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Review

Implications of Regional Droughts and Transboundary Drought Risks on Drought Monitoring and Early Warning: A Review

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Abstract: Regional droughts are increasing in frequency and climate change projections indicate an exacerbation in the occurrence of regional droughts in the future. Droughts are complex hydrometeorological events, and the complexity of cause-and-effect relationships across administrative and political borders can make drought management a challenge. While countries are largely focused on assessing drought impacts within their borders, thereby providing focused information for the relevant administration, the impact on communities, industries, and countries that are distantly connected with the affected location must also be taken into consideration. If not considered, drought impacts can be underestimated, and adaptation actions undertaken may not completely address the drought risks. Understanding transboundary drought risks is an important and integral part of drought risk reduction and it will grow in importance as the world experiences more integration at regional and global levels on multiple fronts. To address drought risks comprehensively, the new paradigm demands that the impacts of regional droughts are fully understood, that this understanding is incorporated into drought monitoring and early warning systems, and that drought early warning information is provided to all stakeholders, including those beyond the boundaries of the affected region, thereby eliciting appropriate action.

Keywords: regional droughts; transboundary drought risks; drought monitoring; early warning; impact-based early warning

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1. Introduction

Drought is a slow-onset disaster. It is a recurring feature for many countries where it often manifests due to a range of climatic, environmental, and socio-economic factors. Droughts occur in various degrees of intensity, extending from local, mild, and seasonal to regional, chronic, and multi-year droughts. While individual countries have been trying to manage droughts that are local and seasonal, they often cannot manage severe, regional, multi-year droughts that have transboundary implications [1,2].

In a globalized world, where regional and global integration is taking place at a rapid pace, the impacts of a drought felt in one country or region can often spill across boundaries, affecting countries and populations beyond the original location of the drought. It is vital to understand how the risks of drought can extend to distant places to carry out effective drought monitoring and early warning.

In general, droughts are more regionally-based compared to other disasters—floods and landslides tend to have a clear demarcation in terms of the regions that are affected. Droughts are classified in various ways. Wilhite and Glantz (1985) identified nearly 150 published definitions of droughts [3]. Using a disciplinary perspective, they classified droughts into meteorological, climatological, atmospheric, agricultural, hydrologic, and water-management droughts. After considering the complexity of drought classification, they proposed to simplify the classification into meteorological, agricultural, hydrologic, and socio-economic droughts. However, this classification still follows a disciplinary perspective. They also indicated that droughts can also be characterized in terms of their intensity, duration, and geographical extent. In terms of geographical extent, droughts can be classified as local, national, or regional [4,5]. Geographical classification provides an important administrative advantage when governments want to communicate and declare droughts. For example, often, governments declare a drought as a 'national drought' if the extent of the drought covers a major part of a country as per the laid-out definitions. Similarly, droughts may be evaluated at the district level and state level as in the case of India [6]. While all kinds of droughts have the potential to impact large sections of society within and outside the area they occur, the focus of this paper is especially on droughts that span multiple administrative and political boundaries, posing specific challenges in terms of drought governance including monitoring, early warning, and using this information for appropriate and coordinated decision-making [7].

Regional droughts are on the rise. Singh et al. (2022) reported a significant rise in the intensity and frequency of regional droughts between 1971 and 2000 [8]. According to this analysis, the historical occurrence of moderate regional droughts doubled, and these regional droughts are projected to continue to increase until the late 21st century (2071–2100). Aadhar and Mishra (2021) projected that the South Asian region will see a 1.5 increase in regional droughts between 2035 and 2100 [9]. These trends signify the need to understand regional droughts so that monitoring and early warning systems can be properly developed and used.

Major regional and transboundary droughts are often extremely difficult to monitor, evaluate, and manage since the cause-and-effect relationships in such droughts are spread across a wide geographical region and often span political boundaries. Thus, it requires a great degree of transboundary cooperation and coordination among institutions and governments to assess, understand, and manage both the impact of the drought and its underlying factors [10]. As globalization continues to grow, we will see even more regional and global integration encompassing society, economy, financial markets, supply chains, and human mobility, and thus the impacts of drought also become more complex. Understanding and addressing these complexities is of utmost importance, especially in a changing climate that tends to compound and multiply risks.

There has been a very limited understanding of regional droughts and of transboundary drought risks that could pose serious challenges to drought risk management and risk reduction [11,12]. Garrick et al. (2018) studied the institutional fragmentation across drought-affected regions covering multiple countries, and identified how such fragmentation hinders effective drought response [13]. They have identified a lack of coordination in drought monitoring and early warning systems as one of the critical hurdles in drought risk reduction in a transboundary context. They argued that institutional fragmentation across borders can lead to undesired impacts across societies. Designing effective drought monitoring and early warning systems require a deeper understanding of the nature of the transboundary risks. It is vital to incorporate this understanding into the technical aspects of monitoring and early warning, communicate this early warning to relevant stakeholders, and then make sure that the early warning system incites appropriate and prompt action [14].

In light of the above, this paper aims to provide an understanding of the transboundary risk aspects of regional and transboundary droughts, by evaluating historical droughts, succinctly looking into various early warning systems in terms of their suitability to address concerns from regional and transboundary drought risks, and provide some suggestions for improving the drought monitoring and early warning systems. The paper achieves this by reviewing the pertinent literature.

2. Characterizing the Transboundary Nature of Droughts

Droughts have been studied for their severe and debilitating socio-economic impacts [15]. Droughts that are prolonged, those that span administrative and political boundaries, and those that cover multiple countries have also been studied [8]. Several efforts have also been made to understand the implications of droughts and for building regional drought monitoring and early warning systems [15–21]. These past efforts signify the need to understand and address regional droughts. These kinds of droughts are also often not well managed due to issues posed by political and geographical boundaries. Such issues are particularly relevant when it comes to how the drought is monitored, how the early warning information is generated and shared, and how drought risk reduction decisions are made and implemented.

