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Review article: Drought as a continuum – memory effects in interlinked hydrological, ecological, and social systems

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S1 - Case study Chile

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Central-south Chile (30°–37°S) is a narrow strip of land (<200 km wide) between the Pacific Ocean and the Andes cordillera, home to more than 9 Mill inhabitants and many economical activities. It features an archetypical Mediterranean climate, with semi-arid conditions (annual precipitation of 100 to 1000 mm/year), strong seasonality (>70% of the precipitation in austral winter: JJA) and large interannual variability. The Andes cordillera is more than 4 km high here and enhances precipitation, most of which is retained as seasonal snowpack.

The multi-year drought afflicting this region started in 2010 and continues up to date, featuring mean precipitation deficits of 30% with some extreme dry years reaching up to 80% (2019 and 2021, as observed in Fig. S1b). Such a long dry spell, partly attributed to anthropogenic climate change (Boisier et al., 2016, 2018), has been the driest decade in local history since the 14th century (Garreaud et al., 2017), and its impacts reveal key memory effects within different subsystems.

Hydrological system

Before the drought, precipitation variability in central Chile featured mostly dry years (below average) interrupted with a few very wet years that permitted the recovery of the hydrological system and natural vegetation. Such recovery capacity has been absent in the last 12 years (Fig. S1b). During the drought, snow-dominated headwater basins with large memory have accumulated the effects of precipitation deficits and generated on average 30% less streamflow than previous single year droughts (Alvarez-Garreton et al., 2021). In some cases, this effect has overlapped with water extractions for human activities in downstream sections, leading to an amplification of drought signal over lowlands and the drying out of water bodies (Barría et al., 2021b; Muñoz et al., 2020).

It remains unclear how long it will take for these new hydrological states to recover after the drought finishes. These recovery times depend on the subsystems memory, as illustrated in Fig. S1. For example, a small reservoir (La Paloma, with 0.75 km3 capacity) had a 80% volume recovery after the year 2016, where precipitation had a slight increase compared to the rest of the decade. On the other hand, the large Laja lake (5.6 km3 capacity) recovered less than 20% in volume during that time.

A similar effect happens at the basin scale. In short memory pluvial basins water supply is more strongly dependent on the meteorological conditions of the current year, and thus a wet year would lead to a faster recovery than in long-memory snow-dominated or groundwater-dominated basins, or where groundwater has been disconnected from shallower water during the drought. The challenge is that most of these long-memory catchments correspond to semi-arid basins in central Chile where irrigated agriculture is concentrated. In those cases, water needs are usually met by exploiting groundwater reservoirs in unsustainable ways, leading to sustained water level depletions as those observed in Maipo, Aconcagua and Rapel (Fig. S1e). The unsustainable use of groundwater in central Chile is already impacting society and ecosystems, and posing an intergenerational dilemma due to the depletion of reserves that will not be recovered within generational time frames (Alvarez-Garreton et al., 2024; Duran-Llacer et al., 2020; Jódar et al., 2024; Taucare et al., 2024).

Ecosystem

According to satellite observations, natural ecosystems have experienced significant vegetation browning following the extreme hyper-dry year of 2019 (Miranda et al., 2023). In the field, there has been mortality of less drought-tolerant tree species, the complete drying out of several branches and even the trunk of more resilient species. The more resilient species have resprouted in the year following the hyper-drought following a vegetative regeneration strategy. These drought effects have led to the lack of seedlings that depicts a risk of altering the composition and structure of these plant communities over time.

The dry conditions during the drought have been related to a higher occurrence of wildfires, as well as a larger burned area. Before the drought, wildfires were concentrated between the months of November and April, but now they extend from October to May, increasing the occurrence period from 6 to 8 months. Over 70% of the megafires reported in Chile have occurred between 2010 and 2018, where 50% of the burned area corresponds to monocultures of exotic tree species (mainly pine and eucalypt) (CONAF, 2019). Notwithstanding this, it is worth noting that 99% of wildfires in Chile are initiated by human actions, whether they are accidental or intentional. Therefore, the behavior of the population is crucial in preventing and mitigating wildfires (González et al., 2018).

