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Exploring drought-to-flood interactions and dynamics: a global case review

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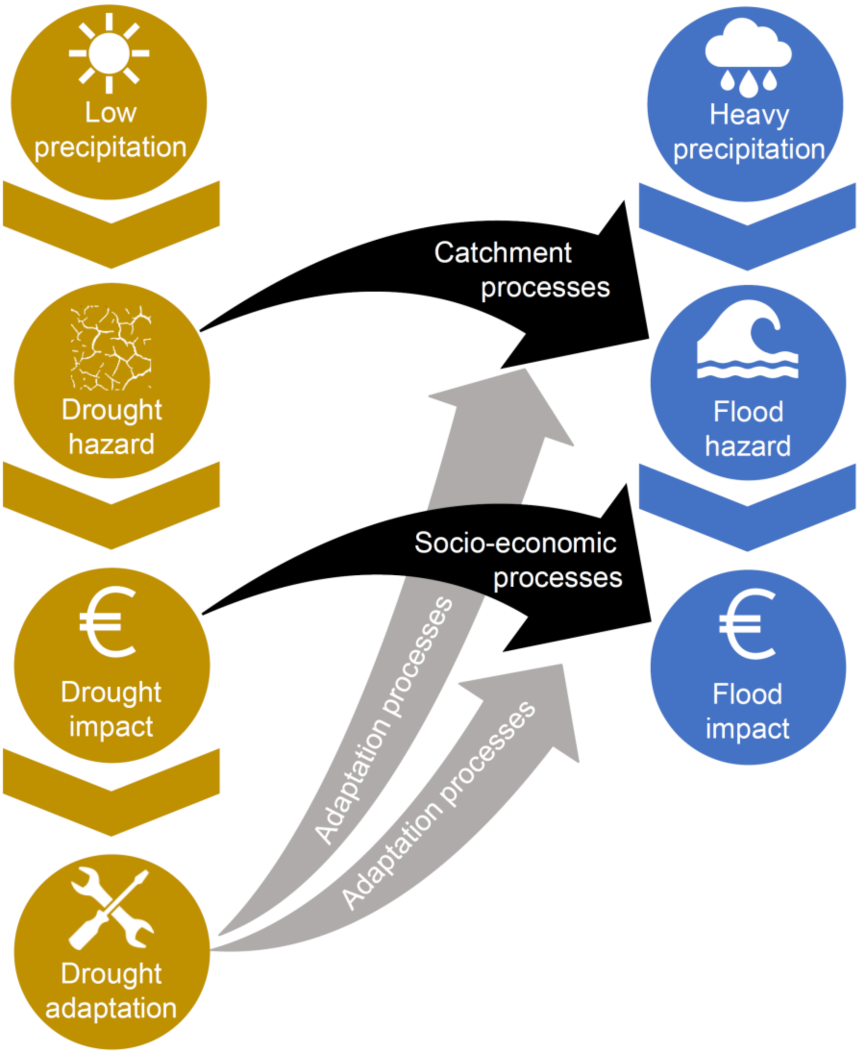
Conflict of Interest

There are no conflicts of interest to declare.

Abstract

This study synthesises the current understanding on the hydrological and human impact and adaptation processes underlying drought-to-flood events (i.e. consecutive drought and flood events), and how they interact. Based on an analysis of literature and a global assessment of historic cases, we show how drought can affect flood risk and assess under which circumstances drought-to-flood interactions can lead to increased or decreased risk. We make a distinction between hydrological, socio-economic and adaptation processes. Hydrological processes include storage and runoff processes, which both seem to mostly play a role when the drought is a multiyear event and when the flood occurs during the drought. However, which process is dominant when and where, and how this is influenced by human intervention should be further researched. Processes related to socio-economic impacts have been studied less than hydrological processes, but in general, changes in vulnerability seem to play an important role in increasing or decreasing drought-to-flood impacts. Additionally, there is evidence of increased water quality problems due to drought-to-flood, compared to drought or flood by themselves. Adaptation affects both hydrological (e.g. through groundwater extraction) or socio-economic (e.g. influencing vulnerability) processes. There are many examples of adaptation, but there is limited evidence of when and where certain processes occur and why. Overall, research on drought-to-flood events is scarce. To increase our understanding of drought-to-flood events we need more comprehensive studies on the underlying hydrological, socio-economic and adaptation processes and their interactions, as well as the circumstances that lead to the dominance of certain processes.

Graphical/Visual Abstract and Caption



A review of the hydrological, socio-economic and adaptation processes underlying drought-to-flood interactions and dynamics.

1. INTRODUCTION

Drought and floods are opposite hydrological extremes, but their risks are not independent. When an extreme flood event occurs shortly after a major drought (i.e. drought-to-flood), its consequences can be catastrophic. Drought-to-flood events are often initially not perceived as a disaster. After a long drought, the first rains are welcome (Little et al., 2001; Parry et al., 2013), as they can result in a recovery of the ecosystem (Bennett et al., 2014) and the replenishment of water resources (Brauer et al., 2011). In some cases, however, this positive situation turns into a disaster, depending on physical and social processes and their interactions. For example, in the Millennium Drought in Australia (2000-10) followed shortly after by widespread flooding in the south and east of the country (Van Dijk et al., 2013); the 2017-18 drought in East Africa quickly followed by floods that killed hundreds (ReliefWeb, 2018) or the 2019 Mozambique deadly flooding that occurred at the end of a long drought in the region (Cowan & Infante, 2019). When, where, and for whom drought-to-flood events are a benefit or a disaster is still unclear. There are several processes through which a drought event can influence a subsequent flood event: atmospheric processes affecting the meteorology; catchment processes affecting the hydrology; socio-economic processes affecting impacts; or adaptation processes, potentially affecting both hydrology and socio-economic impacts.

Both dry and wet climate extremes are occurring more frequently and with increasing severity (Rodell & Li, 2023) and are expected to become even more frequent and intense with ongoing climate change (IPCC, 2023). He & Sheffield (2020) show that, in certain areas across the globe, the frequency of rapid dry-to-wet transitions has also increased over the past 30 years. In addition, the time between consecutive dry and wet events has been shown to be decreasing, implying that there is less time to recover from the impacts of the dry extreme before the wet extreme occurs (Rashid & Wahl 2022). This shows the importance of improving the understanding of drought-to-flood events and how the different processes that occur during and after a drought event increase or decrease the occurrence, severity and impacts of a consequent flood event.

Dry-wet transitions have gained increasing scientific interest, but most studies focus on the atmospheric processes behind shifts from low to high rainfall (e.g. Dong et al., 2011, Singh et al., 2014; Payne et al. 2020). For example, on the US West Coast, 33%–74% of persistent droughts over

1950-2010 were ended by atmospheric rivers (Dettinger, 2013). Other case studies, mostly in the USA revealed that dry-wet transitions resulted from a reversal of the ‘ridge–trough’ circulation pattern, so a persistent high-pressure ridge changing to a persistent low-pressure trough in the same location (e.g. Dong et al., 2011; Yang et al. 2013; Wang et al., 2017). In some studies, this has been related to the migration of the jet stream (e.g. Payne et al., 2020; Parry et al., 2013; Wahl et al. 2019). In addition, large-scale ocean-atmosphere processes seem to play a role in rapid transitions between dry and wet periods. For example, in the Amazon region such an abrupt transition was ascribed to negative sea surface temperature anomalies corresponding to a La Niña-like mode (Espinoza et al., 2013). Several studies in China also relate abrupt dry-to-wet alterations to anomalies in sea surface temperatures and large-scale ocean atmospheric modes (e.g. Wu et al., 2006a; Wu et al., 2006b). Other cases show that drought also enhances rain production, for example by increased convection due to dry soils leading to vertical air motion intensifying precipitation of atmospheric rivers (Gimeno et al., 2014). Both increased moisture transport and more active rain-producing systems may play a role in dry-wet transitions (e.g. Dong et al., 2011; Maxwell et al., 2017; Ma et al., 2019).

