

Caught between extremes: Understanding human-water interactions during drought-to-flood events in the Horn of Africa

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Abstract

Disaster risks are the results of complex spatiotemporal interactions between risk components, impacts and societal response. The complexities of these interactions increase when multi-risk events occur in fragile contexts characterized by ethnic conflicts, unstable governments, and high levels of poverty, resulting in impacts that are larger than anticipated. Yet, only few multi-risk studies explore human-environment interactions, as most studies are hazard-focused, consider only a single type of multi-risk interaction, and rarely account for spatiotemporal variations of risk components. Here, we developed a step-wise, bottom-up approach, in which a range of qualitative and semi-quantitative methods was used iteratively to reconstruct interactions and feedback loops between risk components and impacts of consecutive drought-to-flood events, and explore their spatiotemporal variations. Within this approach, we conceptualize disaster risk as a set of multiple (societal and physical) events interacting and evolving across space and time. The approach was applied to the 2017-2018 humanitarian crises in Kenya and Ethiopia, where extensive flooding followed a severe drought lasting 18-24 months. The events were also accompanied by government elections, crop pest outbreaks and ethnic conflicts. Results show that (1) the fragile Kenyan and Ethiopian contexts further aggravated drought and flood impacts; (2) heavy rainfall after drought led to both an increase and decrease of the drought impacts dependent on topographic and socio-economic conditions; (3) societal response to one hazard may influence risk components of opposite hazards. A better understanding of the human-water interactions that characterize multi-risk events can support the development of effective monitoring systems and response strategies.

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Caught between extremes:

Understanding human-water interactions during drought-to-flood events in the Horn of Africa

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Key Points:

- Integration of semi-quantitative and qualitative methods in a bottom-up approach enhance understanding of dynamic event interactions;
- Flood and drought events do not act in isolation and fragile contextual conditions further aggravate their impacts;
- The close succession of drought and heavy rainfall triggers mechanisms that can increase or decrease disaster risk, both in time and space.

Abstract

Disaster risks are the results of complex spatiotemporal interactions between risk components, impacts and societal response. The complexities of these interactions increase when multi-risk events occur in fragile contexts characterized by ethnic conflicts, unstable governments, and high levels of poverty, resulting in impacts that are larger than anticipated. Yet, only few multi-risk studies explore human-environment interactions, as most studies are hazard-focused, consider only a single type of multi-risk interaction, and rarely account for spatiotemporal variations of risk components. Here, we developed a step-wise, bottom-up approach, in which a range of qualitative and semi-quantitative methods was used iteratively to reconstruct interactions and feedback loops between risk components and impacts of consecutive drought and flood events, and explore their spatiotemporal variations. Within this approach, we conceptualize disaster risk as a set of multiple (societal and physical) events interacting and evolving across space and time. The approach was applied to the 2017-2018 humanitarian crises in Kenya and Ethiopia, where extensive flooding followed a severe drought lasting 18-24 months. The events were also accompanied by government elections, crop pest outbreaks and ethnic conflicts. Results show that (1) the fragile Kenyan and Ethiopian contexts further aggravated drought and flood impacts; (2) heavy rainfall after drought led to both an increase and decrease of the drought impacts dependent on topographic and socio-economic conditions; (3) societal response to one hazard may influence risk components of opposite hazards. A better understanding of the human-water interactions that

characterize multi-risk events can support the development of effective monitoring systems and response strategies.

Plain Language Summary

Drought ending in severe floods has often led to greater than expected impacts in the past, especially when it occurred in fragile socio-economic contexts. Underestimation of these impacts is mainly due to a lack of understanding of how societal and physical systems interact during consecutive risks. In this study, we developed a bottom-up approach, in which we first identified the impacts and then we identified potential societal / physical drivers by reconstructing possible interaction paths between impacts, physical and social factors, risk components and response measures. We combined different evidence types extracted from qualitative and semi-quantitative methods to provide a comprehensive narrative of the interactions between physical and societal systems. The approach was tested for the 2017-2018 humanitarian crises in Kenya and Ethiopia, where a rapid drought-flood transition was accompanied by government elections, crop pest outbreaks and ethnic conflicts. Results show a tight interaction between drought and flood risk components (i.e., hazard, exposure, vulnerability), and between them and the respective societal response. This study reveals the complexity of real-world disaster risks and highlights the need to account for spatiotemporal interactions between societal (e.g., conflict) and physical (e.g., drought) events when forecasting impacts and designing effective response strategies to multiple disasters.

1 Introduction

Socio-economic and ecological impacts from natural hazards have been increasing in recent decades (IFRC, 2020; IPCC, 2021), resulting in numerous humanitarian crises. These impacts have often been attributed to a single hazard event (e.g. drought, flood, cyclone) combined with static exposure and vulnerability conditions (Ciurean, R. et al., 2018). In reality, these impacts are often the result of complex dynamic interactions between societal and physical drivers tightly interlinked with the socio-economic and environmental context in which they occur (Ciurean, R. et al., 2018; Gill & Malamud, 2017). Key examples are drought and flood events, which are strongly connected to physical and societal processes that happen across space and time. Interactions between drought and flood hazards (Brunner & Gilleland, 2021), their impacts (Kreibich et al., 2019) and societal responses (Ward et al., 2020) can lead to severe societal, ecologic and economic damage, particularly if such hydrological extreme events occur in close succession. Drought-to-flood events (i.e., drought ending with flood) not only result in severe impacts (Henn, Musselman, Lestak, Ralph, & Molotch, 2020), but may often require larger risk reduction efforts compared to independent drought or flood events (Brunner et al., 2021; Di Baldassarre et al., 2017; Mazzoleni et al., 2021). A recent example of the strong interconnectedness between drought and flood events can be found in California. A prolonged drought between 2012-2016 ended with widespread floods during the winter of 2017 (Henn et al., 2020; Ullrich et al., 2018). The abrupt drought-flood transi-

tion challenged reservoir operators due to the trade-offs between capturing early season streamflow and maintaining empty space for flood management purposes (Vano et al., 2019).

The interplay of consecutive hydrological extremes and the societal system increases in complexity in fragile contexts, where internal ethnic conflicts, unstable governments, and high levels of poverty can affect human-water interactions (Katuva, Hope, Foster, Koehler, & Thomson, 2020; Peters, Holloway, & Peters, 2019; UNDRR, 2019). In Colombia, for instance, the drought-to-flood event between 2016 and 2018 was accompanied by continuous violence perpetrated by guerrillas and resulted in the displacement of thousands of families (European Commission, 2020). Over the same period, and again in 2019, drought-to-flood events compounded with extreme poverty in the Indian states of Kerala, Karnataka, Maharashtra and Gujarat, resulting in livelihood losses, population displacement, and an increase in food insecurity (Das, 2019). In the Horn of Africa, between 2016 and 2021, abrupt shifts from drought to flood events coincided with the upsurge of crop pest outbreaks and more recently the COVID-19 pandemic and ethnic conflicts, destabilizing the economy (Kassegn & Endris, 2021; Pott, 2020). Despite the potential importance of societal and hydrological interactions between drought and floods with respect to their impacts, we often overlook these relationships (Mazzoleni et al., 2021) and tend to study hydrological extremes in isolation (Brunner & Gilleland, 2021). This can lead to underestimation of hazards, vulnerabilities, exposure, and impacts.

Over the past two decades, a growing number of studies from the socio-hydrology community have explored interactions and associated feedback mechanisms between hydrological and societal processes (Blair & Buytaert, 2016; Konar, et al., 2019; Pande & Sivapalan, 2017). Yet, these studies focus only on a single hydrological extreme (e.g., drought or flood). For drought, a range of studies have investigated how human interventions (from water management strategies to local adaptation measures) influence drought risk through changes in hazard, exposure or vulnerability (Van Loon et al., 2016; Wens et al., 2019). For floods, many more studies are available, with a predominant focus on the dynamics of the human-water system (Barendrecht et al., 2017; Di Baldassarre et al., 2013; Garcia et al., 2020). Only a few recent studies have started to analyse socio-hydrological dynamics between drought and flood events (Di Baldassarre et al., 2017; Mazzoleni et al., 2021; Ward et al., 2020). These studies primarily focus on the coevolution of societal responses and hydrological extremes, carrying out extensive literature reviews of past events (Ward et al., 2020) or simulating identified interactions through system-dynamics models (Mazzoleni et al., 2021). Yet, these studies mainly focus on water management / disaster risk reduction measures, lacking a broader view of the interactions between social and physical factors. Their work calls for an improved understanding of dynamic interactions between hydrological extremes and societal response through empirical research and instrumental case studies.

