Panta Rhei benchmark dataset: socio-hydrological data of paired events of floods and droughts

Heidi Kreibich[1], Kai Schröter[1,68], Giuliano Di Baldassarre[40,41,~~67~~], Anne F. Van Loon[2], Maurizio Mazzoleni[2], Guta Wakbulcho Abeshu[3], Svetlana Agafonova[4], Amir AghaKouchak[5], Hafzullah Aksoy[6], Camila Alvarez-Garreton[7,~~8~~], Blanca Aznar[9], Laila Balkhi[10], Marlies H. Barendrecht[2], Sylvain Biancamaria[11], Liduin Bos-Burgering[12], Chris Bradley[13], Yus Budiyono[14], Wouter Buytaert[15], Lucinda Capewell[13], Hayley Carlson[10], Yonca Cavus[16,17,18], Anaïs Couasnon[2], Gemma Coxon[19,20], Ioannis Daliakopoulos[21], Marleen C. de Ruiter[2], Claire Delus[22], Mathilde Erfurt[18], Giuseppe Esposito[23], Didier François[22], Frédéric Frappart[69], Jim Freer[19,20,24], Natalia Frolova[4], Animesh K Gain[25], Manolis Grillakis[27], Jordi Oriol Grima[9], Diego A. Guzmán[28], Laurie S. Huning[29,5], Monica Ionita[30,70,47], Maxim Kharlamov[31,4], Dao Nguyen Khoi[32,49], Natalie Kieboom[33], Maria Kireeva[4], Aristeidis Koutroulis[34], Waldo Lavado-Casimiro[36], Hong-Yi Li[3], Maria Carmen LLasat[37,38], David Macdonald[39], Johanna Mård[40,41], Hannah Mathew-Richards[33], Andrew McKenzie[39], Alfonso Mejia[42], Eduardo Mario Mendiondo[43], Marjolein Mens[44], Shifteh Mobini[45,35], Guilherme Samprogna Mohor[46], Viorica Nagavciuc[47,30], Thanh Ngo-Duc[48], Huynh Thi Thao Nguyen[49], Pham Thi Thao Nhi[32,49], Olga Petrucci[23], Nguyen Hong Quan[49,50], Pere Quintana-Seguí[51], Saman Razavi[52,53,10], Elena Ridolfi[71], Jannik Riegel[54], Md Shibly Sadik[55], Nivedita Sairam[1], Elisa Savelli[40,41], Alexey Sazonov[31,4], Sanjib Sharma[56], Johanna Sörensen[45], Felipe Augusto Arguello Souza[43], Kerstin Stahl[18], Max Steinhausen[1], Michael Stoelzle[18], Wiwiana Szalińska[57], Qiuhong Tang[58], Fuqiang Tian[59], Tamara Tokarczyk[57], Carolina Tovar[60], Thi Van Thu Tran[49], Marjolein H. J. Van Huijgevoort[61], Michelle T. H. van Vliet[62], Sergiy Vorogushyn[1], Thorsten Wagener[46,20,63], Yueling Wang[58], Doris E. Wendt[63], Elliot Wickham[64], Long Yang[65], Mauricio Zambrano-Bigiarini[8,7], Philip J. Ward[2]

[1]GFZ German Research Centre for Geosciences, Section Hydrology, Potsdam, Germany

[2]Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, The Netherlands

[3]Department of Civil and Environmental Engineering, University of Houston, USA

[4]Lomonosov Moscow State University, Russia, [5]University of California, Irvine, USA

[6]Department of Civil Engineering, Istanbul Technical University, Istanbul, Turkey

[7]Center for Climate and Resilience Research (CR2, FONDAP ~~15110009~~1522A0001), Santiago, Chile

[8]Department of Civil Engineering, Universidad de La Frontera, Temuco, Chile

[9]Operations Department, Barcelona Cicle de l'Aigua S.A, Barcelona, Spain

[10]Global Institute for Water Security, University of Saskatchewan, Canada

[11]LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS, Toulouse, France

[12]Department of Groundwater Management, Deltares, The Netherlands

[13]School of Geography, Earth and Environmental Sciences, University of Birmingham, UK

[14]National Research and Innovation Agency (BRIN), Jakarta, Indonesia

[15]Department of Civil and Environmental Engineering, Imperial College London, London, UK

[16]Department of Civil Engineering, Beykent University, Istanbul, Turkey

[17]Graduate School, Istanbul Technical University, Istanbul, Turkey

[18]Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany

[19]Geographical Sciences, University of Bristol, UK

[20]Cabot Institute, University of Bristol, UK

[21]Department of Agriculture, Hellenic Mediterranean University, Crete, Greece

[22]Université de Lorraine, LOTERR, Metz, France

[23]CNR-IRPI, Research Institute for Geo-Hydrological Protection, Italy

[24]University of Saskatchewan, Centre for Hydrology, Canmore, Alberta, Canada

[25] Environmental and Conservation Sciences, Murdoch University, Murdoch 6150, Perth, Australia

[27]Lab of Geophysical-Remote Sensing & Archaeo-environment, Institute for Mediterranean Studies, Foundation for Research and Technology Hellas, Rethymno, Crete, Greece

[28]Pontificia Bolivariana University, Faculty of Civil Engineering, Bucaramanga, Colombia

[29]California State University, Long Beach, USA

[30]Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Paleoclimate Dynamics Group, Bremerhaven, Germany

[31]Water Problem Institute Russian Academy of Science, Russia

[32]Faculty of Environment, University of Science, Ho Chi Minh City, Vietnam

[33]Environment Agency, Bristol, England

[34]School of Chemical and Environmental Engineering, Technical University of Crete, Greece

[35]Trelleborg municipality, Sweden

[36]Servicio Nacional de Meteorología e Hidrología del Perú SENAMHI, Lima, Peru

[37]Department of Applied Physics, University of Barcelona, Barcelona, Spain

[38]Water Research Institute, University of Barcelona, Barcelona, Spain

[39]British Geological Survey, Wallingford, UK

[40]Centre of Natural Hazards and Disaster Science,, (CNDS), Uppsala, Sweden

[41]Department of Earth Sciences, Uppsala University, Sweden

[42]Civil and Environmental Engineering, The Pennsylvania State University, USA

[43]University of São Paulo, Brasil

[44]Department of Water Resources & Delta Management, Deltares, The Netherlands

[45]Department of Water Resources Engineering, Lund University, Sweden

[46]University of Potsdam, Institute of Environmental Science and Geography, Potsdam, Germany

[47]Forest Biometrics Laboratory, Faculty of Forestry, Ştefan cel Mare University, Suceava, Romania

[48]University of Science and Technology of Hanoi (USTH), Vietnam Academy of Science and Technology, Vietnam

[49]Vietnam National University Ho Chi Minh City (VNU-HCM), Ho Chi Minh City, Vietnam

[50]Institute for Circular Economy Development, Vietnam National University Ho Chi Minh City (VNU-HCM), Ho Chi Minh City, Vietnam

[51]Observatori de l'Ebre (OE), Ramon Llull University – CSIC, Spain

[52]School of Environment and Sustainability, University of Saskatchewan, Canada

[53]Institute for Water Futures, Mathematical ~~Science~~Sciences Institute, Australian National University, Australia

[54]University of Applied Sciences, Magdeburg, Germany

~~[55]Center for Environmental and Geographic Information Services (CEGIS),~~[55] Embassy of the Kingdom of Netherlands, Dhaka, Bangladesh

[56]Earth and Environmental Systems Institute, The Pennsylvania State University, USA

[57]Institute of Meteorology and Water Management National Research Institute, Poland

[58]Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, China

[59]Department of Hydraulic Engineering, Tsinghua University, China

[60]Royal Botanic Gardens Kew, Surrey, UK

[61]KWR Water Research Institute, Nieuwegein, The Netherlands

[62]Department of Physical Geography, Utrecht University, Utrecht, The Netherlands

[63]Civil Engineering, University of Bristol, UK

[64]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, USA

[65]School of Geography and Ocean Science, Nanjing University, China

[67]Department of Integrated Water Systems and Governance, IHE Delft, The Netherlands

[68]Leichtweiss Institute for Hydraulic Engineering and Water Resources, Division of Hydrology and River basin management, Technische Universität Braunschweig, Braunschweig, Germany

[69]INRAE, Bordeaux Sciences Agro, UMR 1391 ISPA, Villenave d'Ornon, France

[70]Emil Racovita Institute of Speleology, Romanian Academy, Cluj-Napoca, Romania

[71]Dipartimento di Ingegneria Civile, Edile e Ambientale, Sapienza Università di Roma, Rome, Italy

Corresponding author: Heidi Kreibich, GFZ German Research Centre for Geosciences, Section Hydrology, Telegrafenberg, 14473 Potsdam, Germany, Heidi.Kreibich@gfz-potsdam.de