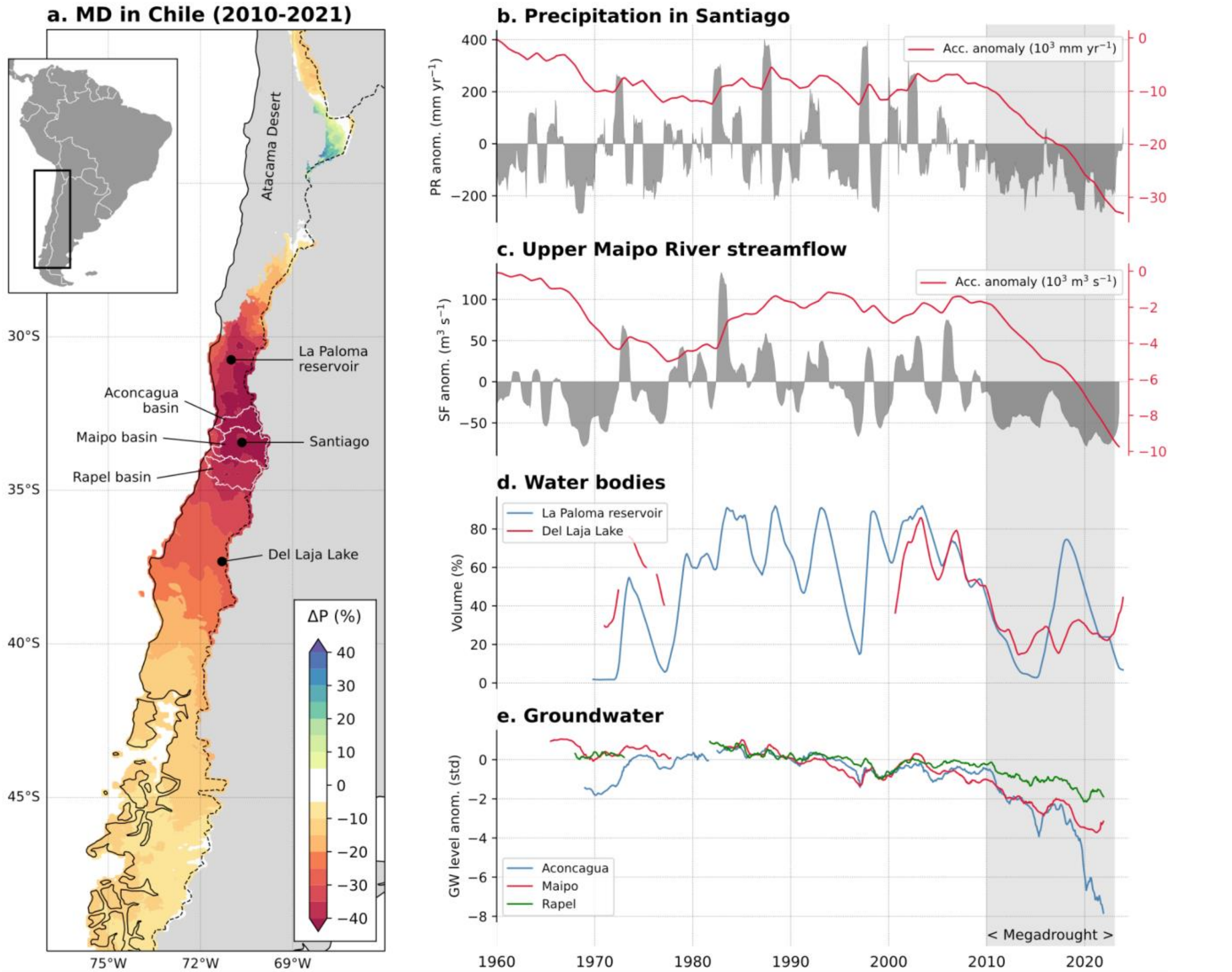

Figure S1: Drought in Chile: a) 2010-2021 mean annual precipitation anomaly in Chile, with respect to the 1980-2010 period (data source: CR2MET, (Boisier, 2023)). b) Monthly precipitation anomaly (12-month running sum) and accumulated precipitation anomaly in Santiago (Quinta Normal station, DMC). c) Monthly streamflow anomaly (12-month running mean) and accumulated streamflow anomaly in the Upper Maipo River (El Manzano station, DGA). d) Monthly water volume level (12-month running mean) in La Paloma Reservoir and Del Laja Lake (DGA). e) Groundwater level anomalies in the Aconcagua, Maipo, and Rapel watersheds (indices based on averaged standardized anomalies from 54, 70, and 49 observation wells, respectively).

Social system

Some parts of the country have precarious water infrastructure, particularly in rural areas, where there are problems of water access even during wet periods. In this context, the drought has impacted a system that was already vulnerable before 2010, and these impacts have not diminished over time. This has led to an environment of increasing discomfort in rural communities. Several assessments of water management in Chile have concluded that the strategies to face drought impacts are reactive and tackle water scarcity in the short term, without an adequate plan for persistent drought conditions (Alvarez-Garreton et al., 2023b).

The vulnerability of social systems varies across sectors. In rural areas, people rely on self-organized communities with inadequate infrastructure and technical capacities for providing subsistence drinking water, leading to water cuts that have been remedied by cistern trucks, which is a non-structural reactive measure to address permanent water access requirements in rural communities (Nicolas-Chloé et al., 2022).

On the other hand, people in urban areas rely on water sanitation companies and have not been affected by water shortages, even when surface reservoirs have been significantly depleted since these companies have adequate groundwater infrastructure. An important adaptive measure taken by governmental agencies to face water scarcity in Santiago has been to build deep pumping wells for supplying drinking water for human consumption. This measure reveals that groundwater is seen as an additional water source, overlooking the fact that these reserves are limited by recharge rates, and that current withdrawals are already exceeding those rates (Alvarez-Garreton et al., 2024; Duran-Llacer et al., 2020; Jódar et al., 2024; Taucare et al., 2024). In this context, some sectors are not experiencing the consequences of a decade-long drought, causing overreliance on a system that has critical vulnerabilities.

From a broader perspective, the slow adaptation of policies to non-stationarity climatic and hydrological processes makes the water management system inadequate to face the drying trends projected for Chile. For example, most of the current water use rights were allocated as absolute flows based on the water availability from decades ago and, in seeking to provide legal certainty, the law does not permit to modify these allocated flows considering the current and projected climatic conditions (Barría et al., 2019, 2021a). This prohibition has led to overallocation of water use rights, as well as impeding the protection of environmental flows, and thus threatening the opportunity to reach water security (Alvarez-Garreton et al., 2023a).

