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COMMENTARY

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Tackling Growing Drought Risks—The Need for a Systemic Perspective

M. Hagenlocher[1], G. Naumann[2], I. Meza[1,3], V. Blauhut[4], D. Cotti[1], P. Döll[5,6], K. Ehlert[7,8], F. Gaupp[9], A. F. Van Loon[10], J. A. Marengo[11], L. Rossi[2], A. S. Sabino Siemons[1], S. Siebert[12], A. T. Tsehayu[13], A. Toreti[14], D. Tsegai[15], C. Vera[16,17], J. Vogt[18], and M. Wens[10]

[1]Institute for Environment and Human Security (UNU-EHS), United Nations University, Bonn, Germany, [2]CIMA Research Foundation, Savona, Italy, [3]WWF Germany (WWF DE), Berlin, Germany, [4]Faculty of Environment and Natural Resources, Environmental Hydrological Systems, University of Freiburg, Freiburg, Germany, [5]Institute of Physical Geography, Goethe University Frankfurt, Frankfurt am Main, Germany, [6]Senckenberg Leibniz Biodiversity and Climate Research Centre Frankfurt (SBiK-F), Frankfurt am Main, Germany, [7]World Meteorological Organization (WMO), Genève, Switzerland, [8]Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, Zürich-Flughafen, Switzerland, [9]Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany, [10]Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands, [11]National Center for Monitoring and Early Warning of Natural Disasters (Cemaden), São José dos Campos, Brazil, [12]Department of Crop Sciences, University of Göttingen, Göttingen, Germany, [13]Intergovernmental Authority on Development (IGAD), IGAD Climate Prediction and Application Centre (ICPAC), Nairobi, Kenya, [14]European Commission, Joint Research Centre (JRC), Ispra, Italy, [15]United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany, [16]Department of Atmospheric and Ocean Sciences, CIMA, University of Buenos Aires, CONICET, Buenos Aires, Argentina, [17]Sistema se Información sobre Sequias para el Sur de Sudamérica (SISSA), Buenos Aires, Argentina, [18]Retired from European Commission, Joint Research Centre (JRC), Ispra, Italy

Key Points:

- Drought risks are on the rise and their effects are increasingly felt across communities, economic sectors, ecosystems, borders and entire societies
- To effectively assess and manage drought risks, a systemic perspective is needed
- We propose a novel systemic framework to better inform drought risk research and policy

Correspondence to:

M. Hagenlocher,
hagenlocher@ehs.unu.edu

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Author Contributions:

Conceptualization: M. Hagenlocher, G. Naumann, I. Meza, V. Blauhut, D. Cotti, P. Döll, F. Gaupp, A. F. Van Loon, A. S. Sabino Siemons, S. Siebert, J. Vogt, M. Wens
Visualization: M. Hagenlocher, G. Naumann, I. Meza, D. Cotti, F. Gaupp, A. F. Van Loon, A. S. Sabino Siemons, J. Vogt
Writing – original draft: M. Hagenlocher, G. Naumann, I. Meza, D. Cotti, A. S. Sabino Siemons

Abstract In the last few years, the world has experienced numerous extreme droughts with adverse direct, cascading, and systemic impacts. Despite more frequent and severe events, drought risk assessment is still incipient compared to that of other meteorological and climate hazards. This is mainly due to the complexity of drought, the high level of uncertainties in its analysis, and the lack of community agreement on a common framework to tackle the problem. Here, we outline that to effectively assess and manage drought risks, a systemic perspective is needed. We propose a novel drought risk framework that highlights the systemic nature of drought risks, and show its operationalization using the example of the 2022 drought in Europe. This research emphasizes that solutions to tackle growing drought risks should not only consider the underlying drivers of drought risks for different sectors, systems or regions, but also be based on an understanding of sector/system interdependencies, feedbacks, dynamics, compounding and concurring hazards, as well as possible tipping points and globally and/or regionally networked risks.

Plain Language Summary In recent years, the world has faced severe and frequent droughts, resulting in significant direct and indirect impacts. However, our understanding and assessment of drought risks are still limited which has important implications for risk management. Here, we propose a new approach—a systemic perspective on drought risks—to effectively assess and manage drought risks. Our framework highlights the interconnected nature of drought risks, impacts and responses. We demonstrate the framework's application by analyzing the 2022 drought in Europe. This research emphasizes the need for a comprehensive understanding of drought risks and offers a practical tool for policymakers and researchers to guide future drought risk research and policy.

