep regional aquifers. In this case the baseflow proportion in streamflow will be reduced and river dynamics will be dominated by fast flow components with fast drought propagation. |
| Related catchment features | Catchments with deep aquifers and regional groundwater flow paths, particularly in dry regions |
| Class 3 | Potential processes |
| IGF increases the catchment’s dynamic storage capacity which leads to a larger importance of subsurface storage for surface water dynamics. This will cause a stronger drought attenuation and slower drought propagation. |
| Related catchment features | Small catchments in mountainous regions with limited storage capacity in the topographic catchment |
| Class 4 | Potential processes |
| Very fast IGF which exhibits abrupt responses to recharge events (e.g. in karstified catchments) will lead to faster streamflow responses and drought propagation. |
| Related catchment features | Steep and small catchments with short groundwater travel times and relatively large head gradients |

input. The water balance deviation indicates the average net amount of groundwater import/exports in the catchment. Hence, positive ECI values correspond to gaining conditions whereas negative ECI stand for losing conditions; and the proportion of IGF relative to net precipitation increases with the absolute value of ECI.

A drought propagation time metric was used to quantify the speed of anomaly propagation in the catchments. To ensure consistency, both precipitation and streamflow monthly time series were transformed into anomalies following the procedure of the Standardized Groundwater Index (Bloomfield and Marchant 2013). To reproduce the attenuation of the meteorological signal by catchment processes the precipitation timeseries was accumulated for different lengths between 1 and 36 months before standardization. The values are transformed using the non-parametric normal scores transform (Bloomfield and Marchant 2013) leading to standard normally distributed time series with negative values indicating dry conditions and positive values indicating wet conditions. All standardized precipitation timeseries were correlated with the standardized streamflow record and the accumulation period of the precipitation time series leading to the highest correlation with streamflow was selected as the catchments typical drought propagation time $T_{prop}$ (see also Hellwig et al 2020). Fast $T_{prop}$ of few months indicate little dynamic storage available to attenuate the meteorological variability whereas slow $T_{prop}$ of up to several years correspond to large dynamic storage in the catchment. ECI and $T_{prop}$ values for all catchments can be found in Hellwig et al (2021).

Both ECI and $T_{prop}$ require steady conditions in the catchment without distorting human activities. Water transfer mechanisms other than IGF (e.g. by anthropogenic activities) as well as long-term storage changes in the catchment (e.g. by glacier retreat) will influence the calculated ECI. Similarly, flow regulations (e.g. dams, sewage discharge) and water use (e.g. groundwater abstractions) can be important factors for $T_{prop}$. Due to the limited available information regarding these points, influences cannot be excluded for this study.

To analyse the role of IGF for drought propagation all catchments with both considerable IGF and relatively fast or slow drought propagation were selected. IGF was rated to be considerable in case of an absolute mean ECI larger than 0.3 and for drought
Figure 1. $T_{\text{prop}}$ over ECI with Classes 1–4, here shows the classifications using ECI $> 0.3$ or ECI $< -0.3$ to define considerable IGF and using $T_{\text{prop}}$ more than 0.5 standard deviation different from the mean of all catchments to define fast/slow propagation.

propagation all catchments with $T_{\text{prop}}$ more than 0.5 standard deviation different from the mean of all catchments were selected as fast/slow (i.e. $T_{\text{prop}}$ smaller/larger than average). To exclude any potential influence of these a priori catchment selection rules, five variants with different thresholds were also tested (ECI selection rule based on the median as well as the 33rd and 25th percentiles, $T_{\text{prop}}$ more than 0.3 or 0.7 standard deviation different from the mean). The selected catchments correspond to the four classes of catchments defined in section 2. Subsequently, catchment characteristics were compared for the different Classes with analyses of variance (ANOVA) and post hoc TukeysHSD tests (for more details on these tests refer e.g. to Hellwig and Stahl (2018)). For all tests we used a significance level of $\alpha = 0.05$.