2.1. Understanding Regional Droughts and Transboundary Drought Risks

There is a need to understand distinctions and commonalities between regional droughts (also termed transboundary droughts) and transboundary drought risks for their implications for drought monitoring and early warning, and drought risk reduction, since this terminology may create some confusion. To better understand the transboundary nature of droughts, both as a transboundary disaster and as a transboundary risk, it is important to have an overall understanding of how hazards and disasters manifest their impacts across boundaries. Some of these concepts are elaborated on in this section.

Transboundary droughts are those droughts that take place across wide regions spanning the boundaries of several provinces within a country or a group of countries (Figure 1). A regional drought is a transboundary drought. Some authors have also used the phrase 'compound droughts' for regional droughts [8]. The boundaries here can be administrative boundaries within a country or the political boundaries of countries. Boundaries can also be viewed as imaginary lines drawn across physical natural resources such as transboundary rivers which delineate the original catchment area of the river. In the case of major and multi-country rivers, the catchment can occupy several countries posing challenges to the way water resources are amicably managed.

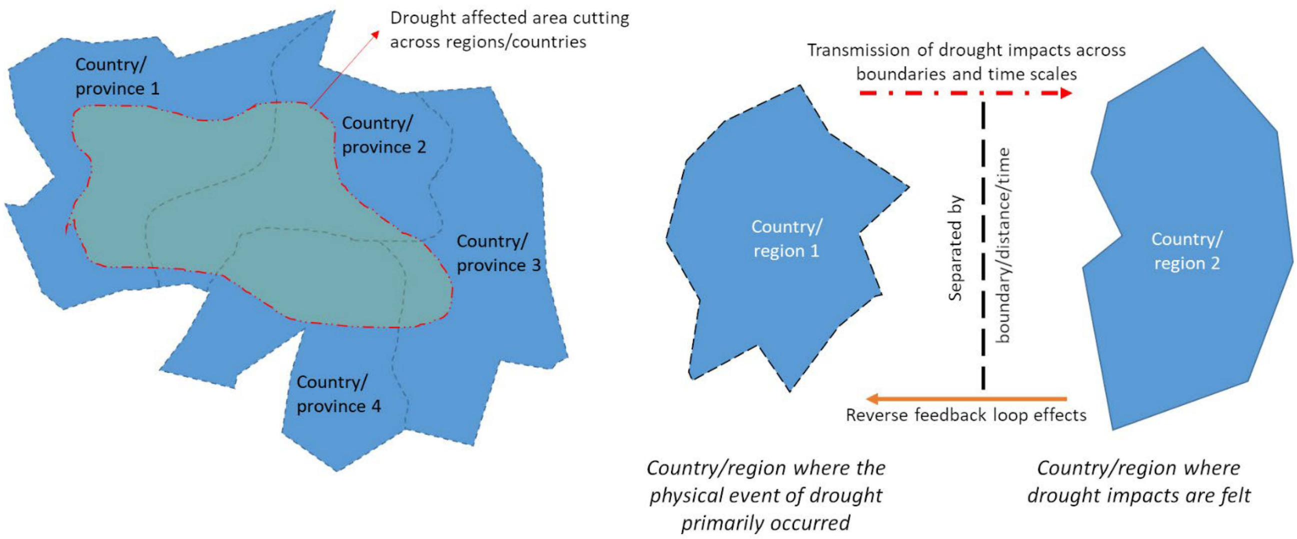

Figure 1. The distinction between a regional drought (**image on the left**) and transboundary drought risk (**image on the right**). The figure on the right depicts how drought risks are transmitted across boundaries.

Transboundary risks can be defined as the impacts of a disaster or a climatic event in countries and regions far from the location where the physical event originally occurred. In other words, the impacts of the drought are not only felt by the country where the physical drought event originally took place but are also felt by a distant population, country, or region with some kind of dependency on the original drought location. There are several examples of such droughts in the recent past. For example, the impacts of the 2008 global food price crisis such as food price rise, loss of livelihoods, and negative health impacts were felt across the world, although the events leading to the food price crisis occurred in only a few countries, i.e., droughts in Australia, land conversion to biofuels in Asia, and food export restrictions imposed by India and the Philippines [22].

2.2. Understanding the Impacts of Regional Droughts

Table 1 lists some examples of droughts, providing some insights into the common transboundary implications, some of which are discussed in this paper. Identifying transboundary implications of droughts can be challenging especially for the multi-country regional droughts when the drought events are prolonged and when drought impacts are mixed with other economic factors at the macro level. Hence, the transboundary implications listed in the table need careful examination. The transboundary implications column presents prominent impacts beyond the area where the drought occurred.

Table 1. Regional droughts and other events with transboundary risk implications.

S No	Drought Event	Transboundary Implications
1	India, droughts of 2008, 2016–2018, 2019	• A decline in the flow of rivers, and a decline in hydroelectricity generation; • Impact on the national economy with considerable effect on national Gross Domestic Product (GDP) especially from the agriculture sector and related secondary sectors.
2	Australia, the drought of 2017–2019	• Loss of jobs in adjacent provinces; • Loss of national-level welfare in GDP; • A decline in international export of food grains.
3	China, the drought of 2009	• Impact on flows of major rivers of Pearl and Yangtze; • Reduced hydropower electricity generation; • Reduced food production in the major food production area.
4	South Asia, the drought of 1999–2006	• Reduction in soil moisture and damage to the second crop; • Increased food import dependency; • Reduced exports and impact on the global economy.
5	Southeast Asia, the drought of 2019–2020	• Increased saline water intrusion; • Reduced flows in transboundary rivers; • Impact on regional food prices and food exports.
6	North America and Eastern Europe, the drought of 2018	• Reduced food exports; • Impact on global food prices.
7	Several drought events in Eastern Africa	• Reduced flow into Lake Victoria due to droughts in Kenya, Uganda, Tanzania, Burundi, and Rwanda; • Reduced fish catch in transboundary rivers and lakes; • Increased livestock migration and transboundary pastoralist migration.

