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OPINION PAPER

How to improve attribution of changes in drought and flood impacts

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Abstract

For the development of sustainable, efficient risk management strategies for the hydrological extremes of droughts and floods, it is essential to understand the temporal changes of impacts, and their respective causes and interactions. In particular, little is known about changes in vulnerability and its influence on drought and flood impacts. We present a fictitious dialogue between two experts, one in drought and the other in floods, showing that the main obstacles to scientific advancement in this area are both a lack of data and a lack of common accepted approaches. The drought and flood experts ‘discuss’ available data and methods and we suggest a complementary approach. This approach consists of collecting a large number of single or multiple paired-event case studies from catchments around the world, undertaking detailed analyses of changes in impacts and drivers, and carrying out a comparative analysis. The advantages of this approach are that it allows detailed context- and location-specific assessments based on the paired-event analyses, and reveals general, transferable conclusions based on the comparative analysis of various case studies. Additionally, it is quite flexible in terms of data and can accommodate differences between floods and droughts.

Keywords: hydrological extremes, damage, dynamic risk, vulnerability, trend attribution, paired catchments, consecutive hydro-hazards

1. Introduction

Droughts and floods have widespread impacts. For instance, globally in the period 1998–2017, floods affected the largest number of people (>2 billion) followed by droughts (1.5 billion) (UNISDR and CRED 2018). In Europe in the period 1998–2009, floods and droughts caused €52 billion and €5 billion, respectively, in overall losses (EEA 2010). There is general agreement that drought and flood risk, as well as their components (hazard, exposure and vulnerability) are dynamic, and should be treated as such (Knutson et al. 1998, Simelton et al. 2009, Kundzewicz 2012). The interplay of human and water systems leading to drought and flood risk has always been dynamic, as already pointed out by Heraclitus about 2500 years ago (Koutsoyiannis 2011, 2013). However, besides change, persistence also plays an important role. For instance, the probability of another dry day increases with the length of the drought period (Pfleiderer and Coumou 2017) and, on larger time scales, persistence may lead to clustering of extreme events (Hurst 1951). The resulting drought rich/drought poor and flood rich/flood poor periods have been described for many regions (Hall et al. 2014; Cook, 2015; Mediero et al. 2015, Hanel et al., 2018). Both persistence and variability at various timescales complicate the change detection and attribution of drought and flood impacts. In this context, hazard is defined as the potential occurrence of an event that may cause adverse effects on social elements; while exposure is defined as the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events. Vulnerability is defined generically as the propensity or predisposition to be adversely affected (IPCC 2012). Finally, impacts, e.g. direct damage such as fatalities or economic damage, are a reflection of risk (Poljanšek et al. 2017). We acknowledge that droughts and floods can also have positive consequences (e.g. Ding et al. 2011, Anthony et al. 2015, Musolino et al. 2018). However, in this paper we focus on the negative impacts.

The number of studies focusing on drought and flood impact changes has increased substantially in the context of climate change. Studies on trends in flood impacts agree on the conclusion that the observed increase in damage is dominated by an increase in exposure, although changes in hydro-meteorological extremes may play a role as well (Bouwer 2011, Merz et al. 2012a). It is suggested that a climate signal might be masked by a counteracting decrease in vulnerability due to human interventions (Jongman et al. 2015, Di Baldassarre et al. 2015, Mechler and Bouwer 2015). Drought impacts in Europe have been found to increase over time (Stahl et al. 2016). This might be caused by changes in the physical aspects of droughts: studies on drought hazard frequency and intensity seem to find increasing trends in southern and western Europe (Spinoni et al. 2015, Gudmundsson and Seneviratne 2015). But it might also reflect an increase in information availability, an increase in awareness of droughts, or specific changes in policy (Stahl et al. 2016). Considerable uncertainties remain about these trends and their causes, due to uncertain damage data (Downton and Pielke 2005, Gall et al. 2009, Stahl et al. 2016) and imperfect methods, such as normalization approaches (Quiring and Papakryiakou 2003, Mishra and Cherkauer 2010, Bouwer 2011, Neumayer and Barthel 2011). Thus, knowledge is lacking on trends in drought and flood impacts and on the underlying processes that drive changes. In particular, little information is available on temporal trends in vulnerability and its influence on impacts (Mechler and Bouwer 2015, UNISDR 2015). Vulnerability may be positively influenced by risk management, but it can also be negatively influenced, e.g. by changes to a more sensitive crop type (droughts) or to more susceptible building materials (floods).

For the development of long-term, efficient management strategies for both hydrological extremes, it is essential to understand the temporal changes of impacts, the causes of these impacts, and their interactions (Bouwer 2011, Merz et al. 2012a). Droughts and floods have different characteristics and are analysed by applying mostly different approaches (Garner et al. 2015, Quesada-Montano et al. 2018). Nevertheless, they should not be treated in isolation, since both the hazard and the socio-economic impacts of one are influenced by the management strategies for the other (Holden and Shiferaw 2004, Di Baldassarre et al. 2017). Optimal water resource and risk management that mitigates drought and flood impacts, e.g. on navigation or crop production, is often only possible when considering both extremes (Duviella et al. 2018, Chen et al. 2018). In addition, research on floods and droughts has largely been done separately, while both research fields could benefit from each other with regard to monitoring and forecasting approaches, assessment methods and analytical tools.

Due to its complexity, the attribution of trends in impacts, i.e. linking a detected change to the most likely causes, if possible with some defined level of confidence, is particularly challenging (Merz et al. 2012b). For understanding trends in both drought and flood impacts, we need to clearly disentangle trends in hazard, exposure and vulnerability, as well as their interactions. The identification of risk drivers helps in the selection of the most effective countermeasures. Additionally, quantitative information about the long-term development of risk is essential for the application of economic evaluation techniques (e.g. cost-benefit analyses) to risk management measures with a long lifetime (e.g. dikes, reservoirs, groundwater well fields).