In this paper, we carry out a retrospective analysis of humanitarian crises re-

lated to drought-to-flood events in fragile socio-economic contexts. Specifically, we ask: (1) What are the physical and social factors that characterized the humanitarian crises under analysis?; (2) How did these factors interact with each other? and (3) How did interactions and feedback mechanisms vary over time and space during these drought-to-flood events? To address these questions in a real-world context, we first proposed a new conceptualization of multi-hazard situations accounting for multiple natural hazard types, societal processes, and a range of interaction types. We then used a bottom-up approach in which impacts were identified first and then underlying variables, processes or phenomena were identified from the impact analysis (Zscheischler et al., 2020). Since impacts are ultimately felt by stakeholders, their perspectives can help to determine the nature of the hazards and their associated spatial and temporal scales (Leonard et al., 2014). Stakeholders can also trace the connections between societal and physical events down to impacts, while also providing information on the types of feedback (Raymond et al., 2020). Accordingly, we used qualitative and semi-quantitative methods in an iterative way. Specifically, we conducted a time series analysis on various hydrological and socio-economic data, performed a semi-quantitative review of peer-reviewed and grey literature, and carried out online surveys and semi-structured interviews.

We tested this bottom-up approach for two case studies in the Horn of Africa in which a humanitarian crisis occurred in 2017-2018. During that time, the rapid transition from the 2016-2017 drought to the 2018 March-May floods was accompanied by conflict and political instability in both Kenya and Ethiopia. An improved understanding of the drivers and socio-hydrological processes that characterized past drought-to-flood events can help us to better understand related future risks of consecutive hydrological extremes and their interactions with the societal system. Before presenting the Methodology (Section 4), Results (Section 5), and Discussion (Section 6) of our study, we discuss the research gaps and present a new conceptualization of interactions during multi-risk events (Section 2), followed by a description of the case studies (Section 3). The definitions of all terminology used in this study are summarized in Table S1 in Supporting Information S1.

2 Rethinking disaster risk domains and dynamic interactions

Humanitarian crises related to drought and floods can be the result of complex feedbacks, with interactions shaped by both physical and social factors. While notable progress has been made in compounding, cascading and multi-hazards research (de Ruiter et al., 2020; Gill & Malamud, 2017; Zscheischler et al., 2020), recent methods and frameworks for disaster risk assessment do not often account for human-water interactions and their spatiotemporal variations (with Mazzoleni et al., 2021 as notable exception). To overcome this knowledge gap, a series of challenges need to be addressed.

The first challenge is linked to the **limited understanding of dynamic changes / feedbacks within and between risk components**. Current risk models account for temporal changes in hazards (Alfieri et al., 2017; Hirabayashi

et al., 2013) but this is rarely the case for exposure and vulnerability (Tabari et al., 2021; Ward et al., 2020). Most studies on multi-risks consider vulnerability and exposure as static (Ciurean et al., 2018; Gallina et al., 2016; Tilloy et al., 2019). However, during long drought events, exposure might change (e.g., as a result of migration (Ward et al., 2020)), as well as vulnerability (e.g., as a result of societal dynamics and cascading impacts; (Gill & Malamud, 2014)). During drought-to-flood events, these spatiotemporal variations become more complex as we need to understand the dynamics of vulnerability and exposure between different types of hazards (de Ruiter et al., 2020).

Second, **societal mechanisms are poorly represented in disaster risk analysis and the same holds for their interactions with physical factors.** Research on multi-hazard events, cascading, compound and connected events has made substantial efforts towards an increased understanding of risks derived by the interactions of multiple factors (de Ruiter et al., 2020; Gill, Malamud, Barillas, & Noriega, 2020; Raymond et al., 2020; Zscheischler et al., 2018). However, these studies tend to ignore societal aspects as they almost exclusively have a natural hazard perspective (Ridder et al., 2020; Zscheischler et al., 2018), or they account only partially for interactions and feedback loops with the societal system (Gill & Malamud, 2017; Raymond et al., 2020).

Third, there is a **lack of in-depth case studies in real-world contexts.** Current multi-risk methods are mainly used for the analysis of one or two natural hazards, focusing on one specific type of process / interaction (e.g., cascading, concurrent or compounding) and are often simulations of synthetic cases (Ciurean et al., 2018). Hence, these methods are not able to provide accurate multi-risk estimates in real-world contexts. The same holds for the analysis of drought-to-flood events in fragile contexts, where events develop through the complex interactions of multiple hazards and societal processes, which are currently not included in most simulation models (Brunner et al., 2021; Prudhomme et al., 2011).

Finally, **droughts and floods are studied separately in past and current frameworks for risk analysis.** One of the reasons for their separate analysis is that these two hydrological extremes evolve from different processes, have different spatial and temporal scales, and result in different cascading impacts (Brunner et al., 2021; Kreibich et al., 2019; Ward et al., 2020). Floods are often fast phenomena occurring in relation to excess rainfall, snowmelt, high soil moisture content and / or high groundwater levels. The effects of these events are commonly limited to one or two catchments. Droughts are slow-onset processes, often occurring in relation to precipitation deficit, high evapotranspiration, and / or over-abstraction. These events might cover larger areas than floods without being limited by the hydrological characteristics of the watershed (Kreibich et al., 2019). Finally, the impacts of droughts evolve over longer time scales than impacts from floods and different societal sectors are impacted by different drought types. Despite those differences, drought and floods are two extremes of the same hydrological cycle and hence it is important to study them in a joint

framework (Brunner et al., 2021).

To address these four challenges, we propose a new conceptualization of the interactions between societal and physical systems in disaster risk analysis (Figure 1). In this conceptualization, societal and physical factors can influence all risk components, and it includes feedback loops between risk components, impacts and responses. In addition, dynamic changes in hazards, exposure, vulnerability and impacts over time and space are considered. Through this increased degree of freedom, we can represent different multi-risk interactions (e.g., cascading, compounding).

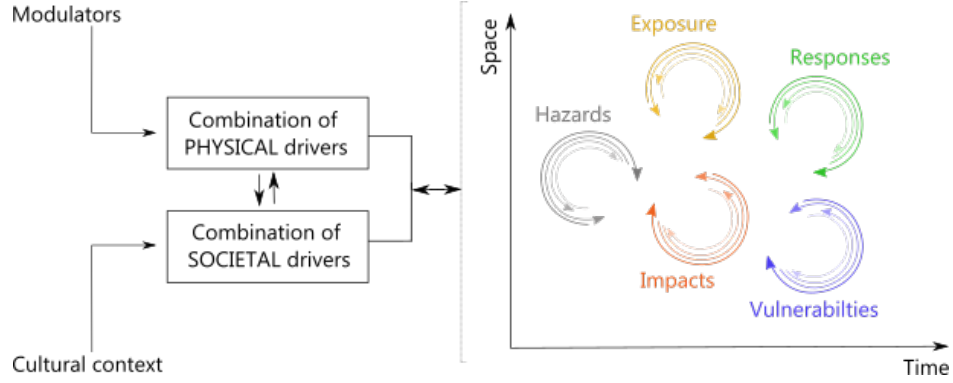


Figure 1. Schematic representation of the interactions between physical and social drivers, risk components (i.e. hazard, exposure, and vulnerability), impacts and societal response over time and space. The risk components can vary over time and space based on the dynamic interactions between physical and societal factors, but also due to the interactions between the risk components themselves and between the risk components, impacts and responses. This dynamic is represented by the circular arrow symbol, while multiple internal arrows represent different hazards, exposure, vulnerability, response and impact types, highlighting their internal interactions. In the diagram, the ‘response’ element refers to both adaptation measures and disaster risk reduction measures. Modulators represent weather patterns that influence or lead to certain physical drivers. The diagram is built upon recent concepts and frameworks of compound (Zscheischler et al., 2020) and connected (Raymond et al., 2020) weather and climate events, and multi-hazard analysis (Gill & Malamud, 2017).

3 Case studies

The proposed conceptualisation was used to analyse the 2017-2018 drought-to-flood related humanitarian crises in Kenya and Ethiopia. Droughts and floods are not new phenomena in these two countries (Ayugi et al., 2020), but in recent years a rapid transition between these two extremes and their increased frequency and magnitude have been experienced (Huho and Kosonei, 2014; Figure 2a and 2b). Although flood events in the last 3-5 years have been substantial in terms of their impacts on both countries, the number of people affected by

droughts is higher: about ten times higher than the number of people affected by floods (Figure 2a and 2b). Analysing these hazards separately, drought remains the most prevalent hazard in terms of socio-economic impacts.