Source: Author.

Regional droughts can be classified into two categories: (a) droughts in a large stretch of areas within a country covering several provinces (referred to as in-country regional droughts from here onwards), and (b) multi-country regional droughts that span several countries often involving a sub-continent or a continent. In-country regional droughts are much more prominent than multi-country regional droughts and these droughts can differ in their impacts as will be discussed subsequently in this paper. In-country regional droughts pose a challenge for drought management by local governments in terms of cooperating and coordinating with other provinces and with the national government which often share considerable responsibility in drought risk management. However, it is relatively easy to build a monitoring and early warning system for these droughts due to institutional and data connectivity within a country. This paper discusses several in-country regional droughts that affected millions of people across multiple provinces in Australia, China, and India.

Multi-country regional droughts pose similar challenges as the in-country regional droughts except that in this case, coordination and cooperation challenges emanate between different national governments and it is often challenging to overcome these limitations. There is relatively scant evidence in the literature on transboundary impacts of multi-country regional droughts compared to in-country regional droughts and such evidence is more recent.

2.2.1. In-Country Regional Droughts

Several central Indian states were severely affected by a drought associated with the positive Indian Ocean Dipole (IOD) during the summer monsoon months of June–September, 2008 [23]. The drought was attributed to the abnormally high sea surface temperatures of the southern tropical Indian Ocean. The drought was further strengthened by ocean–atmospheric processes and climate change as identified through experiments conducted in the atmospheric general circulation models.

Between 2016 and 2018, several states in southern India, including Karnataka, Andhra Pradesh, and Tamil Nadu, declared severe drought that affected nearly 60% of the population in these states [24]. The drought was estimated to be more severe than the great drought of 1874 which resulted in the Madras famine of 1876 due to the failure of consecutive monsoon seasons. During this period, the region experienced a rainfall deficit of 45.4%. The precipitation deficit was much higher in 2016 at 63%. One of the reasons for the rainfall deficit was found to be cool sea surface temperatures in the tropical Indo–Pacific Ocean region which was associated with La Nina conditions in the central Pacific and negative Indian Ocean Dipole conditions in the Indian Ocean. During this drought, not only did field crops suffer but severe water scarcity was observed in megacities such as Chennai. The economic impact of the drought in these states was estimated to be in the range of 2–5% [11].

The Indian drought of 2019 affected nearly 500 million people and it was seen as a compounding impact of the drought conditions that prevailed during 2016–2018. Ten Indian states were affected by the drought and six of the affected states declared droughts [25]. In terms of the transboundary impacts of these droughts, they resulted in a decline in the flow of major rivers such as River Krishna which runs through the states of Maharashtra, Karnataka, Andhra Pradesh and Telangana. Consequently, a water deficit extended to the entire riverine region. Moreover, the reduction in river flow severely affected electricity generation.

Similarly, the Australian drought of 2017–2019 deserves special attention for its transboundary implications. The drought-affected several states, including New South Wales, Victoria, parts of South Australia, and southern areas of Western Australia. The Murray–Darling Basin received 100 mm record low rainfall compared to Australia's previous second driest period. New South Wales received 170 mm less rainfall than the previous driest period in the state [26]. As a result, Australia's national GDP declined by 0.7% and the GDP of New South Wales fell by 1.1% in 2018 and 1.6% by 2019 [27]. Agricultural growth declined as capital investments were affected by the prolonged drought. Furthermore, the drought even had an impact on non-drought-affected areas as well, since jobs in these areas depended heavily on the agricultural outputs of the drought-affected regions. The loss of jobs in non-drought affected areas was estimated to be 0.8% below the forecast [28]. Consequently, the national welfare loss was estimated to be USD 63 billion. International agricultural exports were also severely affected by the drought.

Historically, China is affected by severe, regional, and multi-year droughts [29]. Every year, drought-related crop losses in China are put in the range of 4–8% [29,30]. Although droughts occur in most parts of the country, areas in Northwest China, the southwest of Tibet, Huanghuaihai Plain, and Yunnan–Guizhou Plateau are often considered drought epicentres. Research has indicated numerous active drought processes in the country. Cai et al. (2021) reported 75 regional drought processes in North China alone [31]. Through spatio-temporal analysis, it was found that the droughts in the North and Northeast regions are becoming more severe and longer in duration [30]. In recent times, the drought of 2009 can be identified as one such severe drought, affecting 46.7% of the population in China [32], largely due to low precipitation and high temperatures. The drought-affected 157 Mha of farmland in North China alone. The drought also affected flows in the Pearl and Yangtze rivers as they mainly derive water from the southwest region. These rivers also supply water to nearly 70% of the hydroelectric plants in the country. Consequently, hydroelectric power production was severely affected, resulting in impacts on the rest of the nation [33]. Furthermore, the drought also affected food production in Northern China, as a supplier of food grains to the rest of the country. These experiences prove that transboundary drought risks abound and there is a need to deepen our understanding of such risks.

2.2.2. Multi-Country Regional Droughts

Multi-country regional droughts are the least studied droughts, especially in terms of their transboundary implications. South Asia receives nearly 80% of its rainfall through the summer monsoon from June to September [9]. Aadhar and Mishra (2021) analyzed one of the worst soil moisture droughts during 1999–2006 (identified as the 2002 drought) that affected nearly 65% of South Asia and consequently, paddy crop yields dropped substantially to below 0.5 tons per hectare. The drought had a severe impact on post-monsoon water availability from October to December due to increased air temperatures that further depleted soil moisture. As a result of widespread crop failure, the total value of imports rose from USD 57 billion in 2002 to USD 72 billion in 2003 [34]. The impact of the drought on Pakistan's national economy was estimated to be 1.5% [35]. Along with an increased dependency on food imports, the impact on the balance of trade was also adversely affected. The import of food items in the region rose by USD 2.54 billion in 1999 from USD 5.09 billion in 1995, a 50% increase in 5 years [36].