Whether these meteorological conditions develop into a drought-to-flood hazard and associated impacts is dependent on hydrological, socio-economic and adaptation processes. There are some studies that provide examples of human adaptation to drought (or flooding) and how this affects the other extreme (Ward et al., 2020; De Ruiter et al., 2021; Garcia et al. 2022), but the underlying physical and social processes that play a role in drought-to-flood events have been studied less and an overview of their reducing and enhancing effects is lacking. In this study, we aim to synthesise the current understanding on the hydrological, impact and adaptation processes behind drought-to-flood events, as well as their interactions. Based on an analysis of literature and a global assessment of historic drought-to-flood cases through a review of grey and peer-reviewed literature (for a description of the methods see the Supplementary material), we show the diversity of processes that govern how drought affects flood risk and assess the circumstances under which positive and negative effects and feedbacks occur, subdivided in sections on “Catchment processes” (Section 2), “Impacts”(Section 3) and “Adaptation processes” (Section 4). Besides providing new insights on drought-to-flood interactions, we identify research gaps that should be addressed to better understand and improve the management of drought-to-flood events (Section 5).

2. CATCHMENT PROCESSES INFLUENCING DROUGHT-TO-FLOOD EVENTS

This section explores how drought can alter catchment processes and how these changes can affect a subsequent flood event. In some cases, a drought can exacerbate subsequent flooding. In other cases, a change in catchment processes because of a drought can reduce subsequent flooding or make it less likely to occur. An overview of the different processes is provided, as well as an exploration of when and where different processes may be dominant. We make a distinction between storage and runoff process. We provide an overview of the processes discussed in this section and the factors that influence when and where they are dominant in Table 1.

Table 1. Summary of catchment processes and the factors influencing when and where they are dominant. This overview is based on, in many cases, limited evidence and more research is necessary to get a better overview of the catchment characteristics influencing when and where these processes are dominant.

Process group	**Dominance**	**Process**	**Effect on flooding**
Storage depletion	Dominant in arid catchments, broader and flatter valley catchments, catchments with deeper soils and catchments with more groundwater variability	Dry antecedent soil moisture conditions	Decrease
	Dominant in case of riverine flooding	Groundwater disconnecting from surface water	Decrease
Runoff processes	Generally dominant across climate and catchment types	Vegetation response	Decrease
			Increase in places with low aridity, high baseflow, a shift from snow to rain or

	Dominant in case of flash and pluvial flooding		resilience of high-elevation runoff.
		Decreased infiltration and increased surface runoff	Increase
		Snow related processes	Decrease in case of a lower snowmelt peak because of below normal snowmelt or when precipitation falls as rain instead of snow
			Increase in case of rain falling on snow

2.1 Storage processes

The hydrological conditions at the end of a long drought are not the type of conditions that are prone to result in flooding when heavy rainfall occurs. For example, subsurface storage will be low and will need to be replenished. With dry antecedent soil moisture conditions, a lower flood is expected (Pathiraja et al., 2012; Evans et al., 1999; Blöschl et al., 2015; Berghuijs et al., 2016), making drought-to-flood events less likely or less extreme. For example, the flash flood in the Netherlands in the summer of 2010, was less severe than it could have been because the first rainfall was stored in the dry soils (Brauer et al., 2011). In the UK 2010-12 drought-to-flood event, initial rainfall led to soil moisture recovery. It was only prolonged heavy rainfall that resulted in flooding (Parry et al., 2013), with variability in time to peak discharge between quickly and slowly responding catchments (Parry et al., 2016). This suggests that, with greater storage depletion after more severe drought, recovery takes longer (Bravar and Kavvas, 1991), as found by Parry et al. (2016) in the UK. However, in some catchments in Australia, there was no such buffer effect and the flooding occurred soon after the drought (Yang et al., 2017).

The process of flood mitigation due to empty or low water storage caused by preceding droughts is not frequently mentioned in our case review of past drought-to-flood events. This is likely because this process alleviates flooding, thereby reducing or eliminating impacts. These events are therefore not included in our database (since it only includes cases with reported impacts). There were only two cases, in Saskatchewan, Canada and Iowa, United States of America, where increased storage availability because of the drought was mentioned as a process that caused flooding to be less severe than it could have been (CBC News, 2015; Danielson, 2014).

One of the mechanisms that would explain an additional delay in the response of the hydrological system to excessive rainfall after drought is decreasing groundwater levels during drought, leading to groundwater disconnecting from surface water (Eltahir and Yeh, 1999; Parry et al., 2013). This causes contraction in the stream network, shrinkage of the saturated partial contribution area, and slower pathways for water. One of the reasons is that it takes more water for saturation excess flow to occur (Saft et al., 2016). This would imply that heavier and longer duration rainfall is necessary for flooding to develop as a result of saturation overland flow. However, pluvial flooding from infiltration excess in the case of short heavy rain events would not be affected by this contraction. In addition, with the contraction of the stream network the contribution of groundwater to the stream becomes lower, up to the point that the stream loses the connection with the groundwater and groundwater no longer contributes to the discharge. Large amounts of recharge are needed for groundwater and stream to reconnect and for groundwater to start contributing significantly to the discharge (Poeter et al., 2020). Drought recovery tends to be asymmetric (Eltahir and Yeh, 1999), with changes to the stream network taking longer to recover than to develop. Therefore, it would take longer for flooding to develop after a drought.

2.2 Runoff processes

In the literature, there is also evidence for drought-induced changes in the land surface activating quick runoff pathways, which would suggest that catchments do not need to recover fully, with storage completely replenished, before flooding can occur (Parry et al., 2013). One mechanism that could play a role is vegetation response. In Australia for example, many catchments remained in a lower runoff state for more than seven years after the Millenium drought and showed no sign of recovery to the pre-drought runoff state (Peterson et al., 2021). In this case, the (lack of) recovery is not controlled by refilling of subsurface storage, but rather the authors postulate that it is related to a vegetation response leading to increased evapotranspiration (Peterson et al., 2021). However, the authors only investigated changes in annual runoff, and not changes in runoff extremes. In a study in the southern Appalachians, in California, Scaife and Band (2017) find that stormflow response is higher after a drought, because of a reduction in transpiration. In a study investigating changing rainfall-runoff response during drought in 14 basins in California, Maurer et al. (2022) find that in basins with low aridity, high baseflow, a shift from snow to rain (i.e. more precipitation falling as rain instead of snow) , or resilience of high-elevation runoff (i.e. no significant decreases in high-elevation runoff during a drought), the rainfall-runoff response is higher than expected compared to the rainfall-runoff response under normal conditions. Whether a drought increases or decreases the rainfall-runoff response, therefore seems to depend on the climatic and catchment conditions.

Many studies report increased runoff after drought because of decreased infiltration rates and increased surface runoff (Descroix et al., 2009), for example because of increased soil compaction (Alaoui et al., 2017) or hydrophobicity (Evans et al., 1999). Also, soil cracking can result in quick vertical flow of rainwater (Miller et al., 1997) and land cover changes can affect infiltration excess runoff generation, surface runoff routing and spatial connectivity, usually increasing (but in some cases decreasing) flooding (Rogger et al., 2017). Wildfires, often related to drought, have been found to change flow pathways (Murphy et al., 2018) and increase the risk of other hazards including flash floods, debris flows and landslides (Moftakhari and AghaKouchak, 2019) (see Box 1 for more details on wildfires). The question remains whether these changes in pathways persist long after the end of the drought (Worrall et al., 2007) and whether they are important at the catchment scale (Blöschl et al., 2007; Alaoui et al., 2017).