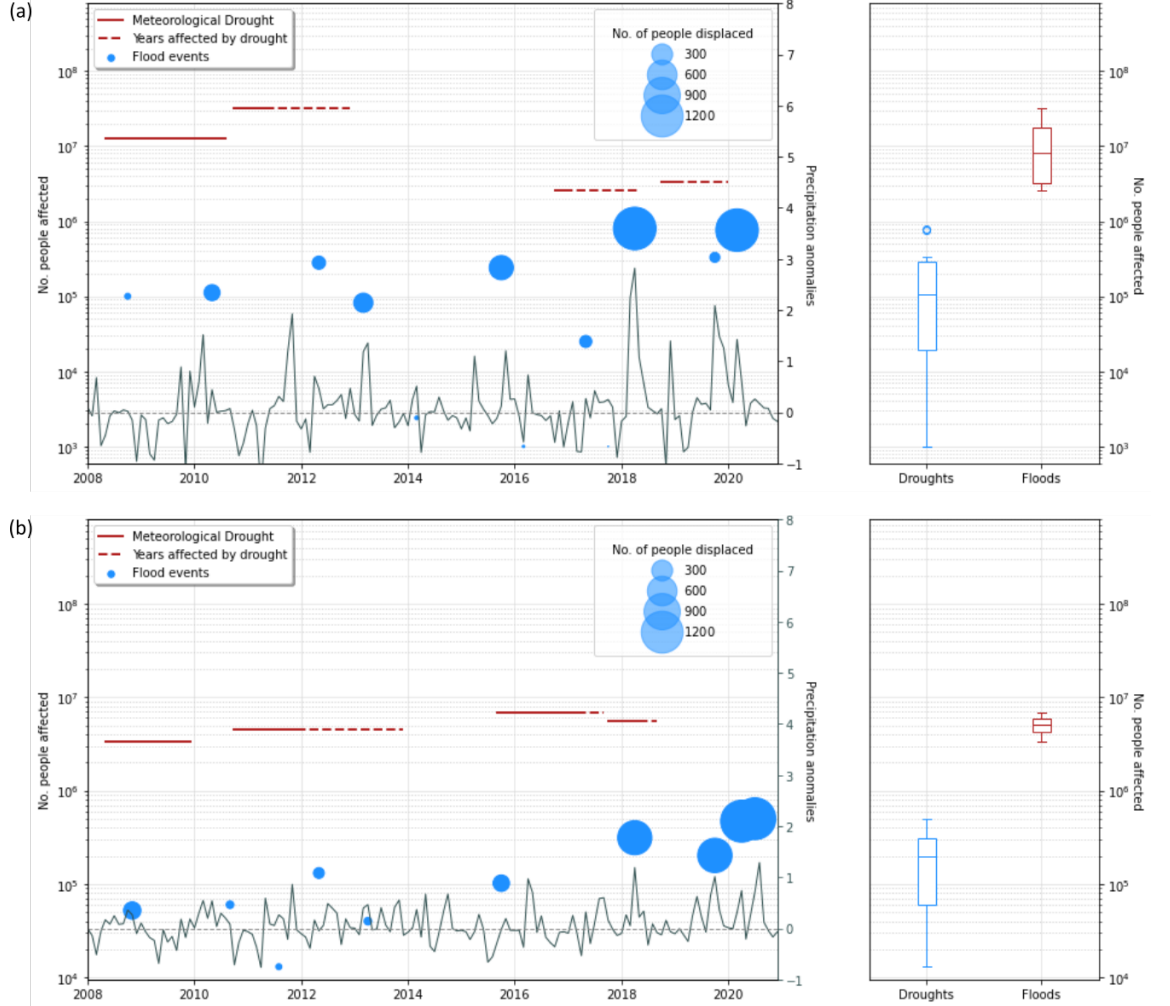


Figure 2. Drought and flood events and impact timeline for Kenya (a) and Ethiopia (b). The dotted line ("Years affected by drought") refers to the years in which the drought impacts are felt. The timeline of drought and flood events as well as the number of affected and displaced people were extracted from the EM-DAT and DesInventar datasets. The time series of the monthly standardized precipitation anomalies (dark green lines at the bottom of the graphs) were computed from CHIRPS data; its values are shown on the right y-axis.

The abrupt transitions from drought to flood experienced in Ethiopia and Kenya in the last five years underscore the need to understand societal and physical

processes characterizing these drought-to-flood events. Accordingly, we analysed the years 2017-2018, in which a severe drought (Funk et al., 2019; Philip et al., 2018; Uhe et al., 2018) ended with widespread floods (Kilavi et al., 2018; Njogu, 2021). Simultaneously, both countries faced crop pest infestations (De Groote et al., 2020; Kumela et al., 2019) and socio-political unrest (Awobamise, Jarrar, & Owade, 2020; D’Arcy & Nistotskaya, 2019; Lavers, 2018). The burden imposed by the two hydroclimatic extremes combined with the fall armyworm infestation, government elections and ethnic conflicts led to 4 million people under food insecurity in Kenya (FEWS NET, 2018) and 8 million in Ethiopia (FEWS NET, 2019). Yet, there is a poor understanding of the main physical and societal drivers of the crisis, the interaction of these multiple events and the resulting cascading impacts.

4 Data and Methods

In this study, a range of qualitative and semi-quantitative methods was used, within a stepwise, bottom-up approach. This approach begins with identifying the impacts, then the factors that could have led to those impacts, and finally we reconstructed the pathways linking the impacts to the drivers. Further, the approach allowed us to investigate interactions and feedback loops between societal and physical factors, risk components, impacts and responses, over time and space, as illustrated in the conceptual diagram presented in Figure 1.

As shown in Figure 3, our approach consists of four main steps: (1) develop the event timeline; (2) develop the impact timeline; (3) identify societal and physical variables; (4) map driver-impact interactions. These methods were used iteratively, which allowed us to refine the methods according to the progressive acquisition of knowledge and data. We brought together the diverse strands of evidence and graphically summarised them in the form of heatmaps and cognitive maps. The heatmaps allowed us to represent interactions between variables and impacts, while the cognitive maps allowed us to represent the multiple pathways from drivers to impacts across time and space. In Section 4.1 we explain the data and the methods used to collect different evidence types. We outline limitations associated with these methods in Section 4.2.

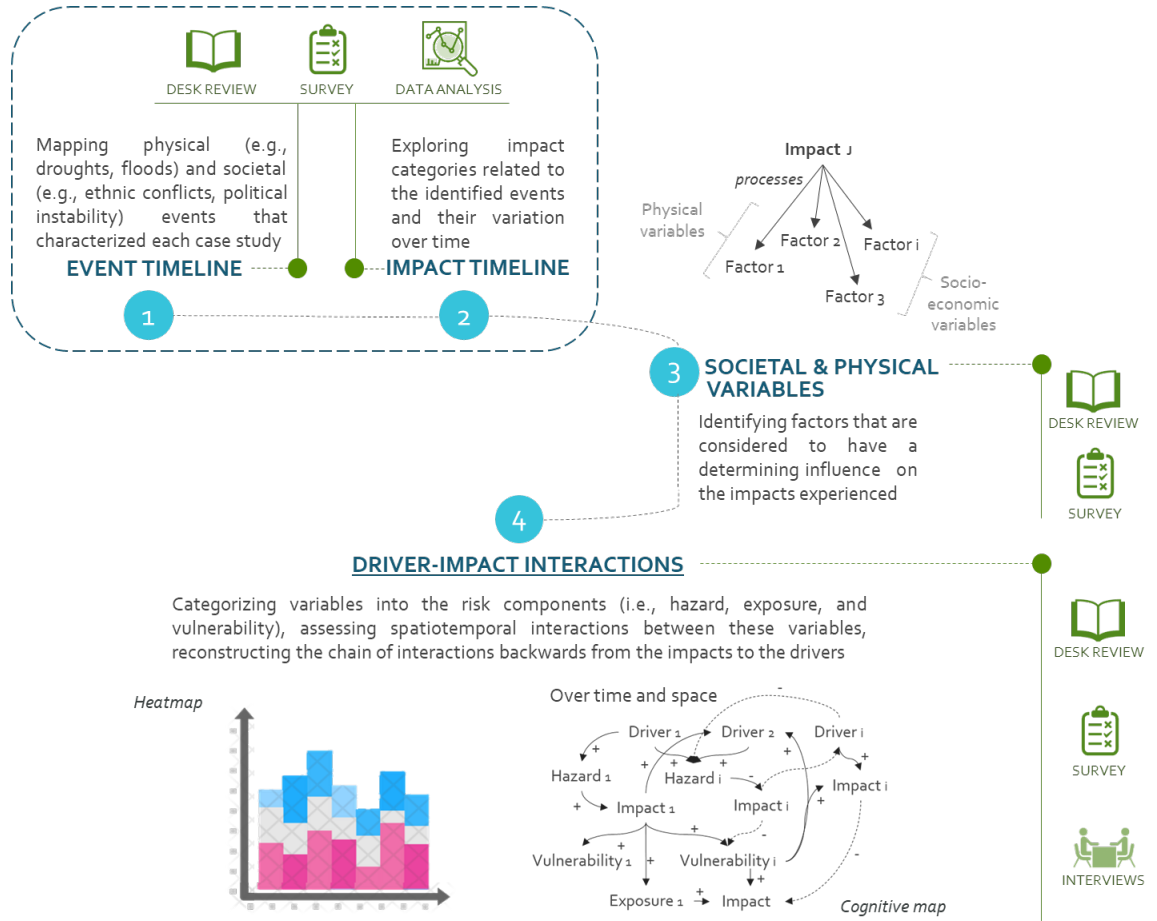


Figure 3. Stepwise, bottom-up approach used in this study to investigate interactions between societal and physical variables during multi-risk events. The green coloured icons represent the methods used in each step.

