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Title: The need to integrate flood and drought disaster risk reduction strategies

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Abstract

Most research on hydrological risks focuses either on flood risk or drought risk, whilst floods and droughts are two extremes of the same hydrological cycle. To better design disaster risk reduction (DRR) measures and strategies, it is important to consider interactions between these closely linked phenomena. We show examples of: (a) how flood or drought DRR measures can have (unintended) positive or negative impacts on risk of the opposite hazard; and (b) how flood or drought DRR measures can be negatively impacted by the opposite hazard. We focus on dikes and levees, dams, stormwater control and upstream measures, subsurface storage, migration, agricultural practices, and vulnerability and preparedness. We identify key challenges for moving towards a more holistic risk management approach.

Keywords

Floods, droughts, disaster risk reduction, risk

1. Introduction

Worldwide, floods and droughts are estimated to have affected ~2.3 billion and ~1.1 billion people respectively, over the period 1995-2015 (UNDRR, 2015). Moreover, their negative impacts have increased over the past century and are projected to increase in the future due to climate change, population growth, and economic growth (see Ward et al., 2020 and references therein). Clearly, there is an urgent need to reduce the negative impacts of floods and droughts, by implementing Disaster Risk Reduction (DRR) measures and strategies aimed at reducing both current and future risk. This is recognised at the global level in the U.N. Sendai Framework for Disaster Risk Reduction, and the last decade has seen a shift from managing flood and drought hazards towards managing risk.

Notwithstanding this progress, most research on hydrological risks tends to focus on either flood risk or drought risk, whilst floods and droughts are two extremes of the same hydrological cycle. Krysanova et al. (2008) show that many major river basins have had to cope with both recent flood and drought events. There are myriad examples of interactions between major flood and drought episodes. For example, after a five year record-breaking drought between 2012-2017, California received large amounts of rainfall, causing major damage to the spillway of the Oroville Dam. Fearing its collapse, authorities evacuated nearly 200,000 people (Vahedifard et al., 2017). Australia's infamous Millennium Drought (1997-2009), which severely affected the environment and economy of a large region (AghaKouchak et al., 2014a), also ended with destructive floods (Van Dijk et al. 2013) that led to the failure of levees along the Murray Riverbank (Vahedifard et al., 2016). After this devastating event the continent returned to a state of severe drought.

While the underlying mechanisms that cause rapid changes from major droughts into destructive floods or vice versa are not fully understood, they are often linked to large scale circulation patterns such as the El Niño-Southern Oscillation (ENSO) (e.g. Zheng et al. 2018). Climate change impacts, including higher precipitation variability, changes in snow water equivalent, and rapid snowmelt can also contribute to rapid drought-flood cycles (e.g. Huning and AghaKouchak, 2018), especially in snow-dominated regions. For example, Afghanistan experienced a snow drought in winter 2017/2018 that added to the existing multi-year drought (Huning and AghaKouchak, 2020). By September 2018, the drought contributed to the estimated 9.8 million people (or ~44% of the rural population) facing food insecurity (FAO, 2019a). In March-April 2019, heavy rainfall and rapid snowmelt then caused floods that resulted in 65 fatalities and affected over 200,000 people (iMMAP, 2019). On the other hand, the natural interplay between floods and droughts is vital for many landscapes and ecosystems. For example, the morphological development of ridge-trough pairs in the Brazos Delta (Texas) is dependent on the natural cycle of floods and droughts associated with ENSO (Fraticelli, 2006). Also in the Amazon basin, floods and droughts alternate naturally resulting in seasonally flooded forest and communities adapted to this variability (Pinho et al., 2015).

In order to better design DRR measures and strategies, it is therefore important to consider interactions between these closely linked phenomena that are parts of the same hydrological cycle. However, in reality DRR measures and strategies usually focus on either floods or droughts. Therefore, actions taken to decrease risk from one hydrological extreme (e.g. flood) may unintentionally lead to an increase in risk from another hydrological extreme (e.g. drought). This issue was discussed in a recent paper by Di

Baldassarre et al. (2017), mainly in the context of reservoir operations. However, there is still a broad lack of understanding on this issue.

Therefore, in this paper we carry out a literature review to examine examples of: (a) how flood or drought risk reduction measures can have (unintended) positive or negative impacts on the risk of the opposite hazard (i.e. flood DRR measures impacting drought risk, or drought DRR measures impacting flood risk); and (b) how flood or drought DRR measures can be negatively impacted by the opposite hazard (i.e. flood DRR measures impacted by drought hazard or drought DRR measures impacted by flood hazard). Note that this paper focuses on inland flooding, although linkages may also exist between coastal flooding and drought risk. This qualitative research is carried out in the context of a collaborative effort between the International Association of Hydrological Sciences (IAHS) Panta Rhei Working Groups on '*Changes in Flood Risk*' and '*Drought in the Anthropocene*'. The paper does not intend to provide an exhaustive review of all studies on this topic, but brings together clear examples of these issues in an attempt to demonstrate its relevance for DRR and DRR science. The review is presented in section 2, with knowledge gaps and challenges discussed in section 3.

2. Review

First, we review measures that are intended to reduce the potential drought or flood hazard, followed by measures that are intended to reduce the potential exposure and/or vulnerability. In Table 1, we summarise the findings for flood DRR measures, showing how they can (positively or negatively) impact on drought hazard, exposure, and vulnerability, and how they can be impacted by drought. Table 2 provides a similar summary for drought DRR measures. Figure 1 gives an example of some of the ways in which the DRR measures mentioned in this paper can lead to a change in hazard, exposure, and/or vulnerability, and as a result flood/drought impacts and risk. It serves both as: (a) a reading guide, showing the numbers of the sections in which each type of DRR measure is addressed; and (b) a demonstration of the complex feedback loops that can exist between measures, flood/drought hazard, exposure, and vulnerability. It should be noted that neither the figure nor the tables are intended to be exhaustive.