In snow-dominated regions, other mechanisms can explain the relation between drought and flooding. Early or below-normal snow melt in dry and warm years, could lower the snowmelt peak, reducing snowmelt floods (Van Loon et al., 2015). The same occurs when precipitation falls as rain instead of snow, resulting in decreased snowfall and snowpack (Tabari, 2020). On the other hand, early snow melt could also lead to higher peak runoff. Hatchett and McEvoy (2018) found that many snow droughts were characterized by lower snow fractions and midwinter peak runoff events. Under higher winter and spring temperatures (often co-occurring with drought), rain-on-snow flood events are expected to shift in occurrence: from spring to winter (Freudiger et al., 2014) and from lower to higher elevations (Musselman et al., 2018). We can also speculate that drought in snow-covered areas could potentially lead to compacted snowpacks that could result in more severe rain-on-snow floods when rainfall occurs (Rössler et al., 2014), but more research would be needed on this.

2.3 Which process is dominant, when and where?

Limited studies exist on effects at the catchment scale to answer the question of where and when storage depletion processes or runoff processes are dominant. Rainfall-runoff relationships are a good overarching metric to study effects at the catchment scale. Rainfall-runoff relationships often decrease during multi-year droughts. In these cases, the same amount of rainfall will produce lower runoff after a prolonged dry period compared to normal circumstances, as seen in Australia (Saft et al., 2015; Peterson et al., 2021) and Chile (Garreaud et al., 2017). In Algeria, however, rainfall-runoff relationships were found to increase, leading to less infiltration, more surface runoff and higher flood hazard (Sofiane et al., 2019). Although in this case it is not clear what specific process may have caused this decrease in infiltration and increase in runoff. Stronger decreases in rainfall-runoff relationships were found to be related to aridity (Saft et al., 2016; Garreaud et al., 2017), broader and flatter valley catchments (Saft et al., 2016; Yang et al., 2017), deeper soils, and more groundwater variability (Saft et al., 2016). Therefore, this may indicate that in areas with larger subsurface water depletion due to an arid climate, permeable geology, or deeper soils, the effect of runoff processes is less dominant and instead the effect of filling up of depleted storage is more dominant, whereas in wetter, more quickly-responding catchments the balance might tip to runoff increase after drought.

In the global case review, we also find that the type of flood is important in drought-to-flood events. We define the type of flood generating process following the typology proposed by Merz & Blöschl (2003). Short-rain flood was the most frequently reported flood process (120 cases), whereas long-rain flood (34), tropical cyclone (20) and snowmelt flood (3) were reported less often as the dominant process causing flooding. The more frequent occurrence of short-rain floods points to high intensity rainfall events and limited infiltration, which may indicate that, in general, across all climate types, drought-induced changes to the land surface activating quick runoff pathways are a dominant process. In addition, flood events reported as flash flood or pluvial flood (rather than a riverine flood or a combination of flash and/or pluvial with riverine flooding) were mentioned more often in case of a multi-year drought than a within year drought (Figure 1a) and flash floods are reported to occur more during rather than after a drought (Figure 1b). This may be because during a multi-year drought the land surface is affected more severely than during a one-year drought, for example with changes in vegetation or soil properties, causing quick-runoff generation processes. However, it could also be that flash floods and pluvial floods after a drought instead of during a drought are not reported in our case review because the excessive rainfall refills depleted storage and did not cause (severe) impacts. In case of riverine flooding (which was reported much less often), storage depletion processes may be more dominant. This may be especially the case in arid regions, as discussed in the previous paragraph. We find some evidence for this in our case review. With groundwater drought most often reported in semi-arid cases as shown in Figure 2 (there are no reports of groundwater drought in arid cases, but this may be due to the low number of cases with an arid climate in our case review). This may indicate an increase in available storage before a subsequent high rainfall period. However, there are also a several cases with sub-humid and humid climate conditions that are reporting groundwater drought, which indicates there may be other factors influencing the importance of storage depletion process, besides aridity.

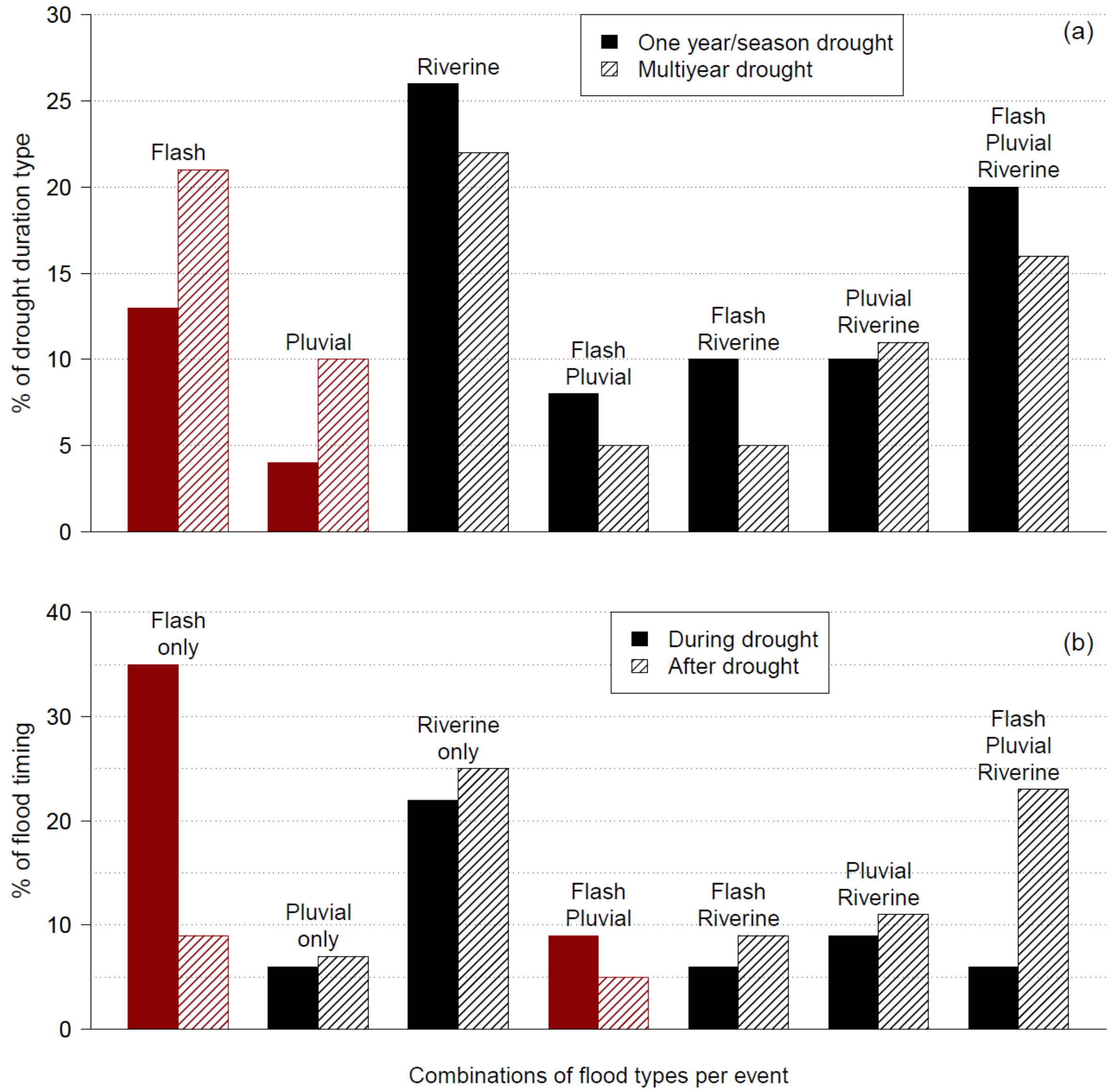


Figure 1. Percentage of cases reporting a certain flood type differentiated by drought duration (a), and percentages of cases reporting a certain flood type differentiated by flood timing during or after the drought (b). Highlighted in red are the event types (flash flood and pluvial flood) that occur more often in relation to a multiyear drought than to a one-year drought (a), and the event types (flash flood and flash and pluvial flood combined) that occur more often during than after a drought (b).