1. Introduction

Droughts are temporary, recurring, usually slow-onset water deficits that can lead to devastating impacts on many sectors and systems and, eventually, affect ecosystems, entire societies and economies (Chiang et al., 2021; IPCC, 2022; Pokhrel et al., 2021; UNDRR, 2021). These water deficits are caused by the interaction of meteorological imbalances propagating through the hydrological cycle and human activities (Bartholomeus et al., 2023; Van Loon et al., 2022). Drought impacts, resulting from an inbalance between water availability and water needs, are severe, spatially and temporally complex, interlinked, and often slowly evolving, rendering their assessment a challenge. Between 2001 and 2021, droughts affected on average about 67 million people globally every year, with variations across the years, and caused global economic losses of USD 146 billion (CRED, 2022). While

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agriculture is the most affected sector, the lack of water due to droughts also affects ecosystems, public water supply, power generation, tourism, water-borne transport and buildings often with non-linear cascading and systemic impacts across economic sectors and systems (UNDRR, 2021). For example, low streamflow directly affects power generation from fossil fuels, nuclear energy and hydropower as well as river-borne transportation, which in turn increases the risk of systemic failure for societies as a whole due to possible cascading effects on entire industries—as it could be observed in Europe in 2018–2019 and 2022. While droughts can develop gradually over several months, they can also act as a sudden and dramatic trigger for famine or ecosystem loss when an ecological or social tipping point is crossed—as experienced in the Horn of Africa in 2022–2023, which is enduring its longest drought in 40 years (WMO, 2022). Droughts also increase the risk of wildfires, as observed in the Amazon and Pantanal in 2020–2021 (Marengo et al., 2021) and during the concurrent drought and heat wave affecting Europe in the summer of 2022. In addition, over the past few decades, the occurrence of droughts, compounded by unsustainable water management practices, have generated severe water crises that affected water, energy and food security, as in Central Chile (Garreaud et al., 2019), California (Mann & Gleick, 2015), South Africa (Meza et al., 2021) and Sao Paulo and the Parana-La Plata basin (Naumann et al., 2023). These characteristics pose a serious challenge to our ability to grasp the complexities of drought risks and to manage them in a comprehensive way. This is particularly concerning as extreme drought-heat compound events are expected to further increase in anthropogenically forced warmer climates (IPCC, 2021, 2022; Kreibich et al., 2022; Naumann et al., 2018) while vulnerabilities of communities, sectors and systems to drought are high in many parts of the world (UNDRR, 2021).

Identifying pathways toward more drought-resilient societies is high-up on global political agendas (UN, 2022). Cross-sectoral assessments of *who* and *what* is at risk to *what* (e.g., lower than normal soil moisture or streamflow as well as temporal water shortages and its cascading effects), *where*, *when*, and *why*, will be key for proactive risk management and adaptation. This has also been underscored by relevant international agendas and initiatives, such as the *Sendai Framework for Disaster Risk Reduction* (UN, 2015), the *Integrated Drought Management Programme* (https://www.droughtmanagement.info) by the World Meteorological Organization and the Global Water Partnership which originated in the *2013 High-level Meeting on National Drought Policy* (WMO, 2013), the 2018/2019 *Drought Initiative* (https://www.unccd.int/actions/drought-initiative) of the United Nations Convention to Combat Desertification (UNCCD) and the *GAR Special Report on Drought 2021* (UNDRR, 2021). Furthermore, UNCCD Parties made a land mark decision to establish an Intergovernmental Working Group (IWG) on Drought at the 14th session of the UNCCD Conference of Parties (COP 14) and a new IWG at COP 15 with the aim to tackle the issue of drought in a deeper, sustainable and more systemic manner (https://www.unccd.int/convention/governance/intergovernmental-working-group-drought-2). Besides, African Nations urged the United Nations to improve research and data on drought and drought risks during the UNCCD Conference of the Parties (COP14) that took place in New Delhi, India (Padma, 2019). Spearheaded by the governments of Spain and Senegal, an International Drought Resilience Alliance was launched in November 2022 at COP27 Leaders' Summit in Egypt (https://idralliance.global/). Moreover, in 2023 the first UN water conference in decades took place, a global event aimed to speed up actions to achieve the internationally agreed goals on water resilience, security and cooperation.