1. Methods

(a) Literature review

A comprehensive review of the literature was undertaken in order to identify the events, the impacts experienced, and the societal and physical variables that may have led to those impacts during the years 2017-2018 in Kenya and Ethiopia. Our review procedure followed the guiding principle proposed by Boaz et al. (2002) and applied by Gill and Malamud (2014, 2017) (Table S2 in Supporting Information S1). To find suitable documents, we used Boolean search methods based on the keywords: (“humanitarian” AND “crisis”) AND (“Ethiopia” OR “Kenya”) AND “2017” OR “2018”. These keywords were used in large web databases for peer-reviewed articles (Google Scholar and Web of Sci-

ence), and general online search engines to identify other relevant grey literature (e.g., newspapers). The identified references were evaluated to determine their relevance. The approach yielded 350 references, which were screened to identify frequently cited societal (e.g. government elections) and physical events (e.g. drought). This process helped us to develop a preliminary timeline of events, which we further investigated through time series analysis and an online survey (Section 4.1.2 and Section 4.1.3).

Subsequently, we prepared a preliminary list of 34 expected impacts associated with the identified events. The list was first developed from the literature review (for droughts: Stahl et al. (2016), for floods: Adhikari et al. (2010), for conflict: Solomon et al. (2018)), and then reviewed by humanitarian experts. Impacts in the preliminary list were used as keywords for a new Boolean search, with the aim of identifying relevant literature. For example, each keyword from the list (e.g., “deterioration of health conditions”) was used alongside “Kenya” OR “Ethiopia” AND “2017” OR “2018”. The approach resulted in the identification of 63 peer-reviewed and grey literature sources for Kenya and 102 for Ethiopia. Relevant literature included journal articles, technical reports, newspaper articles, NGO disaster situation reports, and government and NGO bulletins. For Kenya, we also used the Quarterly Gross Domestic Product reports issued by the Kenya National Bureau of Statistics. The reports provide an overview of the economic conditions of key sectors (e.g., agriculture, hydroelectric power generation, etc.) and include analyses of the causes of economic growth or recessions. Unfortunately, such data were not available for Ethiopia.

For each impact identified, we recorded information on their spatial and temporal occurrence, interaction types and variables. For the latter two, we performed another Boolean search using keyword verbs that suggest a correlation between impacts and societal / physical variables (similar to Gill et al., 2020). Accordingly, we used the following nine keywords: “trigger”, “provoke”, “generate”, “cause”, “increase”, “worsen”, “decrease”, “reduce” and “alleviate”. The approach helped us to systematically quantify the frequency with which a certain correlation was mentioned, and enabled us to understand the direction of these correlations (positive or negative). Building upon earlier work (Gill & Malamud, 2014, 2017), we synthesized and presented the findings in a matrix form.

1. **Time series data analysis**

For the definition of the extreme hydrological events and impacts, we also used time series analysis of rainfall and socio-economic data (Table S3 in Supporting Information S1). We computed standardized rainfall anomalies from CHIRPS precipitation data aggregated at national and regional / county level. Further, through open source and national databases, we collected time series data on crop and livestock production, GDP, population affected by food insecurity, food prices, number of incidences, number of displaced people, and registered disease outbreaks. We selected these variables based on information on events and impacts gathered from the literature review and data availability. The spatial and temporal scale of these data vary from county or regional level to national

level and from monthly to yearly.

The time window of analysis was selected in accordance with the literature review and the analysis of rainfall time series, which revealed that dry spell conditions developed before 2017. To cover these events, we extended the analysis of the time series to 2016-2018 in Kenya and 2015-2018 in Ethiopia.

1. **Stakeholder online survey**

A web-based survey (<https://doi.org/10.5281/zenodo.5866460>) was prepared in order to gain insights on the events, impacts and interaction types that marked the 2017-2018 humanitarian crises in Kenya and Ethiopia. The survey was shared with 150 Kenyan stakeholders and 80 Ethiopian stakeholders identified through snowball sampling. A total of 24 Kenyan and 16 Ethiopian stakeholders participated in the online survey (16 and 20% of those invited, respectively). These included professionals of different levels of seniority, who work in the fields of disaster risk reduction / management, water management, and economics in national / international agencies, NGOs, and universities. About 50 and 60% (for Kenya and Ethiopia, respectively) of these professionals work at the national level, 30% work at the local level, and the remainder at the regional level. The survey was informed by the preliminary literature review and addresses each step of the methodological approach (Section 4), through four dedicated sections, in which a series of multiple choice and open-ended questions were used.

Specifically, the survey addressed: (1) events that occurred in the years 2017-2018; (2) impacts experienced; (3) drivers of the impacts experienced; (4) interaction between drivers and impacts. In the first section of the survey, we asked the participants to recall the main events that characterized the years 2017-2018 in their respective country / region. As the task requires a memory effort, we have prepared video collages of news from the main Kenyan and Ethiopian media channels respectively, to help respondents recall the years under analysis. To avoid influencing stakeholders, the news used in the collage was related specifically to drought and flood events as these two events were already mentioned in the project scope at the beginning of the online survey. Then, we asked respondents to validate the preliminary event timeline obtained from the literature review and to add any relevant events in case these were missing from the timeline.

In the second section of the survey, we investigated the impacts felt in the years 2017-2018. We asked respondents to select (or add any other) impacts that they remember to have occurred in their country during the period under analysis. Then, we asked them to identify the four major impacts among them and to classify them from 1 (highest) to 4 (lowest) according to their magnitude and resources needed to provide adequate responses. With a similar approach, in the third section of the survey, we asked respondents to: (1) identify potential drivers of the impacts experienced, (2) select relevant drivers from a prepared list, (3) identify and rate four major drivers according to their influence on the impacts experienced, and (4) briefly write how the identified drivers led to the

experienced impacts.

In the last section, we explored the interactions and feedbacks between drivers and impacts. In particular, we asked respondents to fill in an empty driver / impact matrix in which the impacts and drivers, on the x and y axes, respectively, were the ones they identified as the most relevant in the previous sections. Participants could define the type of interaction, for each driver / impact combination, according to the following options: 0 (neutral), +1 (slightly amplified), +2 (widely amplified), -1 (slightly reduced), -2 (greatly reduced).

1. Semi-structured stakeholder interview

Additional evidence on impacts, drivers and their interactions was gathered through semi-structured interviews. We selected participants according to their experience and relevance to the research questions, in agreement with MacDougall and Fudge (2001). We interviewed seven Kenyan and four Ethiopian professionals following an expert sampling technique. The interviewees work for the water management sector, hydro-meteorological services, and disaster risk management / reduction in international research centres, NGOs, national government, and private sectors. The persons interviewed were identified from those who participated in the online survey. This facilitated the elicitation of event interactions, since these participants had recently reviewed the events in the period under analysis.

Interviews lasted from 30 to 90 minutes and followed a semi-structured approach (Bryman, 2012). A clear interview schedule tailored to the interview context was prepared. One of the aims of the interview schedule was to ensure that some questions were asked in the same way to each respondent. All interviewees were recorded if they authorized us to do so. Each interview was then transcribed and summarized. Data collection and storage followed the Code of Ethics of Vrije Universiteit Amsterdam (<https://vu.nl/en/employee/social-sciences-getting-started/research-ethics-review-fss>). Before the interview, we drew a preliminary cognitive map representing the pathways from impacts to drivers and the interrelationships between risk components based on the results from the literature review and the online surveys. We rearranged processes and events from the literature review and the online survey in a hierarchical structure to represent dependencies. These allowed us to reconstruct the chain of events from the impacts to their primary drivers. This map was then reviewed by each participant, discussing dominant or missing processes.

1. Limitation of the methods

The methods described in Section 4.1 are each associated with limitations and uncertainties.