The objective of this paper is to encourage a knowledge exchange between drought and flood experts from both the natural and social science domains, and to trigger joint studies on the attribution of impact changes with a focus on vulnerability. In this paper, we present a fictitious dialogue between two experts: one in droughts and the other in floods. The experts 'discuss' available data, information, and methods on drought and flood impacts, their observed changes and possible drivers, and identify challenges. Finally, we suggest a complementary approach for attributing impact changes, i.e. comparative analyses of single or multiple paired-event case studies.

2. Dialogue between flood and drought experts

2.1 How are drought and flood events defined and characterized? How are they interrelated?

Drought expert: Each drought is unique in its physical characteristics, as well as in its geographical scope and timing (Yevjevich et al. 1978). A drought can be generally defined as a period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance (WMO 2006). Drought is a relative concept, i.e. it denotes less water than normal for the region under study and the time of year. It is typically categorized into three types, propagating in the following order: meteorological (lack of precipitation), soil moisture (low content), and hydrological drought (Wilhite and Glantz 1985, Tallaksen and Van Lanen 2004). Hydrological drought can consist of groundwater drought and/or river flow drought, which interact via catchment hydrological processes (Tallaksen and Van Lanen 2004). In contrast to floods, drought has a creeping onset, and can persist up to several years. However, abrupt terminations of severe droughts due to floods may occur (Parry et al. 2013). The physical extent of droughts is unavoidable, so that they cover large areas and are not only limited to the hydrological aspects of watersheds. Nevertheless, drought is also understood to be, to a large extent, socially constructed (Keenan and Krannich 1997): a climate-induced deficit in water availability that triggers economic, social, or environmental impacts (Knutson et al. 1998, Lloyd-Hughes 2014), which in many cases are alleviated or enhanced by people (Van Loon et al. 2016). While water management and, specifically, engineering infrastructure are expected to alleviate hydrological drought downstream (e.g. He et al. 2017), water abstraction and irrigation will aggravate hydrological drought (e.g. AghaKouchak et al. 2015, Rangecroft et al. 2018). However, flood and drought management effects cannot be regarded separately, as negative side effects of flood risk management strategies may aggravate drought and *vice versa*. The occurrence of a drought or flood often triggers respective changes in water management (Mateo et al. 2014), which can then reduce the coping capacity in respect to the other hydrological extreme, particularly if it occurs shortly afterwards. Historic measures to prevent floods by quickly discharging water downstream have resulted in drying out headwater regions, increasing drought severity (Holden and Shiferaw 2004). Water that is stored to prevent a drought, either in artificial reservoirs, as natural sub-surface storage, or in wetlands, reduces the buffering capacity of floods (Di Baldassarre et al. 2017). This implies that there are feedback loops between floods and droughts that can lead to cascading chains of impacts. Therefore, it is interesting to note that some recent studies define drought by its impacts rather than by the exceedence of particular hydro-meteorological thresholds, stressing the socially constructed aspect of drought (Lloyd-Hughes 2014, Blauhut et al. 2015).

Flood expert: A flood can be defined as the temporary covering by water of land that is usually not covered with water (EC 2007), or water levels higher than a defined maximum (Blöschl et al. 2015). The main flood types are coastal floods caused by storm surges, as well as inland pluvial and river floods, including flash floods, caused by extraordinary rainfall events, sometimes in combination with snowmelt, ice jamming, high soil moisture contents or high groundwater levels (e.g. Merz and Blöschl 2003, Danard et al. 2003, Gaume et al. 2009, Skougaard Kaspersen et al. 2015). The focus here is on river floods, which commonly cover several tens to several hundreds of kilometres of river reach, and last from a few hours to several days (Merz and Emmermann 2006). Such floods often develop after prolonged periods of precipitation, short intense rain on saturated soils, local extreme rainfall caused by thunderstorms, snowmelt, or a combination of rainfall and snowmelt (Merz and Blöschl 2003). River floods occur when discharges exceed the conveyance capacity of the river bed and, consequently, overtop river banks or lead to failure of flood protection, such as dikes. Flood probabilities differ because of differences in natural flood regimes, and because of distinct risk management practices. For instance, human-made flood protection standards in rural areas for the Elbe River in Germany require a flood return probability of 1 in 20 years (IKSE 2015), whileit is 1 in 1250 years for the Rhine River in The Netherlands (Aerts et al. 2008). Despite their different characteristics, droughts and floods need to be jointly considered to enable the development of effective risk management strategies (e.g. Watanabe et al. 2018). For instance, Duviella et al. (2018) propose an adaptive allocation planning of water resources under the consideration of droughts and floods to effectively mitigate negative impacts on navigation. Also, for effective risk management in the agricultural sector, it is important to understand and quantify the influence of drought and floods on crop production (Chen et al. 2018). With the aim of creating water sensitive and resilient cities, Rodriguez et al. (2014) developed a framework and specific guidance for maximizing the value and use of water in urban areas and considering drought and flood resilience.