All of these processes and their importance depend on the speed of drought recovery and the time lag between the drought and the heavy rainfall. The rate and duration of drought recovery are strongly dependent on climate and catchment properties, such as elevation, slope, average catchment wetness, and soil conditions (Parry et al., 2016; Yang et al., 2017; Ganguli et al., 2022). Additionally, human activities, including land use change, groundwater abstraction, and reservoir operation, have been found to prolong recovery (Apurv et al., 2017; Margariti et al., 2019) and shift seasonality (Wang et al., 2020). In many locations across the globe, the recovery time (i.e., the time between the drought and the flood event) is decreasing, meaning that there is less time for the system to recover before the next extreme happens (Rashid and Wahl, 2022). In the case review, we find that a flash flood by itself or in combination with pluvial flooding (rather than pluvial or riverine alone or flash flood in combination with riverine) is more often reported during a drought than after a drought (Figure 1b). This may be an indication of runoff processes being dominant showing that heavy rain can lead to floods without terminating the drought. Riverine and compound flooding occurred mostly after the end of a drought (Figure 1b), which may indicate that for riverine floods to develop, depleted storage first needs to be replenished.

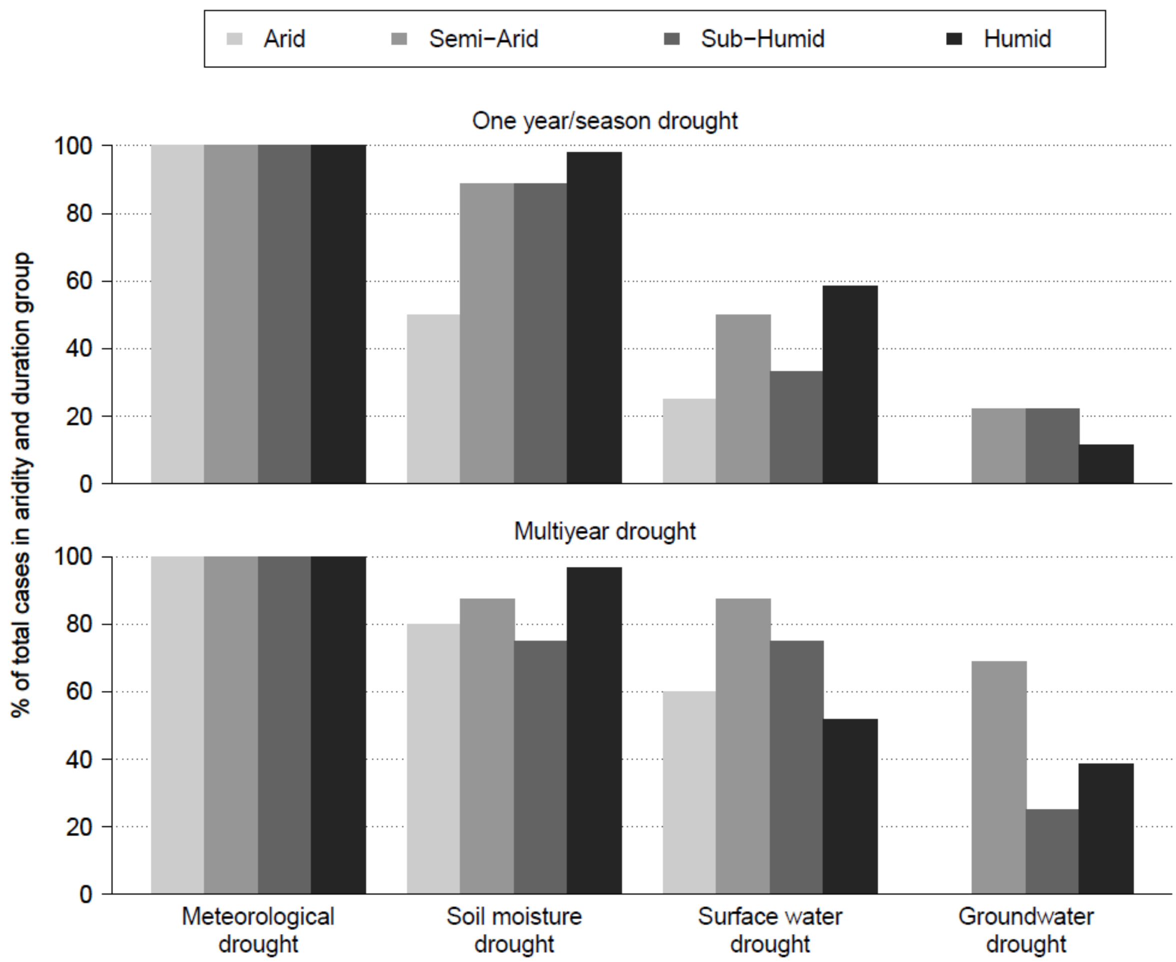


Figure 2. The percentage of cases of a certain drought duration (one year vs. multiple years) reporting a certain drought type, separated by aridity group. Meteorological drought was reported in all cases, whereas soil moisture, surface water and groundwater drought are reported in a decreasing percentage of the cases. There is a clear difference between the propagation for multiyear and one-year events.

Both storage depletion and refilling, and land-surface conditions are influenced by human activities, especially during drought, but there is no empirical research on the effects of human activities on consecutive drought and floods. For example, studies on changes in the rainfall-runoff relationship (Saft et al., 2016; Garreaud et al., 2017; Yang et al., 2017) excluded “impaired” catchments. Recent research has started to quantify the effects of human activities on hydrological drought (Rangecroft et al., 2019), including Van Loon et al. (2022) who show that groundwater abstraction makes a hydrological drought more severe. In addition, human activities can slow drought recovery (Margariti et al., 2019). Flash floods (which, according to the case review, happen more often during a drought) occur more frequently and/or are more severe in human-influenced catchments (Jodar-Abellan et al., 2019; Mohamed and Worku, 2021). Human activities seem to enhance both storage and runoff processes, with increased storage depletion leading to lower floods after droughts, and land-surface changes leading to higher floods after drought in human-dominated catchments. These human activities are discussed in detail in section 4 on adaptation processes.

Sidebar title: Role of wildfires and landslides in drought-to-flood events

Drought increases the frequency and severity of wildfire (Riley et al. 2013), increasing flammability and interacting with other fire spread controls such as the prevalence of fire weather conditions (Littell et al. 2016). Wildfire drives changes in vegetation and soil properties making overland flow the dominant flow path post-wildfire (Rountree et al., 2000) increasing the risk of flooding (McGuire et al. 2021; Moftakhari and AghaKouchak, 2019).

This was illustrated in Australia where the 2019-2020 wildfires were a consequence of a widespread drought and heatwave. While at first, torrential rain assisted in containing the fires, the wildfires had decreased infiltration capacity and flash floods soon followed (Alexandra & Finlayson, 2020). Landslide risk increases up to several years after a wildfire, when a wildfire followed by extreme precipitation causes increased run-off generated debris flows and slope instability (Rengers et al., 2020). In a study of Southern California, Rengers et al. (2020) found that slopes that burned 3 years prior to an extreme rainfall event, had the highest landslide density. Handwerger et al. (2019) report an increased risk in landslides during drought-to-flood events even without wildfires, because a rapid shift from drought to extreme rainfall may trigger the acceleration of landslides.

Our case review indicates that wildfires occur more often when a drought has propagated to a hydrological drought (Figure 3a). In case wildfires are reported during the drought event, landslides are also more often reported after the flood event (Figure 3b).