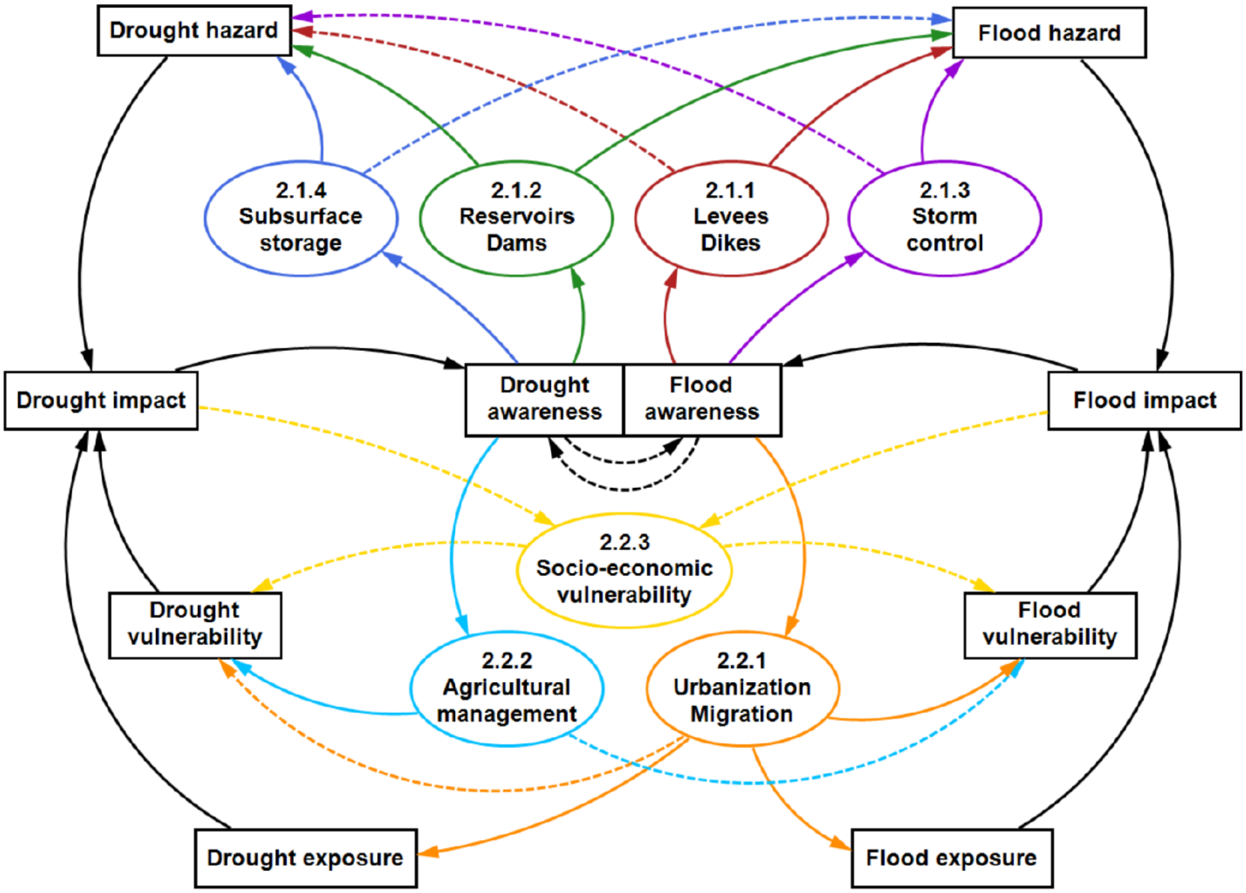

Figure 1: Examples of DRR measures and their interactions with hazard, exposure, and vulnerability across the flood and drought domains. Solid/dotted lines show possible examples of primary/secondary interactions. Numbering refers to the sections in which the measures are addressed in this paper.

2.1. Hazard reducing measures

Structural measures, such as dikes, levees, embankments, and dams have been used for millennia to reduce the potential hazard. Also, subsurface storage has been harnessed historically as a buffer against both flood and drought hazards. In this section, we investigate how such hazard reducing measures can impact, and are impacted by, the opposite hazard.

2.1.1. Dikes and levees

Dikes and levees have been built along large sections of the world's river systems and coastlines to reduce the flood hazard (Merz et al., 2010; Ward et al., 2017). Here, we provide examples of how flood levees and dikes can impact drought risk, and how droughts can increase the chance of their failure.

(Unintended) impacts of measures on risk from the opposite hazard

The failure of levees and dikes can exacerbate drought hazard. For example, Vicuña et al. (2006) simulated economic damages associated with potential levee failure in the Sacramento-San Joaquin delta on Californian farmers. They found that levee failures could lead to the halting of pumping operations, thereby decreasing water supplies, leading to land fallowing, and declines in farm profitability and gross revenue, for up to three years. They also found that this could have knock-on effects in terms of shortage costs for urban water users. Even without levee failure, the entrainment of rivers within dikes and levees can lead to lower infiltration and groundwater recharge (see Section 2.1.4). This is discussed, for example, in Opperman et al. (2009), who state that reconnecting rivers to their floodplains could increase agricultural productivity and lower the need to draw down reservoirs upstream, thereby increasing opportunities for water supply, hydropower and recreation.

During dry periods, dikes and levees are sometimes wettened to reduce failure probability, meaning that less water is available for other uses. For example, Van Lanen et al. (2016) report that during the summer of 2015, Dutch Water Boards had to frequently inspect around 3500 km of drought-sensitive peat dikes, and that these needed to be wetted in cases where cracks were detected. The Dutch Water Act sets out a priority of surface water uses during dry periods (Ministry of Transport, Public Works and Water Management, 2010), with the highest priority being the provision of safety and prevention of irreversible damage, including ensuring the stability of dikes and levees.

The construction of dikes and levees can lead to increased development in the areas protected by dikes, and thereby increased flood risk known as the levee effect (White, 1945; Di Baldassarre et al., 2018). However, this increase in exposure and socioeconomic activity can also place stress on available water resources, therefore also increasing drought risk due to an increased number of water users (exposure) and their vulnerability.

Negative impacts of opposite hazard on measures

There are many examples of dikes and levees that have failed due to drought conditions. Van Baars and Van Kempen (2009) state that drought was the cause of 5% of dike failures in the Netherlands between 1134 and 2006. A well-known example is the dike failure at Wilnis in 2003, which led to 600 flooded houses and the evacuation of 2,000 people (Van Baars, 2005). The failure was caused by the lower weight of the peat dike due to drought compared to the resulting water force, which resulted in horizontal sliding (Van Baars, 2005; Van Baars and Van Kempen, 2009). Several examples also exist in Australia. During the Millennium Drought (1997-2011), Hubble and De Carli (2005) report 68 failures of alluvial riverbanks on the Lower Murray River, resulting from lowered river water levels and banks underlain by soft clay (Hubble and De Carli, 2005), channel widening (Jaksa et al., 2013), and extensive cracking. Examples from the USA include levee breaches and embankment failures in northern California when the 2012-2017 drought ended with a series of extreme rainfall events (Vahedifard et al., 2016, 2017).

2.1.2. Dams

Dams and reservoirs can fulfill many purposes, including storing water to reduce flood hazard and providing water in times of potential drought risk. Most dams have different functions throughout the year or even during one season. Of the currently existing dams, 30% have multiple purposes, 8.5% are used primarily for flood control, and 17% are used for water supply or reducing drought hazard (Lehner et al., 2011).

(Unintended) impacts of measures on risk from the opposite hazard

The fact that dams serve so many different purposes makes them difficult to manage, and conflicting interests and priorities could lead to unintended impacts. Flood protection favours low water storage in the reservoir, thus reducing drought preparedness. On the other hand, drought protection tends to favour high water storage, which makes dams more susceptible to overtopping or failure in the event of extreme rainfall. Where reservoirs serve functions of both flood and drought protection, their management can be adjusted to prepare for each hazard. For example, 40% of the capacity of the Folsom reservoir in California must be assigned to flood control (United States Congress House Committee on Resources, 1997). This can increase drought risk in the case of slow or absent replenishment, such as in 1997. A drought following the 2018 Kerala floods in India was worsened because reservoirs had been drawn down in preparation for the floods (Lal et al., 2020).