Abstract

As the adverse impacts of hydrological extremes increase in many regions of the world, a better understanding of the drivers of changes in risk and impacts is essential for effective flood and drought risk management and climate adaptation. However, there is currently a lack of comprehensive, empirical data about the processes, interactions and feedbacks in complex human-water systems leading to flood and drought impacts. Here we present a benchmark dataset containing socio-hydrological data of paired events, i.e., two floods or two droughts that occurred in the same area. The 45 paired events occurred in 42 different study areas and cover a wide range of socio-economic and hydro-climatic conditions. The dataset is unique in covering both floods and droughts, in the number of cases assessed, and in the quantity of socio-hydrological data. The benchmark dataset comprises: 1) detailed review style reports about the events and key processes between the two events of a pair; 2) the key data table containing variables that assess the indicators which characterise management shortcomings, hazard, exposure, vulnerability and impacts of all events; 3) a table of the indicators-of-change that indicate the differences between the first and second event of a pair. The advantages of the dataset are that it enables comparative analyses across all the paired events based on the indicators-of-change and allows for detailed context- and location-specific assessments based on the extensive data and reports of the individual study areas. The dataset can be used by the scientific community for exploratory data analyses e.g. focused on causal links between risk management, changes in hazard, exposure and vulnerability and flood or drought impacts. The data can also be used for the development, calibration and validation of socio-hydrological models. The dataset is available to the public through the GFZ Data Services (Kreibich et al. 2023, link for review: https://dataservices.gfz-potsdam.de/panmetaworks/review/923c14519deb04f83815ce108b48dd2581d57b90ce069bec9c948361028b8c85/).

1 Introduction

The Panta Rhei initiative of the International Association of Hydrological Sciences (IAHS) aims to increase our knowledge of interactions and feedback between hydrological and social processes. Panta Rhei research focuses on understanding and modelling spatial and temporal dynamics of human-water systems in order to inform water management and hydrological risk reduction under global change, while supporting the achievement of water-related sustainability goals (Montanari et al., 2013;

McMillan et al., 2016; Di Baldassarre et al., 2019). In particular, a large amount of work in Panta Rhei has focused on floods and droughts and their interplay with human societies.

In recent decades, flood and drought impacts have been significantly increasing in many regions of the world (Bouwer, 2011; Stahl et al., 2016), even where flow regimes are heavily engineered and regulated by dams, reservoirs and other infrastructure (Razavi et al., 2020; Van Loon et al., 2022). Due to complex human-water system interactions, the attribution of trends in flood and drought impacts is particularly challenging (Merz et al., 2012a; Van Loon et al., 2016). For instance, trend analyses of flood impacts revealed that the observed increase in impacts is dominated by an increase in exposure, although changes in hazard, driven by climate change, may play a role as well (Bouwer, 2011; Merz et al., 2012b). It is suggested that climate signals leading to an increase in hazard might be masked by a counteracting decrease in vulnerability due to human interventions (Di Baldassarre et al., 2015; Jongman et al., 2015; Mechler and Bouwer, 2015). Vulnerability can be positively influenced by risk management practices, but it can also be negatively influenced, for example by the use of more water-sensitive building materials (floods), or more water-stress sensitive crop types (droughts) (De Ruiter et al., 2021; Kuhlicke et al., 2020; Ward et al., 2020). Few datasets are available on the temporal dynamics of vulnerability and its influence on impacts (Bubeck et al., 2012; De Ruiter and Van Loon, 2022).

There is an urgent need to detect trends in hazard, exposure and vulnerability as well as their joint effects on impacts, in order to understand and, in turn, model and project the dynamics of flood and drought risks (e.g. Sairam et al., 2019; Ward et al., 2020). However, due to a lack of empirical data, little is known about trends in flood and drought impacts and their causes (Kreibich et al., 2019). Impact data are seldom available and, when present, they are highly fragmented and uncertain (Downton and Pielke, 2005; Gall et al., 2009; Hayes et al., 2011; Stahl et al., 2016; Kron et al., 2012).

Some trend analyses of impact data have been undertaken at continental (Barredo, 2009) and global scales (Neumayer and Barthel, 2011), since sufficient data about events and related impacts are available at such large spatial scales. Yet, these studies cannot disentangle the changes in exposure and vulnerability that influence impacts (Bouwer, 2011; Merz et al., 2012a). For such detailed analyses, case studies need to be assessed from a socio-hydrologic perspective (Mostert, 2018).

The objective of this paper is to present a Panta Rhei dataset of paired events, i.e. two floods or two droughts that occurred in the same area. The dataset contains data of 45 paired events in 42 study areas encompassing different socio-economic and hydro-climatic conditions. The benchmark dataset includes detailed reports of events and key processes between events, an overview table of key data for all events, and a table of indicators-of-change indicating the differences between the first and second event of each pair. The innovation and advantages of the dataset lie in its ability to allow detailed context- and location-specific assessments based on the extensive data and reports on each study area, and in turn to allow indicator-based comparative analyses across all paired events. A challenge is the heterogeneity of the data in relation to the different hazard types and monitoring approaches in the study areas, which prevents a quantitative comparison between the 45 paired events. A first comparative analysis based on the dataset revealed the general pattern that risk management normally reduces the impacts of floods and droughts, but faces difficulties in reducing the impacts of unprecedented events of a magnitude not experienced before (Kreibich et al. 2022). In addition, three risk management success factors were identified based on a detailed analysis of two success stories (Kreibich et al. 2022). Additionally, this dataset has the potential to support the development of models that simulate the dynamics of flood and drought risks generated by the interplay of social and hydrological processes. As such, the dataset can support solving one of the twenty-three unsolved problems in hydrology (Blöschl et al. 2019), namely "How can we extract information from available data on human and water systems in order to inform the building process of socio-hydrological models and conceptualisations?".

2 Methods

The concept of collecting and analysing paired events of floods and droughts has been developed in two preceding studies. The Panta Rhei working group "Changes in flood risk" has previously undertaken a comparative paired-event study (Kreibich et al., 2017). Eight risk reduction success stories were compiled, i.e. paired events where the second flood caused significantly lower impact in comparison with the first flood in the same catchment. Subsequently, together with the Panta Rhei working group "Drought in the Anthropocene", the extended concept for the collection of paired events of floods and droughts was developed and presented in the opinion paper "How to improve attribution of changes in drought and flood impacts" (Kreibich et al., 2019).

2.1 Definitions and concept of paired events of floods and droughts

Floods can be defined as the "*temporary covering by water of land not normally covered by water*" (EC, 2007), or as water levels higher than a defined maximum (Blöschl et al., 2015). The main types of floods are coastal floods caused by storm surges, inland pluvial floods, riverine floods, and flash floods, which are usually caused by heavy precipitation, sometimes in combination with snowmelt, ice jams, high soil moisture, or high groundwater levels (e.g. Danard et al., 2003; Gaume et al., 2009; Skougaard Kaspersen et al., 2015; Tarasova et al., 2019, Stein et al. 2019). In contrast, drought can be defined using a precipitation deficiency threshold over a predetermined period of time (WMO, 2006), or more generally as an exceptional lack of water compared to normal conditions (Van Loon et al., 2016). Besides precipitation, temperature can also play an important role as a driver of droughts, either in relation to evapotranspiration or to changes in snow accumulation and melt (e.g. Teuling et al., 2013; Staudinger et al., 2014; Huning and AghaKouchak, 2018, 2020). Droughts are typically categorized into three types, propagating in the following order: meteorological, soil moisture and hydrological drought (Wilhite and Glantz, 1985; Tallaksen and Van Lanen, 2004).

Flood and drought risks and their impacts are determined by hazard, exposure, and vulnerability (UNDRR 2017). Hazard is a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation; exposure is the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas; and vulnerability are the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (UNDRR, 2017). Impacts, e.g. direct impacts such as fatalities or monetary impacts but also indirect and intangible impacts such as microbial infection (De Man et al., 2014), are a manifestation of risk (Poljanšek et al., 2017). The purpose of risk management is to reduce the impact of events by modifying the hazard, exposure, and/or vulnerability. It is defined as the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses (UNDRR, 2017).

An important challenge of trend analyses of extremes is that every event, region, situation, etc. is unique and has its own characteristics and processes. The concept of paired events aims to reduce this heterogeneity by analysing comparable events of the same event type (e.g. two riverine floods or two meteorological droughts) that occurred in the same catchment or region (Kreibich et al., 2017, 2022). This concept is analogous to the one of paired catchment studies, which is well established in hydrology, and can be used to determine the magnitude of water yield variations resulting from changes in vegetation (Brown et al., 2005). The same concept has also been used for analysing whether changes in flood discharge can be attributed to changes in land use (Prosdocimi et al., 2015) and to disentangle the role of natural and human drivers of hydrological drought severity (Van Loon et al., 2019).