4. Results and discussion

4.1. Alterations of drought propagation and catchment characteristics

In 16.5% of the analysed catchments there are both considerable IGF and a slow or a fast drought propagation. In general, the correlation between $T_{\text{prop}}$ and ECI is negative (Spearman Rank Correlation Coefficient $r = -0.21$), with more of the losing catchments showing slow drought propagation and more of the gaining catchments showing fast propagation. However, there are many catchments in each of the four combinations of gaining/losing and slow/fast drought propagation and for the majority of catchments, IGF does not help to understand drought propagation (figure 1). Hence, the loss or gain of water in a catchment and its relationship to drought propagation is not straightforward but depends on different processes. The amount of catchments in the classes varies for the alternative classification rules, however, the general pattern is not influenced.

A large proportion of catchments has a fast drought propagation (46%), but the proportion of catchments with considerable ECI in this group is relatively small (figure 2). The slower the drought propagation is, the higher is the share of catchments with relevant IGF. Hence, for catchments with a slow drought propagation, IGF seems to be a key factor to understand the processes related to drought propagation whereas for catchments showing fast drought propagation other processes are more relevant. Accordingly, the catchments with considerable IGF co-occur more often with a slow drought propagation compared to what would be expected from the overall distribution of $T_{\text{prop}}$. As IGF mostly slow down drought propagation they may increase the potential of the system to buffer meteorological droughts.

A comparison of different catchment characteristics between the classes allows to identify the relevant
conditions for alterations in drought propagation due to IGF (figure 3). The differences between the classes are statistically significant, independent from the exact applied classification rules. According to the analysis, the losing catchments with slow propagation in Class 1 have a large size and are mostly suited in arid regions. They have medium to high elevations and small slopes with medium to high BFI. Similar processes were also reported by Käser and Hunkeler (2016) in a mountainous and humid environment. They found that an important part of recharge of the losing headwater catchment of River Emme in Switzerland is exported to the lower catchment by gauge underflow (i.e. groundwater flow parallel to the river underneath the gauge) in the alluvial plain. The alluvial plain is also responsible for the high persistence of streamflow during dry periods because of its large dynamic storage. Hence, IGF related to slow drought propagation might occur in a range of environments where a highly transmissive hydrogeological structure responsible for gauge underflow, a common feature of groundwater exporting catchments (Fan 2019), exists.

In our dataset also catchments from Class 2 are more common in arid regions and have only small slopes, however, they have smaller catchment areas, are located in lower elevations and have much smaller BFI. This fits to the hypothesis of deeper and more regional groundwater flow paths. The study of Le Mesnil et al (2020) found for a set of catchments in France that the slow flow component (baseflow) is more often diverted in losing catchments. This is in line with the small BFI found in our study for Class 2 as a result of subsurface flow paths disconnected form surface water. If the slow flow component is exported it cannot buffer precipitation deficits within the catchment and droughts will propagate very fast. Contrary to the losing catchments, gaining catchments in our dataset are much smaller in size, less arid and characterized by higher slopes. Catchments
in Class 3 (having the smallest frequency) have a high BFI and high elevations. One example catchment illustrating the processes is the River Rhume catchment in Central Germany. It receives most of its discharge from the Ruhme spring which is one of Germany’s largest karst springs. The spring is fed by a subsurface catchment much larger than the topographic one with contributions from several other surface waters. The contributing subsurface and surface waters form together a huge dynamic storage which attenuates any water deficit by gradual depletion and considerably slows down the propagation of drought in Rhume catchment.

Gaining catchments with fast propagation (Class 4) in our dataset have medium BFI, rather low elevations and are located close to the coast. In these catchments, groundwater gains are known to contribute to the fast flow component and can reduce the BFI in the gaining catchment (Le Mesnil et al. 2020). The gain of a fast flows will also speed up drought propagation.