2.2. What are the impacts of drought and flood events and their drivers?

Drought expert: Droughts can have negative impacts on all socio-economic and ecological systems. When drought propagates from a rainfall deficit to, for example, low reservoir levels, it affects all natural and human activities that depend on stored water (e.g. soil water) and water supply (Figure 1). Stahl et al. (2016) reported over 100 different impact types, such as impacts on aquaculture, tourism, domestic and municipal water use, agricultural production, power generation, industrial production, but also water quality, ecosystems, human health, and conflicts between groups (Stahl et al. 2016). The majority of drought impact studies focus on agriculture. Drought impacts can be direct or indirect, with the potential to linger for years (Tallaksen and Van Lanen 2004, Wilhite et al. 2007), which makes it difficult to attribute impacts to a drought event and to identify temporal changes. As mentioned in the introduction (Section 1), the drivers of drought impacts are the drought hazard, exposure and vulnerability. Different event characteristics result in different impacts, e.g. the 1975/76 Central European drought had, due to its long duration, a strong effect on water supply systems, similar to the 2015 drought, while the 2003 Central European drought, in combination with a strong heatwave, had severe effects on agriculture (Stahl et al. 2016). Therefore, the hazard component is a crucial element of most drought analyses. The hazard is typically described by a drought index, or a combination of drought indices. A wealth of meteorological, soil moisture and hydrological drought indices currently exists (Heim 2002, Zargar et al. 2011), but early-warning systems mainly use meteorological indices due to data availability issues (Bachmair et al. 2016). Drought impacts are also understood to be symptoms of vulnerability (Knutson et al. 1998), which is mostly assessed through a combination of different vulnerability factors, framed in different conceptual models (Tanago et al. 2016). To analyse drought risk, there are different approaches (Blauhut et al. 2016): (i) the "factor approach" systematically assesses the relevant physical, ecological and socio-economic factors that drive drought risk; (ii) the "impact approach" uses past drought impacts as proxy for vulnerability to drought (e.g. impact reports include yield losses, or remote sensing); and the "hybrid approach" combines both kinds of information. A relatively new method to quantify drought risk is a collaborative modelling approach (Basco-Carrera et al. 2017, Mens et al. in prep.). Impact models, translating hydrological model output into national-scale socio-economic impacts, are developed through interviews with stakeholders from various sectors (navigation, agriculture, domestic and industrial water supply). In this approach, even with a lack of observed drought impact data, plausible impact models can be built and used in the decision-making process (Basco-Carrera et al. 2017, Mens et al. in prep.). Overlaying hazard maps with vulnerability maps, as often done to quantify flood risk, does not work for droughts, because water users and their water resources are often not in the same location.

Flood expert: Negative impacts of floods are commonly divided into direct and indirect damage (Smith and Ward 1998), similar to drought impacts (Figure 1). Next to direct impacts (e.g. fatalities and destroyed buildings), indirect damage often occurs with a time lag, and is induced by direct damage or business interruptions (Kreibich et al. 2014). Most flood-risk studies focus on urban areas, particularly on buildings, businesses and infrastructure (Merz et al. 2010b, De Moel et al. 2015). Flood impacts on agriculture are usually lower, and are less often assessed (e.g. Tapia-Silva et al. 2011, Brémond et al. 2013, Klaus et al. 2016). Flood risk is commonly analysed using model chains, comprising hazard, exposure and vulnerability models (De Moel et al. 2015, Falter et al. 2015), which is similar to the factor approach for drought risk. Hazard assessments consist of two steps: first, the discharge related to a specific return period is estimated; and second, the discharge is translated into inundation characteristics via hydraulic modelling (e.g. Pappenberger et al. 2012, Alfieri et al. 2013). Exposure is assessed by overlaying the hazard information with socio-economic information such as buildings datasets or population density (e.g. Wünsch et al. 2009). Finally, hazard and exposure are combined with information on vulnerability, for instance through loss models to estimate damage (e.g. De Moel and Aerts 2011, Kreibich et al. 2017b). Mainly with the aim to improve flood-loss models, damage processes at the building level have been intensively analysed in recent years, so that it is relatively well known which variables are the main drivers of damage at the micro-scale (e.g. Thieken et al. 2005, Chinh et al. 2016, Sieg et al. 2017). Damage influencing variables can be differentiated into impact and resistance parameters (Thieken et al. 2005). Merz et al. (2010b) list 14 damage influencing variables which are considered in different flood damage models. However, most studies identify the inundation depth and the type or use of the element at risk as the most important variables. Thus, depth–damage functions are used most frequently for impact estimation (Merz et al. 2010b). However, the use of multi-variable models holds the potential to further improve impact assessments (Schröter et al. 2014, Wagenaar et al. 2018). Less knowledge is available on the importance of processes or variables determining differences in flood damage between events. An alternative approach for flood risk assessments are indicator-based methods, which are particularly common in large-scale risk assessments (e.g. Schmidt-Thomé et al. 2006, Tessler et al. 2018), or in social sciences disciplines (e.g. Hahn et al. 2009, Fekete 2009, Aroca-Jimenez et al. 2017). Indirect impacts of floods should also be considered, given their potential magnitude, but this is a relatively new field of research (Koks and Thissen 2016, Sieg et al. 2018).

Figure 1. High-impact drought and floods of the 21st century. (Left) River Waal near Nijmegen, The Netherlands, during the 2018 drought: record low river water levels caused high losses for water-borne transport (© Henny A.J. Van Lanen, Wageningen University). (Right) The River Mulde inundating the city of Grimma, Germany, in 2013: severe flooding caused high losses to buildings and infrastructure (© Astrid Krahn, GFZ).