Management

Climate projections for this region show a consistent decrease in precipitation, which may exacerbate current drought impacts in the following decades. Water management measures should prepare for these projections, advancing from the reactive approach currently adopted. Recent studies have provided specific recommendations to achieve this, including the following:

1) Adapting the water management system to account for a changing climate (Barría et al., 2019, 2021a).
2) To recognize that groundwater savings are not an independent source of additional water availability (Alvarez-Garreton et al., 2024).
3) Strengthening the protection of environmental flows to avoid over allocation of water use rights and advance towards water security (Alvarez-Garreton et al., 2023a).

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S2 - Case study Colorado River Basin (southwestern United States*)

***note: region includes states of CA, AZ, NV, UT, CO, NM, WY.**

E. Koebele & M. Garcia

Hydrological system

The Colorado River Basin is arid and semi-arid, with high interannual variability in precipitation and streamflow dependent primarily on snowmelt (Kalra et al., 2017). Due to both its aridity and interannual variability, water management relies on complex infrastructure systems to store, convey, and distribute water (Rajagopalan et al., 2009). The Colorado River Basin has experienced severe drought since 2000, now lasting 23 years. The basin provides water for 40 million people in major urban areas, over 5 million acres of productive farmland, recreation, endangered species, hydropower, and more -- sectors that are all suffering the consequences of drought. Additionally, the region is aridifying due to climate change (Milly and Dunne, 2020; Overpeck and Udall, 2020; Udall and Overpeck, 2017), with temperature increases driving the change in baseline conditions (Whitney et al., 2023b). Snowpacks are becoming smaller and melting earlier in the season, temperatures are increasing, and precipitation is more variable and characterized by extremes (i.e. drought to flood) (Heldmyer et al., 2023). Aridification may exacerbate drought and is sometimes difficult to distinguish from drought.

Meteorological drought in the Colorado River Basin is influenced by the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Hurkmans et al., 2009; Timilsena et al., 2009). Land use and land cover influence the propagation from meteorological to hydrological drought, with disturbance events such as wildfire altering that propagation process (Whitney et al., 2023a). Drought impacts also propagate via regional water supply infrastructure and policies that shape storage and use of water (Barnett and Pierce, 2008). For example, when California was in drought in 2021, the state withdrew water it stored in Colorado River reservoirs (Walton, 2021), exacerbating a multi-decade hydrological drought in the Colorado River Basin.

Additionally, within the Colorado River Bains, several aquifers have experienced long-term groundwater drawdown (e.g.,Prescott Active Management Area, AZ) (Tillman and Leake, 2010). Large reservoirs in the Basin (e.g. Lake Mead & Lake Powell) have also experienced long term drawdown due to overuse of water during drought periods, reaching their lowest levels since construction in 2022 (NASA, 2022). Climate change-driven aridification may also change how catchments in some parts of the basin respond to precipitation by reducing runoff efficiency or groundwater recharge as a result of greater atmospheric water demand and reduced soil moisture, for example (Gordon et al., 2022; Tillman et al., 2020).

At the same time, increased flooding may occur in some parts of the basin due to phase increased variability, more rapid snowmelt, shifts in winter precipitation, and rain-on-snow events (Albano et al., 2020; Harpold and Kohler, 2017; Musselman et al., 2018).

Ecosystem

Drought increases stress on riparian and aquatic species in the Basin, many of which are endemic. Several of these species have long been endangered or extirpated (e.g. the Razorback Sucker) (Mueller et al., 2005). Native species are acclimated to the historic flow regime, including drought; however, water use in conjunction with drought can cause low flows that native species cannot tolerate (Pennock et al., 2022). System reservoirs can be operated to achieve flows suitable for native species, but water management actions taken in response to drought may constrain the ability to meet environmental objectives through reservoir operations (Bruckerhoff et al., 2022).

Additionally, many areas of the Basin are experiencing increased wildfires as a result of both previous/current drought impacts (e.g. dry fuels) and human activities (e.g. a history of fire suppression that has led to the build up of fuels), as well as broader regional aridification (Abatzoglou and Williams, 2016; Holden et al., 2018).These changes in wildfire patterns can feedback to impact streamflow in different water depending on the location and time of year (Biederman et al., 2022).

Social system

Recurring and prolonged droughts affect communities and economies throughout the Colorado River Basin (Bauman et al., 2013; Bennett et al., 2019; Gerlak et al., 2021). Historically underserved and overburdened communities (e.g. Indigenous peoples living on reservations and lower-wealth and rural communities) are likely to experience disproportionate impacts, especially when drought is exacerbated by other stressors, such as COVID-19 (Craig, 2022). These communities may be the first to experience drought impacts and not have the capacity to adapt in the way high-wealth communities do, which affects how they experience both current and future droughts (Bair et al., 2019; Lisonbee et al., 2022). Some Indigenous communities in the Colorado River Basin have rights to water that they can not access due to legal and economic barriers, which are exacerbated by their historical marginalization from policy making processes (Robison et al., 2021).