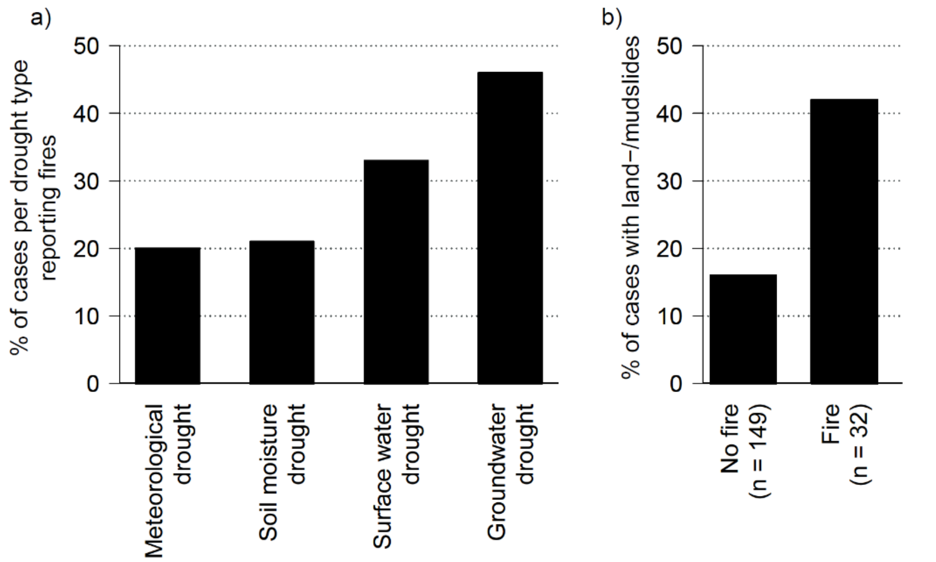


Figure 3. Percentage of cases with a certain drought type also reporting fires (a) and percentage of cases with and without reports of fire reporting land- or mudslides (b). If a case reports a groundwater drought it becomes more likely that there are also reports of fires. In case there are reports of fire, it is more likely that there are also reports of mud- or landslides.

3. IMPACTS OF DROUGHT-TO-FLOOD EVENTS

In this section we explore how drought impacts affect flood impacts. Droughts are generally long-lasting and have a range of cascading impacts on both the physical and societal system (Stahl et al., 2016; Sugg et al., 2020; De Brito, 2021). These impacts can continue into the period after the drought ended. If society is hit by a next event (heavy rainfall resulting in flooding) the impacts of flooding may be increased due to the preceding drought impacts.

3.1 Drought impacts on the physical system

Drought can impact the physical system, thereby making subsequent flood impacts more likely. Drought can cause damage to infrastructure, including infrastructure for flood risk mitigation. For example, during droughts, dikes and levees can suffer from cracking, which can increase the probability of failure (either during the drought itself or during subsequent wet periods). Examples of this are abundant in the literature, especially for the Netherlands (e.g. Van Baars, 2005; Van Baars and Van Kempen, 2009), Australia (e.g. Jaksa et al., 2013; Hubble and De Carli, 2015; IWMI, 2017), and the USA (Vahedifard et al., 2016; Vahedifard et al., 2017). This happens mostly in lowland areas with dikes made of peat and clay or on peat / clay soils that are prone to cracking during drought.

Moreover, drought-to-flood events can increase impacts by degrading water quality and creating favourable conditions for the development of diseases that impact human health. In our case review, we find that impacts on human health were most often reported in low-income countries (Figure 4). We also found examples in the scientific literature. For example, Effler et al. (2001) showed that the E. Coli outbreak in Swaziland and South Africa in 2000 was preceded by intense precipitation following a three-month drought period. It was shown that high concentrations of pathogens occurred during the drought period, because livestock used human water sources, thereby increasing human exposure during consequent heavy rainfall (Levy et al., 2016). Drought-to-flood events can also result in large-scale simultaneous hatching of mosquito eggs, leading to the transmission and outbreaks of, for example, Rift Valley fever virus (Stanke et al., 2013). In addition, these events can alter water quality due to deposition of pollutants within the soil during drought period and their consequent discharge into the river during flood events (Mishra et al., 2021). Moreover, consecutive dry and wet periods result in elevated phosphorus release and consequent water quality degradation (Laudon et al., 2005). Alteration of river nutrients concentration can cause severe fish mortality (Laudon et al., 2005) and eutrophication of surface water bodies (Wurtsbaugh et al., 2019).

3.2 Drought impacts on the socio-economic system

Impacts of drought on the physical system (e.g. water supply infrastructure) can also impact water supply, leading to water insecurity. Drought impacts on agriculture and public drinking water supply were the most common impacts reported in the case review (Figure 4). Drinking water supply is often disrupted during drought, especially if communities or households rely on local sources that are not connected to a network (Mullin et al., 2020). This may not only be due to lower water levels, but also to more sediments in the water intake, more breakage of handpumps, and more damage to pipes because of soil subsidence (Thomas et al., 2020; Wlostowski et al., 2022). Drinking water companies then need to repair pumps and pipes and/or invest in finding other sources of drinking water, thereby depleting financial reserves (Koehler et al., 2018). For example, in the 2011–2017 drought in California (USA), many community water services requested emergency funding from the state to maintain water delivery to low-income populations (Mullin et al., 2020). This left drinking water supply in a vulnerable position in the case of a subsequent flood destroying drinking water infrastructure (Fekete et al., 2019; Njogu, 2021). For women and girls in rural communities in low-income countries walking distance to drinking water sources increases during drought (MacAllister et al., 2020; Arku & Arku, 2010). This creates many cascading impacts, for example increased exposure to sexual harassment, missing school, less time to work on the land to provide food for the family or to work on other sources of income (Tallman et al., 2022), which all potentially increase vulnerability to flooding (and other hazards).

Drought impacts leading to changes in vulnerability, which increase the susceptibility to subsequent flooding, occurs through multiple processes. Multi-year droughts cause long-term impacts such as physical and mental health issues, long-term financial struggles, lack of education, erosion of social coherence, and increase in social conflicts (e.g. Sena et al., 2017; Matanó et al., 2022), especially in low-income countries. Sena et al. (2017), for example, found that in Brazil health and well-being are lower in regions that experience drought more regularly than the rest of the country, implying that drought increases vulnerability. In contrast, repeated extreme flooding has been found to reduce vulnerability in subsequent flood events due to enhanced awareness and adaptation (Kreibich et al., 2017). These studies focus on multiple occurrences of the same hazard, but to understand the social processes behind drought-to-flood events we need to understand cascading impacts and changes in vulnerability between different hazard types (Siegel et al., 2003; De Ruiter and Van Loon, 2022). One study by Rockstrom (2003) mentions how drought-induced unemployment leads to increased financial struggles during flood, but more research is needed on cascading vulnerabilities.

A combination of impacts on agriculture and livestock, from both the drought and the flood event is reported quite often in the case review (although most frequently in low- and lower middle-income countries, see Figure 4). The vulnerability of livestock to flooding may be increased by a preceding drought, as was the case in Queensland in 2019 (Cowan et al., 2022), where cattle was weakened due to a lack of food during a drought which increased their vulnerability during the following flood causing many of them to die from exposure. Vegetation conditions can be an important factor in drought-to-flood events. Agriculture that has suffered during drought can be further impacted by extreme rain events. Cobon et al. (2016) found that, in coffee plantations, alterations of extreme dry and wet periods reduce coffee bean size. Drought-to-flood can have severe effects on crop yield, based on the intensity of the consecutive hydrological extremes, soil conditions, and crop growth stage (Gao et al., 2019; McCarthy et al., 2021). Impacts on agriculture cascade further to health, financial and societal impacts, thereby potentially increasing the vulnerability of the population. If the drought is followed by a flood, food availability could decrease even further and access to water, food and health care could be reduced even more (Matanó et al., 2022).