Information accuracy: It might be difficult to verify the reliability of blended sources of grey literature (Gill et al., 2020), particularly when these include media articles, NGOs and government bulletins. The same is the case with interviews and online surveys where stakeholders bring a personal perspective of

the events under analysis and their interrelationships. To overcome these limitations, we assessed authenticity by comparing information obtained through the literature review with that provided by stakeholder interviews, online surveys, and time series data analysis. By integrating multiple types of evidence, we aimed to reduce the uncertainties and limitations of the methods used.

Cognitive biases. Biases related to a systematic error in thinking might occur during stakeholder interviews and online surveys. The way stakeholders remembered the period under analysis might be biased by individual motivations, personal emotions and experiences. To overcome these limitations and improve the quality of the information elicited, Browne and Rogich (2001) and Pitts and Browne (2004) suggest the use of context-dependent questions. Accordingly, our questions were context specific, addressing precise events of the period under analysis.

Uncertainties and biases in the time series data: Time series data has uncertainties related to systematic errors in the collection process. Uncertainties can also arise from the spatial and temporal aggregation process used. In order to reduce these biases, we crosschecked the same variables from different data sources (when available) to verify that the order of magnitude is similar. Data at highest spatial and temporal resolution were preferred. Another uncertainty was brought about by the selection process of the variables used for the data analysis, which was limited by the availability of the data. Hence, other socio-economic data and finer spatial and temporal resolutions could have further reduced the bias in the analysis.

Hypothetical conditions: Reviewing the humanitarian bulletins, we noted that some of the impacts and interrelations mentioned refer to a hypothetical context that could occur if no effective response was provided. In order to distinguish between real and hypothetical conditions, we screened each document with particular attention to the sentences surrounding the identified keywords and the verb tenses used.

Information omission: Semi-structured interviews and online surveys have a predefined format, discussion points, and options. This increases the likelihood of missing important information (Gill et al., 2020). To overcome this limitation, we started each section of the online-survey with open-end questions so as not to influence respondents by limiting their response to the options offered in the multiple-choice questions. For the latter, we provided the possibility to insert any other answer not listed among the options. In the semi-structured interviews, we reserved 15 minutes at the end of the interview for any points that the participants believed may be relevant to discuss.

Sample size: Sample size is important in both data analysis and qualitative research to reduce possible error. Due to the nature of our event-based study, we focused on a short time frame (three to four years). This limited the type of data analysis methods and their use in the study. For instance, statistical analysis to identify dependencies and correlations could not be applied. Our data analysis,

therefore, primarily aimed at complementing information obtained from the literature review and stakeholder online survey to provide insight into anomalies. This was done by comparing the data of the analysed time period with data of the previous 20 years. Regarding the stakeholder interviews and the online survey, we selected stakeholders with different backgrounds and fields of work in order to capture different narratives and perspectives of the interactions that characterize the period under analysis.

5 Results

In Section 5.1 and Section 5.2, we present the results for Kenya and Ethiopia respectively, addressing each step of the approach described in Section 4.

5.1 Kenya

5.1.1 Event timeline

In 2016-2018, Kenya experienced a succession of drought and floods and other exceptional physical and societal events (Figure S1 in Supporting Information S1). In particular, crop pest infestation and prolonged government elections were two other major events reported in the literature, online survey, and stakeholder interviews.

Rainfall deficits during the ‘short rainy season’ (October-December) of 2016 were perceived as the main cause of drought conditions in the northwest and southeast of Kenya. However, the late onset, poor distribution, and early cessation of the 2016 short rains alone do not explain the drought condition experienced in late 2016. In the southeast, the 2016 short rains compounded with a low soil moisture precondition resulted from rainfall deficit during the ‘long rainy season’ of the same year (March-May 2016).

On February 10th, 2017, the government declared a national drought emergency, which was further exacerbated by another rainfall deficit over the long rainy season of 2017 (March-May). The drought conditions lasted until May 2018, despite several extreme wet events occurring in between. Only the heavy rainfall during the 2018 long rains interrupted the drought cycle. This rainfall event also led to flash floods and widespread riverine floods, landslides, and dam spillage and failure. The complexity of the precipitation event meant that forecast lead times were shorter. As such, the long lead seasonal climate forecasts did not provide enough indication that exceptional rain could occur.

Coinciding with the drought, many counties in Kenya had an infestation of fall armyworm. The pest was first detected in Kenya in March 2017 and was held responsible, along with the drought, for the decrease in the production of maize and sorghum (the crops preferred by the parasite). The worms also targeted wheat and barley crops, which grow mainly in the western counties together with maize. By July 2017, it had infested 40% of farms, affecting around 200,000 hectares of land in the main maize-producing counties. The infestation seemed to have stopped at the beginning of 2018 with a resurgence only in early 2019. The year 2017 also had government elections, which took

place first in August 2017 and then again in October 2017 since the Supreme Court nullified the results of the first election. The electoral campaign was one of the most expensive, and its period was marked by violence and unrest.

5.1.2 Impact timeline

The quarterly distributions of reported impact categories (Figure 4a) illustrate the diversity of the impacts experienced throughout the analysed period. Food insecurity, which was reported throughout almost the entire analysis period (Figure 4a), has also been perceived as the major impact (Figure 4b). From March 2018, food insecurity values decreased (Figure 4h), coinciding with a decrease in the average walking distance to water sources (Figure 4f) and an increase in national maize yields (Figure 4e). In the same period, on the other hand, the impacts on damage to infrastructures and on water supply systems and landslide / mudslide events triggered by heavy rainfall appear prominently (Figure 4a). Yet, these impacts did not affect all parts of Kenya equally. Reports on damage to water supply systems mentioned that this mostly occurred in semi-arid regions and close to riverbanks, while reports on landslide and mudslide events referred mainly to areas in central-western counties where topography is highly variable.

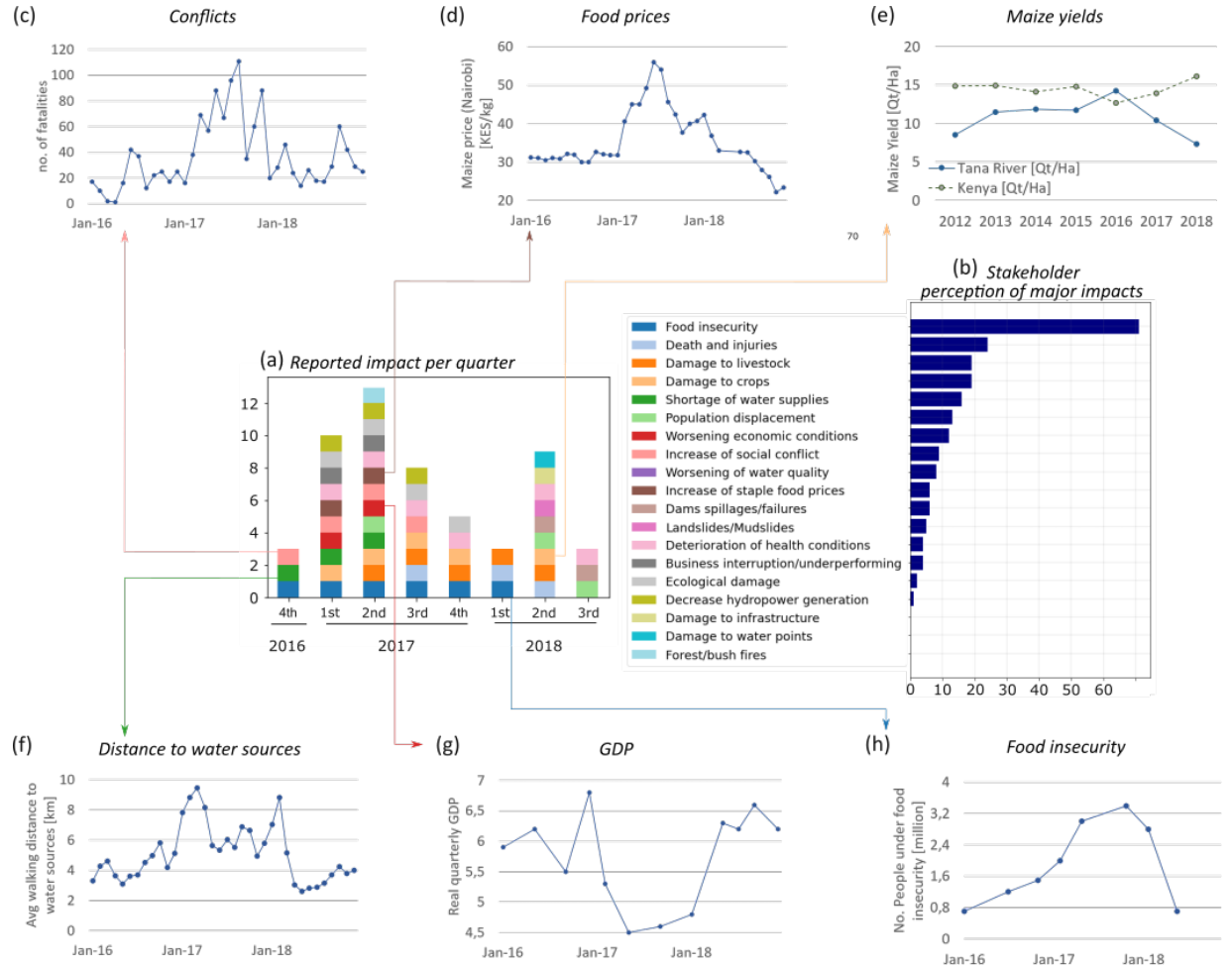


Figure 4. Kenya impact analysis over time, with: (a) quarterly impacts reported in the reviewed literature; (b) their perceived damage in terms of magnitude and needed resources for effective responses according to the online survey, time series data of: (c) number of fatalities, (d) nominal maize price in Nairobi, (e) maize yield in Tana River and Kenya, (f) average walking distance to water sources, (g) real quarterly GDP, (h) number of people under food insecurity.