Based on the relative frequencies (figure 2) the most relevant influence of IGF on drought propagation is a slowing down. However, the characteristics of catchments in classes 1 and 3, as well as the assumed related processes, are relatively specific and are therefore not relevant for a large part of the observed catchments. Contrary to this, for catchments exhibiting characteristics which favour gauge underflow like in Class 1 or add dynamical storage like in Class 3 an influence of IGF on drought propagation will be likely. An important factor in this regard is elevation, which is significantly, positively correlated to $T_{prop}$. Accordingly, catchments in
Class 1 and 3 have higher elevations than most of the other catchments and catchments in high elevations are most likely to show an influence of IGF on drought propagation.

Most of the characteristics found for the different catchment subsets support the hypotheses presented in section 2. For example, the small area and large elevation of catchments in Class 3 fits to the explanation of an otherwise limited dynamic storage that is considerably enlarged by the IGF. Also, the arid environment and low elevations with small slopes found for Class 2 matches the expectation of deep regional groundwater systems that are decoupled from streamflow and surface waters that are mostly fed by direct discharge. However, there are also some surprising empirical results like the significantly lower elevation and distance to the coast for catchments with fast propagation. Further research will be needed to clarify which processes related to these catchment characteristics are responsible for the observed linkage between IGF and $T_{\text{prop}}$.

The limited number of catchments used in this study might be another reason for the unexpected patterns. Additionally, the precipitation data used in this study for the calculation of $T_{\text{prop}}$ do not account for recharge delays due to unsaturated soils, snow cover or anthropogenic activities. For example, the slow drought propagation in classes 1 and 3 corresponds to high elevations where snow storage can be an additional delaying factor. To distinguish the different processes and exclusively assess the groundwater system response, recharge time series would be beneficial.

Human influences were not considered in this study but can be a dominant control for drought propagation (van Loon et al 2016, Tijdeman et al 2018). More detailed data on human water use in the catchments would allow for more reliable estimates of $T_{\text{prop}}$ and ECI and help to investigate the relationship of IGF and drought propagation under human impacts. One known example for the inter-catchment propagation of a human-induced water scarcity is the Faria catchment in the Eastern Mediterranean (Hartmann et al 2012). A large karst spring drains an Eocene aquifer which belongs only partly to the topographic catchment (Gunkel et al 2015). After a relatively long period of constant water consumption, groundwater pumping in the aquifer multiplied in the period 1995–2007. As the resulting drawdown in the aquifer significantly reduced IGF into Faria catchment, the water scarcity propagated into this catchment and Faria spring ran completely dry. With a global increase of groundwater pumping and groundwater flow regulations the human influence on the IGF’s role for drought propagation will amplify as well.

### 4.2. Hotspots of drought propagation alterations

For all catchment classes spatial patterns and hotspots of occurrence were found in our analysis (figure 4). Individual catchments from Class 1 emerged on all continents but are most common in Central North America, South America, Europe, and Australia. The four different classes are highlighted in colours.
America in the proximity of the Great Plains. On the contrary, the hotspots of Class 2 catchments that were found are located in arid regions all around the world: southern North America, eastern South America, South Africa, and Australia. Catchments from Class 3 are in this study solely located in the high elevation regions of North America (Rocky Mountains, Sierra Nevada) and South America (Andes Mountains). The prevalence of catchments from Class 4 in the studied data is very broad including humid, mostly coastal regions in North and South America, Europe, and Australia.

The distinct spatial patterns found for the four catchment classes demonstrate differences in the relevance of the processes relating IGF and drought propagation on the large scale. For example, in Central Europe gaining catchments with a fast propagation are the only common type (indicating fast groundwater flow e.g. in karst; Chen et al 2017), while in South Africa the losing catchments with a fast propagation are dominating (potentially related with deep groundwater leakage). On the contrary, in North America all four classes are prevalent but their main areas differ according to topographic and climatic conditions.

Even though distinct patterns for the four catchment classes could be found, the limited data availability for large regions in Asia, Africa and Central America is an important constraint. It can be hypothesized that in these regions similar catchment characteristics will be related to the occurrence of IGF and relatively fast or slow propagation, however, there is further work needed to validate such a global regionalization approach. Our results suggest which type of influence from IGF on surface water dynamics in different parts of the world and different environments can be expected. These influences will be important to consider for proactive water management. For example, an increase of water withdrawal reducing IGF can also lead to a change in the timing of drought occurrence in the neighbouring catchment.