2. Progress and Persisting Gaps

Over the past decades, major progress has been made in understanding the physical processes underlying drought onset and evolution (Schumacher et al., 2022), the human role in enhancing and mitigating droughts (AghaKouchak et al., 2021; Di Baldassarre et al., 2018; IPCC, 2021, 2022; Rangecroft et al., 2019; Savelli et al., 2022; Van Loon et al., 2016, 2022; Wendt et al., 2020), mutual feedbacks between human and water systems in general (Höllermann & Evers, 2020; Huggins et al., 2022; Sivapalan et al., 2012, 2014), as well as approaches to proactive drought management (Pischke & Stefanski, 2016). Drought hazard monitoring and event-based early warning systems have also been implemented in many countries, regions (e.g., East Africa Drought Watch) and at the global level (e.g., the EC-JRC Copernicus Global Drought Observatory). However, a multi-sectoral global drought hazard early warning system is not yet operational. While a plethora of hazard indicators for monitoring droughts exists, a clear understanding and communication of the conceptual basis of the selected drought hazard indicators and their relation to specific drought risks are less developed (Bachmair et al., 2016). A systematic approach for selecting drought hazard indicators that are specific to the risk system under consideration has recently been presented by Herbert and Döll (2023), who also propose to take into account the habituation of the system at risk to less water than normal when deciding which drought hazard indicators are suitable for a drought risk assessment. Impact-based forecasts that include risk information are largely missing (Sutanto et al., 2019). Meanwhile, the conceptual understanding of risks associated with meteorological and climatic hazards has evolved from hazard-focused and environmental-deterministic concepts to a holistic one that considers environmental, socio-economic, physical and governance-related drivers of hazard, exposure, and vulnerability as well as the dynamic nature of risks and responses (IPCC, 2022). Further advances have been made regarding the conceptualization of (a) risks linked to connected extreme events (Raymond et al., 2020; Zscheischler et al., 2018), (b) the nexus approach to drought risks (Reichhuber et al., 2019), (c) multi-risk (Curt, 2021) and complex climate risk (Simpson et al., 2021) and (d) cascading and systemic risks and impacts linked to multiple hazards, threats and shocks (Chatzopoulos et al., 2021; Hochrainer-Stigler et al., 2023; Sillmann et al., 2022; UNDRR & UNU-EHS, 2022), including compound and cascading drought impacts (Cotti et al., 2023; de Brito, 2021; Niggli et al., 2022). These concepts are now widely used to assess the risks associated with floods, storms, tsunamis, or earthquakes. However, according to recent reviews of drought risk and impact assessments (Blauhut, 2020; Hagenlocher et al., 2019) the most used conceptual frameworks aiming to explain the propagation from drought hazards to drought impacts (Van Loon et al., 2016; Wilhite & Glantz, 1985) have not been updated with these recent developments and remain largely hazard-focused, deterministic and do not consider cascading or systemic effects. Efforts to quantify drought risks on multiple systems through a probabilistic risk assessment approach at continental scale have been recently carried out (Rossi et al., 2023), but focus remained confined to direct losses on individual systems. Severe droughts in recent years have however clearly shown that impacts are not only linked to the onset, duration, severity and frequency of drought events. Instead, the risk of drought impacts depends on the degree of direct and indirect exposure, the intrinsic and dynamic vulnerability conditions of different communities, sectors and systems, as well as (transient) adaptation decisions and their interconnectedness (Wens et al., 2019). A static and incomplete view of the system bears the potential for insufficient and conflicting solutions.

3. A Novel Systemic Framework

Recognizing the recent conceptual advances in the field of drought evolution, drought and society, socio-hydrology and complex risk (incl. compounding, cascading, systemic and multi-risk), we aim to bring together these separate contributions into a comprehensive framework to advance drought risk research. We propose a novel conceptual framework that captures the complex, dynamic and non-linear interactions of drought (and possible concurring) hazards, direct and indirect exposures and vulnerabilities of interconnected sectors and systems across scales from a systemic perspective (Figure 1). This framework aims to provide guidance for drought risks assessments and the identification of integrated solutions to reduce and manage risks holistically which in turn can help to inform drought policies now and in the future.