Several Southeast Asian countries, including Thailand, Vietnam, Singapore, and Malaysia, were severely affected by a regional drought in 2014. In 2019–2020, the number of countries affected by drought increased to nine countries in the Southeast Asian region, all apart from Singapore, due to severe El Nino conditions [37], with nearly 52 million people affected. The rainfall in some areas of the region was below 40% of the normal amount. Consequently, water levels in several reservoirs were reduced to 20–60% of their designed capacity [37]. During this drought, the Mekong River flow was severely reduced, recording one of the lowest flows in the past 40 years [38] due to the combined effect of low rainfall in the river catchment area and reduced inflow from China.

The low flow observed in the Mekong River during the 2019–2020 drought was estimated to have a return period of 50–100 years. Some compounding impacts of droughts could be seen during the drought. For example, in Vietnam, the drought-related reduction in river flow led to the intrusion of saline water in several rivers, which affected agricultural production and further exaggerated drought conditions [39]. Additionally, the drought coincided with one of the worst pandemics of the century, COVID-19, and so more compounding impacts were observed. These include constraints on local administration and other stakeholders in implementing community outreach measures such as relief distribution, and in implementing other drought alleviation measures which were further hampered by the heavy economic burden of the drought and pandemic-related economic stress [39].

In Southeast Asia, an interesting case of transboundary drought impacts can be found between Malaysia and Singapore. More than half of Singapore's water needs are met from the water supplied from the Johor River in Malaysia, which has been possible thanks to a water agreement signed between both countries in 1962 that will expire in 2061 [40]. Past experiences suggest that during drought spells in the Johor state of Malaysia, combined with saline water intrusion, serious water shortages were observed in Singapore [41]. Due to decreased water supply from the source, impacts such as the decline in water quality, a decline in the water rationed to consumers, and increased energy consumption for water treatment for the production of NEWater (recycled water that is purified using membrane technologies and ultra-violet disinfection) were observed in Singapore.

The drought of 2018 and associated heat waves affected crop production in several countries of North America and Eastern Europe. Some of these regions make significant contributions to global food exports and are known as the food baskets of the world. In this way, drought can affect food exports and food security for millions of people [42]. However, there are very few cross-border drought impact assessments that consider the future changing climate. Ercin et al. (2021) assess the cross-border impacts of future droughts on the European Union (EU) and concluded that 44% of EU agricultural imports will become vulnerable to droughts occurring in Indonesia, India, Brazil, Thailand, Vietnam, and Turkey by 2050.

African countries are highly vulnerable to drought. In 2019, nearly 9.3 million people were affected by droughts in East and Southern Africa [43]. The analysis of historical droughts in Africa suggests that droughts have become frequent, intense, and widespread, particularly over the past 50 years [44]. The frequency and intensity of droughts are projected to increase in the future, particularly in Southern Africa [45]. Africa is unique in that it has experienced more continental droughts than any other region in the world. In addition, Africa has also experienced a significant number of multi-year droughts, with northwest Africa, eastern Africa, and southern and southeastern Africa having experienced severe droughts in the past 50 years. Furthermore, droughts in Africa have transboundary implications. African countries formed the African Union which has greatly facilitated transboundary trade and human mobility. Eight regional economic communities facilitate regional trade and cooperation on several fronts of development. These regional integration mechanisms act as conduits for the transmission of drought impacts from one country to another, similar to other regions described above. Consequently, drought conditions in large parts of Africa remain an endemic problem. Even if a drought happens elsewhere in Africa, other countries on the continent are often exposed to the impacts of these droughts.

African water bodies, such as Lake Chad and Lake Victoria, are regional in nature as they draw water from a wide basin spanning multiple countries. This means that drought in any country can severally affect the water level in these lakes, impacting all the countries and communities that depend on these lakes. In addition, African countries are also highly vulnerable to droughts happening outside the African continent as many African countries are dependent on imported food. For example, countries such as Senegal and Nigeria are highly dependent on imported food and faced severe food scarcity in 2007–2008 as droughts in exporting countries led to a ban on food exports [46]. Several African countries are also facing rapid desertification—the process of desertification is a true transboundary event and repeated droughts further expose these countries to a deepening of the desertification process. Similarly, locust movements are often influenced by droughts. As an example, when drought occurs in Malawi, the border areas of Mozambique are also affected by locusts [47].

In summation of the above-discussed cases, it is evident that the regional droughts not only affect monsoon crops, but also affect groundwater recharge and surface water reservoirs including lakes and depressions. These tend to dry out leading to the failure of crop production in the subsequent seasons. Seasonal winter crops often rely on residual soil moisture from the previous monsoon season and also rely on irrigation facilities that are recharged by the surface runoff from monsoon rains [48]. Furthermore, prolonged droughts push farmers to rely on groundwater leading to long-term groundwater depletion that could further intensify the short-term meteorological droughts that otherwise could have been ameliorated by relying on groundwater [49]. As a result, these droughts have the potential to affect wider areas, larger sections of the society, multiple sectors, and for a longer period. Due to reduced economic activity in wider areas and sectors, the ability of national and local governments to manage drought impacts is severely hampered due to reduced government income.

2.3. Drivers of Transboundary Drought Risks

A study of past drought events revealed some of the major factors that could lead to the transmission of drought risks. These factors can be classified into two categories: (a) intrinsic drivers of the location where the drought event has taken place, and (b) extrinsic drivers of the location, i.e., the linkages of the location with the rest of the world, also known as network drivers. Climate change influences a range of intrinsic and extrinsic drivers, and these are discussed separately (it should be noted that extrinsic drivers are the large majority).