2.2 Data acquisition

The development of this Panta Rhei benchmark dataset of socio-hydrological data of paired events of floods and droughts was driven by a core group of five people (Heidi Kreibich, Kai Schröter, Giuliano di Baldassarre, Anne Van Loon, Philip Ward) from the Panta Rhei working groups “Changes in flood risk” and “Droughts in the Anthropocene”. The aim was to collect data on paired events of pluvial, riverine, groundwater and coastal floods, as well as of meteorological, soil moisture and hydrological droughts. For drought paired events, authors could choose to provide hazard data relative to one drought type (meteorological, soil moisture, hydrological), or even two or three types, depending on the data available and/or the focus on specific impacted sectors. In contrast to the previous paired event data compilation which contained eight flood paired events (Kreibich et al., 2017), the collection of paired flood or drought events was not limited to success stories but aimed to compile a set of diverse and contrasting cases.

The campaign to collect data on paired events started at the EGU General Assembly in April 2019 in Vienna and was continued with talks promoting the paired event data collection at the international conferences KOSMOS (August 2019), REKLIM (September 2019), System-Risk (September 2019), and INQUIMUS (November 2019). Communication with the Panta Rhei community and other flood and drought experts identified through snowballing technique was important. Thus, data on paired events were provided by professionals with excellent local knowledge of the events and risk management practices. The academics and practitioners involved were either based in the study areas or worked with local partners (data providers are all co-authors of this paper).

Based on templates, (provided in the appendix of the data description (Kreibich et al. 2023)), detailed review-style reports describing the events and key processes between events in the study areas were collected, with a focus on characterising impacts, management, hazard, exposure and vulnerability. The paired event reports are between 3 and 18 pages long and are structured in the following sections: 1) short description of events with a focus on impacts; 2) descriptions of processes between events with a focus on risk management 3) event comparison in respect to hazard; 4) event comparison in respect to exposure; 5) event comparison in respect to vulnerability; 6) summary; 7) references. The reports contain qualitative and quantitative information and data. Qualitative information includes e.g. the description of risk management, quantitative information includes e.g. the amount of discharge or the number of fatalities.

2.3 Data processing and quality assurance

The processes implemented to assure data quality followed the Delphi Method (Okoli and Pawlowski, 2004), which is built on structured discussion and consensus building among experts. First, an internal review process of the collected reports was undertaken by the core group for quality assurance, homogenization and data gap filling. Each paired event report was reviewed by two experts from the core group. Firstly, it was important to ensure that there is sufficient information and data in the reports to comprehensively characterise management shortcomings, hazard, exposure, vulnerability and impacts of both events in the study area. Secondly, the information and data provided for the first and second events of a pair must be comparable. This means that, if possible, the same variables must be used for characterising both events. For instance, if the Standardized Precipitation Index (SPI-12) is used to assess the severity of the first drought, it should also be used for the second drought of the pair.

Based on the review-style reports, two further data sets were developed, namely the key data table and the indicators of change, which were compiled in a second table.

2.3.1 Compilation of key data

The core group developed the key data table. This means that information and data were compiled to assess various indicators characterising management shortcomings, hazard, exposure, vulnerability and impacts (Table 1). As far as possible, the same indicators were used for all event types. For management shortcomings, exposure and vulnerability, the indicators are the same for all event types. The impact indicators are the same, except for 'number of fatalities' which was not used for droughts, since in our cases fatalities during drought events were not caused by lack of water, but by a concurrent heatwave. Necessarily, the hazard indicators are different, not only between floods and droughts, but also e.g. between coastal floods and riverine floods (Table 1).

Commonly, more than one variable is provided per indicator, e.g. extreme rainfall at several meteorological stations to assess the severity of pluvial floods. Examples of how to describe or measure variables to assess the indicators of flood and drought impacts, hazard, exposure, vulnerability and management shortcomings are provided in the data description (Kreibich et al. 2023). For the assessment of the indicators, the same variables resulting from comparable measurements are used for both events of a pair as far as possible. Thus, variables compiled for the first and second event of a pair are comparable. However, the variables and the data quality differ strongly between the paired events and study areas due to the different event types, monitoring facilities and detailedness of event documentations. This data heterogeneity makes comparative analyses across the paired events challenging.

~~In addition~~Our aim was to compile as complete data as possible on the ~~data, their~~events, but not for all indicators of impacts, hazard, exposure, vulnerability and management shortcomings of all events peer-reviewed data sources were available. Thus, we also resorted to e.g. newspaper articles or expert knowledge. For transparency reasons, and to give data users the opportunity to judge the quality of the data themselves, data source information (citations, references) is also compiled in the key data table. ~~Sources~~According to our personal assessment, the sources of the data are ~~classified~~categorised in descending quality as follows: scientific study (peer reviewed paper and PhD thesis), report (by governments, administrations, non-governmental organisations (NGOs~~,~~), research organisations, projects), own analysis by authors, based on database (e.g. official statistics, monitoring data such as weather, discharge data, etc.), newspaper article, and expert judgement.

Table 1: Indicators characterising management shortcomings, hazard, exposure, vulnerability and impacts of flood and drought events. In general, the indicators are relevant for all event types. If an indicator is only relevant for certain event types, this is indicated in brackets. These indicators are column headers in the key data table.

Management shortcomings	Hazard	Exposure	Vulnerability	Impacts
• Problems with water management infrastructure • Non-structural risk management shortcomings	• Duration of meteo. drought (only meteo. droughts) • Severity of meteo. drought (only meteo. droughts) • Duration of soil moisture drought (only soil moisture droughts) • Severity of soil moisture drought (only soil moisture droughts) • Duration of hydro. drought (only hydro. droughts) • Severity of hydro. drought (only hydro. droughts) • Tidal level (only coastal floods) • Storm surge (only coastal floods) • Antecedent conditions (only pluvial & riverine floods) • Precipitation / weather severity (only floods) • Severity of flood (only floods)	• People/area /assets exposed • Exposure hotspots	• Lack of awareness and precaution • Lack of preparedness • Imperfect official emergency / crisis management • Imperfect coping capacity	• Number of fatalities (only floods) • Direct economic impacts • Indirect impacts • Intangible impacts

The data compiled in the key data table were first individually quality checked by the respective data providers (i.e. report authors) for each paired event. In a second step, the whole key data table was reviewed by all authors to improve homogeneity across paired events.

2.3.2 Assignment of indicators-of-change

On the basis of the key data table, indicators-of-change between the first and second event of a pair were assigned to enable comparative analyses across the paired events. All indicators-of-change were designed such that consistently positive correlations with impact changes are expected, e.g. "lack of awareness and precaution”. Thus, a decrease in “lack of awareness and precaution” is expected to lead to a decrease in impacts, and relates to a decrease in vulnerability. The first event was used as the baseline. The changes are indicated as follows, using a Likert scale ranging from -2 to 2. Values of -2/2 indicate large decrease or increase, values of -1/1 indicate small decrease or increase and a value of 0 indicates no change. In cases where more variables are associated with an indicator, a combination or selection of the variables was used for the derivation of the indicator-of-change based on hydrological reasoning on the most relevant piece of information. In case of quantitative variables (e.g. precipitation intensities) commonly a change of less than 50% is treated as small, and above 50% as large. For drought paired events, if more hazard indicators on different drought types (i.e., meteorological, soil moisture and hydrological drought) are provided, these were taken together to get an overall assessment of change in drought duration and severity. If the drought types showed different behaviour, the most representative value was chosen. The development of the indicators-of-change had to take into account expert judgements that considered the whole context of the paired event. Representative examples are provided from flood and drought paired events showing how differences in quantitative and qualitative variables between the two events of a pair correspond to the values of the indicators-of-change (data description of Kreibich et al. 2023).

Additionally, five summary indicators-of-change were derived for management shortcomings, hazard, exposure, vulnerability and impacts to enable an easy comparison between flood and drought paired events. These summary indicators-of-change were derived by qualitatively comparing and integrating the values of their related indicators-of-change, according to Table 1. For instance, the summary indicator-of-change of exposure is derived from the two indicators-of-change of People/area/assets exposed and Exposure hotspots.

Indicators-of-change were assigned in an iterative process following a quality assurance protocol: for each paired event, first a core group member suggested values for the indicators-of-change and consequently the five summary indicators-of-change based on the key data table. Next, another member of the core group reviewed these suggestions. In case of doubt, both core group members checked again the variables in the key data table and also the paired event report, and provided a joint suggestion. All suggested values for the indicators-of-change for all paired events were discussed in the core group to assure comparability across paired events. Then, again individually per paired event, the suggested values of the indicators-of-change were cross-checked with the respective data providers (i.e. report authors of the paired event). Finally, the completed table of indicators-of-change was reviewed again by all authors to improve homogeneity across paired events.