Persistent anomalies in large-scale atmospheric circulation patterns leading to reduced rainfall and/or increased temperatures can cascade through the hydrological cycle leading to severe droughts, with less water than normal in snow packs, soils, groundwater and surface water bodies—aggravated or alleviated by human activities (Figure 1, panel a), such as water abstractions (Di Baldassarre et al., 2018; Van Loon et al., 2022) and water use regulations. The severity of the resulting impacts, however, depends on the vulnerability of who or what is exposed to specific water shortages (Gonzáles Tánago et al., 2016; Hagenlocher et al., 2019; IPCC, 2022; UNDRR, 2021). Analyzing the root causes and dynamics of direct and indirect exposure and vulnerability of communities, interconnected economic sectors and human and natural systems (e.g., ecosystems) is therefore vital to understand why communities, sectors or systems facing the same drought event may experience fundamentally different impacts (Figure 1, panel a). For example, the 2018 drought event that led to widespread water shortages and almost to "Day Zero" in Cape Town has shown that human actions exacerbated the drought hazard (here: streamflow, reservoir and groundwater storage) through overconsumption, but also that socio-economic disparities influenced access to information as well as the choices households had to prepare for and cope with the drought (Savelli et al., 2021, 2023; Ziervogel, 2019). In a review of governmental financial assistance in Tropical Asian countries, Goodwin et al. (2022) found that even when institutional schemes are available, high levels of social vulnerability prevent many potential beneficiaries from accessing them, therefore leaving vulnerable communities/sectors (e.g., farmers) with little to no options to cope with drought impacts. The impacts of droughts, however, are not only exacerbated or ameliorated by social, economic, or institutional factors that influence societal susceptibilities and the ability of communities economic sectors and systems to cope and adapt,