2.3.1. Intrinsic Drivers

Intrinsic characteristics of a location determine the degree or magnitude and the nature of drought risks that can be transmitted from the primarily affected location. Intrinsic drivers are largely related to the socio-economic and biophysical nature of the location and its people. Intrinsic drivers could include the exposure, sensitivity, and capacity of a location that predisposes it to drought. Factors such as heavy groundwater use with limited or no water recharge facilities, and crop production choices, such as growing wetland paddy using groundwater, could make an area vulnerable to drought over time. Furthermore, these factors could be overlooked by the administration until drought events become serious. Some of these factors can be seen in the case of the Barind Tract of Bangladesh where the groundwater extraction exceeded the rate of recharging [50].

Barind Tract in Bangladesh is a contiguous area that enjoyed sufficient water supply for an extended period due to the installation of groundwater tube wells, but the region reached a stage where the Government of Bangladesh had to declare a state of a water emergency, thereby halting permission for further groundwater withdrawal [51]. The lesson learned from this example is that short-term decisions can lead to long-term and serious drought issues. It proved to be a failure in groundwater monitoring since the existing mechanisms failed to forecast the impending water shortages once groundwater extraction continued beyond the recharge rate in the region. The agricultural prospects obtained during peak groundwater use did contribute to the socio-economic benefit of the people in the region. However, since no significant recharge mechanisms were implemented, the region's ability to export food was severely hampered, affecting regions that depended on such exports within Bangladesh. This is a clear example of how short-sighted policy decisions can have far-reaching consequences.

Other intrinsic drivers that could exacerbate drought include traditional drivers of drought such as population explosion that puts excessive demand on water, change in water allocation to different sectors including demand from households, manufacturing and agriculture sectors, type of crops grown (e.g., wetland paddy or sugarcane as opposed to upland crops), and the nature of irrigation practices (e.g., flood irrigation as opposed to furrow or intermittent wetting and drying).

2.3.2. Extrinsic Drivers

The extrinsic drivers of a location are also called its network drivers, and these determine the extent to which risks are transmitted, i.e., how far-reaching the risks can be. However, both the extrinsic and intrinsic drivers of a location can be related and, hence, they may not be mutually exclusive depending on the location-specific conditions. For example, a region that produces a particular type of crop for export purposes will have more pronounced transboundary risk implications than if the same crop is produced for domestic consumption with more local implications. One of the implications of network drivers is that drought exposure is enhanced especially on the downstream side of drought impacts since the impacts spread beyond the incident location. This understanding has implications even for drought risk and vulnerability assessments when the traditional approach has been to limit these assessments to a specific geographical area where the physical phenomenon of drought takes place.

When looking at the extrinsic drivers of a location, an understanding is required of the supply chains that connect the location with other regions in terms of input supply and marketing of outputs and produce. Understanding the extrinsic drivers of a location is important even if the location does not produce goods for export purposes. There are two reasons for this: (a) the region may depend on inputs that may originate from elsewhere, and (b) there may not be a choice in terms of where inputs come from. When regions depend on water coming from elsewhere, as in the case of an upstream or downstream location on a river or a city dependent on drinking water drawn from a distant river, then the decisions made by the upstream communities can have serious implications for those downstream. Similarly, the decisions made by the downstream communities can drive the upstream communities to make accommodative choices which could lead to conflicts and put pressure on institutions that carry out the management of water resources. Since supply chains cannot be organically arranged when and where required, a careful selection is necessary for supply chains and building supply chain resilience. These elements should be fully understood and factored in when putting drought monitoring and early warning systems in place.

Climate Change as a Driver

Climate change is a complex extrinsic driver and since it can influence both the intrinsic and extrinsic drivers, it deserves a separate discussion. Climate change will have profound implications for both regional droughts and the way the drought risks are transmitted [52]. Climate change acts as a risk multiplier and it can have a compounding effect on droughts. As a risk multiplier, climate change exaggerates the underlying vulnerabilities, by forcing communities to move closer to zones that are predisposed to disaster impacts [53,54]. For example, communities that are living in a social setup characterized by exclusion and other social disparities tend to be pushed closer to being affected by drought as climate change limits their access to natural resources during drought conditions [55].

The available evidence suggests that climate change will exacerbate regional droughts and compounding impacts of droughts by between 40% and 60% by the middle to late 21st century [8]. Further, Singh et al. (2022) concluded that the exposure of agriculture to severe and regional droughts will increase 10-fold in the future. Continents such as Australia are projected to experience mega-droughts or centennial droughts that can last longer than a decade [56]. Based on the historical study of mega-droughts in the Eemian climate of southeast Australia, McGowan et al. (2020) have cautioned that climate change could worsen drought conditions in the future.

According to Singh et al. (2022), the amplification of droughts is largely due to the compounding of disaster impacts including at distant locations due to the increasing interconnectedness of regions on the socio-economic front. The networking of countries and regions has been projected to increase in the future with implications for global food prices, food security, and businesses. The interlinking of supply chains and specialization of supply chains, in particular, makes them vulnerable to such compounding impacts. This is especially true as global food production is increasingly concentrated in the most vulnerable and developing parts of the world. These impacts could be further exacerbated if drought occurs in areas critical for the food security of an entire region such as the food basket of India (i.e., Indo–Gangetic basin) or rice-producing regions of Thailand or Indonesia that aspire to be the food basket of Asia.

2.4. Risk Transmission Pathways and Transboundary Drought Impacts

Having understood the nature of regional droughts and their impacts in previous sections, this section focuses on various pathways through which these risks are transmitted. The way drought risks are transmitted from one location to another deserves special attention for drought monitoring and early warning. This is because distant locations would also have to be informed about the drought conditions for some precautionary measures to be taken. As indicated previously, people and countries are intricately linked with one another in an increasingly globalized world. Drought risk managers and policymakers alike must turn their attention to how monitoring and early warning systems can take these linkages as an opportunity to mitigate drought risks.