2.3 What impact data is available?

Drought expert: Information on production rates, such as agricultural yields, hydropower production or water abstraction, can be gathered from a variety of subnational, national and international agencies (e.g. Eurostat, Aquastat, World Energy Council). However, due to the spatial and temporal resolution of the information, but also due to the impacted assets, the indirect and diffuse relationship with droughts, and the different mechanisms in which droughts can cause damage in different sectors, such information has to be filtered and carefully attributed to identify the effect of droughts. Consequently, there is a lack of direct and indirect drought impact data (Hayes et al. 2011), but recent initiatives have started collecting such data. For example, the US Drought Impact Reporter (http://drought.unl.edu/monitoringtools/droughtimpactreporter.aspx) and the European Drought Impact Inventory (EDII, http://www.geo.uio.no/edc/droughtdb/index.php) collate, categorise, and represent drought impacts based on a variety of sources. The EDII is the only open database for reported drought impacts that covers the variety of possible drought impacts, especially those that are typically difficult to quantify (e.g. ecological impacts) (www.europeandroughtcentre.com). Additionally, national programmes such as the Chinese disaster database (Hao et al. 2012), where municipalities have to report every 10 days on disasters related to crops, create novel data series. Additionally, there are international impact databases, which cover various natural hazards including droughts and floods. Well-known examples are the global EM-DAT International Disaster Database (www.emdat.be) and the Disaster Inventory System - DesInventar with a regional focus on Latin America (www.desinventar.org).

Flood expert: Flood impact data, aggregated at the event level, are available from several global, regional and national databases; overviews are provided by Tschoegl et al. (2006), Gall et al. (2009), Bubeck and Kreibich (2011), EEA (2013) and Rudari et al. (2017). Examples are the global NatCatSERVICE (www.munichre.com/natcatservice) of the Munich Re (Kron et al. 2012), the regional Disaster Information Archive of the Asian Disaster Reduction Center (ADRC, http://www.adrc.asia), and the national Swiss flood and landslide damage database hosted at the Swiss Federal Research Institute WSL (Hilker et al. 2009). Comprehensive information, including discharge, inundation maps and some aggregate impacts (e.g. affected area and people) of past flood events since 1985, are available via the Dartmouth Flood Observatory hosted at the University of Colorado, USA (http://floodobservatory.colorado.edu/Archives/index.html). Some flood impact data at the object level, e.g. damage information per building, are available, for instance from the flood damage database for railway infrastructure of the Austrian Federal Railway (Moran et al. 2010), and the German flood damage database, HOWAS21, hosted at the German Research Centre for Geosciences (Kreibich et al. 2017a). Public and private insurance agencies are another important source of data. However, these object-specific databases contain often only limited information on potential damage drivers and only fragmented samples, which cannot provide information about the total impact of an event (Kreibich et al. 2017a). Thus, additional data at the object level is required (e.g. Jongman et al. 2015) and the collection of such data should not be left to scientific organizations alone. More collaboration across all stakeholders who deal with the consequences of flooding (e.g. government agencies, civil protection, and insurance companies) is required to improve the availability and quality of data of impacts and drivers (Molinari et al. 2018).

2.4 Are flood and drought impacts changing over time and what are the potential drivers of observed trends?

Drought expert: Detecting and, even more, attributing trends in drought impact data is challenging. Naumann et al. (2015) analysed drought impacts on crop production, hydropower and waterborne transportation, and De Stefano et al. (2015) assessed vulnerability to drought based on a wealth of vulnerability factors and EDII information on a pan-European scale. Both studies reveal changes in drought impacts over time; however, a detection of general trends was not possible. Hawkins et al. (2013) detected an increase in maize yield since the 1960s, which is likely due to irrigation and technology improvements and not, as commonly believed, related to precipitation and hot days (as major drivers of maize yield). Hlavinka et al. (2009) observed several fluctuations in yield gains from 1961 to 2000 in the Czech Republic, mainly attributing these to socio-economic changes, e.g. the apparent yield decline in the 1990s was mainly attributed to the transformation of the farming industry after 1989, when "Gentle Revolution" ended the planned economy and one-party government of the Communist Party. This shows that trends in impacts are not easily linked to drought and that socio-economic factors might play an important role. Blauhut et al. (2015) discussed major legislative changes as drivers for an increase in drought impacts on agricultural production. Stahl et al. (2016) detected a strong increase in drought impact reports for Europe and attributed that to improved public and governmental awareness, but also faster communication and easier accessibility of information though the Internet. Studies like those of Tanago et al. (2016) and Naumann et al. (2018) are essential to improve our understanding of changes in vulnerability; however, quantitative studies on the dynamic characteristics of vulnerability and exposure to drought are lacking. These examples show that available knowledge on trends in drought impacts is still scarce and fragmented.

Flood expert: Some studies have undertaken temporal trend analyses on flood damage data (e.g. Pielke and Downton 2000, Llasat et al. 2008, Barredo 2009, Arghius et al. 2011, Pérez-Morales et al. 2018). Additional literature is available on trends in damage due to hydro-meteorological events, including floods (e.g. Changnon 2003, Choi and Fisher 2003, Crompton and McAneny 2008, Neumayer and Barthel 2011, Pinkswar et al. 2012). Bouwer (2018) provides an overview of the results of 34 studies, which analysed records from natural hazard losses in economic terms. All these studies detect a clear increase in damage due to floods and other hydro-meteorological events; however, in terms of attribution, most studies find that the observed increase is due to societal change and economic development. An effect on damage from changes in flood hazard due to climate change has hardly been observed to date (Merz et al. 2012a). Considerable uncertainties about these results remain, since exposure and vulnerability are largely influenced by human interventions such as flood protection (Aerts et al. 2018), and their interaction and influence on risk can only be roughly accounted for over time (Bouwer 2011). Some studies at global (Jongman et al. 2015) and regional scales (Di

Baldassarre et al. 2015, Mechler and Bouwer 2015, Kreibich et al. 2017c, Bouwer and Jonkman 2018) suggest that an increase in flood hazard can be counteracted via a decrease in vulnerability, e.g. via effective flood-risk management, including protection, early warning and preparation. In particular, protection infrastructures such as levees and other flood protection measures have significantly reduced flood risk (e.g. Paprotny et al. 2018).