Dams play a key role in flood management, by reducing high flows and flooding downstream (Sordo-Ward et al., 2012). Dams with gated spillways have greater levels of water conservation and flood abatement than those with a fixed-crest spillway, but are more susceptible to operational failure, which can increase flood hazard downstream. For small floods, dam safety is of less concern for dam managers, since dams are designed to withstand floods of a certain magnitude safely. When there is a possibility of larger floods, dam safety becomes a priority. This problem is exacerbated when flash floods occur between drought periods, due to a false perception of security (Mediero et al., 2007). It has also been shown that the building of dams to create large reservoirs may lead to considerable volumes of water being lost to evaporation (Bond et al., 2008), increasing drought hazards. In addition, dams can lead to a perception of safety, which can lead to increased exposure and vulnerability downstream. For example, Di Baldassarre et al. (2018) state that the presence of dams can lead to *supply-demand cycles* and *reservoir effects,* where increased demand for water can lead to higher levels of extraction and increasing vulnerability to drought due to over-reliance on the reservoir.

A focus on drought management can also have negative consequences for the flood hazard. An example relating to the floods in Brisbane in 2011, happening after a multi-year drought, is provided by Van den Honert and McAneney (2011). They examined the water releases from the dam that serves as Brisbane’s main water supply. According to their analysis, dam operations may have been sub-optimal due to neglecting forecasts of further rainfall and assuming a ‘no rainfall’ scenario.

Negative impacts of opposite hazard on measures

While dams and reservoirs are effective long-term measures that help in reducing both flood and drought hazards, they can themselves be negatively impacted by floods and droughts. As the flow velocity in reservoirs is reduced, sedimentation of suspended sediments takes place in most reservoirs (Vörösmarty et al., 2003). As river sedimentation is dependent on flow velocity, floods contribute significantly to this sedimentation, thereby reducing water storing capacity for reducing drought hazards. Vahedifard et al. (2017) report threats to dams and levees due to excessive sediment and debris flow, exacerbated by wildfires during droughts. A classic example is the infamous Devil's Gate dam in southern California, which has turned into a large debris basin because of a series of postfire flood events (Karlamangla, 2014). However, the sedimentation of suspended solids behind a dam can also be used as a drought mitigation measure by enlarging the local aquifer storage capacity, which is the principle of (multiple) sand dams (see section 2.1.4).

2.1.3. Stormwater control and upstream measures

Urbanisation impacts the hydrological cycle in many ways. For example, through increased imperviousness that intensifies runoff formation and accelerates runoff response to precipitation, leading to shortened times of concentration and possible effects on downstream flooding, or through reduced evapotranspiration, infiltration, and groundwater recharge, which may result in a decline in river baseflow and higher peak discharges. In urban areas, alterations of the hydrological cycle also include a network of sealed areas, flow conveyance, and piped drainages. In this context, Stormwater Control Measures (SCM, Fletcher et al., 2015) are becoming increasingly popular as a supplement to, or substitute for, sub-surface piped systems. SCM encompass a broad range of technologies that aim at changing the urban water management system to reduce flood hazard or improve pollution management. Likewise, upstream measures intend to retain water in the landscape and reduce flood and drought risk. Examples of SCM at the parcel scale include green roofs, rain gardens, vertical gardens, soakaways, and swales, while on a larger scale they resemble natural systems with lakes, dual-profile channels in rivers, and dry areas where restrictions benefitting the hydrological cycle are applied, such as the Dutch Room for the River approach (Van Vuren et al., 2015). Room for the River puts new river intervention works into place, like dike setback, lowering flood plains, reconnecting side channels and removal of bank defences.

(Unintended) impacts of measures on risk from the opposite hazard

SCM are fairly new and typically only one of the hazards is considered (UACDC, 2010). While Ashley et al. (2017) and Rauch et al. (2017) propose theoretical frameworks for comprehensive assessments of SCM, practical experiences from applications are not provided. In this regard, Rozos et al. (2013) and Voskamp and van de Ven (2015) have examined the effects of integrated blue-green infrastructure approaches in terms of synergies for both flood and drought hazard, and suggest that the storage of water provides a source for evaporative cooling during heatwaves and a water source to prevent drought. Also, they mention the increased recreational benefits of spaces intended for stormwater storage during dry spells. Examples include planting vegetation with retention ponds in the East Lents Floodplain project in Portland, Oregon, USA (Hoang et al., 2018) and multifunctional spaces for surface water storage with examples in New York and Phoenix (USA) and Copenhagen (Denmark) (Rosenzweig et al., 2019). There are examples of extensive infiltration leading to local flooding because of substantial recharge of groundwater in Perth, Australia (Locatelli et al., 2017), as well as examples where the systems have been indicated to manage floods well in spite of the measures being relatively small, such as the Scotchman's Creek catchment in Melbourne, Australia (Löwe et al., 2017).

Negative impacts of opposite hazard on measures

Droughts may have negative impacts on SCM that use green areas and vegetation. For example, droughts adversely affect plants and mosses on green roofs by disabling the proper functioning of the water holding capacity. Nagase and Dunnett (2010) find that diverse or species-rich vegetation on green roofs might be more resistant and resilient to drought. They conclude that a diverse plant mix is more advantageous than monoculture in terms of survival rate and visual rating under dry conditions. Farrell et al. (2012) evaluated the effects of severe drought on growth, water use, and survival of five succulent species planted in three different green roof substrates differing in water holding capacity. They conclude that green roofs in yearround or seasonally hot and dry climates should be planted with species that have high leaf succulence and low water use in substrates with high water holding capacity.

2.1.4. Subsurface storage

Besides dikes, dams, and stormwater control, which focus on managing surface water, the subsurface is also used for implementing DRR measures. Groundwater naturally acts as a buffer to both floods and droughts (Foster and MacDonald, 2014). For example, floods can recharge groundwater levels, which can mitigate droughts (e.g. Miguez-Macho and Fan, 2012). In arid and semi-arid areas, groundwater is often the most (or only) reliable source of water, with seasonal floodwaters in wadi systems the main mechanism of groundwater recharge. In particular, extreme floods are of great importance for groundwater recharge in these areas, especially because abstraction rates exceed recharge in many of these aquifers. Implementation of flood control measures and peak discharge capturing measures is therefore important for drought mitigation (Gevaert et al., 2020). The subsurface is increasingly actively used for water storage, for example with techniques such as sand dams, Managed Aquifer Recharge (MAR), and Aquifer Storage and Recovery (ASR). With these techniques, water available in abundance during the wet season (or wet years) is captured and stored in the subsurface, in order to be recovered and used during the dry season (or dry years). Subsurface storage is mainly used as a drought mitigation measure but it can also be applied for flood mitigation, tackling the dual challenges of (seasonal) floods and (seasonal) water scarcity.

(Unintended) impacts of measures on risk from the opposite hazard

Substituting the use of surface water with groundwater can lead to unintended consequences for flood hazards. For example, continued pumping of groundwater during dry periods can lead to overdraft and lowering of the water table, which in turn can lead to land subsidence due to the compaction of unconsolidated aquifer systems (Scanlan, 2019). The subsidence is often incremental, but can sometimes be dramatic, such as during California's drought in 2008-2010, where subsidence reached up to 270 mm per year in some places (Faunt et al., 2016). The subsidence itself and the reduction in storage space can lead to an increase in flood risk. For example, when Hurricane Harvey hit Houston in 2017, areas with the highest subsidence experienced the worst flooding (Miller and Shirzaei, 2019).

An innovative approach at the river basin scale to co-manage floods and groundwater depletion is 'Underground Taming of Floods for Irrigation' (UTFI), which was piloted in South Asia (IWMI, 2017). This involves targeted recharging of excess wet season flows in aquifers to protect lives and assets downstream and boosting agricultural productivity in the region. An evaluation to capture flood flows for direct groundwater recharge on private farmlands in the Kings River Basin, California, shows that flood flow capture, when integrated with irrigation, is more cost-effective than groundwater pumping (Bachand et al., 2014).