Critically, the governance system in the Colorado River Basin is highly polycentric (many nested centers of legal power and rights), sometimes leading to a lack of coordination or collective action on drought management efforts. However, substantial efforts at more collaboratively managing the basin's limited water supplies have prompted innovative and forward-looking thinking about on-going drought management within this complex governance system (Karambelkar and Gerlak, 2020; Koebele, 2020; Wiechman et al., 2023). For instance, strides have been made in increasing the efficiency, conservation, and recycling of municipal water supplies by cities in the Colorado River Basin, such as Las Vegas, which can help mitigate the impacts of prolonged and recurring drought (Brelsford and Abbott, 2017; Garcia et al., 2019).

At the same time, agriculture is the largest water user in the region but often has the least incentive to adapt due to their higher priority water rights with shift risk to other users during shortages (Smith and Edwards, 2021; York et al., 2020). Moreover, some adaptation behaviors may also be maladaptive over longer time scales (Hung et al., 2022). For instance, large reservoirs can "buy time" for response but may dampen the signal of drought severity and lead to water overuse (e.g. Lake Mead; Garcia et al., 2020).

Natural variability in the system may also impact actors' willingness to pursue adaptation to drought across sectors (e.g. awet winter in 2023, following many years of drought, affected policy discussions in the Colorado River Basin around the stringency and timing of drought response measures). Similarly, highly partisan politics in the U.S., coupled with continued disbelief in climate change/science by some groups, may also lead some decision makers to "forget" or "ignore" drought impacts and expected future trends or delay adaptation (e.g. hesitance to raise water prices or invest in infrastructure adaptations, unwillingness to implement unpopular conservation measures in some areas, promotion of "natural variability" while ignoring broader climate and drought trends).

Management

The U.S. federal government has recently allocated historic amounts of funding for drought mitigation in the Colorado River Basin (2022-2023), recognizing the recurrence and "stacking" of drought impacts. However, there is concern that much of this money will be spent on temporary conservation measures (e.g. compensated fallowing of agricultural lands), which may not prepare the Basin for future droughts or a more arid future. Funding has also been allocated to help Indigenous communities address unsettled water rights and lack of infrastructure, and additional adaptation funding is available to some communities through state (e.g. California) and federal programs (e.g. WaterSMART). To be more resilient in the future, all states and sectors in the Basin must consider how to incorporate expectations of repeated and recurring droughts, against a background of broader aridification, into their response and adaptation actions.

Fortunately, water managers are increasingly incorporating observed and predicted climate change into their management efforts (e.g. urban utilities like Denver, Colorado; Phoenix, Arizona). Similarly, scientists and managers are working collaboratively to model Colorado River flows at different levels that represent a range of historical and predicted drought conditions. Increasing collaboration and the sharing of innovation across geographies and sectors within the basin can help support adaptation and reduce the negative consequences of drought, though such actions must continue even in wetter times to prepare for expected future climatic conditions.

Finally, governance processes must continue to become more inclusive of the wide variety of actors impacted by drought, including those who have been historically marginalized, such as Indigenous communities and the environment, to promote equitable adaptation and sustainability (Berggren, 2018; Koebele et al., 2023). There is a well-recognized need for increasing adaptiveness and flexibility in governance to deal with greater hydrologic variability and extremes and their impact on people and the environment.

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S3 - Case study Northeast Brazil

S. Kchouk, L. Cavalcante and G. Ribeiro Neto

Hydrological system

The catchment memory is influenced by anthropogenic modifications related to the high concentration of small dams that retain water to their maximum capacity. Multi-year drought causes these structures to remain dry longer as low precipitation levels are easily overcome by high evaporation rates characteristic of this region. This results in reduced hydrological connectivity with subsequent reduction of runoff and recharge of large reservoirs that serve multiple purposes (Ribeiro Neto et al., 2022). These large reservoirs play an important role in urban supply and a delay in their recharge can be seen as a prolongation of the hydrological impacts of drought.

Ecosystem

The prolonged droughts experienced in Northeast Brazil, especially intense from 2011 to 2020, inflicted considerable damage on the Caatinga biome; such damages were exacerbated by land use and occupation practices (Caballero et al., 2023).The Caatinga is the only uniquely Brazilian biome, one of the world's most populated and biologically diverse semi-arid regions. However, it is considered to be one of the least studied biomes in Brazil despite undergoing significant changes in land use and cover, as well as facing unsustainable land resource utilization (Beuchle et al., 2015; Santos et al., 2011). The Caatinga semi-arid climate and heterogeneous vegetation cover consist of scrubland and seasonally dry forest (Leal et al., 2005; Santos et al., 2011). Human activities such as fires and deforestation have led to the loss of vegetation cover and increased soil water deficit, accelerating desertification. This initial desertification, compounded by intensified drought conditions, has furthered the desertification process, altered the microclimate, and hindered subsistence agriculture and rural development (Gutiérrez et al., 2014; Marengo Orsini et al., 2018; Silva et al., 2020; Tomasella et al., 2018). Consequently, the compromised resilience of the ecosystem increased vulnerability to future droughts and worsened socioeconomic conditions in the region.