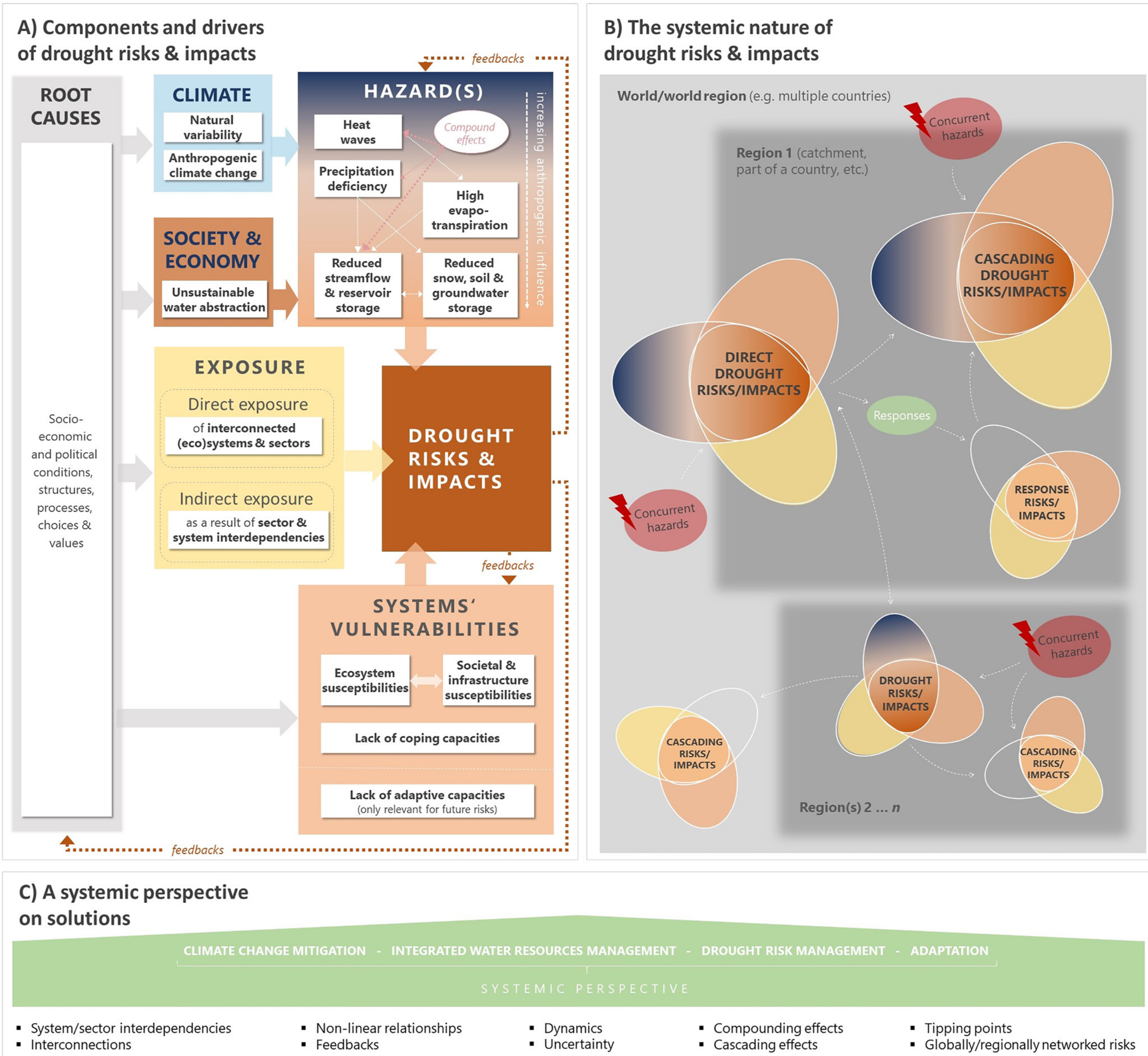

Figure 1. Characterizing the systemic nature of drought risks and impacts: (a) drought risks and impacts for communities, sectors and systems result from the complex, dynamic, non-linear interaction of drought hazards, direct and indirect exposure and systems' vulnerabilities. Drought hazards are influenced by climate change as well as societal pressures on water resources, such as unsustainable water abstraction leading to water scarcity. Underlying these components of risks are root causes that stem from socio-economic and political structures, processes, choices and values. (b) Direct drought risks and impacts can lead to further cascading effects on communities, sectors and systems in the same region or distant areas (indicated as region(s) 2 to n) which are not necessarily directly affected by the drought hazard (indicated by a blank hazard propeller) as a result of indirect exposures through the interdependence of sectors and systems and their vulnerabilities. Often these risks and impacts are compounded and further exacerbated by concurrent hazards. Furthermore, risk management and adaptation responses to drought impacts can lead to possible response risks. (c) The systemic nature of drought risks calls for systemic solutions, that is, actions that consider system/sector interdependencies, interconnections, non-linear relationships, feedbacks, dynamics, compounding and cascading effects, possible tipping points, globally/regionally networked risks, and account for uncertainty.

but are also directly linked to physical and biological factors determining the susceptibility of ecosystems and the services they provide (Figure 1, panel a).

As a result of the interdependence of economic sectors and systems in our highly connected world, direct drought risks and impacts can lead to cascading effects (Figure 1, panel b) on (a) other sectors and systems in the same region, (b) other regions that are not even directly affected by the drought hazard or (c) global repercussions