3 Results

3.1 Overview of paired events

In total 45 paired events of floods and droughts from all over the world were collected in 42 study areas (Table 2). In three study areas we have data on three flood events that formed two paired events, e.g. pluvial floods in 2007, 2010 and 2014 in Malmö, Sweden with the first paired event: pluvial floods in Malmö 2007 and 2010 (paired event ID 27); second paired event: pluvial floods Malmö 2010 and 2014 (paired event ID 45). Our dataset includes 26 flood and 19 drought paired events. Most events occurred between 1970 and 2019, with three exceptions: the drought in 1947 in southwest Germany, the riverine flood in 1951 in Kansas, USA, and the riverine flood in 1963 at the Baiyangdian River, China (Table 2). The average time between the two events of a pair is 16 years with a range of 1 to 71 years. The geographical distribution of the paired events encompasses 3 paired events in South America, 7 in North America, 2 in Africa, 22 in Europe, 10 in Asia and 1 in Australia (Figure 1).

Table 2: Overview of paired events, sorted according to the summary indicator-of-change of impacts

Paired event ID	Event type	Area: Catchment / region	Area: Country	Year(s) 1st event	Year(s) 2nd event	indicator-of-change in impact
1	pluvial flood	City of Beijing	China	2012	2016	-2
2	riverine flood	Kansas catchment	USA	1951	1993	-2
3	riverine flood	Baiyangdian catchment	China	1963	1996	-2
4	riverine flood	Jakarta	Indonesia	2007	2013	-2
5	coastal flood	North Wales	UK	1990	2013	-2
6	meteorological drought	Maule region	Chile	1998	2013	-1
7	meteorological & hydrological drought	Lorraine region	France	1976	2018	-1
8	meteorological & hydrological drought	South-West Germany	Germany	1947	2018	-1
9	meteorological drought	Central Europe		2003	2015	-1
10	hydrological drought	Limpopo catchment	Mozambique	1991	2005	-1
11	groundwater flood	West Berkshire	UK	2000-2001	2013-2014	-1
12	pluvial flood	Barcelona city	Spain	1995	2018	-1
13	riverine & pluvial flood	Piura region	Peru	1998	2017	-1
14	riverine flood	Mekong River	Cambodia	2000	2011	-1
15	riverine flood	Danube catchment	Austria & Germany	2002	2013	-1
16	riverine flood	Crete	Greece	1994	2015	-1

17	riverine flood	Sukhona catchment	Russia	1998	2016	-1
18	riverine flood	Jakarta	Indonesia	2002	2007	-1
19	coastal flood	Charleston	USA	2016	2017	-1
20	coastal flood	Coastal Region	Bangladesh	2007	2009	-1
21	soil moisture drought	Wielkopolska Province	Poland	2006	2015	0
22	hydrological drought	Ver catchment	UK	2003-2006	2010-2012	0
23	meteorological & hydrological drought		UK	2003-2004	2005-2006	0
24	hydrological drought	Meuse and Rhine catchments	The Netherlands, Germany & Belgium	1976	2003	0
25	meteorological soil moisture & hydrological drought	Don catchment	Russia	1972	2010	0
26	meteorological drought	Seyhan River basin	Turkey	1973	2014	0
27	pluvial flood	Malmö	Sweden	2007	2010	0
28	pluvial flood	Ho Chi Minh City	Vietnam	2010	2016	0
29	riverine & pluvial flood	Birmingham	UK	2008	2016	0
30	riverine & pluvial flood	Birmingham	UK	2016	2018	0
31	riverine flood	Assiniboine catchment	Canada	2011	2014	0
32	riverine, pluvial & coastal flood	Can Tho city, Hau River	Vietnam	2011	2016	0
33	Meteorological soil moisture & hydrological drought	North Carolina	US	2000-2002	2007-2009	1
34	meteorological drought	Catalonia	Spain	1986-1989	2004-2008	1
35	meteorological drought	Melbourne	Australia	1982-1983	2001-2009	1
36	hydrological drought	California	USA	1987-1992	2012-2017	1
37	hydrological drought	Sao Paulo	Brazil	1985-1986	2013-2015	1
38	meteorological & hydrological drought	Raam catchment	The Netherlands	2003	2018-2019	1
39	meteorological soil moisture & hydrological drought	Central Highlands	Vietnam	2004-2005	2015-2016	1
40	pluvial flood	Corigliano-Rossano city	Italy	2000	2015	1
41	riverine flood	Ottawa River	Canada	2017	2019	1

42	riverine flood	Delaware catchment	USA	2004	2006	1
43	riverine flood	Cumbria	UK	2009	2015	1
44	meteorological drought	Cape Town area	South Africa	2003-2004	2015-2017	2
45	pluvial flood	Malmö	Sweden	2010	2014	2

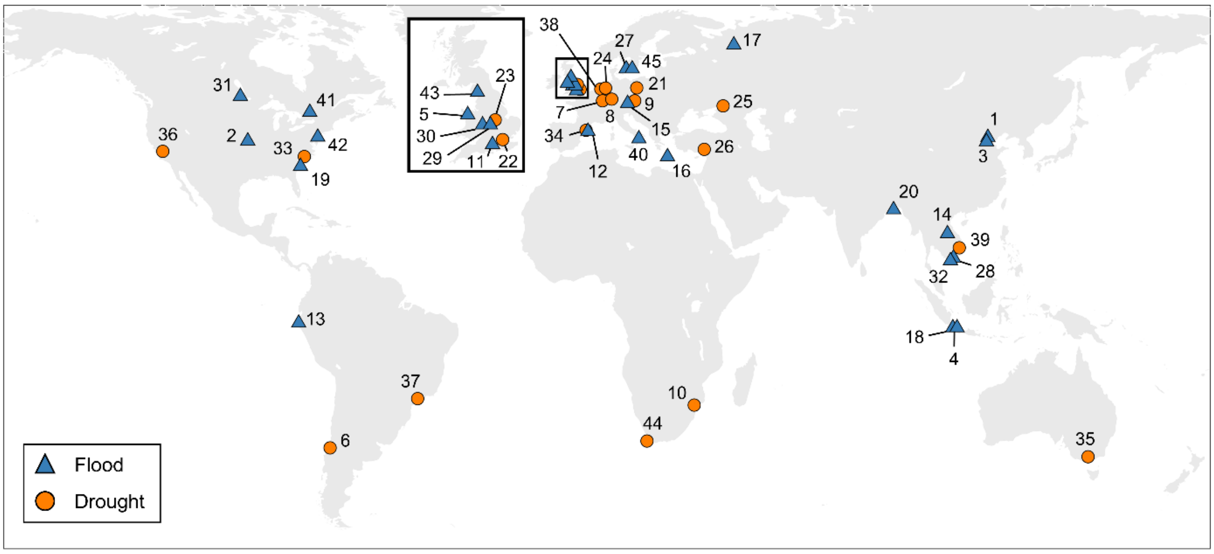

Figure 1: Geographical distribution of the paired events, numbers represent the IDs of the paired events.

3.2 Content of the Panta Rhei benchmark dataset

The dataset comprises: 1) the paired event reports, i.e. review style reports about the events and key processes between the events, particularly with respect to changes in risk management; 2) the key data table containing variables that assess the indicators which characterise management shortcomings, hazard, exposure, vulnerability and impacts of all events; and 3) the table containing the indicators-of-change, including the summary indicators-of-change. These three parts of the dataset are described in detail in the following sections.

3.2.1 Paired event Reports

The reports about the paired events are all written in the style of review papers, i.e. they primarily compile and analyse available information and data from various sources about the events and key processes between the events. For some reports, the authors also undertook their own analyses and included statements based on their expert judgement. The reports are between 3 and 18 pages long and are structured in the following sections: 1) short description of both events with a focus on impacts; 2) description of processes between events with a focus on risk management; 3) event comparison in respect to hazard; 4) event comparison in respect to exposure; 5) event comparison in respect to vulnerability; 6) summary; and 7) references. In the three cases where we have three events, i.e. two paired events in one study area, all three events and processes between events are described in one report. Thus, the dataset contains 43 reports which enable detailed contextual insights into physical and socio-economic changes between the paired drought or flood events in an area.

3.2.2 Key data table

The key data table is an Excel file with the following ~~2~~two spreadsheets: 1) “key data”, which contains the data of the flood and drought paired events, 2) “references”, which contains the references cited in the key data ~~compilation~~spreadsheet, separated by paired events and linked via the paired event IDs.