With a substantial gap, deaths / injuries and damage to livestock / crops follow food insecurity as major impacts perceived by the stakeholders (Figure 4b). Damage to crops was reported in the 1st quarter of 2017 (Figure 4a) and coincided with a decrease in national crop yields in late 2016 (Figure 4e). In the same period, staple food prices rose markedly (Figure 4d), while GDP growth decreased (Figure 4g). In the 2nd quarter of 2018, however, the damage to crops (Figure 4a) was not reflected clearly in a decrease in national agricultural production (Figure 4d), which instead shows a full recovery in that year. Crop

losses were mainly reported in the arid and semi-arid Kenyan regions, which present a minimum contribution to the annual average national production. Finally, an increase in social conflicts was recorded from the 4th quarter of 2016 until the 3rd quarter of 2017, with the number of incidences increasing from June 2017, close to the election period.

5.1.3 Societal and physical variables

Through the systemic literature review, for the 34 impacts investigated, we identified the following eight societal and physical variables: drought, flood, heavy rain, landslides, fall armyworm, government elections, ethnic conflicts, and dam spillage / failure. Although the flood in 2018 was triggered by heavy rainfall, we analysed both floods and heavy rain as potential drivers because different interaction types emerge. Further, the literature review shows that floods, landslides and dam spillage are both driving factors (of crop losses, damages to infrastructure, etc.) and impacts (as resulting from other events such as heavy rains, drought, etc.). Therefore, we explored those events as both drivers and impacts with the aim of considering cascading processes. In the online survey, 83% of respondents indicated drought as one of the drivers for the events experienced in Kenya between 2017-2018. This was followed by flood, government response and conflict (mentioned by around 75%, 45% and 41% of respondents, respectively). In contrast, when we asked to indicate which of the drivers had a major influence on the impacts experienced, drought and flood stood out, followed by conflicts.

5.1.4 Driver-impact interactions: heatmaps

The interactions between societal / physical variables and impacts were recorded in a matrix and summarised graphically in the form of a heatmap (Figure 5). In particular, the figure summarises the predominant drivers / impacts interactions at national level according to the different sources of evidence explored (heatmap from the literature review process in Figure S2 and heatmap from the online survey in Figure S3 in Supporting Information S1). The analysis revealed the occurrence of 72 interactions in the years under analysis. Among the identified interactions, we notice that the occurrence of one event influenced (or caused) others. This means that in some cases a driver increased a certain impact (i.e., negative interaction), while it supported the mitigation of other(s) (i.e., a positive interaction). For instance, *Heavy rain* increased *Flood*, but also decreased *Water shortage*. At the same time, we can also observe that, in some cases, an impact became a driver of a subsequent event. For instance, *Drought* led to *Migration* / *Displacement* which in turn exacerbated *Ethnic dispute* / *violence* (Figure 5).

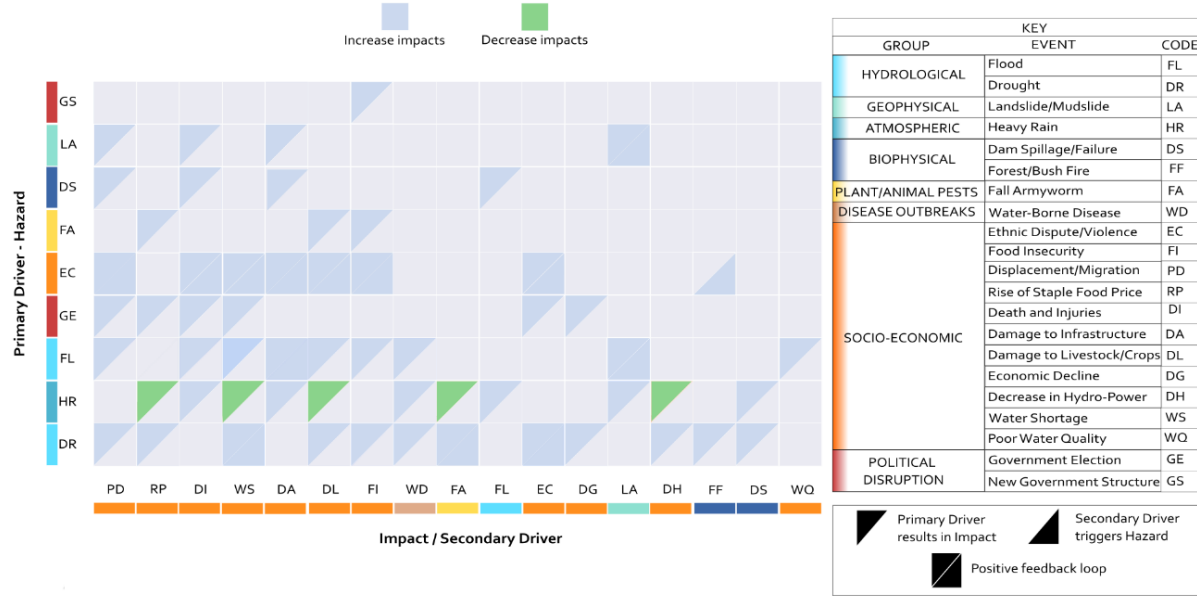


Figure 5. Heatmap summarising the predominant interactions between physical / societal variables and impacts at national level according to the different sources of evidence explored. Negative interactions (blue) increase the impacts while positive interactions (green) decrease the impacts. Shading in the upper-left triangle indicates that the variable is either increasing (blue) or decreasing (green) the relative impact. Shading in the lower-right triangle indicates that the driver / impact can increase the probability of a hazard. Shading in the whole cell indicates positive feedback loops and hence reinforcing mechanisms that further increase the impacts and the drivers. Event classification modified from (Gill & Malamud, 2014).

Analysing the heatmap (Figure 5), we can observe that *Drought*, *Floods* and *Ethnic dispute / violence* present the largest number of negative interactions with the investigated impacts (each related to 12, 10 and 8 impacts, respectively). *Heavy Rain* also has a large number of interactions with the identified impacts (11), but compared to the other drivers it has both negative and positive interactions. In detail, *Heavy rain* was related to the increase of *Floods*, *Landslides* and *Dam spillage / failure*. At the same time, *Heavy rain* (driver) was also related to a decrease in *Water shortage* (impact), increase in *Hydropower* production (impact), reduced *Damage to livestock / crops* (impact) and reduced *Fall armyworm* infestation (impact). Further, *Ethnic violence* (impact) were mainly driven by the *Government elections* (driver) and *Drought* (driver).

5.2 Ethiopia

5.2.1 Event timeline

In 2017-2018, Ethiopia experienced droughts, widespread riverine floods and flash floods, fall armyworm infestation, political power change, and two ethnic conflicts (Figure S4 in Supporting Information S1). To capture possible drivers from before the period under analysis, we explored rainfall anomalies starting from 2015. The analysis shows two periods of meteorological drought: one that occurred in 2015-2017 (which mainly affected the western regions) and another that occurred in 2016-2017 (which mainly affected the eastern regions). The first drought was caused by subsequent below-normal rainfall in 2015, 2016 and early 2017. The drought conditions ended with above-normal rainfall rates during Kiremt summer season (June-September; spatio-temporal distribution of the rainy seasons in Ethiopia is shown in Figure S5 in Supporting Information S1) in 2017, which also resulted in riverine floods and flash floods in Afar, Amhara and the Oromia regions. On the other hand, the normal rainfall of Deyr (October-December) in 2017 was not sufficient to reverse the effects of drought conditions in the eastern regions. Only the heavy rains of the late Belg / Gu season (February-May) of 2018 helped to break the drought cycle in the eastern regions. The extremely wet event also led to widespread flooding and landslides in the regions of Somali and Eastern Oromia. Drought conditions in 2017 compounded with the fall armyworm infestation, threatening crop production. The crop pest was detected in February 2017 and quickly began spreading to several maize plantations in southern Ethiopia.