2.5 What do we know about vulnerability and its influence on drought and flood impacts?

Drought expert: Knowledge about the role of vulnerability in changes in drought impacts is scarce. Approaches to assess vulnerability to drought are diverse and the results scattered (Tanago et al. 2016). The assessments that do exist describe the socio-cultural characteristics of the assessed system, while the characterization of water uses and resources is less common. The most commonly used vulnerability factors (used in the factor approach) are measures of population, irrigation and economic resources (Tanago et al. 2016). This is in contrast to Blauhut et al. (2016), who found that vulnerability factors that quantify land surface characteristics or water reservoirs are most relevant to predict the likelihood of drought impact occurrence. In a unique attempt, Gil-Guirado et al. (2016) reconstructed vulnerability to droughts and floods of two Hispanic cities since the 17th century, highlighting the importance of understanding the past to foster future resilience, but also the difficulty of characterizing the dynamics of vulnerability over time through an indicator. Whereas overall vulnerability has decreased due to better adaption strategies, they observed that, during droughts, new possibilities of water withdrawal result in increased environmental problems and overexploitation of water resources. Dougill et al. (2010) found that policy changes are key drivers of dynamic drought vulnerability of pastoral systems in Kalahari (southern Africa): whereas government land privatization policy helped wealthier ranchers, it increased the vulnerability of poorer communal pastoralists. Eriksen and Silva (2009) detected uneven opportunities and differentiation, both socially between households and geographically between villages, driving patterns of vulnerability. Leichenko and O'Brien (2002) highlight the influence of global economic changes on rural vulnerability. Hence, to understand vulnerability, its evolution across spatial scales has to be understood (Westerhoff and Smit 2009). Studies such as that of Simelton et al. (2009), who undertook a detailed analysis of crop vulnerability to drought for various events, make a big step in the right direction. A further strategy, proposed by Leichenko and O'Brien (2002), is to assess dynamic vulnerability via multi-scale analysis. Additionally, there is a need for more longitudinal surveys (Eriksen and Silva 2009), which should be related to larger-scale vulnerability factors, especially changes in economic policies (Leichenko and O'Brien 2002), governmental policies and market conditions (Belliveau et al. 2006). In Table 1, some examples of approaches for investigating changes in vulnerability of droughts and floods are presented.

Flood expert: Knowledge on the role of vulnerability in flood risk changes, of temporal trends in vulnerability, and of the quantitative effects of potential drivers of vulnerability change is also limited (Mechler and Bouwer 2015). At the global level, vulnerability seems to have declined substantially since about 1980, which is reflected in decreasing mortality and losses as a share of population and gross domestic product exposed to river flooding (Jongman et al. 2015), as well as storm surge mortality (Bouwer and Jonkman 2018). In Bangladesh, economic vulnerability and vulnerability of loss of life has strongly decreased since 1974, which seems to be due to substantial improvements in flood-risk management (Mechler and Bouwer 2015). An empirical analysis of eight case studies around the world showed that an observed reduction in flood impacts was mainly driven by reductions in vulnerability (Kreibich et al. 2017c). However, vulnerability aspects and processes influencing flood impacts are strongly context- and location-specific (Dzialek et al. 2016). For instance, socio-economic, cultural and environmental settings influence what options for reducing vulnerability are realistic (McCubbin et al. 2015, Kreibich et al. 2017c). Vulnerability can be positively influenced by flood-risk management (Merz et al. 2010a, Klijn et al. 2015, Kreibich et al. 2015). Integrated flood-risk management complements flood protection with non-structural solutions, e.g. private precaution, land-use planning and insurance (Bubeck et al. 2017, Kunreuther et al. 2009). However, vulnerability can also be negatively influenced by changes in building materials, increasing dependence on critical infrastructure, or changes in business processes. For instance, recent reports of insurers emphasize that floods cause tremendous losses, particularly to modern buildings with good thermal insulation and innovative building materials. While these buildings perfectly fulfil the requirements of energy-saving standards that are important to mitigate climate change in the long run, it seems that such constructions tend to increase average building losses due to their high susceptibility to flooding.

2.6 What are the challenges with impact trend detection and attribution?

Drought expert: Two major challenges are prevailing: the lack of consistent long time series of impact and vulnerability information, and the lack of commonality in approaches to investigate vulnerability to drought. The inherent lack of data is a big challenge. Impact information stems either from annual national statistics and, as such, is not directly linked to drought, or from information that is gathered with a focus specifically on drought, which makes it very time-consuming and therefore limited. Annual national statistics can be influenced by a variety of factors (e.g. annual crop yields may have suffered from drought in spring and wetness in summer, or the other way around, and it is unclear whether the drought or the wetness had more impact on the annual values). However, reported drought impacts are still not collected and standardized comprehensively with regard to space and time. Furthermore, annual trends can be related to sampling or reporting biases due to differences in impact report availability and incomplete information. The growing public awareness of droughts as well as social media enable the public to communicate about drought impacts much faster and easier than before. The crowdsourcing of impact information is an encouraging option to increase information on natural disasters (e.g. Horita et al. 2013, Enenkel et al. 2015), but it might also lead to a reporting bias in impact data. Furthermore, governmental monitoring networks have become more efficient, partly due to remote sensing developments (Bachmair et al. 2018), so that much more impact information is collected nowadays than a few decades ago. Additionally, there is no common framework for studies on trends in drought impacts, vulnerability or drought risk. Comparative studies, in which different approaches are tested for one region, or the same approach is tested in different parts of the globe, do not exist. Reasons for this might be the qualitative nature of the information, i.e. it is very hard to get quantitative data on drought vulnerability and impacts, or the fact that it is strongly dependent on the context and, as such, extremely region-specific (drought vulnerability and impacts are so different between economies and cultures that transferability of methods might be low). In conclusion, there is a lack of reliable, consistent drought impact and vulnerability data, and our current knowledge about drivers of drought impacts and root causes of drought vulnerability is still very limited.