These effects are not uniform throughout society. Natural hazards do not affect people equally (Neumayer & Plümper, 2007) and differences in societal vulnerabilities can exacerbate the inequality of impacts of consecutive droughts and floods. Low-income groups are more at risk of damages caused by hydrological extremes due to structural inequalities (Andrijevic et al., 2020). Moreover, social groups are impacted differently by hazards because of the different access to resources for preventing, mitigating, or recovering from extreme events (Masozera et al., 2007). As a result, groups that possess resources for adopting individual prevention and mitigation actions against one hazard type can become less vulnerable to another consequent hazard compared with groups that do not have such means. In addition, the recovery of people and economies after a drought ends is important. Societies that quickly bounce back or even forward will be less vulnerable to a next event than societies that recover slowly (Di Baldassarre et al., 2018). The latter are more prone to collapse when faced with subsequent extreme events (Weiss and Bradley, 2001; Kuil et al., 2016).

The differences between groups (or countries) with different amounts of resources is also reflected in our case review. While we do not find evidence of specific drought impacts causing an increase in a specific flood impact, we do find evidence of income levels as a common driver to the type of impacts that are reported most in a country. Figure 4 shows that drought impacts on public water supply, energy/industry and ecosystems are more often reported in higher-income countries (the darker coloured upper right and lower right quadrants) than in lower-income countries (the lighter coloured lower left and upper left quadrants) and this coincides with a higher reporting of the flood impacts of damage to properties and road infrastructure and more reported evacuations. In contrast, damage to agriculture as a flood impact is more often reported in lower-income countries and often coincides with reported agricultural impacts from drought (which is generally high across all income groups). In addition, drought impacts on human health and public safety are mostly reported in low-income countries and they often coincide with a high frequency of reported loss of life due to flooding as well as with damage to agriculture and/or livestock due to flooding.

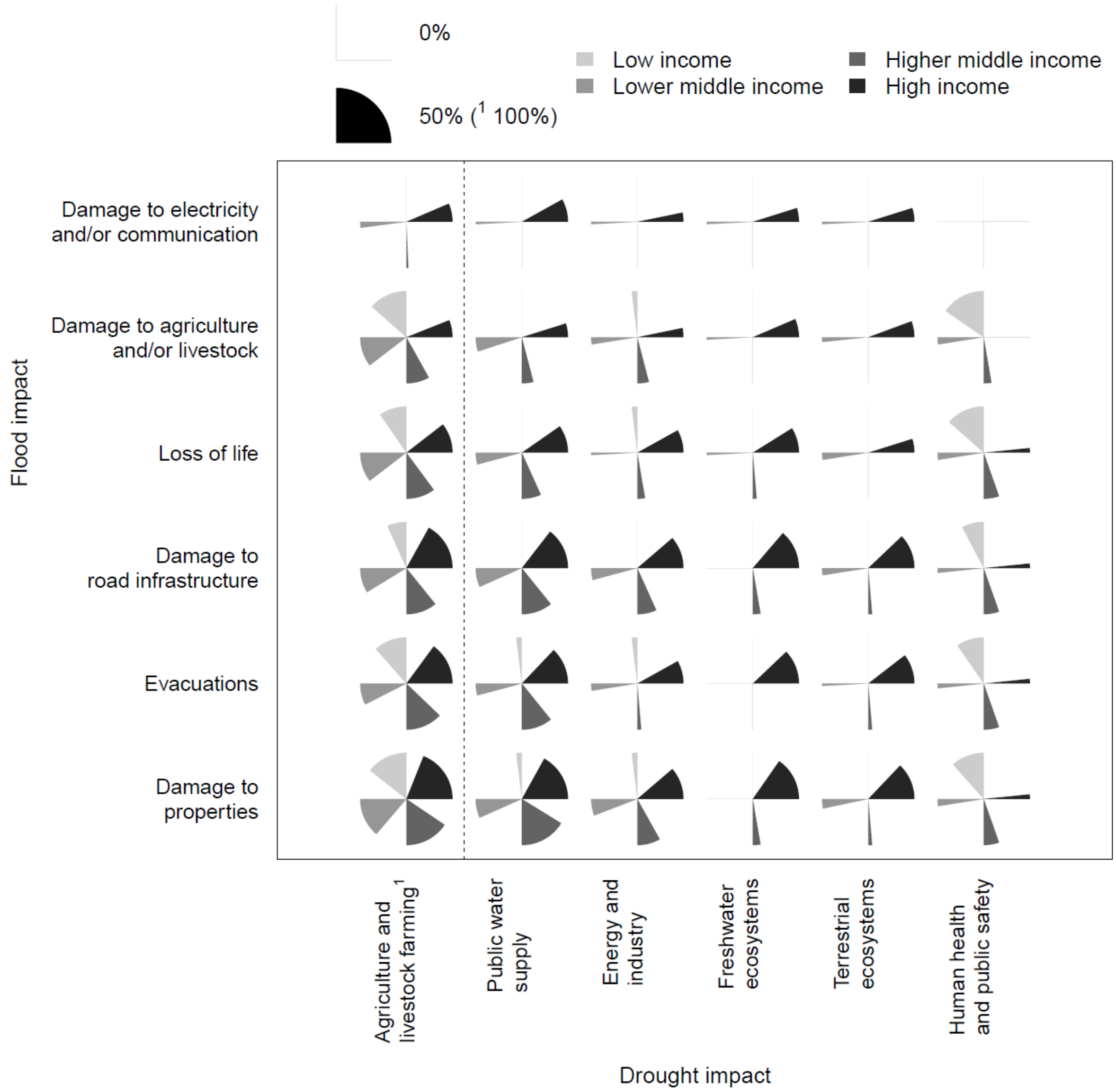


Figure 4. Percentage of cases per income group reporting both a certain drought impact (x-axis) and flood impact (y-axis). The four quadrants represent the four income groups. An empty quadrant means zero % of the cases in the corresponding income group report this combination of impacts and a full quadrant means 50 % of the cases report this combination of impacts. Note that for the first column of drought impacts "Agriculture and livestock farming" a full quadrant means 100 % of the cases report this impact combination. This was done for visualisation purposes.

4. ADAPTATION PROCESSES AFFECTING DROUGHT-TO-FLOOD EVENTS

In this section, we discuss how human adaptation to drought can affect flood risk. Besides leading to more impacts and increased vulnerability (Section 3), long, multi-year droughts allow ample time for drought responses, management and adaptation (Watts et al., 2012). Human adaptation processes can affect the catchment processes and impacts discussed in the previous sections, both positively and negatively. Responses to drought that increase flood risk are sometimes called maladaptation (Adger et al., 2005; Ward et al., 2020). Ward et al. (2020) provide an extensive review of how drought adaptation measures can influence flood risk (and how flood adaptation measures can influence drought risk). Here, we provide a summary of their findings and compare them with the evidence from the case review.

4.1 Adaptation processes affecting hydrological processes

As mentioned in Section 2, increased groundwater abstraction in response to a drought can potentially reduce flooding. Groundwater abstraction is often increased during drought, which depletes storage and potentially slows drought recovery (Wendt et al., 2021; Apurv et al., 2017), making drought-to-flood events less likely, depending on the local geology and the type of flood event that follows the drought. Groundwater abstraction is one of the drought adaptation measures that was reported most often in the case review (Figure 5). This measure is mostly reported in higher-income (i.e. both high- and higher middle-income) countries (Figure 6). Ward et al. (2020), discuss how increased groundwater abstraction can also increase the risk of flooding, because it can lead to subsidence. Stopping abstraction can also lead to flooding, for example, in the case of the foggaras (a traditional irrigation system) of Bouda in Algeria. An initial increase of groundwater extraction through boreholes caused the foggaras to run dry and their long disuse caused a state of disrepair. When the groundwater pumping through boreholes was reduced, the foggaras started flowing again, but could not handle the amount of water due to their state of disrepair, causing flooding of sebkhas and palm groves (Boutadara et al., 2018). The opposite of groundwater abstraction, managed aquifer recharge, or the construction of other water storage infrastructure, such as sand dams, can be beneficial for both drought and flooding (Ward et al. 2020). The construction of new water infrastructure in response to a drought was found in several cases in the case review (Figure 5). In addition, there are several examples of drought adaptation measures that can have a negative effect on subsequent flooding by influencing catchment processes, such as reservoir operation strategies and agricultural practices and land use change (Ward et al., 2020).