Areas with high inter- or intra-annual rainfall variability can use MAR to capture and store water from extreme flood events and pump this water to supplement rain water harvested to mitigate the impact of drought events on agriculture (Rawluk et al., 2013). In the Chao Phraya River Basin in Thailand, this technique is used to capture peak flows, which can significantly reduce flood impacts and generate extra earnings for farmers who can grow high water-demanding crops even in dry years (Pavelic et al., 2012).

Also, in the Mediterranean region and the south-west of the USA, managed aquifer recharge is seen as a water resources management technique able to mitigate water crises (Scanlon et al., 2016; Bachand et al. 2014). Maliva and Missimer (2012) note that it is important that MAR systems designed to increase infiltration and water availability during drought do not cause unintended flooding in low-lying areas, which happened for example in Mexico when infiltrated wastewater flooded agricultural fields (Jimenez and Chávez, 2004). Also, unmanaged aquifer recharge, such as recharge from urban irrigation during drought, can cause flooding of basements (Al-Sefry and Şen, 2006).

Sand dams are rainwater harvesting structures used to store water in sandy riverbeds, improving water availability during dry times. For example in Kitui, Kenya, 500 of such sand dams were built over the last 10 years, leading to more than 100,000 people with better access to water through a relatively low cost measure (Lasage et al., 2007). However, the positive effects on water safety are compromised when scoop holes are used as an access point, causing pollution and resulting in water scarcity of good quality water.

Negative impacts of opposite hazard on measures

Droughts can make the subsurface less suitable for storing floodwater, for example due to subsidence and compaction and by increasing surface runoff. Since subsidence permanently reduces storage space, it also increases flood risks, as has been demonstrated in San Jose, California, and the Houston-Galveston area of Texas, among other places (Scanlan, 2019). On the other hand, flooding can damage the MAR infrastructure (Lluria, 2009) and cause clogging of infiltration ponds (Maliva and Missimer, 2012), which can impede infiltration into the aquifer.

More frequent flooding increases risks to groundwater pollution, as overflowing latrines and surface flows can transport contaminants to the groundwater. For example, a devastating flood in Alberta, Canada, in 2013 caused contamination of drinking water wells with E. coli along the floodways and flood fringes (Eccles et al., 2017). A study of Ramachandran et al. (2019) in India showed that a flood event of the contaminated Adyar River negatively influenced the groundwater quality of the region. This pollution of groundwater can result in increased water scarcity when quality standards are not met.

2.2. Exposure and vulnerability measures

2.2.1. Migration

The movement of people away from their usual place of residence is a common response to natural hazards. The largest increases in displacement of people due to natural hazards are related to sudden-onset climate-related hazards, and floods in particular (IOM, 2019). Migration is generally seen as an increasingly important measure to reduce natural hazard risks (Black et al., 2013; Burrows & Kinney, 2016). Migration as a DRR measure can either be part of a government planned relocation, occur due to individual voluntary decisions, or take place as forced displacement (Black et al., 2013; Mortreux et al., 2018). Migration can increase and decrease natural hazard risk, as discussed in this section.

(Unintended) impacts of measures on risk from the opposite hazard

Migrants following unplanned, forced displacement processes often face a lower socioeconomic status and higher vulnerability (Black et al., 2013; Wang et al., 2012). These migrants are vulnerable due to their precarious socioeconomic status, limited resources, and lack of access to job opportunities and social security. Moreover, the vulnerability of migrants can stem from a lack of knowledge and information on extreme events due to language barriers and distrust of authorities (Donner and Rodriguez, 2008). For instance, while studying migrants' perceptions and personal experiences of typhoon hazards in Shanghai, Wang et al. (2012) observed that they had a much lower risk perception compared to non-migrants.

Another source of vulnerability is the characteristics of locations in which migrants settle. Floodplains often have favourable conditions for human settlements and economic development, but are also prone to flood hazards. Increasing urbanisation and migration pressure lead to an expansion of cities in more hazard-prone areas, such as mega-deltas, or water-insecure areas with limited access to services (Kummu et al., 2011). Migrants, when poor, often end up in less-favourable areas and slums (Black et al., 2013). For example, in Senegal people populated the outskirts of Dakar when escaping droughts and poverty conditions in rural areas (Schaer, 2015). The World Bank reports that 40% of new migrants arriving in Dakar, Senegal, between 1998-2008 have moved to zones with high flood potential (Foresight, 2011), and currently the peri-urban areas in Dakar face serious flooding almost every wet season.

At the same time, moving away from floods can also increase drought risk. For example, in 2000 Mozambique suffered its worst flood in 50 years. One measure taken after the floods was to relocate people to new settlements. Over 40,000 families were resettled from the hardest hit areas to less flood-prone but more drought-prone upland areas (Wiles et al., 2005). For agriculture, these upland areas are extremely poor and crop yields are low, and here farmers are more prone to drought events (Brida et al., 2013). For farmers who resettled into flood-safe areas, and later suffered from water scarcity and drought, the droughts were perceived to be more catastrophic than floods. This often led farmers to return to the lowlands, where they were again exposed to floods (Brida et al., 2013).

Another factor that makes migrants more vulnerable to hazards is the extensive urbanisation of the areas to which they move. Of the 17 million people at risk of being displaced by floods each year, more than 80% live in urban and peri-urban areas (IDMC, 2019). The urban sprawl, with increased impermeable surfaces, can increase surface water runoff and erosion and therefore lead to more regular floods. Extensive urbanisation can also put excessive strain on local resources and infrastructure, leading to water shortages or human-induced drought (e.g. De Sherbinin et al., 2007). As a result, migrants in search of land, resources, jobs, and livelihoods, may increase their vulnerability to recurring hydrological extremes. An example of these dynamics can be found in Athens, Greece, where uncontrolled and unplanned urbanisation mainly resulted from the entry of thousands of refugees during the Asia Minor migration in 1922 and from internal migration after World War II. Urbanisation resulted in a substantial reduction of water infiltration, and led to increased runoff and erosion, which has contributed to increased flooding in the city for the last 100 years (Lasda et al., 2010).

Negative impacts of opposite hazard on measures

There are also ways in which flood or drought hazards themselves can have negative impacts on migration as an effective DRR measure. Vulnerable populations exposed to a natural hazard may face significant barriers to migration as they either do not have the means to migrate, or the means to migrate as far as they would prefer (Black et al., 2013). For example, being exposed to a drought event was found to reduce migration flows in several contexts, such as a reduction of international migrants from Burkina Faso (Henry et al., 2004) and female internal migrants in Ethiopia (Gray and Mueller, 2012). Moreover, when populations migrate as a result of being exposed to a flood or drought event (hazard), migration will become more disruptive as the migrants tend to be poorer and the migration is unplanned (Barnett and Webber, 2009).