A large body of work has been published on the topic of teleconnections in various academic domains including environment, financial markets, meteorology and climate change [57–66]. This work signifies how distant processes can be connected in terms of cause and effect. Globalization and regional integration can result in a significant distance between cause and effect both in terms of geographical and time aspects. Such distancing of cause and effect can be a challenge to understanding the risks and implementing appropriate solutions. The available literature can provide us with a good understanding of processes that lead to such teleconnections and can also help us understand how disaster events at one place can cause effects elsewhere.

Further to the above work, there has been a more recent understanding of the transboundary risks, mostly inspired by the demands, complexity and urgency brought about by climate change [67–86]. This body of work focuses on climate change, how climate change impacts are transmitted across borders, and what it means for adaptation planning, supply chains, and how to track the transboundary impacts through quantitative approaches such as indices. A significant amount of research has also gone into understanding how climate change impacts are transmitted from one place to another through various risk transmission pathways. The work has stressed the need to understand linkages between distant countries, communities and ecosystems and that these linkages should be consciously monitored and managed to mitigate possible transboundary impacts.

From the above work, risk transmission pathways can be categorized into four categories: (a) risk transmission through the trade of goods and services, (b) risk transmission through loss of biodiversity and ecosystem services, (c) risk transmission through labor markets and human mobility including migration, and (d) risk transmission through financial markets. These pathways are not mutually exclusive—they can interact with each other and produce complex combinations that could manifest drought risks at a distant place.

In terms of drought events, although all these pathways may operate at various degrees depending on location-specific conditions, the discussion presented in the section on past regional droughts indicates evidence for at least two prominent pathways of transboundary impacts, i.e., impact through trade and supply chains with effect on food prices, and impact through physical resource flows such as the flow of rivers that affect electricity generation and produce other upstream and downstream effects.

The impact of drought on global food prices has attracted much attention in the literature. The trade of food can act as an effective risk transmission pathway both within and between countries. One prominent example is the 2008 global food price crisis that was partially aggravated by droughts in 2005–2006. Successive droughts affected wheat production in Australia which in turn seriously affected the global supply of food grains leading to the 2008 crisis [22,87]. Other past incidences include the drought of 1972 and a drought in Russia in 2011, which resulted in export restrictions that are known to contribute to high food prices and massive civil unrest in Central Asia [42,88,89]. During the 2021 US drought, there was a nearly 40% decline in the wheat crop resulting in implications for global wheat prices [89,90]. Consequently, global food prices rose by 1.2%, the highest since 2011, after adjusting for inflation in 2021. There are concerns that carry-forward stocks may be depleted to a level such that food prices continue to increase in 2022.

In addition to the impact on global food prices, other cases involving transboundary drought impacts include a decline in water levels of rivers with resulting consequences on electricity generation for a wider region. For example, the Nam Ngum I Hydropower station built on the Nam Ngum River provides an important opportunity for the Lao People's Democratic Republic to export surplus power to Thailand. During the drought of 2007, hydropower generation was severely affected and the utilization rate of the power plant declined by 40%, impacting electricity exports to Thailand [91]. There were no clear estimates on the extent of the deficit in power export to Thailand in this event.

In India, the drought of 2016 was reported to have resulted in a deficit in electricity production by 14 terawatt-hours of electricity [92]. The impact was pronounced at Farakka, Raichur, and Tiroda power plants. The shutdown of the Farakka power plant during the drought caused power prices to surge at the central level including at the India Energy Exchange [93]. The plant supplies power to the neighboring states of Bihar, Jharkhand, and Odisha and the power supply to these states was severely affected due to the power plant shutdown.

The Indian state of Karnataka exports power to the adjacent state of Kerala, but in 2014, the state had to ban power export to Kerala due to a deficit in power production due to drought conditions and increased power demand [94]. A drought in India and the related deficit in hydropower production provided an opportunity for neighboring countries such as Bangladesh, Nepal, and Bhutan to export power to India. Analysis by Bergner [95] suggested that Nepal has immense potential to supply surplus power to India, especially during drought years and this can be an important part of its power expansion strategy. Conversely, Rahman et al. [96] suggested that establishing an electricity grid between India and Nepal can also benefit Nepal during droughts in Nepal, creating a win–win situation for both countries from such a grid. This suggests the positive transboundary opportunities provided by droughts.

In the Mekong River region, a downstream drought as a consequence of upstream water management decisions made in China could be seen as a reversal of the transboundary drought risk phenomenon discussed in this paper. In 2019, the operation of the Nuozhadu dam constructed on the China part of the Mekong River was meant to normalize seasonal flow differences. The flow normalization operations have further exacerbated the drought conditions in lower Mekong countries such as Thailand, Cambodia, Lao PDR, and Vietnam [97].

Upstream dams were intended to retain the wet season flows, thereby evenly distributing electricity production between wet and dry seasons. However, this has serious consequences for countries downstream. Even though the flow indices predicted more than average river flows and record rainfall upstream during 2019, the drought conditions in the lower Mekong region were compounded by decisions related to upstream dams and reservoirs. As such, the dams constructed in the China part of the Mekong River constitute 56% of the total reservoir capacity of the entire Mekong River [98]. This signifies a need for greater cooperation between China and lower Mekong countries to avoid future water shortages and man-made droughts.

3. Implications for Drought Monitoring and Early Warning

According to Pulwarty and Sivakumar (2014), major elements of a drought monitoring and early warning system include (a) knowledge of the risk, (b) technical aspects of the drought monitoring, (c) dissemination of early warning to relevant stakeholders, and (d) preparedness and ability to respond. The discussion in the previous sections focused on understanding the risk element of regional droughts. The review informs us of the complexity of drought impacts that are not extensively captured by the current literature and scientific research. The review also revealed that there is a need for more research to understand and quantify the transboundary impacts of regional droughts so that the information is useful for building robust monitoring and early warning systems and inciting effective responses. Based on the available limited understanding of regional drought impacts, this section provides some insights on the implications of regional droughts in designing and use of drought monitoring and early warning systems.