Adding to these climatic shocks and biological hazards, widespread anti-government protests broke out in Oromia and Amhara region in July 2016, followed by an escalation of civil unrest on the Somali-Oromia border in September 2017 through February 2018. Subsequently, intercommunal violence occurred along the borders of the Gedeo (SNNPR) and West Guji (Oromia region) areas in April 2018. Tensions between the two groups have been centred on land, border demarcation, and ethnic minority rights and lasted until June 2018.

5.2.2 Impact timeline

The quarterly distribution of the impact categories from the literature review has some agreements with the stakeholder impact perception. Food insecurity is reported for almost the entire period analysed (Figure 6a) and was also perceived as being one of the major impacts experienced (Figure 6b). From the end of 2015 until the end of 2016, the number of food-insecure people increased to over 9 million (Figure 6f). At the same time, agricultural production declined (Figure 6e) and GDP growth slowed by 1% (Figure 6g). Another increase in food insecurity was recorded in early 2017 with around 8 million people registered in conditions of food insecurity (a value that remained constant throughout 2017 and 2018; Figure 6f). This increase in food insecurity coincided with a sharp rise in staple food prices, driven by the poor yield of the Belg harvest (harvested period: June-July) and concerns over the fall armyworm infestation on the Meher harvest (harvested period: October-December). However, thanks to the abundant harvest, prices began to decline in most markets from August 2017

(Figure 6d). This decrease in staple food price did not occur in areas affected by conflicts (e.g., Somali and east Oromia; Figure 6c), where the series of clashes disrupted the normal flow of commodities from surplus areas to deficit markets. Additionally, in the same areas, the drought conditions had repercussions on smallholder farmers and pastoralists (Figure 6e), further contributing to their food insecurity. Prices began to decline in whole regions only from early 2018, although they remained 20-40% above their respective monthly average prices (Figure 6d). After food insecurity, population displacement was perceived as the second largest impact. The highest numbers of displaced persons (Figure 6h) occurred at the same time as the increase in the number of fatalities (Figure 6c), due to the Somali-Oromia and Gedeo-West Guji conflicts. In the same period, GDP growth showed a decline of around 3%.

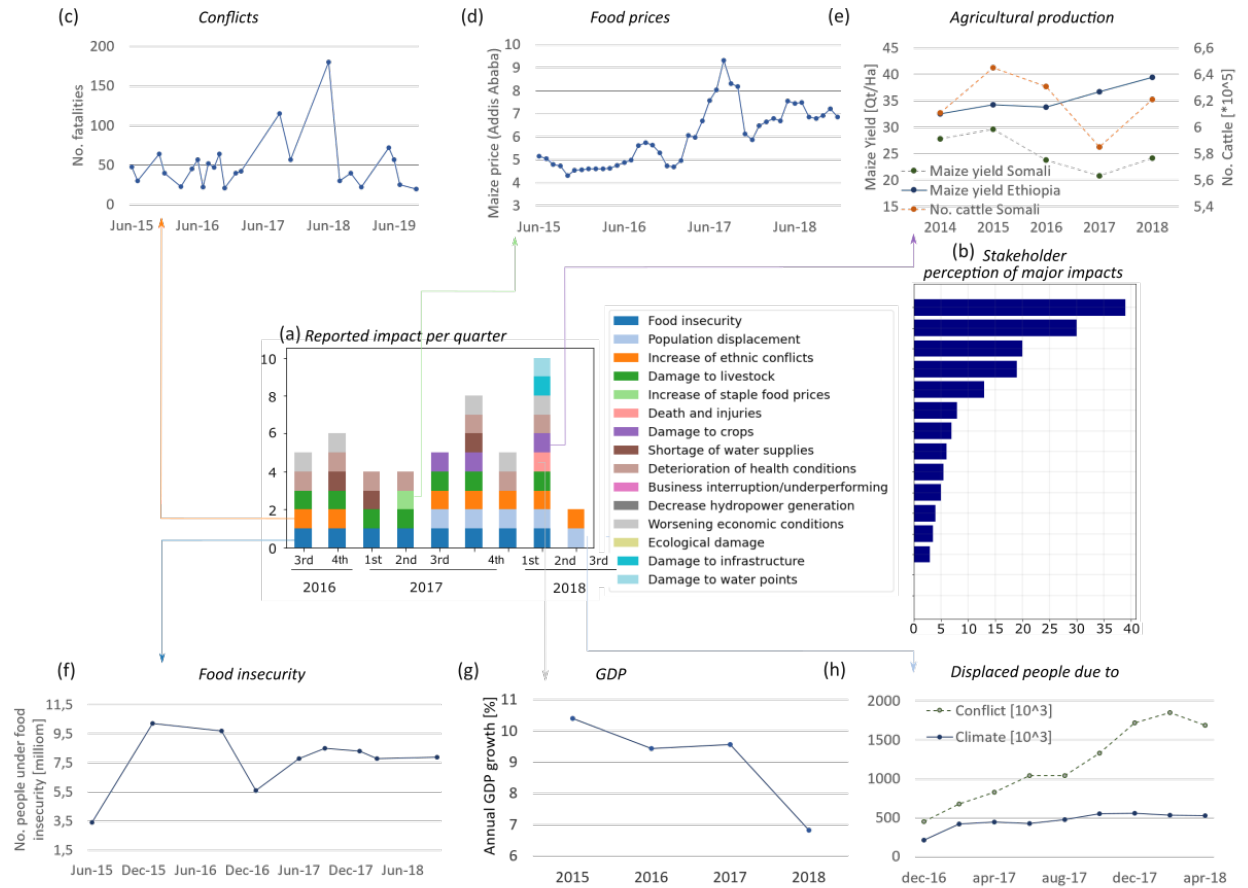


Figure 6. Ethiopia impact analysis over time: with (a) quarterly impacts reported in the reviewed literature, (b) their perceived damage in terms of magnitude and needed resources for effective responses according to the online survey,

time series data of: (c) number of fatalities, (d) nominal maize price in Addis Ababa, (e) maize yield in Somali and Ethiopia, (f) number of people under food insecurity, (g) annual GDP growth, (h) number of people displaced.

5.2.3 Societal and physical variables

Through the systematic literature review, for the 34 impacts investigated we identified the following eight drivers: drought, flood, heavy rain, landslides, fall armyworm, political instability, ethnic conflicts, economic decline, and population displacement. Like in Kenya, heavy rains and floods show different types of interactions with other social and physical variables. Furthermore, economic decline and population displacement were found in the literature review as both impacts and drivers of subsequent events. In the online survey, conflict was identified as a driving factor of the experienced impacts, with a broad consensus among respondents. This was followed by political unrest, drought and floods (indicated by approximately 75-70% of respondents). On the other hand, when we asked to indicate which of the drivers had a major influence on the impacts experienced, conflict, drought and political disruption stood out.

5.2.4 Driver-impact interactions: heatmaps

Bringing the diverse evidence types together (Figure S6 and Figure S7 in Supporting Information S1), we identified 74 interactions during the years under analysis (Figure 7). *Drought*, *Conflicts / Violence* and *Floods* present the largest number of negative interactions (increasing impacts) with the investigated impacts, with 11, 9 and 8 related impacts respectively. *Heavy rain* also shows a large number of interactions with impacts (7), but most of these interactions are positive, hence resulting in a decrease of certain impacts such as *Damage to livestock / crops* and *Water shortage*. Compared to Kenya, these positive interactions were less marked and occurred over a longer period (around 4-6 months). Other interesting interactions highlighted in the heatmap are those related to *Population displacement*. According to our analysis, *Population displacement / Migration* (impact) was driven by *Drought*, *Ethnic conflicts*, *Floods*, *Landslides*, *Political instability* and *Economic decline* (drivers). At the same time, *Population displacement* (driver) was associated to increase in *Food insecurity*, *Water shortage*, *Ethnic conflicts* and *Water-borne diseases* (impacts).