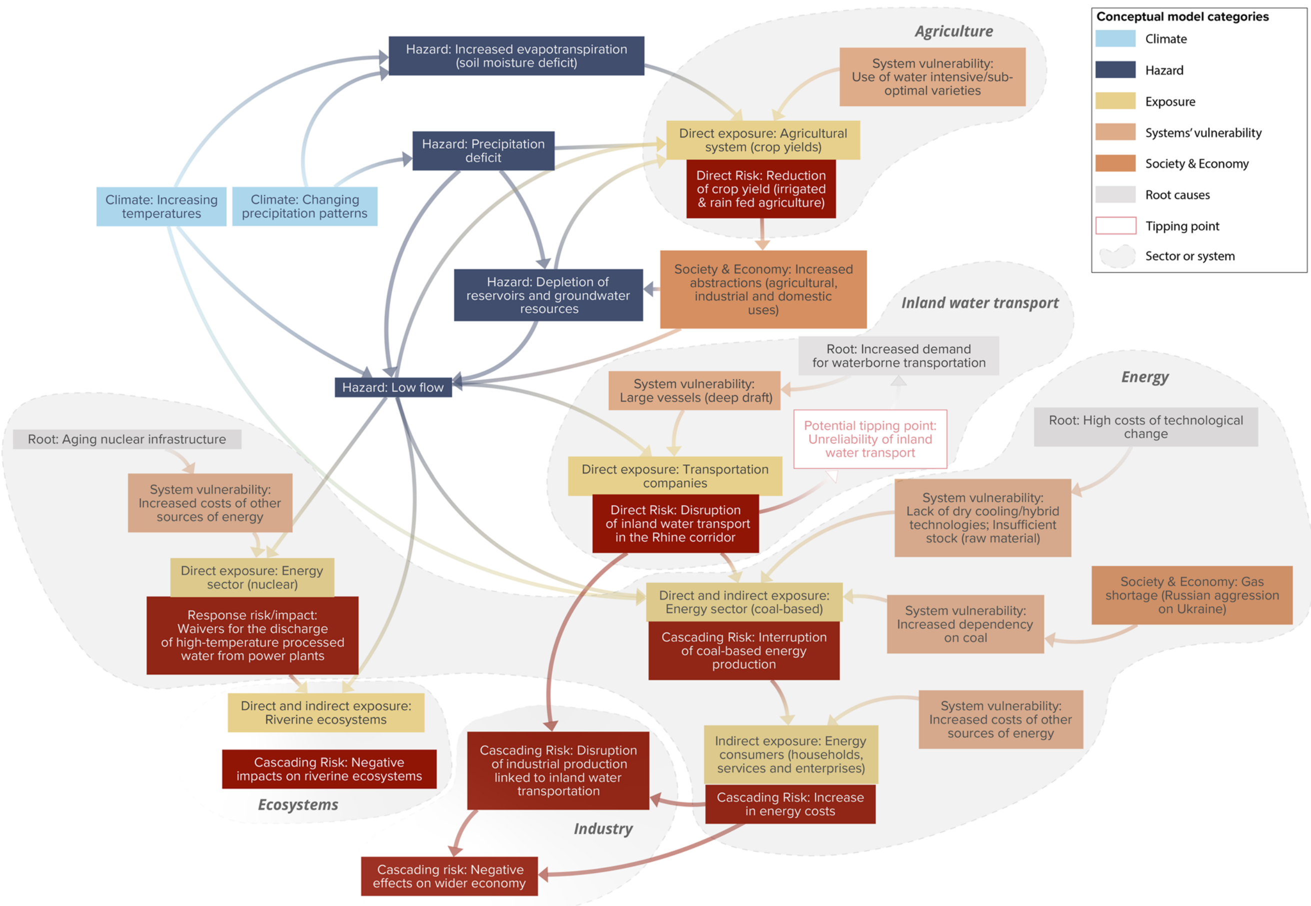

Figure 2. Application of the conceptual risk framework to illustrate the systemic nature of drought risks and impacts using the drought that affected Europe in summer 2022 as an illustrative example (cf. text below for a description). The figure applies the categories of the conceptual risk framework (Figure 1) to the example (see legend in top right corner), using connectors to showcase the relationships between interconnected risks and drivers. To facilitate the interpretation, elements were clustered in sectors or system of interest (gray shading).

(Challinor et al., 2018; Chatzopoulos et al., 2020; UNDRR, 2021). At the same time, research has shown that responses to climate-related hazards such as droughts can also lead to response risks (IPCC, 2022). For example, Di Baldassarre et al. (2018) have highlighted how the establishment of reservoirs in response to droughts can lead to an overreliance on these reservoirs and in turn increase the vulnerability of communities, sectors and systems to droughts. This is reflected by the propeller labeled "response risks/impacts" in the framework shown in Figure 1 (panel b). Furthermore, often the effects of droughts are compounded by concurring hazards and shocks (Kreibich et al., 2022; Lin et al., 2023; Mishra et al., 2021; Mukherjee & Mishra, 2020; Singh et al., 2022; Toreti et al., 2019; Yaddanapudi & Mishra, 2022) and their risk management strategies (e.g., Ward et al., 2020), such as heat waves, wildfires, floods, global pandemics or armed conflict as the global COVID-19 pandemic and the Russian aggression on Ukraine have revealed (Figure 1, panel b). Given the systemic nature of risks, a systemic perspective is also needed to manage and adapt to growing drought risks (Figure 1, panel c). These solutions should not only consider the drivers of drought risks presented in Figure 1 (panel a), but also be based on an understanding of key characteristics of the systemic nature of drought risks, such as sector/system interdependencies, feedbacks, dynamics, compounding and concurring hazards, as well as possible tipping points and globally and/or regionally networked risks.

To illustrate how the framework can be applied, we draw on lessons from the concurrent drought and heat wave event that affected Europe in the summer of 2022 to illustrate the systemic nature of drought risks and impacts across economic sectors and systems (Figure 2).