In terms of implications of transboundary drought risks to drought early warning, we consider here two overarching aspects: (a) the designs of the early warning systems itself, covering the understanding of the transboundary risk at hand and the technical part of the early warning, and (b) communication of early warning for inciting action, covering the dissemination and awareness to act.

3.1. Implications for the Design of Drought Early Warning Systems

An extensive review of drought monitoring and early warning systems is beyond the scope of this paper, and there is already a large body of work reviewing drought monitoring and early warning covering various aspects [99–105]. This section aims to look at the available drought monitoring and early warning systems from the lens of regional droughts and transboundary drought risks. In terms of design aspects of an early warning system, two elements are considered, i.e., understanding the risk, and incorporating this understanding into the technical design of the early warning system.

From a review of regional droughts, it is apparent that drought early warning systems need to capture three aspects of regional droughts—complexity, geographical scale and timeliness. Further, the understanding gained from risk transmission pathways should inform the drought early warning systems. Risk transmission pathways can affect the complexity of droughts, geographical scale of the droughts and timeliness of drought information. A region with a greater number of risk transmission pathways has the potential to make the drought impacts more complex, and impact more sectors. Similarly, the presence of more risk transmission pathways can increase the geographical reach of drought impacts. Hence, the risk transmission pathways discussed in this paper have the potential to significantly influence the design and implementation of drought early warning systems.

3.1.1. Complexity

Drought risks tend to be complex and often interact with multiple sectors and sections of society as the scale of drought increases from local to regional. The permutations and combinations of impacts become more complex depending on the size of the area covered and the duration of the drought, i.e., the longer the drought and the bigger the area, the more complex the drought impacts are. Capturing all the complexities of a regional drought is probably beyond the scope of any single drought monitoring and early warning system. While most drought early warning systems employ meteorological indices including the Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI), their application across the boundaries may not be possible due to differences in climatological conditions.

The advent of indices such as the Normalized Difference Vegetation Index (NDVI) has strengthened the utility of these indices for targeted application in the agriculture sector and has also strengthened the spatial component of drought monitoring and early warning. There have also been efforts to integrate indices such as SPI with the NDVI framework [106,107]. Since not all these indices can apply to all climatological conditions, the emphasis is to identify a suitable index for a particular location [108]. However, wherever similarities exist, it has been suggested that countries should coordinate and cooperate to harmonize their definitions of droughts and drought monitoring and early warning systems [10].

3.1.2. Geographical Scale

The geographical scale aspect of drought early warning systems has received increasing attention in recent years. There has been a gradual expansion in the scope of drought monitoring and early warning systems from local to national to regional scales. Some of the national level drought monitoring and early warning systems include the United States

Drought Monitor (USDM) [15], the United States regional drought early warning system that covers sub-regions within the United States [16], the India drought monitor developed by IIT-Gandhinagar [19], and the Australian Combined Drought Indicator (CDI) that was developed based on the experiences of USDM [18]. The India Meteorological Department (IMD) monitors droughts using an aridity anomaly index (AI) which is based on potential and actual evapotranspiration. Some examples of regional drought monitoring systems include the North American Drought Monitor (NADM) [17], the South Asia Drought Monitoring System (SADMS) [20], the Southwest Asia Drought Monitoring System [109], Sub-Saharan African drought monitoring and seasonal forecasting system [110], and the European Drought Observatory (EDO).

The NADM covers Mexico, Canada, and the United States of America. Southwest Asia drought monitor covers western India, Pakistan, and Afghanistan. The SADMS covers Afghanistan, Pakistan, India, Nepal, Bangladesh, and Sri Lanka. Drought monitors such as USDM combine the bottom-up approach of bringing drought evaluation at the subnational level to that of continental-scale information derived from hydrological models, and remote sensing information [110]. The African drought monitor employs a stratified and ensemble approach wherein it integrates climate models and hydrological models and derives a set of indices for drought monitoring (See Table 2). The EDO uses a Combined Drought Indicator (CDI) using meteorological, hydrological, and remotely sensed biophysical information. It combines three indicators of SPI, soil moisture anomaly (SMA), and the FAPAR anomaly (Fraction of Absorbed Photosynthetically Active Radiation) [111].

Table 2. Elements covered by some of the drought monitoring and early warning systems.

Name of the System	Elements Covered
The United States Drought Monitor (USDM) North American Drought Monitor (NADM)	CPC Soil moisture model, PDSI, SPI, stream flow
India drought monitor	NDVI-LST, Standardized Soil Moisture Index, SPI, Standardized Runoff Index (SRI)
Australia Combined Drought Indicator (CDI)	SPI, NDVI, soil moisture, and evapotranspiration
Southwest Asia drought monitor and South Asia drought monitor	NDVI, drought severity index (DSI), Vegetation Condition Index (VDI), Temperature Condition Index (TVI)
African flood and drought monitor	Employs a cascading dynamic modelling system that includes climate models, Variable Infiltration Capacity (VIC) land surface hydrological model, remotely sensed precipitation and atmospheric elements. Derives SPI, soil moisture indices, NDVI and stream flow percentiles
European Drought Observatory (EDO)	Combined Drought Indicator (CDI) based on SPI, soil moisture anomaly, vegetation productivity anomaly, heat cold wave index, water storage anomaly, and low-flow index.

Source: Author.

The elements covered and the methodology followed by these drought monitoring and early warning systems is presented in Table 2. The development of these drought monitors is largely inspired by the United States Drought Monitor. These drought monitors provide a unified view of drought conditions and provide an opportunity to strengthen communication, data sharing, and early warning among provinces and countries. With the development of these regional drought monitoring and early warning systems, the stage is set to develop a truly global drought monitoring and early warning system [21]. The table indicates that for these drought monitors to apply to a wide area, they have to employ multiple indices instead of a single index, and cover a range of elements including capturing temperature, rainfall, and soil conditions. Hence, a compound index is the most appropriate way to effectively capture the regional drought conditions.