Flood expert:

Trend analyses on aggregated flood damage data from past events suffer from similar problems and uncertainties. Impact databases are affected by different uncertainties and biases (Downton and Pielke 2005, Gall et al. 2009). For example, small events are lacking in global databases as opposed to national databases, and an increasing loss trend may be driven by increased reporting of natural hazard events over time (Neumayer and Barthel 2011). Due to the event level and large spatial scales of analysis, e.g. continental (Barredo 2009), or global (Neumayer and Barthel 2011), the studies cannot provide insights into damage processes. For event-level information, the effect of exposure and vulnerability that influence impacts cannot be separated or analysed in detail (Bouwer 2011, Merz et al. 2012a). There are various influences on flood impacts, comprising climate change and variability, land-use change, dike construction along rivers, economic development in floodplains, and risk management actions such as early warning, emergency response and precautionary measures (Bouwer 2011, Vorogushyn and Merz 2013). Some of these drivers may counteract each other (Jongman et al. 2015, Mechler and Bouwer 2015, Di Baldassarre et al. 2015). Since impacts are influenced by such complex interactions of various physical and societal processes, it is difficult to attribute changes in impacts to specific drivers. An alternative to these normalization studies based on highly aggregated data (e.g. Barredo 2009, Neumayer and Barthel 2011) is case study analyses, which are able to consider the different influences on flood impacts, and the broader context, including flood-risk management and local specificities (e.g. Kreibich and Thieken 2009, Kreibich et al. 2011, Kienzler et al. 2015). However, long-term analyses in local case study areas are only very rarely possible; an exception is that by Gil-Guirado et al. (2016). Empirical data analyses are complemented by modelling approaches, used to unravel the effects of multiple causes (Merz et al. 2012b, Elmer et al. 2012, Jongman et al. 2015, Mechler and Bouwer 2015). However, modelling is also associated with uncertainties, particularly due to uncertainty propagation through the model chain (e.g. Hall et al. 2003, te Linde et al. 2011). For instance, 'probabilistic event attribution', as described by Pall et al. (2011), showed that in nine out of ten cases the model results indicate that greenhouse gas emissions increased the risk of damaging floods occurring in England and Wales in 2000 by more than 20%, and in two out of three cases by more than 90%. A sensitivity analysis applied to the Mulde catchment in Germany showed that flood risk can vary substantially and components that have not received much attention, such as changes in dike systems or in vulnerability, have a high influence on flood risk (Metin et al. 2018). A modelling study comparing two scenarios in Bangladesh, one with decreasing vulnerability (based on past reductions) and one with static vulnerability, revealed for future flood risk that, in the dynamic scenario risk would still increase, although at a much slower pace compared to the static scenario (Mechler and Bouwer 2015).

3. Suggestions for how to progress in attributing changes in drought and flood impacts

The fictitious dialogue between the drought and flood experts 'discussed' data and approaches available for the analysis of changes in impacts and vulnerability. It also showed that drought and floods, and their management, are closely linked and that more interdisciplinary learning from each other and cooperation between drought and flood experts is crucial. As Belliveau et al. (2006) stated for viticulturists, they *"work within a multi-risk environment. Furthermore, it is the presence and interaction of these various risks that influences producers' exposures, sensitivities, and responses."*. Thus, a common framework for the analysis of drought and flood impacts would be beneficial. We therefore propose a number of future directions for research on the attribution of changes in drought and flood impacts.

Knowledge and data on past impacts are key to understanding vulnerabilities, but such information is still lacking at high spatial and temporal resolutions. Hence, we propose to foster efforts to collect and standardize impact information (Van Lanen et al. 2016). International, sector-specific standards for impact data collection should be developed and implemented. Reporting bias can be mitigated by having clear thresholds that define under which circumstances an event impact will be included in a database. For instance, the Sigma database (www.sigma-explorer.com) uses a quantitative threshold of overall loss of US$86.6 million, insured loss of US$43.3 million (both in 2010 values), or 20 fatalities/people missing (Kron et al. 2012). The EM-Dat uses the following threshold: more than 10 fatalities and over 100 people affected, or if a state of emergency is declared or an appeal for international assistance made (Kron et al. 2012). A similar approach to mitigate the effect of reporting bias is to analyse only major events, for which a reporting bias is less likely (e.g. Barredo 2009).

Additionally, it seems reasonable to collect more detailed impact data, e.g. differentiated between sectors and regions to enable the consideration of sector- and region-specific characteristics, and to avoid having counteracting trends. To enable the consideration of other influences such as differences in awareness, changes in coping capacity, economic stressors and political impacts, data on these aspects need to be collected complementary to hazard, exposure and impact information. An attempt in this direction has been made for floods by Elmer et al. (2010), who used a Delphi method expert survey to define standards for flood damage data collection and decide which complementary data (e.g. lists of parameters) should be collected.