2.2.2. **Agricultural practices and land use changes**

Extreme floods and droughts have large impacts on agriculture, which is also one of the human activities that consumes the most water. Given the close linkage between the agricultural sector and the water cycle, many DRR measures are used to reduce agricultural drought and flood risk (e.g. structural measures to protect cropland from floods, dams and reservoirs to increase agricultural water supply, in-field water harvesting, flood- and drought-resistant crops, crop or livestock insurance; D'Odorico et al., 2018; IPCC, 2012). Some of these measures include those discussed in other sections of this paper, such as dikes and levees (Section 2.1.1), dams and reservoirs (Section 2.1.2), subsurface storage (Section 2.1.4), and migration (Section 2.2). In this section, we refer to other examples that are not described in the aforementioned sections.

(Unintended) impacts of measures on risk from the opposite hazard

To reduce drought and flood impacts on agriculture, some water-stressed countries have developed water and soil conservation methods, including water harvesting and waste-water reuse in agriculture. For example, in Brazil successive dams of stone have been built to create micro-basins for soil moisture conservation, involving local communities (Gutiérrez et al., 2014). This resulted in over 3000 successive dams being built during the period 2001-2009, which created microclimates that provided increased forestation, recovered riverine vegetation, recovered degraded areas, increased biodiversity, and decreased drought risk. These small dams could also be favourable for flood mitigation (e.g. Navarathimam et al 2015). Measures to enhance rainfall infiltration in the soil are often used to reduce agricultural drought risk. An example is cross-slope barriers, which can pose problems during heavy rainfall, as the reduction in drainage capacity can result in waterlogging of crops and reduced yields (Liniger et al., 2011; Makurira et al., 2009). This effect has also been observed when conservation agriculture is applied (Dile et al., 2013).

Water harvesting interventions are often integrated in headwater catchments of rural semi-arid and arid regions to reduce runoff, increase infiltration, and reduce flood risk downstream. These interventions may be used for restoration of the productivity of land with insufficient precipitation, increasing productivity of rainfed agriculture, and minimising the risk of drought and desertification (Prinz et al., 1996). Al-Seekh and Mohammed (2009) showed that runoff in the West Bank is reduced by 65–85% with stone terraces and semi-circle bunds compared to a control site. The major advantages of water harvesting interventions are that they are simple, cheap, replicable, efficient and adaptable (Reij et al., 1988). However, wrongly implemented or upscaled interventions may result in increased topsoil erosion and gully formation, and therefore increase sedimentation and flood risk downstream.

More water-efficient irrigation technologies have a high potential to reduce water demand, thereby reducing agricultural drought risk. Drip or micro-sprinkler irrigation systems are more efficient than pivot or flood irrigation. Spate irrigation is an ancient irrigation technique that harnesses seasonal floods of rivers and streams to fill irrigation channels and is especially common in arid and semi-arid regions. As such, applying spate irrigation combines drought mitigation with flood mitigation (Gevaert et al., 2020).

Another measure to reduce agricultural drought risk is the extensification of agriculture. Antwi-Agyei et al. (2018) discuss potential negative effects of this measure based on a study in northern Ghana. For example, the conversion of natural forest land to agriculture could lead to a decrease in ecosystem services, such as flood prevention. The associated deforestation and stream bank cultivation can increase erosion, leading to the sedimentation of rivers, thereby increasing the probability of flooding. For example, in Niger, land degradation with increased river runoff, soil erosion and sedimentation in the Niger River enhances flood risk at Niamey, and also negatively impacts food production as irrigation water abstraction has become more complicated due to sediment deposition at pumping station inlets and in irrigation canals in the floodplains (SOFRECO, 2007; Saaf et al., 2019).

The use of different crops and cropping practices can be used as a drought or flood risk measure, leading to complex interactions. For example, reducing agricultural irrigation demands by changing to crops with higher water use efficiency could increase flood risk due to low evaporative losses producing more runoff during periods of intense rainfall (Fallon and Betts, 2010). In flood-prone areas, farmers take the flood regime and susceptibility of crops to floods into account when selecting crops for cultivation (Klaus et al., 2016). Farmers in sub-Saharan Africa, for example, plant short duration crops and have changed the timing of planting and harvesting to avoid intense rainfall periods (Sani and Chalchisa, 2016) or dry spells (Ochieng et al., 2017).

Re- or afforestation (sometimes called Eco-DRR) of degraded land, is also viewed as a viable flood mitigation measure for DRR and climate change adaptation (FAO, 2019b) in many agricultural areas. However, in dry periods, the higher evapotranspiration and reduced groundwater recharge of plantations can significantly reduce dry season flow and cause water shortages. In Fiji, establishment of plantation forests on degraded grassland caused reductions in dry season flows causing shortages to the urban water supply (Waterloo, 1994). In Argentina, establishment of Eucalypt plantations caused a decrease of 50% in groundwater recharge days and an average decline of the groundwater level by 0.38 m (Jobbágy and Jackson, 2004). Soil infiltration conditions play an important role in the impact of reforestation on dry season minimum flows (Bruijnzeel, 2004). Similar to observations by Van Meerveld et al. (2019), where higher infiltration capacities in the forested area favoured subsurface flow generation, Ogden et al. (2013) observed higher baseflow in a forested catchment in comparison to disturbed catchments in Panama and attributed this to higher infiltration rates in the forest catchment and lower peak flow runoff in the wet season.

Early warning systems (EWS) allow farmers to adjust their cropping and harvesting practices when a particularly dry or wet season is expected. Seasonal forecasts have proven to be of high value, especially in tropical and subtropical regions, where a number of seasonal rainfall forecasts are currently operational (Murphy et al. 2001). Local trust in seasonal forecasts and in the organisations and governments that provide them takes time to develop (Patt and Gwata, 2002; Tall et al., 2012) and the impacts of wrong forecasts (e.g. farmers being hit by a flood event when having prepared for a drought season) can lead to major losses and mistrust (Changnon and Vonnahme, 2003; Murphy et al., 2001). Traditional forecast methods have been important in farming communities that lack or have limited access to scientific forecasts (Recha et al., 2008). However, an increasing exposure to erratic, and more frequent, severe extreme events has led to a decline in accuracy and reliability of some indicators that the farmers have used (e.g. rain onset), causing adverse consequences on crop production (Reid et al., 2009).

Negative impacts of opposite hazard on measures

Farmers in rainfed production systems have to choose their crop planting dates at the onset of the rainy season. A false start to the season increases the risk of crop failure. If it remains too dry, sowing later in the season might be a good drought risk reduction measure. However, heavy rainfall and flooding at the onset of the season can result in leaching of nutrients out of the root zone, thereby jeopardising its effectiveness (Bussmann et al., 2016; Raes et al.. 2004). Furthermore, conscious crop selection can reduce agricultural impacts (Klaus et al., 2016). For example, farmers in areas facing reduced precipitation in sub-Saharan Africa have switched from high to low water-requirement crops (Sani and Chalchisa, 2016). This entails the risk of lower harvests during (unpredicted) higher precipitation and flood periods (Patt and Schröter, 2008).

In terms of re- or afforestation, drought and heat are known to amplify tree mortality through increased fire and pest hazards (Allen et al., 2015). For example, in the Philippines, fire has been identified as the major risk to the success of reforestation projects (Ancog et al., 2016). Forest fires have caused significant postfire increases in runoff, peak flows and erosion leading to damaging floods and debris flows (De Graff, 2018). In this sense, droughts may affect the impact of forestation measures as a means to reduce flood risks.