Europe is widely understood to be at risk of suffering major and costly cross-sectoral impacts from droughts, especially in the context of expected climate change (Naumann et al., 2021). In the summer of 2022, a concurrent

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drought (which already started in winter with precipitation deficits) compounded with a sequence of heat waves affected Europe (Copernicus Climate Change Service, 2023; Toreti et al., 2022b). These manifested in a precipitation deficit as well as increased evapotranspiration, contributing to significant low flows in surface water, a reduction of soil moisture and of the water volume stored in reservoirs (Baruth et al., 2022a, 2022b; Toreti et al., 2022a). Consequently, reduced water availability resulted in water demands for both rain fed and irrigated agriculture not being met, which negatively affected crop yields in large parts of Europe (Baruth et al., 2022a, 2022b, 2023; BMEL, 2022). Water intensive crop varieties, such as rice, were particularly affected, resulting also in a decrease in farmers' sowing area and high percentages of unproductive fields (Baruth et al., 2022a; Ente Nazionale Risi, 2022). Compounding with decreased water availability, the decrease in yield was exacerbated by the acceleration in the phenological cycle induced by increased temperatures/heat stress, which reduced the length of the grain filling phase (Baruth et al., 2022a, 2022b, 2023). As a response to the unavailability of sufficient surface water, multiple European countries restricted abstractions for irrigation purposes (ibid.) in order to reduce the competition for water resources between sectors (Toreti et al., 2022a) which was also a partial cause for yield losses.

The 2022 low flow event also had severe effects on major European rivers, such as the Rhine corridor (Toreti et al., 2022a), where it significantly affected the inland water transport (IWT) sector. The Rhine is one of the river systems that compose the European network of almost 40,000 km of navigable inland waterways. This network has undergone exponential growth in terms of traffic and tonnage of goods transported in the last four decades (Notteboom, 2007), establishing itself as a reliable and high-capacity mode of transportation for a variety of goods, including raw materials. This means that disruptions of IWT can be of significant importance for the region and beyond. Driven by the growth of IWT volumes (Vinke et al., 2022)—a reflection of the increase in global maritime container transport (Bishop et al., 2011; Corbett et al., 2010; Notteboom, 2007)—riverine transportation companies increasingly make use of large vessels with deep drafts. Because of the reduced navigable depth during the low flow in the Rhine, such vessels had to restrict their load factors, in order to decrease their drafts and still be able to navigate safely (Federal Institute of Hydrology, 2022). In addition to transportation surcharges (Federal Institute of Hydrology, 2022), this load reduction affected, for instance, coal and oil transport in the Netherlands (Toreti et al., 2022c). Moreover, to compensate for the reduced loads, a higher number of vessels had to be employed (Wrede, 2022), a response that can lead to an increase in traffic intensity and berth occupancy in ports (Vinke et al., 2022). Added to the reduced vessel speeds resulting from the low water depth at local levels, this contributed to further delays and interruptions of deliveries of goods in the Rhine corridor (Connolly, 2022; Wrede, 2022).

The high level of interconnectedness between different sectors and systems meant that the disruption of IWT in the Rhine posed for example, a cascading risk for the coal-based energy sector, notably in Germany, which is dependent on riverine transport of the raw material. Especially since the gas shortages caused by the Russian aggression on Ukraine, the European energy sector has an increased dependency on coal (European Commission, 2022a; Wrede, 2022), which augments its vulnerability to shortages of the material. For example, in the third quarter of 2022 more than 36% of the total energy produced in Germany stemmed from coal, with an increase of over 13% compared to the same quarter in 2021 (DESTATIS, 2022). It is not inconceivable that an increased recurrence of prolonged low-flow conditions due to climate change may push the sector to a tipping point, where other industries might look into alternative supply chains to avoid regular disruptions.

At the same time, thermoelectric energy production is directly dependent on water at a suitable temperature for power plant cooling (De Stefano et al., 2015). This means that warmer river water as a result of the heatwave has a decreased plant cooling capacity, making it unsuitable for this purpose (De Stefano et al., 2015). Moreover, the excessive discharge of the warmed-up water used for cooling processes back into the river is a major disturbance to riverine ecosystems due to its disruption of the environmental flow, and as such is usually regulated through a restriction of abstractions and discharge in case of too high temperatures (Carlino et al., 2021; De Stefano et al., 2015). In France, however, these restrictions were waived in 2022 for operational nuclear plants to avoid further disruption to production, given the unavailability of multiple other plants due to maintenance (Boulle, 2022). As such, this constitutes an example of response risk, whereby an intervention to safeguard a system (energy) resulted in aggravated negative consequences for another (riverine ecosystems). Outside this specific case, pre-existing drivers of vulnerability contributed to impacts in the energy sector. The lack of implementation by energy producers of dry and hybrid cooling technologies due to the high costs of technological change exacerbates this problem, which is aggravated during low-flows (De Stefano et al., 2015). As a result of these processes and cascading impacts, energy prices in Europe soared during summer 2022, affecting consumers all throughout the continent (European Commission, 2022b).