3.1.3. Timeliness

Another technical aspect that determines the reliability of a drought monitoring and early warning system is its ability to provide real-time and timely information. Timeliness is a function of how frequently the background data are updated and how quickly the information is shared with stakeholders [101]. One of the major limitations of current early warning systems is that, although they are developed to provide near-real-time monitoring and early warning functionality, they are only able to do so when the data are inputted regularly. Often such operations are manual and time-consuming. Data may not be readily available especially when it requires coordination among multiple institutions across administrative boundaries.

This limitation is largely overcome by automating the meteorological data collection systems and seamless integration with the satellite data [112–115]. The implementation of these automated telemetry systems worldwide is constantly being developed, and there is a need to make substantial progress on this front in many countries [115,116]. Bottlenecks related to technology availability, cost, capacity to maintain the equipment, especially in remote locations, and ability to phase out old systems with appropriate matching financial and human resource capacity development are all aspects that must be dealt with [117].

3.2. Implications for Drought Risk Communication

While there has been significant progress in terms of developing national and regional drought monitoring and early warning systems, the real impact of these systems will only be evident when they are effectively used by target stakeholders. The effective use of drought risk information is only possible when appropriate stakeholders receive the drought risk information. Currently, it is not very clear how the information generated from drought monitoring and early warning systems is being communicated to various stakeholders. This is especially the case when there is institutional fragmentation across political borders in the drought-affected regions [13]. There is a need to evaluate the information communication channels and ensure they are efficient.

From the review of regional droughts, it is evident that drought impacts can be complex ranging from agriculture and water resources to industrial production. Further to the sectoral complexity, the supply chains that connect drought-affected areas with distant locations make information communication even more complex. Hence, communication of impact is an important and integral part of drought monitoring and early warning systems. However, the current drought monitoring and early warning systems largely miss the impact component of the drought. It makes it difficult for the recipient of the information to understand the nature and degree of impacts the impending drought may cause.

With the growing emphasis on impact-based early warning systems across the world, it is time that drought monitoring and early warning systems adopt the impact-based approach [117–119]. There have been efforts to build impact-based early warning systems, mostly for rapid-onset disasters, and the concept and practice are slowly being taken up by the drought risk management community [118]. The impact-based early warning system emphasizes specific actions to be taken, translating what a drought index value means in terms of the impact on specific stakeholders, sectors and geographical regions. Such an approach has a high potential to incite effective action compared to communicating just the drought conditions. The impact-based early warning also emphasizes the need to build capacity among information recipients so that they can act swiftly and effectively. Issues associated with the attitudinal aspects of information recipients also must be addressed. However, regional droughts and transboundary drought risks could make it challenging to extend the domain of impacts associated with a projected drought. While the collection and reporting of meteorological information are well standardized, the same is not applicable in the case of drought impacts. To implement the impact-based early warning, there is a need to standardize how the impacts are systematically assessed, measured and reported so that it is easy to incorporate the impacts into drought early warning systems and that all stakeholders across borders can understand the information as it is meant to be understood.

In the context of regional droughts and transboundary drought risks, there is a need to identify appropriate stakeholders, expanding the stakeholder network from the traditional notion to that of open architecture so that these stakeholders can work across borders and address the issue of institutional fragmentation. This process also should address issues such as reprioritizing the water users including households, industry, and agriculture, both local and distantly connected. This involves communicating the information both to local stakeholders and also to those who are connected with the drought-affected location through various risk transmission pathways including supply chains discussed in the previous section.

A change in the risk information communication architecture is also needed to move beyond the objective of informing about risk, to informing about appropriate and timely actions. The focus should not only be on immediate actions, but it should also provide an outlook of possible actions for an extended period. Radical change is vital so that drought monitoring and early warning systems can communicate across-the-board risk information communication that extends beyond boundaries.

The information communication architecture needs to be built into the current drought monitoring and early warning systems [119]. Once drought conditions are communicated and distant drought conditions are understood, countries can utilize the information for strategic planning. For example, the precipitation-related soybean crop losses in India were found to be negatively correlated with the precipitation and soybean production in South America. Such an understanding opens up new avenues for a country to establish trade linkages with these regions to ensure food security [11,42].

Effective governance of regional droughts also requires enhanced coordination vertically across administrative levels from local to national to regional to global levels, as well as horizontally across sectors in a cross-cutting manner. The role of various institutions, including government, civil society, private sector, and citizens, needs to be emphasized in drought risk communication. Risk communication should happen across borders, but it can face a hurdle when it comes to the fragmented definitions of droughts across the borders [10]. Hence, wherever possible, such differences should be harmonized to ensure more effective communication and coordination. Development planning needs to be coordinated at all levels in such a manner that the drought risks are mitigated and the water demand is minimized. Wherever applicable, a multi-hazard approach should be prioritized in particular to harness synergies between floods and droughts.

4. Conclusions

Droughts are capable of causing complex, prolonged impacts on the development of communities and nations. Regional droughts are occurring more often and climate change projections indicate that regional and intense droughts will be even more frequent in the future. This has serious consequences in an increasingly globalized world. Regional and global integration processes mean that local risks are being expanded to a global scale. There is a growing body of evidence suggesting that there will be an increase in regional droughts with far-reaching transboundary impacts. The transboundary impacts of droughts are hard to assess, so it is essential to strengthen the evidence base for these impacts, and transform both the way droughts are monitored and how early warning is communicated.

Regional droughts and transboundary drought risks are extremely relevant to how drought risks are assessed, how the risk information is shared, and for actions that early warning information invokes. While it is important to enable timely drought early warning, transboundary drought risks take the discussion further and demand that this information be shared with a wide variety of stakeholders that have not previously been considered. There is a need to review how the drought risk information is packaged and shared with stakeholders, with emphasis on the actions that they can take. There is a need to identify appropriate stakeholders and review both the risk information communication, as well as the measures to be taken to effectively stop the drought impacts from spilling beyond boundaries. Approaches such as impact-based forecasting provide a good solution to address the transboundary impacts of droughts.

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