Approaches for impact trend detection and attribution should be further developed via a transdisciplinary exchange, and learning between drought and flood experts from research and practice as well as experts from various domains such as natural sciences, social sciences and economics. This will help us understand the context in which changes in impacts have happened, and shed light on changes in vulnerability (e.g. Leichenko and O'Brien 2002, Eriksen and Silva 2009, Thomas et al. 2013). Thus, to make progress in attributing changes in drought and flood impacts, we suggest to undertake more detailed, local to regional analyses, i.e. considering various hazard, exposure and vulnerability aspects, as well as the broader context, including risk management and specificities of the affected location. It might be difficult to compile and find significant trends in time series of impacts and related drivers at local to regional levels, due to problems with rare events, cascading effects of multiple hazards, data scarcity, biases, etc. Thus, in addition to time series analyses, we suggest to analyse relationships and patterns between causes and consequences based on paired events in the same catchment or region (Kreibich et al. 2017c). The approach is analogous to the concept of 'paired-catchment studies' (Brown et al. 2005), consisting of analysing two events that occurred in the same catchment or region and the processes between the events that might have caused changes in hazard, exposure or vulnerability, irrespective of the time between events. This enables detailed contextual insights into physical and socio-economic changes (e.g. vulnerability changes, adaptive behaviour) between those events, as well as into the variety and complexity of relationships between causes and consequences. This approach is not limited to one pair of events, but the more events that are considered for the same region, the better.

Already, some studies have been analysing floods and droughts in combination, but with rather coarse data at a large scale (e.g. Neumayer and Barthel 2011). We suggest all components of the drought and flood risk process be considered and a large variety of variables analysed (Table 2), including new data sources such as satellite data and social media (e.g. Fohringer et al. 2015). Vulnerability is of particular interest, since this seems to be the least understood risk component in comparison to exposure and hazard, and it may explain much of the impact dynamics (Mechler and Bouwer 2015, Jongman et al. 2015). Intensifying interdisciplinary cooperation seems particularly helpful for analysing one or multiple paired-event case studies, and also to understand what drives changes in vulnerability. For instance, the protection-motivation theory developed in health science (e.g. Grothmann and Reusswig 2006, Bubeck et al. 2012b, 2013, Keshavarz and Karami 2016), as well as theories from psychology and behavioural economics (e.g. Grothmann and Patt 2005, Van Duinen et al. 2015), can help us to understand why and when people act or do not act to reduce their risks. Econometric techniques, such as propensity score matching (Dehejia and Wahba 2002, Hudson et al. 2014), or regression analysis (Wooldridge 2003, Poussin et al. 2015), can be used to quantitatively estimate the effect of precautionary measures in reducing impacts. For the paired-event study approach, a much more detailed monitoring and documentation of events, but also of the processes between events which influence the risk, is necessary, together with a closer link between data-driven and modelling-driven analyses. Processes and variables that are difficult to monitor might be represented via modelling approaches or via proxies derived from new data options. Thus, we suggest that a large number of paired-event case studies from around the world are collected and analysed, and detailed studies are undertaken on processes leading to the resulting impacts on an event level with a focus on changes in vulnerability between events.

A problem of extreme event analysis is that every event, region, situation, etc. is unique and has its own characteristics and processes, which makes it challenging to draw general, transferable conclusions. To yield generic results, we propose to combine two approaches: (a) analysing one or multiple pairs of events as described above; and (b) undertaking a comparative analysis of various paired-event case studies from different hydro-climatic and socio-economic settings. The approach of paired catchment studies is well established for determining the magnitude of water yield changes resulting from changes in vegetation (Brown et al. 2005) and has also been used for investigating whether changes in flood discharge can be attributed to changes in land use (Prosdocimi et al. 2015). When this approach is complemented with semi-qualitative data on exposure and vulnerability, and transferred to event comparisons, it is useful for the investigation of drivers of risk change, as demonstrated for floods by Kreibich et al. (2017c), and as suggested for droughts by Van Loon et al. (2016). In Table 2 we suggest information (e.g. measured data, indicators or proxies) which should be compiled for the analyses of single or multiple paired-event case studies. To account for comparability with floods and the previous paired-event case study by Kreibich et al. (2017c), the components of drought risk have also been categorized according to exposure and vulnerability. However, it should be noted that such an arrangement critically depends on the background of the study, and that classifications are debatable. Recent comparative studies (Tanago et al. 2015, Blauhut et al. 2016) have moved away from such fixed categorization schemes. Comparative analysis aims to find general patterns by analysing a large set of case studies from all over the world (e.g. Duan et al. 2006, Blöschl et al. 2013). Combining these two approaches in collecting a large number of paired events seems a promising way forward for attributing changes in impacts of hydrological extremes. The advantages of this approach are as follows: (i) it is flexible in terms of data, e.g. it is not necessary that homogeneous measurements, surveys etc. are undertaken in all case studies; (ii) it allows detailed context and location specific analyses; and (iii) it can accommodate commonalities and differences between floods and droughts. The resulting analysis can be used to explain trends and current factors that determine impacts. But more importantly, it can also be used for forward looking studies; either to project future risks (Bouwer 2013), but also to be used as baseline against which the effects and efficiency of flood risk management measures can be tested, evaluated and decided upon.

4 Concluding remarks

To develop sustainable and efficient risk management strategies for droughts and floods, it is essential to understand the temporal changes of impacts, their causes and interactions. Drought and flood experts need to work together more closely and initiate joint studies on attribution of impact changes with a focus on vulnerability. To make scientific advances in this area, available databases as well as data collection initiatives should be strengthened and further improved, e.g. via the development of international standards for data collection, collecting more detailed data and broadening the collected data towards more information on potential drivers, like vulnerability characteristics. Available approaches for impact trend detection and attribution should be further developed via a transdisciplinary exchange and learning between drought and flood experts. Additionally, we suggest a complementary approach, i.e. to collect a large number of single or multiple paired-event case studies from different hydro-climatic and socio-economic settings around the world, undertake detailed analyses of changes in impacts and drivers, and carry out a comparative analysis. The advantages of this approach are that it allows detailed context and location-specific assessments due to the paired-event case study analyses and reveals general, transferable conclusions due to the comparative analysis of various case studies. Additionally, it is quite flexible in terms of data and can accommodate differences between floods and droughts. We hope to motivate a broader international initiative to collect and analyse a large number of paired-event studies, for example, in the framework of the Panta Rhei initiative of the International Association of Hydrological Sciences (IAHS).