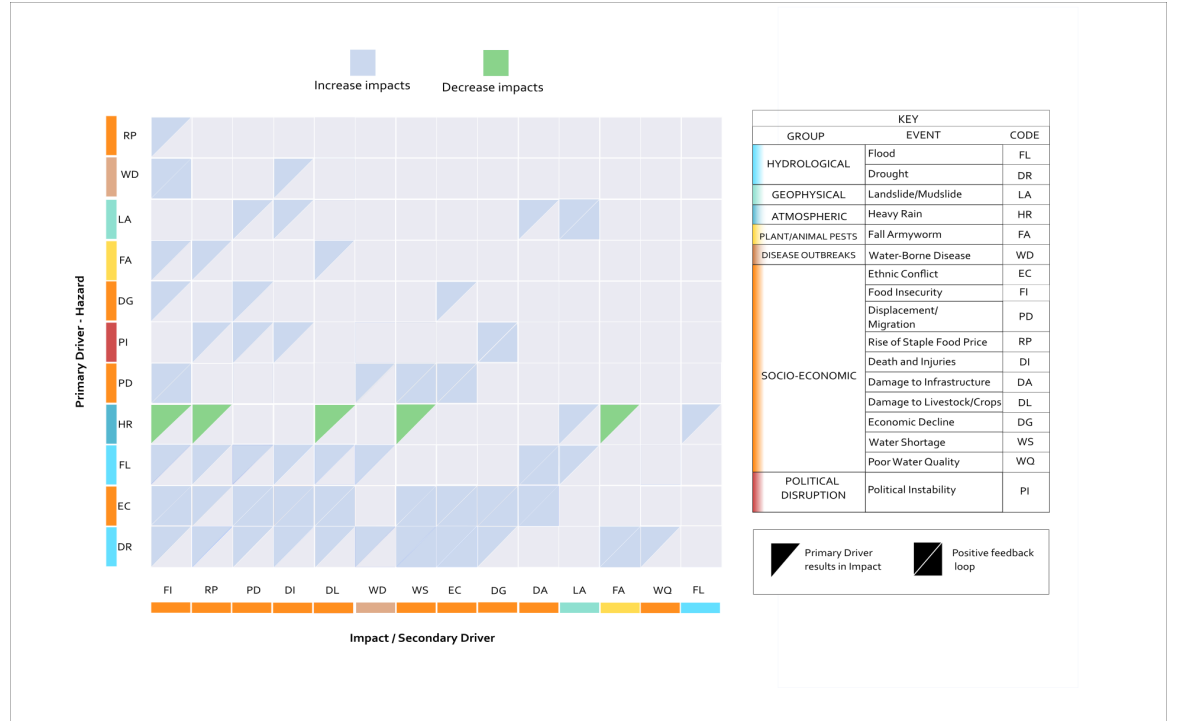


Figure 7. Heatmap summarising the predominant interactions between physical / societal variables and impacts, predominant in the arid and semi-arid regions of Eastern Ethiopia, according to the different sources of evidence explored. Negative interactions (blue) increase the impacts while positive interactions (green) decrease the impacts. Shading in the upper-left triangle indicates that the driver is either increasing (blue) or decreasing (green) the relative impact. Shading in the whole cell indicate positive feedback loops and hence reinforcing mechanisms that further increase the impacts and the drivers. Event classification modified from (Gill & Malamud, 2014).

6 Discussion

Disentangling trends in hazards, exposure, vulnerabilities and impacts, as well as understanding their spatial-temporal interactions, is essential for assessing the risk of humanitarian disasters related to drought-to-flood events. Acquiring this information and knowledge in fragile contexts can be challenging given the limited availability of data and their reliability. As shown in this study, the integrated use of different evidence types helps overcome the lack of data, while providing broader perspectives on socio-hydrological interactions and their space-time variations. To the best of the authors' knowledge, this is the first study proposing the integration of qualitative and semi-quantitative methods framed in a bottom-up approach to identify interactions between societal and physical factors and risk components in real-world, multi-hazard events. This

contrasts with many existing studies on multi-hazard events that focus on a single type of interaction, are based either on a quantitative or a qualitative approach, or do not take into account the spatial-temporal variations of the risk components.

Results from the case studies highlight that **drought and flood events did not act in isolation but compounded with the Ethiopian and Kenyan fragile context**, exacerbating the impacts. For example, the combination of drought, ethnic conflict and displacement / migration led to a number of mutually reinforcing interactions (Figure S8 and Figure S9 in Supporting Information S1). Drought affected the migration patterns of pastoralists, exacerbating resource-based conflict and inter-municipal competition for land. This resulted in increased violence and insecurity, hindering the access of humanitarian aid to drought-affected communities. The impacts of floods were also exacerbated by the absence of a specific authority or institutional framework for flood response in arid and semi-arid regions, as the primary focus was on drought relief.

Further, the **co-occurrence of drought conditions with intense rainfall resulted in different socio-hydrological processes according to socio-economic and topographic characteristics**. In central-northern Kenya, the heavy rainfall quickly replenished water sources due to the presence of adequate infrastructure (e.g., dams). Additionally, sufficient vegetation cover allowed better retention of rainwater, reducing the development of floods. In the central-western counties of Kenya, on the other hand, the dry and cracked soil caused by the two years of drought, combined with the abundant rainfall and the highly variable topography, caused landslides. Finally, in the arid and semi-arid region of Kenya and in the Somali region of Ethiopia, the heavy rains occurred in an area with a lack of infrastructure and a compacted soil, resulting in widespread riverine flooding and flash floods. The flood events washed away boreholes, thereby increasing water shortage and food insecurity. In the latter two cases, negative interactions (increasing impacts) predominated over positive interactions (decreasing impacts) on a short timeframe.

Finally, **drought hazard, impacts and responses influenced the flood risk components**. In particular, the drought hazard led to the degradation of the vegetation cover and the compaction of the soil. Consequently, sub-surface water storage and infiltration were reduced, leading to an increase in the runoff coefficient. This favoured the development of flash floods and riverine floods. Drought impacts instead affected the social system's ability to cope with a subsequent flood due to limited recovery time and hence increasing flood vulnerability. Finally, drought response increased both flood hazard and exposure. During the early rainfall, dam operators were confronted with the decision to capture the early season streamflow or to maintain empty space for flood management purposes. This challenge, coupled with the poor reliability of the long rainy season forecast, led to sudden overflows during heavy rains, which further increased flood risks. At the same time, we found that poor dam maintenance by farmers during the drought contributed to the dam failure. Moreover, some Ethiopian

and Kenyan communities, in response to water scarcity due to drought, migrated closer to water sources further increasing their exposure to floods.

The approach proposed in this study can be replicated and scaled up or down to different geographical settings, since it takes into account different methods / evidence types depending on their availability. Once the case study has been selected, spatial and temporal boundaries of the analysis need to be carefully defined. Societal and physical events are continuously interconnected in time and space: current socio-economic and environmental conditions could be the result of past events that occurred in the analysed area and / or in other inter-connected locations. Furthermore, the spatial resolution used also has an influence on the range of interactions that can be captured. Results of this study show that the same physical and societal drivers could lead to different interactions based on different environmental and socioeconomic contexts. Therefore, as the level of heterogeneity in the area of analysis increases, a finer resolution is needed to be able to capture the wider range of interactions. Finally, the use of a fine resolution and / or large spatial boundaries allow investigating spatial dependencies between events.

7 Conclusions

In this paper, we developed a stepwise, bottom-up approach to unravel spatiotemporal interactions between societal and physical variables during drought-to-flood events in fragile contexts, looking at two case studies in the Horn of Africa. We explored event timelines, impacts, physical / societal variables and driver-impact interactions through the iterative use of literature review, time series analysis, stakeholder online surveys and stakeholder interviews. This interdisciplinary approach allowed us to move beyond the analysis of interactions of physical drivers, offering a holistic narrative of relationships underlying drought-to-flood risks and societal events in fragile contexts. Further, the approach helps to overcome limitations on data availability in fragile contexts by making use of (and integrating) different evidence types. Finally, the approach can be used for a wide range of extreme events and multi-risk interaction types (e.g., compounding, cascading), and can be applied to different geographical settings.

Our analysis in Kenya and Ethiopia shows that the drought and flood events in 2017-2018 did not develop in isolation, but their risks stem from multiple, dynamic interactions between risk components, impacts, and responses, closely linked to the contextual fragile conditions. Further, we have seen that cascading and concurrent processes can develop both negative interactions (increasing the impacts) and positive interactions (decreasing the impacts). With this study, we showed the complexity of disaster risk in real-context conditions. Therefore, we encourage the integrated use of qualitative and quantitative methods framed in a bottom-up approach, to conceptualize disaster risks as a set of multiple (societal and physical) events interacting and evolving across space and time.

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Open Research

The data sources used for the time series analysis are listed in Table S3 in Supporting Information S1. The raw data used to develop Figure 2 are available through the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) dataset (<https://www.chc.ucsb.edu/data/chirps>), the EM-DAT (<https://public.emdat.be/>) and DesInventar (<https://www.desinventar.net/>) databases.

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