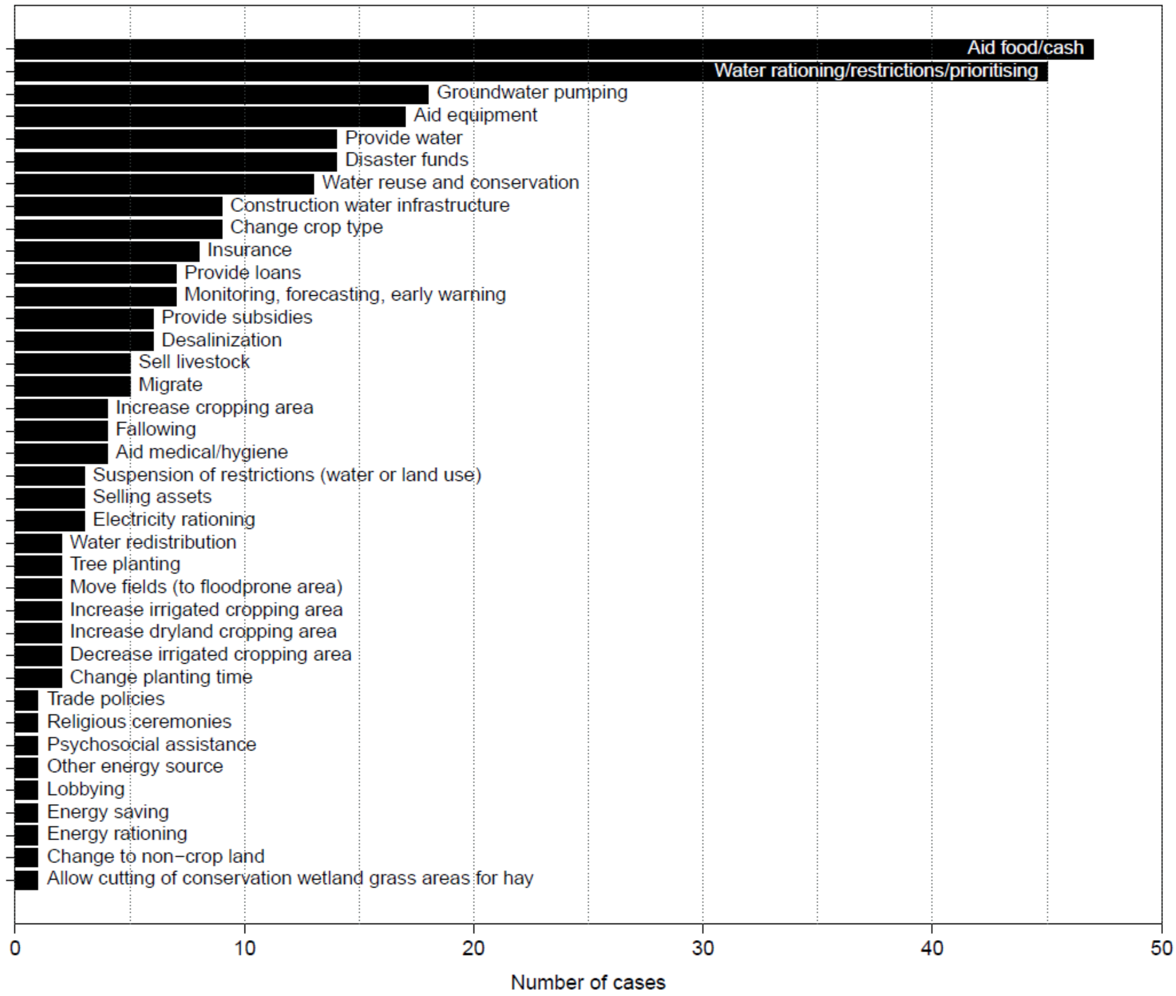


Figure 5. Number of cases reporting a drought adaptation measure.

4.2 Adaptation measures affecting impacts

Ward et al. (2020) also discuss how awareness and risk perception of flooding can be influenced by drought experience and how a focus on drought preparedness can decrease the preparedness for flooding. These processes can increase the vulnerability to flooding. There are also several drought adaptation measures or coping strategies that increase exposure to flooding, such as migration (Ward et al. 2020). Flood exposure could be increased by drought-induced migration resulting in people living in floodplains (FGS, 2018), but migration is complex and not always directly attributable to drought (Black et al., 2013). However, it was reported as a drought response in some instances in the case review (Figure 5). Another example of a drought coping mechanism that results in a higher exposure to flooding is when farmers decide to delay planting until the rains start. When the rains do start, but are extreme, they may wash away seeds or make sowing impossible, as happened, for example, in Bundhelkhand, India (Pateriya, 2016). In addition, the uptake of drought resistant crops which may be vulnerable to heavy rain (Tirado & Cotter, 2010) and food aid reducing outmigration in drought-struck and flood-prone areas (Salite & Poskitt, 2019) are other drought measures that increase exposure to flooding.

In the case review we found that in low-income countries food aid or cash aid is the most reported adaptation measure (Figure 6). Government and NGO support could be exhausted during the drought, meaning that limited aid would be available during a subsequent flood (Matanó et al., 2022). On the other hand, responses that aim to reduce vulnerability to drought can also be beneficial during floods. Mavhura (2019) found, for a case in Northern Zimbabwe, that vulnerability to flood and drought was influenced by the same drivers, such as low incomes or few savings. Measures and policies that address these drivers, would be beneficial for reducing both flood and drought vulnerability.

Another adaptation measure reported frequently in the case review is water rationing or the prioritising of certain users (Figure 6). This measure is more often reported in high-income countries and semi-arid countries. The latter could be because these places may be more experienced with dry conditions and have regulations in place for the rationing and prioritising of water use in case of a drought. However, there is also a high percentage of cases with a humid climate reporting this measure, which may indicate that high-income is a more important factor, possibly because high-income countries more often have a regulated public water supply system in place. These regulations may lead to unequal impacts because water users may face different levels of reduction in water supply, depending on the legislation, prevailing water rights and social inequalities (Lund et al., 2018; Savelli et al., 2021). Therefore, different water users may experience different levels of increases in vulnerability, which may influence their ability to cope with a subsequent flood. These unequal effects hold for adaptation measures in general, just like for impacts. Adaptation measures benefit some groups more than others and responses that are beneficial for one group may not be for another group (Masozera et al., 2007; Savelli et al., 2021). In California, for example, cuts in water supply did not severely affect the agricultural sector, who used groundwater as an alternative, but the combination of cuts in water supply and the effects of adaptation measures taken by the agricultural sector (such as groundwater extraction) led to increased vulnerability of ecosystems and the people that rely on them (Christian-Smith et al., 2015). Another example of increased vulnerability of ecosystems because of human adaptation is the case of Guadiana wetlands in Spain, where groundwater abstraction was found to have four times higher impact on the ecosystem than drought (Van Loon and Van Lanen, 2013).

In general, risks are experienced differently and lead to varying adaptation strategies, depending on the management structure (e.g. public, private or community responses) and the type of hazard (e.g. drought or flood). In a review on pre-disaster planning and preparedness for droughts and floods, Raikes et al. (2019) found that drought management tends to be responsive, while flood management is more risk-based, including prevention and preparation. In addition, some countries may have a more centralised approach to flood and drought risk management, such as the Netherlands and Poland, while in other countries, such as the United States, risk management is increasingly privatised (Raikes et al., 2019). This affects the type of adaptation measures that may be adopted.