2.2.3. Socioeconomic vulnerability and preparedness

Socioeconomic vulnerability can cascade from one drought or flood event to the next (Gallina et al., 2016). For example, drought-induced unemployment can result in increased financial struggles during floods (Rockström, 2003) and flood-induced migration leads to increases in drought vulnerability through social marginalisation (see Section 2.2.1). Measures aimed at reducing this socioeconomic vulnerability to one type of hazard can influence the risk to another type (Dilling et al., 2015). However, most scientific papers look at all hazards together. The assumption is that measures to reduce socioeconomic vulnerability are beneficial for all hazards or can be regarded as “no-regret” (i.e. measures to reduce vulnerability to flood are also beneficial for drought and vice versa) (e.g. Dilley, 2000; White et al., 2001). Measures that increase overall socioeconomic development do indeed seem to reduce vulnerability to natural hazards in general, e.g. improving infrastructure (Kalantari et al., 2019), health care and hygiene (Few, 2007), food and water security (Pelletier et al., 2016), diversification of agricultural activities or drinking water supply (Head, 2014), access to markets (Bebbington, 1999), urban planning (Houghton, 2012), and insurance (Surminski et al., 2016). Measures to increase preparedness, awareness, education, or information (early-warning systems) can also be beneficial for both extremes (e.g. Hajito et al., 2015), but these do not always result in vulnerability-reducing actions, for example due to a lack of agency of the most vulnerable groups in society (Muzenda-Mudavanhu et al., 2016; Sangita, 2016). Some of these measures can, however, also lead to maladaptation, unintentionally increasing vulnerability to floods and/or droughts.

(Unintended) impacts of measures on risk from the opposite hazard

The preparedness of a society is defined by UNDRR as the knowledge and capacity to respond to and recover from the impacts of disasters, and is affected by risk perception. Risk perception relates to how people and institutions perceive the severity and likelihood of a hazard event (Urquijo and De Stefano, 2016). Scolobig et al. (2012) explain that one of the reasons for inadequate preparedness to natural hazards is low awareness. Societies' risk perception might differ from reality due to biases in risk information, trust in weather services, people's memory, and risk-adversity (Loucks, 2015). A focus on preparedness for one hazard can therefore decrease the preparedness to another hazard and thereby increase its risk. Conversely, preparedness for one particular hazard can increase the general hazard-awareness irrespective of the type of hazard and thus positively influence the risk of another hazard (Siegel et al., 2003). The media plays an important role in influencing risk perception. After a systematic analysis of daily news for a period of 25 years of the most popular newspaper in Catalonia (NE Spain), Llasat et al (2009) show that the largest number of news items were related to droughts and forest fires followed by floods and heavy rainfalls, although floods are also a major risk in this region. This can lead to a false perception of low flood risk that affects individual and societal behaviour.

Flood-early warning systems suffer from uncertainties and false-alarms that could result in considerable costs. For example, information from a flood early-warning could prompt reservoir managers to release water, but if the predicted flood does not come or is less severe than predicted, this might result in water shortage (Rogers and Tsirkunov, 2010).

Insurance, micro-credit schemes, and diversification of agriculture have been found to reduce incentive for taking measures and undermine investment (Ray-Bennet, 2010; Shiferaw et al., 2014; Surminski et al., 2016) and disaster relief projects by donors and NGOs can increase vulnerability by creating dependency and undermining local initiatives (Lo and Diop, 2000; Salim et al. 2019; Schaer, 2015). Another example of where such vulnerability reduction measures aimed at one hazard can increase vulnerability to the other hazard can be taken from Mexico City, where residents of illegal settlements who do not have access to piped water can buy water from water trucks. This can lead to increased poverty and a reduced ability to cope with flooding (Eakin et al., 2016).

Several examples relating to water policy and governance also exist. For example, during the 2001-2008 Millennium Drought in Southeast Queensland, Australia, the state government initiated major changes in water governance, including a centralisation of authority replacing more cooperative models for water management. This led to high levels of distrust and conflict amongst stakeholders. The centralised system could not prevent building in the floodplain, which increased flood exposure and therefore the impacts of the 2010 flood event (Head, 2014).

Negative impacts of opposite hazard on measures

Because most vulnerability-reducing measures are intangible, they are often not directly affected by an event. There are indirect effects, for example related to preparedness, awareness, perceptions, and distribution of limited resources. During a flood or drought event, crisis management takes away attention, resources, and priority from other water-related issues, potentially increasing the risk of the other extreme. It can be expected that flood memory decays more rapidly during a multi-year drought, as is exemplified by this quote of a local government representative in Australia: "you forget, because of 10 years of drought, that land floods" (Bohensky and Leitch, 2014, p.483).

3. Knowledge gaps and challenges

Despite the fact that floods and droughts are two extremes of the same hydrological cycle, measures and strategies for their risk reduction usually focus *either* on flooding *or* on droughts. To some extent this may be explained by the fact that their typical temporal and spatial scales are generally different. As a result of these scale differences, as well as the complexity of different hydrological extremes, researchers and practitioners often specialise in one extreme or the other. Moreover, because many hydrological studies have focused on the catchment scale, linkages between hydrological extremes across larger spatial scales are less well studied (Guimarães Nobre et al., 2019).

A more holistic risk management approach that addresses both extremes would allow us to better address tradeoffs and synergies between hazards, measures, decision objectives, and different temporal and spatial scales. In this regard, an important question is who wins and who loses? For example, who benefits from the construction of a levee and/or dam, and which parts of the population may face detrimental impacts? How do benefits from structural measures change from the short term towards the distant future? In terms of SCM, many of the technologies are based on very local measures, but what is their influence on the hydrological cycle (and floods and droughts) outside the area in which they are taken? In terms of migration, what are the benefits and problems faced by migrants and the inhabitants of the areas facing in- and out-migration? How will these change in the future? How are these benefits and problems related to socioeconomic factors such as wealth, gender, age, and so forth? We need to develop methods to explicitly examine these kinds of questions from a holistic perspective. To achieve this, DRR research and practice must be closely linked with climate change adaptation, since both of these are essential for achieving the Sustainable Development Goals (SDGs). The urgent need to integrate DRR, climate change adaptation, and sustainable development is reiterated in the UNDRR’s Guidance Note on Using Climate and Disaster Risk Management to Help Build Resilient Societies (UNDRR, 2020). In this section we reflect on some key challenges for achieving this holistic approach that are specifically related to interactions between floods and droughts and their respective DRR measures.

More *basic research is required on interactions between physical climate processes* that can ameliorate or aggravate floods and droughts. Dettinger (2013) examined the role of atmospheric rivers as ‘drought-busters’ in the USA, and Huning and AghaKouchak (2018) discuss how changes in snow water equivalent and rapid snowmelt can contribute to rapid drought-flood cycles. However, such research is scarce, and an increased focus could improve our understanding of these interactions. Indeed, the last five years have seen an increased attention for so-called compound climate events, defined by Zscheischler et al. (2018) as ‘the combination of multiple drivers and/or hazards that contributes to societal or environmental risk’. Initiatives such as the COST Action DAMOCLES (UnDerstanding And Modeling cOmpound CLimate and weather EventS) are identifying key processes and combinations of variables that contribute to compound events, developing new statistical and dynamic modelling approaches to better simulate compound events, and developing a framework to improve their assessment. Much of this knowledge could be applied to improve our understanding of interactions between flood and drought risk.