The key data spreadsheet is structured as follows: The first columns identify and roughly characterise the paired event and study area, i.e. their headers are: “Paired event ID”, ”Event type”, “Area: Catchment/region”, “Area: Country”, “Year of event”. The following columns contain the data (every second column) and the category of the data source (every second column). The data columns contain variables that assess the management shortcomings, hazard, exposure, vulnerability and impacts indicators, structured in analogue to Table 1. Citations leading to the source of the data are included, e.g. citation of a scientific paper. In the following column, the category of the data source is provided~~.~~ to give data users the opportunity to judge the quality of the data themselves. Always 2 rows belong to one paired event, the first line contains the information of the first event, the second line contains the information of the second event. The variables compiled for the first and second event of a pair are comparable, i.e. the same variables resulting from comparable measurements are provided as far as possible. Any missing data which could not be retrieved for the specific event is indicated as not available (NA). The indicators which are not relevant for the specific event type are indicated as not relevant (NR).

The references spreadsheet contains the following columns: “Paired event ID”, “DOI”, “Web-link”, “Accessed (web-link)”, “References”. If possible, DOIs are given, which is mainly the case for scientific studies. Otherwise, the web link is given if possible, this is often the case for reports. In these cases, additionally the date is provided on which the data source provided via a web-link was last accessed. References are provided for all citations contained in the key data spreadsheet, this is mainly the case for scientific study and report categories of the data source.

3.2.3 Table of indicators-of-change

The table containing the indicators-of-change is structured in analogue to the key data spreadsheet of the key data table. Differences are the following: 1) the indicators-of-change characterising drought hazard are aggregated into two indicators-of-change: “Duration of drought” and “Severity of drought”, for all drought types; 2) the five summary indicators-of-change are additionally included; 3) Each event pair is represented by one row, since the indicators-of-change represent the difference between the data of the first event (1st row of paired event in key data) and of the second event (2nd row of paired event in key data).

Overall, the flood and drought paired events have similar amounts of data availability for the indicators-of-change, with only 12% and 14% NAs, respectively. However, for both floods and droughts, data on indirect and intangible impacts are scarce (Figure 2). For droughts, hazard and exposure data are readily available, while data on coping capacity is scarce. Additionally, storm surge data for coastal floods is scarce (Figure 2).

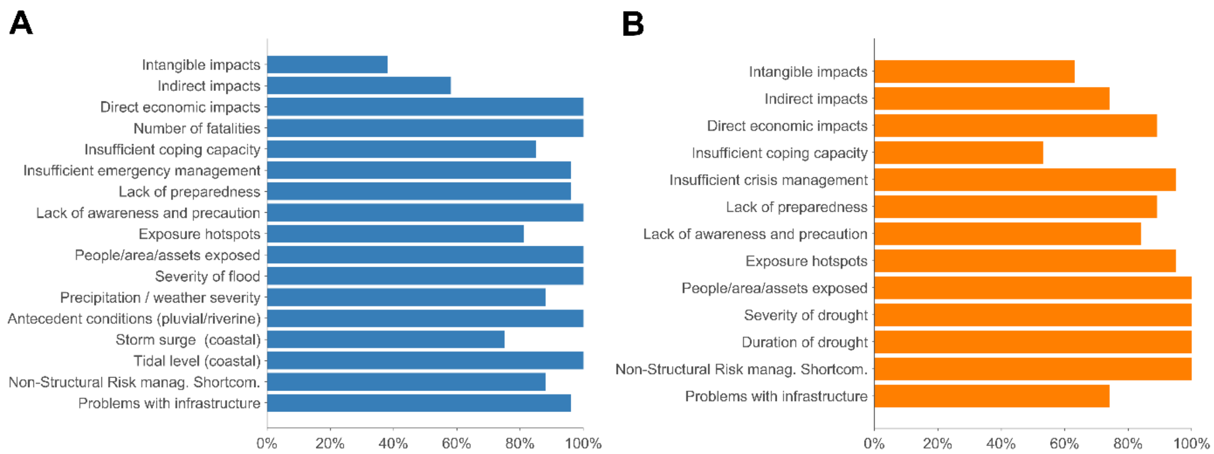

Figure 2: Fraction of entries in [%] (in contrast to NA values) for each indicator-of-change of flood (A) and drought (B) paired events.

Across all paired events, a small decrease and no change were the most common values across all summary indicators-of-change, with 43% and 25%, respectively (Figure 3). Large changes (-2/2) are rare, with counts below 10% across all indicators-of-change. Changes in hazard, exposure and impact show a relatively even distribution (except for large changes), whereas changes in vulnerability and management shortcomings mainly show a decrease.

Differences between the collected flood and drought paired events are apparent for exposure and impacts. Flood paired events include one pair with a large decrease in exposure, two pairs with a large increase in exposure and a rather even distribution across small decreases, no change and a small increase for the rest of the pairs. However, most common is a small decrease in exposure, apparent in 38% of the flood paired events. In contrast, no large changes (-2/2), and only one pair with a small decrease in exposure occurred among the drought paired events. Most common is a small increase in exposure, reported in 53% of the drought paired events, with the remaining 42% reporting no change in exposure. In five flood paired events, a large decrease in impacts was reported and many flood paired events showed a small decrease in impacts (38%). In the collected drought paired events, no large decrease in impacts occurred and most common is a small increase in impacts (37%).

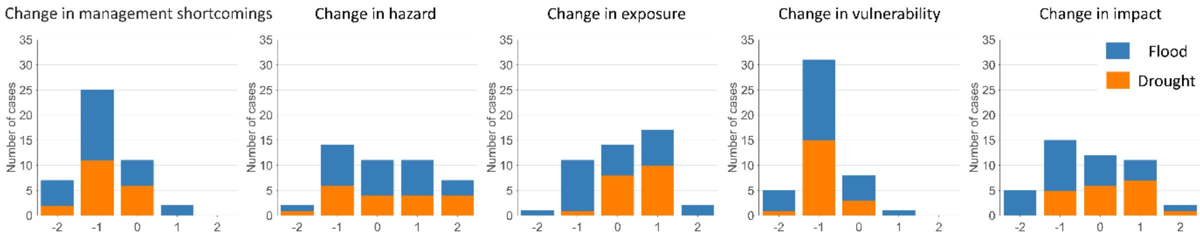

Figure 3: Histograms of summary indicators-of-change for flood and drought paired events, indicating large decrease or increase (-2/2), small decrease or increase (-1/1) and no change (0) between the fist and the second event.

4 Potential uses of the dataset

The presented dataset supports detailed context- and location-specific assessments of the paired events, based on the paired event reports and the key data table. Based on the descriptions and the comparable variables per paired event that characterise the management shortcomings, hazard, exposure, vulnerability and impacts, it is possible to qualitatively attribute changes in impact to their drivers and identify successful or unsuccessful risk management strategies. During the first data analyses, only two paired events, i.e. “Pluvial floods in Barcelona, Spain” and “Riverine floods in Danube catchment in Germany and Austria” were analysed in detail and successful risk management strategies identified (Kreibich et al. 2022). This leaves a lot of room for further detailed analyses, e.g. of drought success stories (e.g. droughts in the Wielkopolska Province in Poland and in the Don River catchment in Russia), or impact attribution studies. Detailed suggestions for the attribution of changes in drought and flood impacts are provided by Kreibich et al. (2019).

~~The table of indicators-of-change can support comparative analyses across all paired events or separately for flood paired events and drought paired events. The latter eases the comparison of the hazard indicators-of-change, since these differ between floods and droughts. Such~~While the variables describing the first and second event of a pair are comparable, variables and data quality differ strongly between the paired events. The great heterogeneity of data and events represents both the strength and the weakness of the Panta Rhei dataset with regard to comparative analyses. As quantitative comparative analyses across all paired events are impossible, such analyses can only be undertaken on the basis of the indicators-of-change. Although these indicators were created with great care according to the quality assurance protocol, they are subject to uncertainties and caution is required when interpreting the results. Still, such comparative analyses are analogous to other comparative studies in hydrology, which have shown their value especially for obtaining more generic, transferable results (Duan et al., 2006; Blöschl et al., 2013). Conclusions can be drawn about the attribution of impacts or the effectiveness of risk management, based on common patterns of the paired events across socio-economic and hydro-climatic situations. During the first data analyses, only the five summary indicators-of-change for management shortcomings, hazard, exposure, vulnerability and impact were analysed. So, there is still much scope for further more detailed comparative analysis by including all indicators-of-change. Examples of comparative analyses of socio-hydrological data of paired events are provided by Kreibich et al. (2017, 2022).