As highlighted in our framework, understanding growing drought risks for people, communities, economic sectors and systems hence calls for a systems perspective that considers the non-linear feedbacks and dynamics between human, environmental, technological and governance-related drivers of multiple interconnected drought risks. Accordingly, in our highly interconnected world, where the effects of droughts on one sector or system can lead to cascading effects on other sectors and systems even in distant areas, that is, regionally or globally networked risks (Challinor et al., 2018; Chatzopoulos et al., 2020), more efforts are needed to better understand and map how sectors and systems are interconnected in order to strengthen resilience towards cascading effects and reduce the risk of systemic failures. While the framework has been designed with a specific view on droughts (Figure 1a), elements of it, such as the notion of the systemic nature of risks, impacts and responses (Figure 1b) and the systemic perspective on possible solutions (Figure 1c), can also inform research and policies linked to other hazards and shocks where systemic perspectives are also less common to date.

4. Implications for Drought Risk Management

In times when interconnectedness characterizes growing drought risks, we need to move beyond crisis and hazard-oriented, sectoral perspectives, and instead develop just/fair, prospective, risk-informed, multi-scale, multi-sectoral and adaptive drought risk management policies, plans and strategies that consider the whole spectrum of compounding and cascading effects. The proposed novel conceptual framework offers an entry point to understand this complexity, and aims to inspire addressing growing drought risks from a systemic lens. This implies that for managing the systemic nature of drought risks, we need to expand and broaden the actor space toward a transdisciplinary, whole-of-society approach. To achieve this, multi-level governance frameworks and associated working groups that share responsibilities for drought risk/water management and increase collaboration across sectors, spatial scales, borders and actors (incl. citizens, authorities, private sector, civil society organizations, decision makers), are needed (Blauhut et al., 2022; UNDRR, 2021), calling for institutional reform where these are not in place.

Addressing the systemic nature of drought risks requires actions in multiple domains. First and foremost, more actions are needed to prevent drought hazards from becoming more frequent and severe. This includes accelerated and deeper efforts for greenhouse gas emissions reductions to tackle anthropogenic climate change. To limit the impacts of droughts, it is also important to incentivize sustainable water management, including water saving, equitable water sharing and ecosystem restoration practices. In addition, an enhanced evidence base is needed on direct as well as cascading and systemic impacts of droughts, responses and adaptation to drought, and their feedback on vulnerability dynamics of systems and sectors. Drought hazard monitoring, forecasting and impact-based warning capacities should be strengthened and scaled up, but also approaches and methods for systemic risk assessment should be developed that can provide actionable knowledge for comprehensive drought risk management and adaptation.

New analytical tools have become available that could support these efforts. In particular, the emergence of systems thinking, network and system approaches, such as causal loop diagrams or impact webs (Sparkes et al., 2023), but also agent-based modeling (e.g., Wens et al., 2019) are promising developments for systemic risk analysis. Scenarios, serious games and adaptation pathways (Schlumberger et al., 2022; Werners et al., 2021) can be useful tools to bring stakeholders together to engage with the complexity of drought risks, and co-create pathways toward systemic risk management—both in the short and the long-term.

All this means that we, as society as a whole, need to be open to transformative and more radical changes to our risk management approach overall. For example, existing water/drought risk management and adaptation plans and strategies should be reviewed, and where necessary revised, to evaluate if and how these are cognizant of possible compounding, cascading and systemic effects of droughts and potentially concurring hazards, and also of possible response risks and maladaptations. In some cases this might require transformation of the water management system, rather than modest revision and optimization (Bartholomeus et al., 2023). As risks cannot be eliminated from systems, managing the systemic nature of drought risks also implies that we have to engage with questions of which risk levels are acceptable and fair for whom, and if, and how, the possible impacts of exceeding safe and just water boundaries can be transferred for example, through drought/climate risk insurance or financial instruments, such as dedicated drought funds. Further, as the COVID-19 pandemic has shown, scaling up social protection might also help buffering against the direct and cascading effects of hazards and prevent people from falling (back) into poverty (UNDRR & UNU-EHS, 2022). If we want to achieve the goals of the Sendai Framework and the SDGs, supra-national systemic efforts are needed to address the transboundary effects and globally networked risks linked to droughts. Without these changes, despite our best efforts, adverse impacts of droughts will further increase, and stories of successful drought risk management will remain scarce (Kreibich et al., 2022), thus undermining sustainable development.

Data Availability Statement

This commentary reflects the opinion of the authors and does not build on any specific data next to the references listed in the manuscript.

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