Social system

The vulnerability to drought and related impacts fluctuated over time in the semi-arid drought-prone rural community of Riacho da Cruz, in Northeast Brazil (Kchouk et al., 2024). This fluctuation of vulnerability resulted from the progression of a multi-year drought event coupled with drought responses. To address the drinking water insecurity in the community, a reservoir was introduced by national- and state-level water agencies. The rural population previously having their livelihood based on manual workforce and subsistence farming started intensive livestock farming with forage irrigated from the dam. In the first years, the newly autonomous farmers decreased their vulnerability to drought by additionally relying on irrigation during the dry season to increase their income through high-value market livestock products. However, multiple years of drought and having their livelihood depend on this single activity made the farmers over-rely on the reservoir and irrigate the whole year; farmers' vulnerability to drought started increasing. Once the reservoir completely dried, the loss of production coupled with buying forage from markets shocked by the drought, progressively depleted the finances of the farmers in the community. Ultimately, the lack of recovery and the prolongation of the drought lead to the collapse of the farmers' livelihoods.

In Brazil, the Northeast has a reputation of "a problem region, the poorest in the country, the most disadvantaged" (Théry, 2012). In addition to drought often invoked, the poverty and social vulnerability of the Northeast region are mostly linked to the original latifundia system. The family farming system, representing nowadays 80% of the agriculture in Northeast Brazil but detaining only 37% of the agricultural lands (de Aquino et al., 2020), originates from a colonial law in 1850 that led to the division of large farms into small communities (Sabourin and Caron, 2001). With droughts making agricultural production uncertain, the small farming economy remained limited to meeting consumption needs. In addition, latifundists restricted equal access to water by maintaining the reservoirs on their own lands. Successive divisions by inheritance led to the fragmentation of farms into strips, where plots are in length and aligned, to guarantee access, even limited, to water and the most fertile soils of the lowlands. This configuration turns collective management at the lowland or watershed scale particularly difficult and complicates the construction of water use infrastructure (e.g. receding, irrigation, access for herds, fences) (Sabourin and Caron, 2001).

The government's memory of solutions to drought events was that the impacts could be solved by increasing the water supply. The common practice to deal with drought events was to build large water infrastructure, such as dams and water basin transfers. This approach is known as the fight-against-drought paradigm. Over time, another paradigm gained prominence incrementally, the cope-with-drought paradigm, a proactive attitude toward nature, seeking to adapt to the environmental and climatic context. Both paradigms co-exist and compete within the governance system, however with dominance of fighting-against-drought (Cavalcante et al., 2022).

Drought is managed mainly with a reactive approach by drought commissions commanded by the Presidency at the federal level and by committees at the state level. These are temporary organizations, often criticized for not being able to respond quickly with comprehensive and integrated actions (Martins et al., 2016). A proactive approach started to be adopted with a policy instrument called Drought Monitor (Gutiérrez et al., 2014). In its most visible form, it is a monthly map that describes the current state of drought. However, more important than the map are the processes that encompass monthly meetings to discuss the current drought conditions locally. This routine improves institutional and operational capacities to respond in an ongoing manner (Cavalcante et al., 2023).

The reactive approach to fight-against-drought resulted in two decades of reservoir building, strongly supported by the state (Silva, 2003). This fostered a safe development paradox with rural populations overly relying on reservoir storage for their income and livelihood (Campos, 2015). Conversely, the broad implementation of cisterns decreased this overreliance. These water infrastructures of rainwater harvest at a household scale, alleviated farmers' dependence on reservoirs, ensured water- and food security and improved farmers' knowledge and confidence to deal with drought risks (Cavalcante et al., 2020; Mesquita and Cavalcante, 2021).

Management

There is a need to elaborate and integrate into existing DEWS, indicators that take into account the dynamism proper to drought vulnerability. Such approaches can be based on the resilience of Social-Ecological Systems (SES), as it allows to understand a system's (in)ability to cope with and recover from drought events, as a result of always-evolving and dynamic biophysical and socio-cultural processes (Kchouk et al., 2024). Another possibility is to continuously monitor the drought impacts on affected populations, just like drought drivers are monitored and integrated into DEWS. In Northeast Brazil, drought impacts have been monitored by a network of local observers since 2019 (Walker et al., 2024).

Drought impacts monitoring is conducted on the ground in much of Brazil, since 2019, by local observers at monthly and municipality scale to support the Brazilian Drought Monitor. The open nature of the questionnaire means the programme is a globally rare and consequently valuable example of drought impacts monitoring by the people "on-the-ground" who experience the impacts. Crucially, this type of regular spatially distributed monitoring should provide both baseline conditions and the effects of any disturbances (Walker et al., 2024).

The memory of past dry events is directly linked to hydrological aspects, such as the reduction of hydraulic connectivity due to the presence of a dense network of reservoirs, as well as social factors, such as the history of public policies to fight against/cope with drought. Therefore, it is necessary to consider these dynamics in the process of modeling drought impacts. Traditional approaches based only on the representation of the physical components of the hydrological cycle are not able to englobe this complexity, requiring multidisciplinary approaches, such as the application of socio-hydrological models (Ribeiro Neto et al., 2024). Some studies in Ceará have been successful in this regard by using agent-based models (Van Oel et al., 2008, 2012).

Planning and integration among institutions have been one of the main challenges related to government responses to droughts in Brazil. The most recent aspect of governance has been the implementation of policy instruments aligned with the idea of drought preparedness, for instance, the Drought Monitor. This policy instrument is the first attempt to overcome the challenges to proactive and integrated governance at distinct levels continuously, not only when the drought impacts are identified.