The table of key data can further support the development of socio-hydrological models, individually per paired event. The empirical data available for two points in time (i.e. first data points: data of first event in first row of paired event and second data points: data of second event in second row of paired event) can be used to estimate the parameters of socio-hydrological flood or drought risk models through Bayesian inference (Barendrecht et al. 2019; Schoppa et al. 2022). Even better would be if complementary data for some of the ~~variable extent~~variables extended the two points in time to build a time series. This might be rather easily possible for monitored data like precipitation amounts or discharge as well as statistical data like exposed population or assets. Bayesian inference is suitable for the incorporation of different types of socio-hydrology data, i.e. qualitative and quantitative data, less or more uncertain data, many data points versus only a few data points (Gelman et al., 2014). The gain of using a socio-hydrological modelling approach in combination with empirical data is that it allows for a consistent interpretation of all available data together, including their interactions (Barendrecht et al. 2019). This approach enables the simulation of historical risk dynamics for the study areas and allows to inform adaptation planning by exploring the possible system evolutions in the future (Schoppa et al. 2023). The dataset has not yet been used to calibrate socio-hydrological models. Due to the diversity of hazard types as well as diverse socio-economic and hydro-climatic situations covered by the 45 paired events from all continents, the table of key data can be used to benchmark the performance of socio-hydrological flood or drought risk models. Examples of how heterogenous socio-hydrological data (e.g. discharge time series, level of protection, settlement density, flood awareness, level of private precaution, direct economic damage) can be used to estimate the parameters of socio-hydrological flood models are provided by Barendrecht et al. (2019) and Schoppa et al. (2022).

5 Data availability

The “Panta Rhei benchmark dataset: socio-hydrological data of paired events of floods and droughts (version 2)” is published under the Creative Commons Attribution International 4.0 Licence (CC BY 4.0) via GFZ Data Services (Kreibich et al., 2023, the review link is the following: https://dataservices.gfz-potsdam.de/panmetaworks/review/923c14519deb04f83815ce108b48dd2581d57b90ce069bec9c948361028b8c85/

Conclusions

Developing sustainable and efficient risk management strategies under non-stationary conditions requires understanding of the temporal changes of flood and drought impacts and their causes. The comprehensive Panta Rhei dataset presented in this paper can support detailed context and location-specific assessments of changes in impacts and their drivers and of risk management strategies based on the detailed paired event reports and key data regarding the individual paired events. The dataset can support indicator-based comparative analyses across all paired events, and eventually reveal generic and transferable conclusions in the occurrence of common patterns. Such analyses might be particularly useful to attribute changes in flood and drought impacts, including understanding of the role of human activities and decisions in reducing or exacerbating the impacts of drought and flood events. Ultimately, the dataset can support the development and benchmarking of socio-hydrological models and as such can supports solving the following unsolved problem in hydrology “How can we extract information from available data on human and water systems in order to inform the building process of socio-hydrological models and conceptualisations?” (Blöschl et al. 2019).

Additionally, we want to encourage more collection of socio-hydrological data of floods and droughts, but also of other water-related phenomena. Such data are scarce, but essential to understand spatial and temporal dynamics of human-water systems and inform and support improved water management under global change. The contact author, Heidi Kreibich, will be happy to advise and help with data collection if desired. Templates for the collection of socio-hydrological data on paired events of floods and droughts are provided in the appendix of the data description (Kreibich et al. 2023).

Author contributions. Heidi Kreibich initiated the compilation of the Panta Rhei benchmark dataset. Heidi Kreibich, Kai Schröter, Giuliano di Baldassarre, Anne Van Loon and Philip Ward developed the concept for the data collection (including templates and structure of the data tables), coordinated the data collection and undertook the internal review process, data quality control and homogenisation. All co-authors contributed data included in the paired event reports. The authors of each paired event report are responsible for the data of their case study. Maurizio Mazzoleni additionally designed the figures. Heidi Kreibich, Kai Schröter, Giuliano di Baldassarre, Anne Van Loon and Philip Ward wrote the manuscript with valuable contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgement

The present work was developed by the Panta Rhei Working Groups "Changes in flood risk" and "Droughts in the Anthropocene" within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS).

The work, particularly data collection, was partly undertaken under the framework of the following entities and projects: Center for Climate and Resilience Research (ANID/FONDAP/~~151100009~~1522A0001), joint research project ANID/NSFC190018, project ANID/FSEQ210001, PIRAGUA project funded by FEDER through the POCTEFA Programme of the EU, M-CostAdapt project (FEDER/MICINN-AEI/CTM2017-83655-C2-2-R), project RIESGOS (BMBF, 03G0876B), project MYRIAD-EU (H2020, 101003276), project PerfectSTORM (ERC-2020-StG 948601), project DECIDER (BMBF, 01LZ1703G), project FLOOD (01LP1903E) as part of the ClimXtreme Research Network, HUMID project (CGL2017-85687-R, AEI/FEDER, UE), project funded by the US National Science Foundation (EAR #1804560), NASA Award No. NNX15AC27G and NOAA Award No. NA19OAR4310294, CENTA NERC grant (NE/lL002493/1), Groundwater Drought Initiative (NE/R004994/1), MaRIUS and ENDOWS projects funded by NERC grant number NE/L010399/1, NERC RAHU project grant NE/S013210/1, AWI Strategy Fund Project PalEX, Helmholtz Climate Initiative REKLIM, Russian Scientific Foundation project (Proj. № 19-77-10032), Turkish State Meteorological Service, Formas (grant no. 942-2015-149), Vietnam National University – Ho Chi Minh City under grant number C2018-48-01, Vietnam National Foundation for Science and Technology Development (grant no. 105.06-2019.20), The US National Science Foundation project (EAR #1804560), MSCA ETN System-Risk (grant 676027), The Russian Foundation for Basic Research project (№ 18-05-60021-Arctic), Dutch Research Council (NWO) VIDI Grant 016.161.324, National Natural Science Foundation of China (grant 92047301), CNES TOSCA grant SWHYM, the University of California, Division of Agriculture and Natural Resources California Institute for Water Resources and U.S. Geological Survey Grant G21AP10611-00 and a California State University Water Resources and Policy Initiatives grant. David Macdonald and Andrew McKenzie publish with the permission of the Director, British Geological Survey. Funding for their input was provided by UK Research and Innovation (UKRI) National Capability resources, devolved to the British Geological Survey, and through the LANDWISE project (NERC grant NE/R004668/1).

We thank the Barcelona City Council, the Länsförsäkringar Skåne, VA SYD and the Center for Climate and Resilience Research for valuable data and help with data processing.

Financial support

Elisa Savelli received funding from European Research Council (ERC) within the project 'HydroSocialExtremes: Uncovering the Mutual Shaping of Hydrological Extremes and Society', ERC Consolidator Grant No. 771678. Elena Ridolfi was supported by the Centre of Natural Hazards and Disaster Science (CNDS) in Sweden (www.cnds.se). Thorsten Wagener was partially supported by a Royal Society Wolfson Research Merit Award (WM170042) and by the Alexander von Humboldt Foundation in the framework of the Alexander von Humboldt Professorship endowed by the German Federal Ministry of Education and Research. Jim Freer was partly supported by the Global Water Futures program, University of Saskatchewan. Yonca Cavus was supported by the DAAD "Research Grants - Bi-nationally Supervised Doctoral Degrees / Cotutelle" Program. Hafzullah Aksoy performed a portion of his contribution to this study during his stay at University of Illinois, Urbana-Champaign, USA, supported by Fulbright Academic Research Scholarship, Istanbul Technical University (Project number MUA-2019-42094) and the Scientific and Technological Research Council of Turkey (TUBITAK). Dao Nguyen Khoi was supported by the Vietnam National Foundation for Science and Technology Development (grant no. 105.06-2019.20). Qiuhong Tang was supported by the National Natural Science Foundation of China (41730645, 41790424). Philip Ward was supported by the Netherlands Organisation for Scientific Research (NWO) (VIDI; grant no. 016.161.324) and the MYRIAD-EU project, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No ~~101003276.~~101003276. Maurizio Mazzoleni was supported by the Swedish Research Council FORMAS and the Centre of Natural Hazards and Disaster Science (CNDS) in Sweden. Laurie Huning was partially supported by the University of California, Division of Agriculture and Natural Resources California Institute for Water Resources and U.S. Geological Survey Grant (G21AP10611-00) and a California State University Water Resources and Policy Initiatives grant. Anaïs Couasnon was supported by a VIDI grant from NWO that was awarded to Philip Ward (016.161.324). Marleen de Ruiter was supported by the MYRIAD-EU project, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No ~~101003276. Animesh K Gain is~~101003276. Animesh K Gain was financially supported by Marie Skłodowska Curie Global Fellowship of European Commission (Grant Agreement No. 787419~~).~~) and Murdoch University, Australia. Liduin Bos-Burgering and Marjolein Mens were supported by the Deltares research program on water resources, funded by the Dutch Ministry of Economic Affairs and Climate. Fuqiang Tian was partly supported by the National Natural Science Foundation of China (grant

92047301). Johanna Mård was supported by the Centre of Natural Hazards and Disaster Science (CNDS). Wouter Buytaert acknowledges funding from the UK Natural Environment Research Council (grant NE/S013210/1). Gemma Coxon was funded by a UKRI Future Leaders Fellowship award [MR/V022857/1]. Saman Razavi, Hayley Carlson, and Laila Balkhi were supported by Integrated Modelling Program for Canada. Huynh Thi Thao Nguyen was supported by NUFFIC/NICHE VNM 104 project, which was co-funded by the Netherlands Government and Vietnam National University – Ho Chi Minh City. Michelle van Vliet was financially supported by a VIDI grant (Project No. VI.Vidi.193.019) of the Netherlands Scientific Organisation (NWO). Anne Van Loon was supported by the European Research Council (ERC) project 'PerfectSTORM: Storylines of future extremes' (ERC-2020-StG 948601). Guta Worku Abeshu and Hong-Yi Li were supported as part of the Energy Exascale Earth System Model (E3SM) project, funded by the US Department of Energy, Office of Science, Office of Biological and Environmental Research. Thanh Ngo-Duc was supported by the Vietnam National Foundation for Science and Technology Development (grant no. 105.06-2021.14).