Moreover, an increased understanding is needed of *how interactions between physical-climate processes will change in the future*. Some regions may see an increase in both flood and drought hazard, whilst others may see an increase in one hazard and a decrease in the other (Arnell et al., 2019). In this regard, a major challenge is knowing how climate change will affect the frequency and severity of both floods and droughts, and importantly, the likelihood of consecutive, compound, and concurrent (flood and drought) events (e.g. AghaKouchak et al., 2014b; De Ruiter et al., 2020a; Wahl et al., 2015; Zscheischler and Seneviratne, 2017). This has major implications for some of the DRR measures discussed in this paper. For example, future climate change introduces a large uncertainty in delimiting 'safe areas' for natural hazard-related migration. Some local areas will become increasingly marginal as places to live in or in which to maintain livelihoods. In such cases, migration and displacement could become permanent and could introduce new pressures in areas of relocation (Gemenne, 2011). Increasingly, climate studies are focusing on trying to capture the correct combinations of variables in large ensemble probabilistic climate modelling studies. However, the uncertainty remains large, and so other methods are also being developed that could be harnessed to improve the understanding and assessment of flood and drought interactions. An example is the storyline approach, in which studies try to develop descriptive 'storylines', 'narratives' or 'tales' of plausible future climates, instead of trying to quantify probabilities (Shepherd et al., 2017). This approach should be applied not only to single hazards, but also to compound drought-flood events.

Beyond these physical processes, it is of utmost importance to better understand complex *human decision-making processes and how they are influenced by (interactions and feedbacks between) hazard, exposure, and vulnerability*. In natural hazard risk assessments, dynamic feedbacks between these components are very poorly represented (Gill and Malamud, 2016). By improving this understanding, we will be better able to understand potential implications of future changes in extremes and water availability around the world (Di Baldassarre et al., 2018). Agent-based models provide a potential opportunity to assess these aspects, such as that employed by Haer et al. (2019) to assess flood risk at the European scale. A key aspect with regards to human behaviour is risk perception, trust, and uncertainty. For example, migrating from a flood-prone area to a drought-prone area, or planting drought-resilient crops in a period of heavy rains (Patt and Schröter, 2008) are faced with large uncertainties. These uncertainties affect both trust in the usefulness of measures and risk perception, and these aspects remain less well studied. Increasing our understanding of these processes would not only contribute to improved flood and drought risk management, but also to the growing field of multi-hazards and multi-risk studies more broadly (e.g. Ciurean et al., 2018; De Ruiter et al., 2020a, Gallina et al., 2015).

We need to enhance our understanding of the *effectiveness of measures themselves*. For example, whilst there is already some understanding of the mechanisms that lead to drought-induced dike and levee failure within the engineering discipline, there is a lack of understanding of how these mechanisms can influence overall (flood and drought) risk at local and regional scales (Jaksa et al., 2013), with Vahedifard et al. (2016) suggesting that there is a need to develop a framework for integrating drought and climate change risk in dike engineering design. In terms of SCMs, there is a lack of understanding of how the underlying technologies interact with other components of the urban and natural water cycle, and quantitative knowledge is often scattered and site-specific (Shuster et al., 2005). Despite the importance of groundwater, groundwater management is often neglected, especially in unmonitored areas. Often, the population is fully dependent on groundwater resources for their livelihood, but there is little awareness of the need for protection of recharge areas and groundwater management.

We must also *improve our understanding of interactions and feedbacks between DRM* measures. This paper shows many examples of how DRR measures designed to reduce one of the risk drivers (i.e. hazard, exposure, and vulnerability) can unintentionally lead to an increase in one of the other risk drivers. A particular challenge is quantifying how DRR measures designed for one specific hazard (e.g. floods) can increase risk from another hazard (e.g. droughts), termed asynergies by De Ruiter et al. (2020b). These asynergies have been assessed in a handful of studies for various hazards (e.g. Crosti et al., 2010; De Ruiter et al., 2020b; Kennedy et al., 2008; Li et al., 2012; Wood and Good, 2004), which could provide a starting point for studies specifically relating to flood and drought interactions. This could allow decision makers and policy makers to make more informed decisions that consider optimal measures (and combinations of measures) across multiple hazard types. When resources are limited, DRR planning often prioritises one extreme, although maladaptation and unintended effects on risks from other hazards might outweigh the positive effects of the investment. Kreibich et al. (2014) suggest an integrated cost assessment cycle in risk management of multiple natural hazards; it involves the continuous monitoring of all associated costs, thus enabling the early detection of inefficient risk mitigation strategies. Kull et al. (2013) discuss how the use of a Cost-Benefit Analysis (CBA) in DRR could be used to account for these ‘disbenefits’, thereby decreasing the likelihood of maladaptation

As always, a key to improving our understanding is *good data based on reliable monitoring and observation systems*. This includes data on physical and socioeconomic aspects (e.g. climate, soil moisture, river discharge, groundwater, population, wealth, vulnerability, etc.), as well as ecological aspects and the effectiveness of measures. As a complementary approach to available monitoring, Kreibich et al. (2019) suggest to collect a large number of paired-event case studies of floods and droughts, i.e. collecting data and information about various hazard, exposure, vulnerability and impact characteristics in the same region, and how these changed between two consecutive events. This Panta Rhei benchmark dataset looks at paired flood and drought events separately but could be extended to include flood-drought and drought-flood event pairs. Additionally, we need to also devise other new ways to monitor changes in the effectiveness of measures over time. For example, the performance of SCMs is likely to change over time, with periods of drought being detrimental for the intended performance. There is little long-term empirical analysis that tests the effectiveness of small scale water harvesting interventions, such as sand dams, during droughts. Therefore, continued observations are essential, but importantly data need to be made available for use in research if we are to improve our understanding. For example, most reservoir operating data are not publicly available, which hampers the development of new knowledge when it comes to understanding human responses to flood and drought hazards. The availability of such data would allow us to better quantify the economic, social, and ecological damage caused by floods and droughts, as well as the pros and cons of DRR measures.

To achieve a more holistic, multi-hazard approach to floods and droughts, *changes in governance structures* will be required. A framework for multi-risk governance has been developed by Scolobig et al. (2017), which includes decision-making processes related to all phases of DRR. In its development, the authors describe several institutional barriers faced by practitioners, namely: single risk-centred regulation and institutional framework; different goals and priorities of the agencies in charge of hazard management; unsatisfactory public-private partnerships; different responsibilities for risk reduction at household level; lack of interagency communication; and lack of capacities at the local level. Many of these considerations are pertinent for the management of floods and droughts (and their interactions). For example, flood and drought (risk) management practices are often part of separate government departments (Head, 2014), and whilst the European Union has developed a Flood Directive, there is no specific European Directive on droughts. Raikes et al. (2019) argue that flood (risk) management focuses on land use and urban planning and is increasingly risk-oriented and proactive, whereas drought management focuses on water supply and agriculture and often mostly still consists of emergency responses. Interaction between the institutions involved in flood and drought management may lead to mutual gains for both hazards.