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S4 - Case study Kenya (Horn of Africa)

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Hydrological system

The Horn of Africa (HOA) region has high variability in climate and catchment characteristics, and therefore also how drought propagates. Odongo et al., (2023) found that arid and semi-arid areas in the region, propagation from meteorological to soil moisture drought is influenced by surface processes, such as soil properties, land cover and the time of the last rain – variables which are all linked to the storage capacity of the catchment. In areas where the soil is very dry, the soil surface needs to be wetted before infiltration starts. Therefore, catchments in the region with a high aridity and high sand content have a slow response of soil moisture to precipitation. In the HOA, the propagation from meteorological to streamflow drought is largely influenced by catchment-scale hydrogeological processes, such as geology and land cover.

Despite increasing frequency of droughts in the Horn of Africa, including Kenya, since the early 2000s, sustained water storage has increased. How is this possible? Heavy rainfalls in the Horn can play an important role in dampening subsequent drought duration and severity. High intensity rainfalls, especially during the OND (October-November-December) rainy season, lead to large seasonal increases in water storage that persist over multiple years. Therefore, increasingly recurrent drought damages could be mitigated with groundwater resources recharged by heavy rainfall events (Adloff et al., 2022).

Ecosystem

In Kenya, recurrent droughts and rising temperatures cause more and more often food and water shortages for herbivores, resulting in an ecosystem response of greater movements and likelihood of contacts between wildlife, people and livestock. For example, in Narok County, during the severe drought years of 2008-2009, there were the highest recorded number of human-wildlife conflict. The conflicts resulted from wild herbivores encroaching on crop farms, or predators attacking livestock (Mukeka et al., 2019). Human-wildlife conflicts in Kenya often result in long term damages for both sides: crop farmers and livestock herders experience a reduction incapacity to recover from droughts and prepare for the next.. Wildlife often pay with their lives, especially nonhuman primates, which are often trapped and killed by farmers protecting their precious crops, usually out of sight of the authorities of the Kenya Wildlife Service (KWS).

Riparian forests in Kenya, often forming thickets, used to provide habitat for wildlife and act as an insurance against drought for both humans and wildlife. The strong decline in riparian forest area in Kenya because of agricultural encroachment have thus removed this ecological buffer against droughts in many areas (Schmitt et al., 2019). The ongoing removal of riparian forests is likely to speed up and intensify drought impacts, and reduces the resilience of riverine ecosystems, including its human and nonhuman inhabitants, to recover from droughts and prepare for the next.

Also in mountainous forests, in the Mt Kenya region, human activities in the form of agricultural intensification and the expansion of horticulture agribusinesses have increased pressure on water resources, pasture, and idle land because of a shrinkage in area of natural and agro-pastoral landscapes (Eckert et al., 2017).

Social system

In 20th century Kenya, droughts generally took place every 5 to 10 years and were usually considered, by both pastoralists and drought experts, as 'events' that one could recover from. In the last two decades however, more frequently recurring droughts (every 2-3 years) have impoverished pastoral communities and thereby changed the younger generation of pastoralist' perception of drought risk. In northern Kenya for example, the recurrent droughts in the last decade, the current one having started in 2020, has disabled pastoralists to restock their livestock herds, and has forced them to reconsider their grazing management. Previous grazing management systems, based on 5-to 10-year droughts and therefore having long recovery times, have demonstrated not to be adaptive anymore in 21st century Kenya. As Thomas et al., (2020) state, because of the increase in drought frequency, there is no longer enough time for pastoralists to recover their herds and crops in between droughts, thus the destabilizing impact increases with each successive drought, leading to drought vulnerability.

Realising this, a new generation of pastoralists has come to see droughts as an ever-recurring state of affairs; one that requires a renewed, more strict graze zoning management to allow pastures to recover from recurring drought conditions (NRC, 2023b, 2023a). By doing so, they acknowledge the importance of land cover, and hence land use, in the propagation of recurrent drought.

In Southern Kenya, local authorities and NGOs have responded to consecutive droughts in the 1990s and 2000s by constructing public dams, water reservoirs and irrigation systems for crop-farming in previously pastoral areas. These schemes, when implemented and managed locally, can help in improving resilience to droughts, by giving pastoralists an alternative source of income and food supply which is not solely dependent on livestock production. It has led to the intended resilience building, at least for those able to reap its benefits. The vulnerable however have ended up in poverty traps: now, they had to compete in their extensive pastoral land and water uses with even more crop farmers, all of them attracted to settle around the new water infrastructures (the infrastructure set in motion a divergence in adaptation trajectories (Weesie and García, 2018). Besides, these types of irrigation schemes in sparsely populated areas tend to induce growth of people and livestock numbers, who all rely on the newly available, publicly accessible, water. It puts not only more pressure on the water source to perform, but also on surrounding natural resources, such as pastureland and seasonal rivers. Hence the schemes, while having short term benefits, on the long run induce an overreliance on reservoir storage, leading to a landscape with a higher likelihood of even heavier drought impacts in the future (Weesie and García, 2018).