References

Barendrecht, M. H., Viglione, A., Kreibich, H., Merz, B., Vorogushyn, S., Blöschl, G. (2019). The value of empirical data for estimating the parameters of a sociohydrological flood risk model. Water Resources Research, 55. https://doi.org/10.1029/2018WR024128

Barredo, J.I., 2009. Normalised flood losses in Europe: 1970–2006. Natural Hazards and Earth System Sciences, (9), 97–104

Blöschl, G., Bierkens, M. F., Chambel, A., et al. (2019): Twenty-three unsolved problems in hydrology (UPH) – a community perspective. - Hydrological Sciences Journal - Journal des Sciences Hydrologiques, 64, 10, 1141-1158. https://doi.org/10.1080/02626667.2019.1620507

Blöschl, G., et al., 2015. Increasing river floods: fiction or reality? Wiley Interdisciplinary Reviews: Water, 2 (4), 329-344

Blöschl, G., M. Sivapalan, T. Wagener, A. Viglione, and H. Savenije (2013), Runoff Prediction in Ungauged Basins. Synthesis across Processes, Places and Scales, Cambridge University Press, New York

Bouwer, L. M., 2011. Have disaster losses increased due to anthropogenic climate change? Bulletin of the American Meteorological Society, 92(1), 39–46.

Brown, A. E., et al., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology, 310, 1-4. doi 10.1016/j.jhydrol.2004.12.010

Bubeck, P., et al., 2012. Long-term development and effectiveness of private flood mitigation measures: an analysis for the German part of the river Rhine. Natural Hazards and Earth System Sciences, 12 (11), 3507-3518. doi: 10.5194/nhess-12-3507-2012

Danard, M., Munro, A., and Murty. T., 2003. Storm surge hazard in Canada. Natural Hazards, 28(2–3), 407–431. doi:10.1023/A:1022990310410

De Man H, Van Den Berg HHJL, Leenen EJTM, Schijven JF, Schets FM, Van Der Vliet JC, Van Knapen F, De Roda Husman AM (2014) Quantitative assessment of infection risk from exposure to waterborne pathogens in urban floodwater. Water Research 48 (1): 90–99 DOI: 10.1016/j.watres.2013.09.022

De Ruiter, M.C., De Bruijn, J.A., Englhardt, J., Daniell, J.E., de Moel, H., Ward, P.J., 2021. The Asynergies of Structural Disaster Risk Reduction Measures: Comparing Floods and Earthquakes. Earth's Future, doi:10.1029/2020EF001531

De Ruiter, M.C., Van Loon, A.F. (2022) The challenges of dynamic vulnerability and how to assess it, iScience, 25(8), 104720, https://doi.org/10.1016/j.isci.2022.104720

Di Baldassarre, G., et al., 2015. Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. Water Resources Research, 51, 4770–4781.

Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., Konar, M., Mondino, E., Mård, J., Pande, S., Sanderson, M. R., Tian, F., Viglione, A., Wei, J., Wei, Y., Yu, D. J., Srinivasan, V., Blöschl, G. (2019): Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals. - Water Resources Research, 55, 8, 6327-6355. https://doi.org/10.1029/2018WR023901

Downton, M. W., and Pielke, R. A. Jr, 2005. How accurate are disaster loss data? The Case of U.S. flood damage. Natural Hazards, 35, 211–228

Duan, Q., et al., 2006. Model Parameter Estimation Experiment (MOPEX): An overview of science strategy and major results from the second and third workshops. Journal of Hydrology, 320, 3–17.

EC (European Commission), 2007 Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. Off J EU 6, L 288/27–34

Gall, M., Borden, K. A., and Cutter, S. L., 2009. When do losses count? Six fallacies of natural hazards loss data. Bulletin of the American Meteorological Society, 90 (6), 799–809.

Gaume, E., et al., 2009. A compilation of data on European flash floods. Journal of Hydrology, 367 (1–2), 70–78. doi:10.1016/j.jhydrol.2008.12.028

Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2014). Bayesian data analysis (Vol. 2). Boca Raton, FL: CRC Press.

Hayes, M., et al., 2011. The Lincoln declaration on drought indices: universal meteorological drought index recommended. Bulletin of the American Meteorological Society, 92 (4), 485–488.

Huning, L. S., and AghaKouchak, 2020. Global snow drought hot spots and characteristics. Proceedings of the National Academy of Sciences, 117(33), 19753-19759. https://doi.org/10.1073/pnas.1915921117.

Huning, L. S., and AghaKouchak, A., 2018. Mountain snowpack response to different levels of warming, Proceedings of the National Academy of Sciences, 115(43), 10932-10937, https://doi.org/10.1073/pnas.1805953115.

Jongman, B., et al., 2015. Declining vulnerability to river floods and the global benefits of adaptation. Proceedings of the National Academy of Sciences, E2271–E2280.

Kreibich, H., Van Loon, A.F., Schröter, K., et al. (2022): The challenge of unprecedented floods and droughts in risk management. - Nature, 608, 80-86. https://doi.org/10.1038/s41586-022-04917-5

Kreibich, H., Blauhut, V., Aerts, J. C. J. H., Bouwer, L. M., Van Lanen, H. A. J., Mejia, A., Mens, M., Van Loon, A. F. (2019): How to improve attribution of changes in drought and flood impacts. - Hydrological Sciences Journal - Journal des Sciences Hydrologiques, 64, 1, 1-18. https://doi.org/10.1080/02626667.2018.1558367

Kreibich, H., Di Baldassarre, G., Vorogushyn, S., Aerts, J. C. J. H., Apel, H., Aronica, G. T., Arnbjerg-Nielsen, K., Bouwer, L. M., Bubeck, P., Caloiero, T., Do, T. C., Cortès, M., Gain, A. K., Giampá, V., Kuhlicke, C., Kundzewicz, Z. W., Llasat, M. C., Mård, J., Matczak, P., Mazzoleni, M., Molinari, D., Nguyen, D., Petrucci, O., Schröter, K., Slager, K., Thieken, A. H., Ward, P. J., Merz, B. (2017): Adaptation to flood risk - results of international paired flood event studies. - Earth's Future, 5, 10, 953-965. https://doi.org/10.1002/2017EF000606

Kreibich, H., Schröter, K., Di Baldassarre, G., Van Loon, A., Mazzoleni, M., Abeshu, G. W., Agafonova, S., AghaKouchak, A., Aksoy, H., Alvarez-Garreton, C., Aznar, B., Balkhi, L., Barendrecht, M. H., Biancamaria, S., Bos-Burgering, L., Bradley, C., Budiyono, Y., Buytaert, W., Capewell, L., Carlson, H., Cavus, Y., Couasnon, A., Coxon, G., Daliakopoulos, I., de Ruiter, M. C., Delus, C., Erfurt, M., Esposito, G., François, D., Frappart, F., Freer, J., Frolova, N., Gain, A. K., Grillakis, M., Grima, J., Guzmán, D. A., Huning, L. S., Ionita, M., Kharlamov, M., Khoi, D. N., Kieboom, N., Kireeva, M., Koutroulis, A., Lavado-Casimiro, W., Li, H., LLasat, M. C., Macdonald, D., Mård, J., Mathew-Richards, H., McKenzie, A., Mejia, A., Mendiondo, E. M., Mens, M., Mobini, S., Mohor, G. S., Nagavciuc, V., Ngo-Duc, T., Nguyen, H. T. T., Nhi, P. T. T., Petrucci, O., Quan, N. H., Quintana-Seguí, P., Razavi, S., Ridolfi, E., Riegel, J., Sadik, M. S., Sairam, N., Savelli, E., Sazonov, A., Sharma, S., Sörensen, J., Souza, F. A. A., Stahl, K., Steinhausen, M., Stoelzle, M., Szalińska, W., Tang, Q., Tian, F., Tokarczyk, T., Tovar, C., Tran, T. V. T., van Huijgevoort, M. H., van Vliet, M. T., Vorogushyn, S., Wagener, T., Wang, Y., Wendt, D. E., Wickham, E., Yang, L., Zambrano-Bigiarini, M., Ward, P. J. (2023): Panta Rhei benchmark dataset: socio-hydrological data of paired events of floods and droughts. https://dataservices.gfz-potsdam.de/panmetaworks/review/923c14519deb04f83815ce108b48dd2581d57b90ce069bec9c948361028b8c85/