Addressing these knowledge gaps and challenges requires *interdisciplinary research and collaboration between science and practice*. Various frameworks, networks, and partnerships are developing to address this at international levels, such as the UNDRR Global Risk Assessment Framework (GRAF), the Knowledge Action Network on Emergent Risks and Extreme Events (Risk KAN), and the newly launched European Geosciences Union Multi-Hazards Subdivision. Guidelines are also being developed to help train water managers to take a more integrated approach to flood and drought risk management (UNESCO, 2015). The research leading to this paper is a collaboration between flood and drought-related Panta Rhei Working Groups of the IAHS (Working Groups on '*Changes in Flood Risk*' and '*Drought in the Anthropocene*' respectively), demonstrating that there is now increasing impetus to move (water-related) disaster risk management towards a more holistic, multi-risk approach. The findings in this paper serve to illuminate the relevance of more explicitly examining flood and drought interactions in DRR and DRR science. By taking this more holistic approach, more explicit links could be made with reducing the impacts of climate change and addressing global development issues, thereby ensuring a linkage between policy related to DRR, climate change adaptation, and the SDGs.

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Table 1: Non-exhaustive overview of how flood DRR measures can impact on drought hazard, exposure, and vulnerability, and how they can be impacted by droughts. Table 2 provides a similar summary for drought DRR measures. NB: + and - symbols indicate a positive and negative impact, respectively.

	Impacts on flood DRR measure on drought...			Negative impacts of drought on the flood DRR measure
Flood DRR measure	**Hazard**	**Exposure**	**Vulnerability**	
Dikes and levees	(-) Less water supply due to failure of pumping (-) Water use for wettening of dikes (-) Reduced infiltration and groundwater recharge	(-) Levee effect (more people and water demand)	(-) Levee effect (reliance on water source)	(-) Increased probability of dike failure
Dams	(**+**) Can be used for water supply during drought (-) Lowering reservoir levels can lead to lower water availability downstream (-) Water loss due to evaporation	(-) Increased development downstream can lead to increased exposure	(-) Supply-demand cycles and reservoir effects (i.e. higher extraction and over-reliance on reservoir)	(-) Increased upstream erosion due to wildfires and droughts increases debris flow and sedimentation, thereby reducing reservoir storage capacity
SCM and upstream measures	(**+**) storage of water for evaporative cooling and water source during drought (**+**) upstream contour bunds and gully plugs to reduce runoff (and soil erosion) increase groundwater recharge			(-) Adverse effects on plants and mosses of green roofs, disabling the proper functioning of water holding capacity

Subsurface storage	(**+**) Managed aquifer recharge to reduce peak flows can increase water availability during drought		(**+**) Underground Taming of Floods for Irrigation (UTFI) to mitigate floods are effective in enhancing groundwater availability making irrigated agriculture less vulnerable to droughts than conventional rainfed agriculture	(-) Drought can make the subsurface less suitable for storing floodwater for example by subsidence and compaction and by increasing surface runoff.
Migration	(-) Migration can increase drought hazard by adding to unsustainable water consumption in host areas	(-/**+**) Migration can decrease or increase exposure in the areas from/to which people migrate	(-/**+**) Migration can lead to worsened/improved socioeconomic status and income opportunities	(-) May 'trap' populations not able to move
Agricultural practices and land use changes	(**+**) Reservoirs & land use management can reduce both drought and flood risk (-) Reforestation can lead to decreased dry season flows (**+**) Reforestation can reduce irrigation water extraction on irrigated land	(-) Migration to low flood hazard areas in uplands can increase drought exposure (-) Reforested land may be needed for food production (**+**) Establishment of plantations can increase economic return of degraded land	(-) Wrong flood forecasts can lead to higher drought vulnerability (-/**+**) Competition between agriculture and forest socio-economic gains	(-) Drought increases fire risk, which is a factor determining the success of afforestation and reforestation projects
Vulnerability and preparedness	(-) Flood-early warning systems giving false alarm can cause increased water scarcity if actions taken to discharge water		(-) Micro-credit schemes can create dependency and undermine local initiative (-) Focus on flood DRR measures can lead to less focus on drought risk	(-) Limited financial resources; if spent on flood preparedness, there are no funds left to prepare for droughts

			(**+**) Raising awareness of flood risk can raise general risk awareness (-) EWS false alarms can decrease trust in warnings	

Table 2: Non-exhaustive overview of how drought DRR measures can impact on flood hazard, exposure, and vulnerability, and how they can be impacted by floods. Table 1 provides a similar summary for flood DRR measures. NB: + and - symbols indicate a positive and negative impact, respectively.

	Impacts on drought DRR measure on flood...			**Negative impacts of floods on the drought DRR measure**
Drought DRR measure	**Hazard**	**Exposure**	**Vulnerability**	
Dams	(-) High reservoir levels can lead to susceptibility to overtopping and dam failure in event of high discharge	(-) Increased development downstream of dams can lead to increased exposure	(-) Supply-demand cycles and reservoir effects (i.e. higher extraction and over-reliance on reservoir)	(-) Upstream erosion and sedimentation in reservoir during flooding reduce water storage capacity
SCM and upstream measures	(-) increased infiltration leading to flooding because of substantial groundwater recharge (+) area downstream can experience reduced flood hazard as more water captured/delayed upstream			
Subsurface storage	(-) continued pumping of groundwater during dry periods can lead to land subsidence and permanent reduction in storage space (+) area downstream can experience reduced flood hazard as more water			(-) Flooding can damage MAR infrastructure and cause clogging, which can impede infiltration into the aquifer (-) Floods can make underground stored water less suitable for consumption due to pollution

	captured/delayed upstream			
Migration	(-) Migration can lead to poorly planned urban expansion, with resulting impacts on flood water infiltration, increased runoff, and erosion	(-/+) Migration can decrease or increase exposure in the areas from/to which people migrate	(-/+) Migration can lead to worsened/improved socioeconomic status and income opportunities	(-) May lead to distress migration, which is more disruptive
Agricultural practices and land use changes	(-) Overdraft of groundwater leads to lowering of water table, with resulting subsidence and reduction of water storage (-) Enhanced rainfall infiltration in dry areas can lead to waterlogging during heavy rains (+) Successive dams for soil and water conservation can be favorable for flood hazard (-) Extensification of agriculture can lead to conversion of natural lands used for flood protection (-) Changing to high water-use efficiency crops could increase flood risk due to low evaporative losses (+) Reforestation can lead to increased dry season flows if soil infiltration capacity improves (-) Wrongly implemented water harvesting interventions may	(-) Cultivating floodplains increases flood exposure (+) Reduces exposure to floods and shortens flood periods	(+) Better early-warning can lead to decreased drought and flood vulnerability (-) Reforested areas susceptible to tree mortality (which can increase peak flows) in response to fires, pest and diseases	(-) Planting later in season as drought measure can be jeopardised when heavy rains wash away nutrients (-) Planting low water-requirement crops entails risk of lower harvest during (unpredicted) higher precipitation (-) Flooding of forests (floodplains) after reforestation over longer periods of time can increase tree mortality

	result in increased topsoil erosion and gully formation			
Vulnerability and preparedness	(-) Drought early warning systems giving false alarm can increase flood probability if actions taken to retain water	(-) Water provision to illegal settlements and changes in governance (centralised system not able to prevent building in floodplain) increase exposure to floods	(-) Water provision to illegal settlements increases poverty & vulnerability to floods (-) Micro-credit schemes can create dependency and undermine local initiative (-) Focus on drought DRR measures can lead to less focus on flood risk (**+**) Raising awareness of drought risk can raise general risk awareness (-) EWS false alarms can decrease trust in warnings	(-) Limited financial resources; if spent on drought preparedness, there are no funds left to prepare for floods