In the Horn of Africa, historically, policy responses to drought have been reactive. Change was promised after the heavy 2010-11 drought in Kenya, when the Kenyan National Drought Management Authority (NDMA) formulated several key response activities during drought emergencies: a) maintenance of groundwater boreholes, b) installation of temporary ‘dry-season’ boreholes c) water trucking of purified drinking water to affected communities (GoK 2015, in Thomas et al., 2020). While such efforts can be praised, it reveals how policy responses still are of a rather ad-hoc and reactive nature, with institutions only slowly learning after heavy droughts.

The Horn of Africa is currently facing high food insecurity, affecting millions of people. Several failed rainy seasons have caused the 2020-23 drought period to be one of the worst in recent decades. However, drought hazard is not the only driver of food insecurity. Food insecurity and systems are complex and have many other drivers than climatic ones (Sandstrom and Juhola, 2017). The current food insecurity situation in the HOA is compounded by instability, conflict, the impact of the COVID-19 pandemic and rising food prices (WHO, 2023). The understanding of these food insecurity systems is advancing, however, there does not seem to be a change in the humanitarian responses. Short-term emergency relief remains evident (common practice?), partly due to the ‘blaming of the rain’, instead of moving towards more advanced approaches that consider other drivers of food insecurity (Sandstrom and Juhola, 2017).

Management

- In 2016, the Kenya National Drought Management Authority (NDMA, 2023) changed their assessment from an event-based approach to continuous drought impact monitoring. They now produce a monthly national drought early warning bulletin to coordinate drought risk management and to establish measures to mitigate drought emergencies in Kenya, either on their own or in collaboration with stakeholders.
- The East Africa Drought Watch (2023) uses similar indicators as EDO to monitor drought hazard conditions in the East African region, but allows for mapping these indicators on different timescales from 10 days and monthly, to seasonal and yearly.

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S5 - Case study Rhine River Basin (northwest Europe)

A.F. Van Loon, M. Werner, M. Ionita

Hydrological system

The Rhine basin is the largest and socio-economically most important basin in northwestern Europe. Over the 1233 km course of the main river and catchment area of some 200,000 km2, the basin flows through nine riparian countries, supporting a population of over 60 million and a great many functions, including; (drinking) water supply, ecology, agriculture, navigation, energy, industry, tourism.

The climate of the Rhine basin ranges from temperate oceanic to continental, with precipitation occurring in both the winter and summer periods. Mean annual precipitation varies from 2000 mm in the Alpine basin, to 500-1000 mm in the middle and lower basins (Bronstert et al., 2007). Hydrologically, different regimes can be found in the basin. The regime in the Southern Alpine part of the basin is characterised by snow accumulation and melt, while the larger tributaries of the middle Rhine have a largely pluvial regime (Rottler et al., 2021), with low (high) flows in the summer (winter). These different characteristic “memories” interface, with the low summer flows in the middle and lower basin increased by the summer high flows from snow and glacier melt in the upper basin (Stahl et al., 2022). Droughts in the Rhine basin, such as the 2003 and 2015 events, typically occur due to atmospheric blocking of anticyclonic conditions (Ionita et al., 2017), causing anomalies in atmospheric moisture conditions (Benedict et al., 2019) with persistent low precipitation and high temperatures. This results in low flows and hydrological droughts in the tributaries of the middle and lower Rhine, though (Laaha et al., 2017) point out the importance of the “memory” of dry (or wet) preconditions, which can influence the severity of the propagation to hydrological droughts. Hydrological droughts in the middle and lower Rhine may, however, be exacerbated due to preceding winter droughts with low precipitation and snowfall over the alps (Pfister et al., 2006). Projected changes to the current nival-pluvial regime due to the warming climate will mean the buffering of summer low flows by melting ice from glaciers and snowmelt may reduce, causing more frequent hydrological droughts (as well as floods) compared to present day climate (Rottler et al., 2021; Stahl et al., 2022).

Interfacing of signals with different memories are also apparent in aquifers across the basin. Tijdeman et al., (2022) show in their study in Southern Germany that fast-responding aquifer systems may respond to meteorological drought conditions before streamflow in subbasins underlain by slower responding large storage aquifers. Such slow response aquifers can buffer short meteorological droughts, as happened in 2011 and 2014, with groundwater anomalies negligible compared to negative anomalies in streamflow and soil moisture. This buffering however strongly depends on antecedent conditions, with dry pre-conditions leading to groundwater systems being severely threatened by short dry spell (Tijdeman et al., 2022). The long memory of groundwater systems can also lead to slower recovery, particularly if groundwater levels have been significantly depleted such as in the 2018-2022 drought in groundwater-dominated systems in the eastern part of the Netherlands, which recovered slowly despite relatively wet conditions in the winter of 2021 (Brakkee et al., 2022). However, conditions rapidly returned to a drought state in 2022, raising questions about whether changes in recharge rates or rainfall-runoff processes have occurred.

One of the most notable impacts of the 2022 drought was on the Rhine River, Europe's most important inland waterway. The low water levels in the Rhine disrupted shipping, threatened biodiversity, and highlighted the vulnerability of the river to climate change. In August, the streamflow at Köln, Germany, reached a historic low of 652 m3/s. Over most of the month of August, the water levels reached unprecedented low levels over the last 140 years (Fig. S2). Moreover, on the 17th of August 2022, due to the extreme ongoing drought, the water level of the Rhine in Emmerich, near the Dutch border, had reached a historic low of -3 cm. These low water levels were caused by a combination of factors, including: reduced rainfall, high temperatures and groundwater depletion. The prolonged drought also led to depletion of groundwater reserves, which are a major source of water for the Rhine and other rivers.