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Table 1. Examples of approaches from the natural and social sciences for investigating changes in vulnerability.

Approach	Droughts	Floods
Longitudinal studies (surveys or interviews)	Analysing the association between drought and mental health of women in Australia with a longitudinal study from 1996 to 2008 (Powers et al. 2015) Analysing the dynamics of vulnerability and multiple stressors through a case study in the Afram Plains, Ghana (Westerhoff and Smit 2009)	Analysing consequences of climate-related natural disasters for long-term population mobility in Bangladesh using longitudinal survey data spanning 15 years (Gray and Mueller 2012) Study of recovery following the floods of 2007 in England (Medd et al. 2015)
Time series analyses of proxies or indicators	The dynamics of vulnerability to drought from an impact perspective (Blauhut et al. 2015) Integrated index for assessment of vulnerability to drought, case study: Zayandehrood River Basin, Iran (Safavi et al. 2014)	Change in flood insurance coverage in California, USA (Hanak 2011) Changes in implemented private flood risk mitigation measures and flood losses in the Rhine basin (Bubeck et al. 2012a) Study of flood mortality fractions over time (Bouwer and Jonkman 2018)
Detailed analyses of case studies	Reconstruction of vulnerability to floods and droughts of two Hispanic cities since the 17th century (Gil-Guirado et al. 2016) Anticipating vulnerability to climate change in dryland pastoral systems: using dynamic systems models for the Kalahari, southern Africa (Dougill et al. 2010) The vulnerability context of a savanna area in Mozambique (southern Africa): household drought coping strategies and responses to economic change (Eriksen and Silva 2009)	Change in flood coping capacity in Dresden, Germany (Kreibich and Thieken 2009) Changes in flood preparedness in Germany between 2002 and 2006 (Kreibich et al. 2011) Changes in flood preparedness, response and recovery (2005–2011) in Germany (Kienzler et al. 2015)
Model-based analyses	Crop yield modelling (e.g. Semenov and Srewry 2011, Pogson et al. 2012) Modelling both floods and droughts (Peduzzi et al. 2009)	Modelling of global vulnerability to river floods (Jongman et al. 2015) Modelling of flood vulnerability in Bangladesh (Mechler and Bouwer 2015) Modelling drivers of flood risk change at the Mulde River, Germany (Elmer et al. 2012)

Table 2. Important information for compiling single or multiple paired-event case studies. Examples of data, indicators or proxies which might be used are listed, as well as the potential sources of these data.

	Information	Example data/indicators/proxies for droughts and floods	Data sources
Hazard	Meteorology	Precipitation (e.g. Funk et al. 2015), precipitation index (Schröter et al. 2015), standardized precipitation index, snow cover, standardized snowmelt and rain index (Staudinger et al. 2014), temperature, (potential) evapotranspiration, standardized precipitation evaporation index (Vicente-Serrano et al. 2010), wind speed	Meteorological monitoring (e.g. raingauges, weather stations), radar/satellite observations
	Soil moisture conditions	Soil moisture, antecedent precipitation index, wetness index (Schröter et al. 2015), soil moisture anomaly (SMA, Orlowsky and Seneviratne 2013)	Satellite data, modelling based on meteorological data
	Hydrology	Groundwater time series, standardized groundwater index (Bloomfield and Marchant 2013), standardized runoff index (Shukla and Wood 2008), discharge, flood severity index (Schröter et al. 2015), reservoir levels	Monitoring data from gauging stations, groundwater wells, reservoirs, hydrological modelling based on meteorological data
	Vegetation	State of vegetation cover (preferably normalized such as NDVI, fAPAR, VCI, VHI)	Remote sensing products of photosynthetic activity
	Protection failures	Number/severity of dike breaches or dam breaches	Reports, visual inspection, remote sensing
Exposure	Affected people	Number of affected people	Reports, surveys, EM-DAT (2015)
	Area affected	Spatial extent , settlement area affected, asset values affected (De Moel et al. 2011)	Estimated on basis of drought indicators, remote sensing, hydraulic modelling, overlay of flood extent and land use/exposure maps
	Exposure hotspots	SEVERELY affected major cities, industrial areas, critical infrastructure, crop production hotspots (i.e. drought in major crop producing areas can lead to global food shortage), exposure defined by reoccurrence of past	Event documentation, news reports, remote sensing

		drought impacts and hazard frequency (De Stefano et al. 2015), water exploitation index	
	Object characteristics	Water users of watersheds, land surface characteristics (e.g. CORINE landcover), crop types, drinking water supply system, building/household/company characteristics, precautionary measures	Statistical information, remote sensing, surveys
Vulnerability	Awareness and precaution	Time since last event in region, risk perceptions, private precaution undertaken, awareness (Aerts et al. 2018)	Social media, surveys, event documentation
	Preparedness	Emergency management plans, emergency exercises, early warning, use of forecasts	Interviews, surveys, plans and documents
	Organisational emergency management	Water-use restrictions, public management organization, emergency plans, early warning system	Emergency plans, event documentation, 'lessons learned' studies, news reports, legislation
Consequences / damage	Impact on people	Number of evacuated people, fatalities (e.g. Jonkman et al. 2008), health issues, migration	Event documentation, news reports, surveys, EM-DAT (2015)
	Economic damage	Direct and indirect damage (Koks et al. 2014): e.g. crop yield losses, structural damage, production losses, water quality issues	Event documentation, news reports, compensation programmes, government and insurance industry data and estimates, national statistics , EM-DAT (2015), NatCatSERVICE (Kron et al. 2012)
	Impact on nature	Dried out land, contamination due to floods	Event documentation, news reports, assessments