5. Conclusions

IGF affects drought propagation in 16.5% of the catchments. This study used a global dataset of streamflow and catchment characteristics to demonstrate the influence. Both, in gaining and losing catchments different processes affect drought propagation. Catchment characteristics are linked to these processes causing spatial patterns which help to learn about the relevance of IGF for drought propagation in various environments. Surface waters in a catchment will respond fast to drought events given that slow groundwater flows are diverted to another catchment or fast groundwater flows are gained. Contrary, hydrogeological structures with a large dynamic storage can co-occur with IGF as well (both in gaining and losing catchments) and will lead to a slow surface water response on droughts. Overall, catchments with a slow propagation are most often influenced by IGF.

On the continental and global scale IGF with influences on drought propagation are abundant. Given the large efforts in the last years to analyse and forecast drought events and their impacts we assume the consideration of IGF as a logical next step. This study allows model developers and drought management planners to judge the relevance of IGF for drought characteristics in the specific context. Future research on the impacts of human activities on the link of IGF and drought propagation will complement our work to allow for more robust drought mitigation.

Data availability statements

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.6094/UNIFR/222587 (Hellwig et al 2021). Unprocessed precipitation data can be downloaded for non-commercial purposes by filling the form on the website of GloH2O (www.globh2o.org/mswep/). Streamflow data are under responsibility of seven national and international agencies; we provide the links for downloading data in the supplement.

Acknowledgments

We acknowledge Hylke Beck and the data providers at the responsible agencies for the streamflow (i.e. US Geological Survey, Global Runoff Data Centre, Brazilian Agência Nacional de Águas, European Water Archive of the European Flow Regimes from International Experimental and Network Data, Water Survey of Canada Hydrometric Data, Australian Bureau of Meteorology, and Chilean Center for Climate and Resilience Research) and precipitation data. We thank two anonymous reviewers who provided valuable reviews which significantly helped to improve the quality of the paper. JH, YL and AH have been supported by the Deutsche Forschungsgemeinschaft, Grant Nos. STA632/4-1 (JH) and HA8113/1-1 (YL and AH). We acknowledge support by the Open Access Publication Fund of the University of Freiburg.

ORCID iDs

J Hellwig https://orcid.org/0000-0001-7331-7656
Y Liu https://orcid.org/0000-0002-9871-8920
K Stahl https://orcid.org/0000-0002-2159-9441
A Hartmann https://orcid.org/0000-0003-0407-742X

References

Aputur T and Cai X 2021 Regional drought risk in the contiguous United States Geophys. Res. Lett. 48 e2020GL092200
Barker L J, Hannaford J, Chiverton A and Svensson C 2016 From meteorological to hydrological drought using standardised indicators Hydrol. Earth Syst. Sci. 20 2483–505

Beck H E, Wood E F, McVicar T R, Zambrano-Bigiarini M, Alvarez-Garretón C, Baez-Villanueva O M, Sheffield J and Karger D N 2019a Bias correction of global high-resolution precipitation climatologies using streamflow observations from 9372 catchments J. Clim. 33 1299–315

Beck H E, Wood E F, Pan M, Fisher C K, Miralles D G, van Dijk A I J, McVicar T R and Adler R F 2019b MSWEP V2 global 3-hourly 0.1° precipitation: methodology and quantitative assessment Bull. Am. Meteorol. Soc. 100 473–500

Bloomfield J P and Marchant B P 2013 Analysis of groundwater drought building on the standardised precipitation index approach Hydrol. Earth Syst. Sci. 17 4769–87

Bouaziz L, Weerts A, Schellekens J, Sprokkereef E, Stam J, Barker L J, Hannaford J, Chiverton A and Svensson C 2016 From hydrological drought to continental hydrologic drought: investigations of continental hydrologic droughts Environ. Res. Lett. 17 094008 J. Hellwig et al