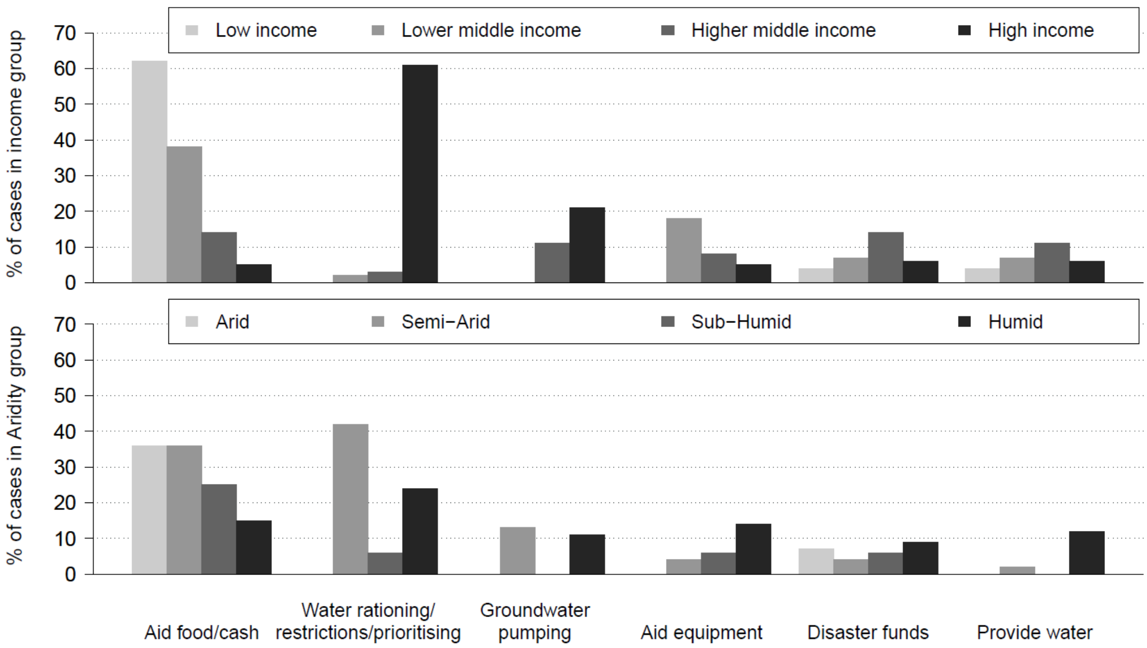


Figure 6. Percentage of cases per income group (top) and aridity group (bottom) reporting a certain drought adaptation measure. Food and cash aid are reported more often in lower income countries

while water rationing and groundwater pumping are reported more often in higher income countries. Water rationing is reported slightly more often in semi-arid countries.

5. CONCLUDING REMARKS

5.1 Main findings

This review has provided an overview of the processes and feedbacks that are important in drought-to-flood events. We find that drought can increase subsequent flood occurrence and severity due to increased surface runoff, but it can also decrease subsequent flooding due to storage depletion. There is little evidence as to which process may generally be dominant. Storage depletion processes seem to be more prevalent in arid places, as well as in broader and flatter valley catchments and places with deeper soils or more groundwater variability. This also depends on the type of flood that occurs during or after the drought event. For high-intensity rain events and flash floods, storage depletion process are less important. Both increased runoff and storage depletion processes seem to mostly play a role when the drought is a multi-year drought and when the flood occurs during the drought (e.g. the drought is not ended by the flooding). Human activities seem to enhance both processes, with increased storage depletion leading to lower floods after droughts and land-surface changes leading to higher floods after drought in human-dominated catchments.

In terms of impacts, there is clear evidence that drought-to-flood events cause more impacts than if the hazards would occur on their own; clear examples are breaking levee systems and causing water quality problems. In general, the socio-economic processes that underlie drought-to-flood events seem to be mostly related to changes in vulnerability. The drought may cause increases in the vulnerability of people, crops or livestock, which causes impacts of a subsequent or co-occurring flood to be worse than from two separate events alone. This depends on the initial vulnerability and how quickly communities are able to recover. Impacts and changing vulnerability are not the same for everyone. Which process is dominant where, when, and for whom, is strongly dependent on the context of the drought-to-flood event. Characteristics like climate, geology, land use, and socio-economic, cultural, and political context determine the impacts and responses and therefore the interactions between drought and flood impacts.

The case review has shown that there is a huge diversity in adaptation measures implemented. Several adaptation measures are focused on reducing the overall vulnerability of the population, which makes them beneficial for both flood and drought risk management. In addition, there are several measures that focus on storing excess water, which can reduce both drought and flood risk (e.g. managed aquifer recharge, sand and earth dams). Groundwater abstraction (reported most often in higher income and arid places) can have a positive effect on flood risk, by increasing storage space, but can also increase subsidence. Finally, the awareness or memory of flood risk may decline due to a drought, which can negatively affect flood risk. Adaptation processes in response to a drought can affect socio-economic processes in several ways, changing the risk perception, exposure and vulnerability to flooding.

5.2 Outlook

We argue that more research is needed on drought-to-flood events. In particular, further investigation would be useful regarding which characteristics, such as climate, geology, land use, and socio-economic, cultural, and political context, determine which drought-to-flood processes and feedbacks are important. In terms of hydrological processes, it would be interesting to further investigate when and where storage depletion and runoff processes are dominant and how human interventions affect this. There is still a lot unknown about processes related to impacts and further research into whether certain drought impacts make certain flood impacts more likely, or into whether there are common drivers of these impacts and when and where these occur. In addition, changes in vulnerability require further investigation in drought-to-flood events (De Ruiter & Van Loon, 2022). This review does not provide much evidence of which adaptation measures are taken when and where and how this affects flood risk. Characteristics of the social and hydrological system that influence the feasibility and effectiveness of adaptation measures, as well as their influence on flood risk could be further investigated. In addition, adaptation measures may be beneficial for some while they are harmful to others. When and where this is the case is something that could be addressed in future research.

Methods that can increase our understanding of the specific hydrological and social processes happening during drought-to-flood events include detailed case study analyses, as suggested by

Mostert (2018). Qualitative case studies can also be compared to find generalizable results, especially if and when a larger body of case study analyses becomes available, for example using qualitative comparison analysis (Srinivasan, 2012). System characteristics (both social and hydrological) that lead to certain processes being dominant, or certain adaptation measures being feasible or not, can be investigated using large-scale comparative studies. This approach has already been applied in hydrological studies to, for example, investigate which characteristics influence the seasonality and magnitude of maximum annual flows (Berghuijs, 2016). These qualitative and quantitative case studies can be combined to both create new insights and report the findings to different audiences (e.g. Grainger et al. 2016). Finally, management alternatives can be explored using models that incorporate both the hydrological and social processes (e.g. Mazzoleni et al. 2021). Using these models, scenarios can be developed and explored using for example adaptation pathways (Werners et al., 2021), where not only the effects of management and adaptation choices on drought risk are taken into account, but also the effects on flood risk.

Improving our knowledge on drought-to-flood events and their interactions will help in designing more robust measures that do not have adverse effects on the opposite risk, now or in the future. The necessity for the analysis of system-wide, short-term and long-term implications is already recognised for both drought and flood risk management separately. Here we argue that this should also be expanded to the study and management of drought and flood risk together. Identifying drought-to-flood processes and their characteristics would not only help in the design of robust measures that hold under future risk scenarios but would also help identify opportunities for reducing both drought and flood risk at the same time, by implementing measures that are beneficial for both, such as the reduction of overall vulnerability or measures such as managed aquifer recharge.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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