Kron, W., Steuer, M., Löw, P., Wirtz, A. (2012) How to deal properly with a natural catastrophe database – analysisof flood losses. Nat. Hazards Earth Syst. Sci., 12, 535–550, doi:10.5194/nhess-12-535-2012

Kuhlicke, C., Seebauer, S., Hudson, P., Begg, C., Bubeck, P., Dittmer, C., Grothmann, T., Heidenreich, A., Kreibich, H., Lorenz, D. F., Masson, T., Reiter, J., Thaler, T., Thieken, A. H., Bamberg, S. (2020): The behavioral turn in flood risk management, its assumptions and potential implications. - WIREs Water, 7, 3. https://doi.org/10.1002/wat2.1418

McMillan, H., Montanari, A., Cudennec, C., Savenjie, H., Kreibich, H., Krüger, T., Liu, J., Meija, A., van Loon, A., Aksoy, H., Di Baldassarre, G., Huang, Y., Mazvimavi, D., Rogger, M., Bellie, S., Bibikova, T., Castellarin, A., Chen, Y., Finger, D., Gelfan, A., Hannah, D., Hoekstra, A., Li, H., Maskey, S., Mathevet, T., Mijic, A., Acuña, A. P., Polo, M. J., Rosales, V., Smith, P., Viglione, A., Srinivasan, V., Toth, E., van Nooyen, R., Xia, J. (2016): Panta Rhei 2013-2015: Global perspectives on hydrology, society and change. - Hydrological Sciences Journal - Journal des Sciences Hydrologiques, 61, 7, 1174-1191. https://doi.org/10.1080/02626667.2016.1159308

Mechler, R. and Bouwer, L.M., 2015. Understanding trends and projections of disaster losses and climate change: is vulnerability the missing link? Climatic Change, 133, 23. doi:10.1007/s10584-014-1141-0

Merz, B., et al., 2012a. Detection and attribution of changes in flood hazard and risk. In: Z.W. Kundzewicz, Ed., Changes in flood risk in Europe. Wallingford, UK: International Association of Hydrological Sciences, IAHS Special Publication no. 10, 435–454.

Merz, B., et al., 2012b. More efforts and scientific rigour are needed to attribute trends in flood time series. HESS Opinions: Hydrology and Earth System Sciences, 16 (5), 1379–1387.

Montanari, A., et al., 2013. "Panta Rhei – everything flows": change in hydrology and society – the IAHS scientific decade 2013–2022. Hydrological Sciences Journal, 58 (6), 1256–1275. doi:10.1080/02626667.2013.809088

Mostert, E. 2018, An alternative approach for socio-hydrology: case study research. Hydrol. Earth Syst. Sci., 22, 317–329, https://doi.org/10.5194/hess-22-317-2018

Neumayer, E. and Barthel, F., 2011. Normalizing economic loss from natural disasters: A global analysis. Global Environmental Change, 21, 13–24

Okoli C. & Pawlowski S. D. The Delphi method as a research tool: an example, design considerations and applications. Information & Management 42(1) 15-29 doi.org/10.1016/j.im.2003.11.002 (2004).

Poljanšek, K., et al., Eds., 2017. Science for disaster risk management 2017: knowing better and losing less. EUR 28034 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-60679-3. doi10.2788/842809, JRC102482

Prosdocimi, I., Kjeldsen, T. R., and Miller, J. D., 2015. Detection and attribution of urbanization effect on flood extremes using nonstationary flood frequency models. Water Resources Research, 51, 4244–4262

Razavi, S., Gober, P., Maier, H. R., Brouwer, R., & Wheater, H. (2020). Anthropocene flooding: Challenges for science and society. Hydrological Processes, 34(8), 1996-2000.

Sairam, N., Schröter, K., Lüdtke, S., Merz, B., Kreibich, H. (2019): Quantifying Flood Vulnerability Reduction via Private Precaution. - Earth's Future, 7, 3, 235-249. https://doi.org/10.1029/2018EF000994

Schoppa, L., Barendrecht, M.H., Sieg, T., Sairam, N., Kreibich, H. (2022) Augmenting a socio-hydrological flood risk model for companies with process-oriented loss estimation, Hydrological Sciences Journal, DOI: 10.1080/02626667.2022.2095207

Schoppa, L., Barendrecht, M.H., Paprotny, D., Sairam, D., Sieg, T., Kreibich, H. (2023) Projecting Flood Vulnerability Dynamics for Effective Long-term Adaptation. Earth's Future (under review).

Skougaard Kaspersen, P., et al., 2015. Influence of urban land cover changes and climate change for the exposure of European cities to flooding during high-intensity precipitation. Proceedings of the International Association of Hydrological Sciences, 370, 21–27.

Stahl, K., et al., 2016. Impacts of European drought events: insights from an international database of text-based reports. Natural Hazards and Earth System Sciences, 16 (3), 801–819. doi10.5194/nhess-16-801-2016

Staudinger, M., Stahl, K. and Seibert, J., 2014. A drought index accounting for snow. Water Resources Research, 50(10), pp.7861-7872.

Stein, L., Pianosi, F, Woods, R. (2019) Event-based classification for global study of river flood generating processes, Hydrological Processes 34, 1514–1529, DOI: 10.1002/hyp.13678

Tallaksen, L.M. and Van Lanen, H.A.J., Eds., 2004. Hydrological drought. Processes and estimation methods for streamflow and groundwater. The Netherlands: Elsevier Science BV, Developments in Water Science 48.

Tarasova, L., Merz, R., Kiss, A., Basso, S., Blöschl, G., Merz, B., Viglione, A., Plötner, S., Guse, B., Schumann, A., Fischer, S., Ahrens, B., Anwar, F., Bárdossy, A., Bühler, P., Haberlandt, U., Kreibich, H., Krug, A., Lun, D., Müller-Thomy, H., Pidoto, R., Primo, C., Seidel, J., Vorogushyn, S., Wietzke, L. (2019): Causative classification of river flood events. - Wiley Interdisciplinary Reviews: Water, 6, 4, e1353. https://doi.org/10.1002/wat2.1353

Teuling, A.J., Van Loon, A.F., Seneviratne, S.I., Lehner, I., Aubinet, M., Heinesch, B., Bernhofer, C., Grünwald, T., Prasse, H. and Spank, U., 2013. Evapotranspiration amplifies European summer drought. Geophysical Research Letters, 40(10), pp.2071-2075.

UNDRR (United Nations office for Disaster Risk Reduction) 2017. Update of the publication "2009 UNISDR Terminology on Disaster Risk Reduction", https://www.undrr.org/terminology

Van Loon, A., Gleeson, T., Clark, J. et al. Drought in the Anthropocene. Nature Geosci 9, 89–91 (2016). https://doi.org/10.1038/ngeo2646

Van Loon, A.F., Rangecroft, S., Coxon, G., Breña Naranjo, J.A., Van Ogtrop, F. and Van Lanen, H.A., 2019. Using paired catchments to quantify the human influence on hydrological droughts. Hydrol. Earth Syst. Sci, 23(1725-1739).

Van Loon, A. F., Rangecroft, S., Coxon, G., Werner, M., Wanders, N., Di Baldassarre, G., ... & Van Lanen, H. A. (2022). Streamflow droughts aggravated by human activities despite management. Environmental Research Letters, 17(4), 044059.

Ward, P. J., de Ruiter, M. C., Mård, J., Schröter, K., Van Loon, A., Veldkamp, T., ... & Capewell, L. (2020). The need to integrate flood and drought disaster risk reduction strategies. Water Security, 11, 100070.

Wilhite, D.A. and Glantz, M.H., 1985. Understanding the drought phenomenon. The role of definitions. Water International, 10, 111–120

WMO (World Meteorological Organization), 2006. Drought monitoring and early warning: Concepts, progress and future challenges. Geneva, Switzerland: World Meteorological Organization, WMO-No. 1006.