Chen Z et al 2017 The world karst aquifer mapping project: concept, mapping procedure and map of Europe Hydrogeol. J. 25 771–85

Fan Y 2019 Are catchments leaky? WIREs Water 6 e1386

Gunkel A, Shaded S, Hartmann A, Wagener T and Lange J 2015 Model signatures and aridity indices enhance the accuracy of water balance estimations in a data-scarce Eastern Mediterranean catchment J. Hydrol. Reg. Stud. 4 487–501

Hartmann A, Goldscheider N, Wagener T, Lange J and Weiler M 2014 Karst water resources in a changing world: review of hydrological modeling approaches Rev. Geophys. 52 218–42

Hartmann A, Lange J, Aguado Á V, Müzyed N, Smiatek G and Kunstmann H 2012 A multi-model approach for improved simulations of future water availability at a large Eastern Mediterranean karst spring J. Hydrol. 468 130–8

Hellwig J, Graaf I E M, Weiler M and Stahl K 2020 Large-scale assessment of delayed groundwater responses to drought Water Resour. Res. 56 e2019WR025441

Hellwig J, Liu Y, Stahl K and Hartmann A 2021 Effective catchment indices and drought propagation times for 8701 catchments all over the world FreiDok (https://doi.org/10.6094/UNIFR/225287)

Hellwig J and Stahl K 2018 An assessment of trends and potential future changes in groundwater-basinflow drought based on catchment response times Hydrol. Earth Syst. Sci. 22 6209–24

Käser D and Hungeler D 2016 Contribution of alluvial groundwater to the outflow of mountainous catchments Water Resour. Res. 52 680–97

Konapala G and Mishra A 2020 Quantifying climate and catchment control on hydrological drought in the continental United States Water Resour. Res. 56 e2018WR024620

Le Mesnil M, Charlier J B, Moussa R, Caballero Y and Dörfliger N 2020 Interbasin groundwater flow: characterization, role of karst areas, impact on annual water balance and flood processes J. Hydrol. 585 124583

Liu Y, Wagener T, Beck H E and Hartmann A 2020 What is the hydrologically effective area of a catchment? Environ. Res. Lett. 15 104024

Liu Y, Wagener T and Hartmann A 2021 Assessing streamflow sensitivity to precipitation variability in karst-influenced catchments with unclosed water balances Water Resour. Res. 57 e2020WR028598

Schaller M F and Fan Y 2009 River basins as groundwater exporters and importers: implications for water cycle and climate modeling J. Geophys. Res. Atmos. 114 D04103

Staudinger M, Weiler M, Hungeler D, Cochand F, Stoezl M and Seibert J 2019 Your work is my boundary condition! Challenges and approaches for a closer collaboration between hydrologists and hydrogeologists J. Hydrol. 571 235–43

Tijdelman E, Barker L J, Svoboda M D and Stahl K 2018 Natural and human influences on the link between meteorological and hydrological drought indices for a large set of catchments in the contiguous United States Water Resour. Res. 54 6005–23

van Lanen H A J, Wanders N, Tallaksen L M and van Loon A F 2013 Hydrological drought across the world: impact of climate and catchment characteristics Water Resour. Res. 49 1715–32

van Loon A F and Laaha G 2015 Hydrological drought severity explained by climate and catchment characteristics J. Hydrol. 526 3–14

van Loon A F, Stahl K, di Baldassarre G, Clark J, Rangecroft S, Wanders N and van Lanen H A 2016 Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches Hydrol. Earth Syst. Sci. 20 3631–50

WMO 2008 World Meteorological Organization: manual on low-flow, Estimation and prediction Operational Hydrology Report No. 50, WMO-NO. 1029

Yevjevich V M 1967 An objective approach to definitions and investigations of continental hydrologic droughts Hydrology Papers vol 23 (Fort Collins, CO: Colorado State University)