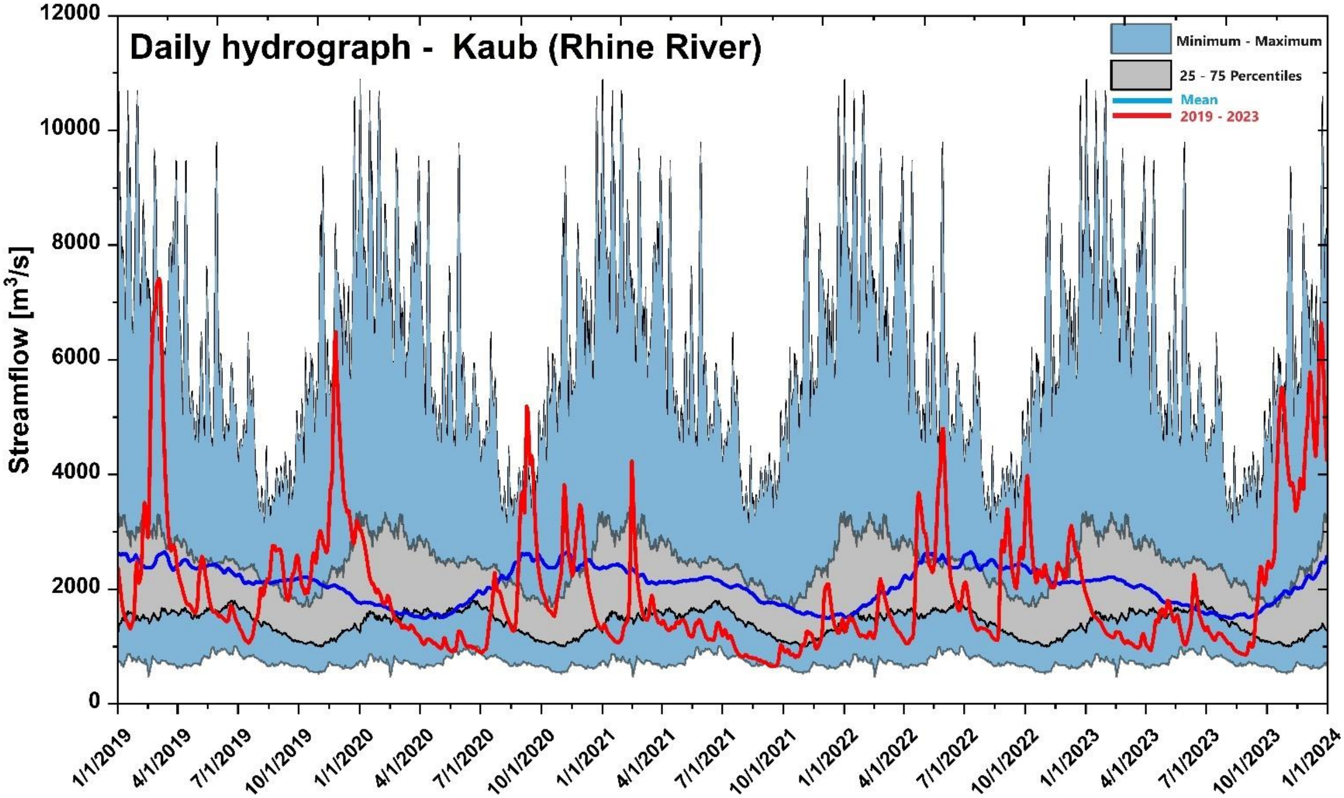

Figure S2: Daily hydrograph at Köln gauging station (Rhine River) over the period 1.01.2019 - 31.12.2023. The period 1881–2018 was used to compute the daily streamflow climatology.

Ecosystem

The relationship between anomalies in soil moisture and vegetation in the Rhine basin is complex and soil moisture droughts do not always correspond directly to negative vegetation anomalies (Van Hateren et al., 2019). In some years, drought conditions result in a positive response of the vegetation, in other years negative vegetation anomalies occur in periods that are not extremely dry, probably because other factors play a role as well. The role of antecedent conditions seems crucial, especially in spring, and only later in the year the relation between soil moisture and vegetation anomalies becomes more synchronous (Van Hateren et al., 2019). But a wet spring does not always result in a higher resilience to drought later in the year. In the Netherlands, the winter and spring of 2021-22 showed wet pre-conditions for the drought that developed in summer 2022. However, the extensive drainage system that historically was used to discharge any excess water quickly also meant that the water was not stored and that starting conditions of the hydrological system were sub-optimal, so that the dry summer could result in drying out of local streams and ponds and impacts on aquatic ecosystems (Natuurmonumenten, 2022).

During the recent droughts in Europe (2018-2020) several legacy effects became apparent in ecosystems in the Rhine basin. Buras et al., (2020) showed that pastures and arable land were more vulnerable to variabilities in the climatic water balance and had a stronger immediate response to drought than forests. These differences are largely associated with the forest-grass differences in rooting depth-related hydroclimate conditions. In some cases, forests tend to have larger rooting depth (Schenk and Jackson, 2002) and larger root-zone water storage capacity to buffer severe droughts (Mackay et al., 2020; Wang-Erlandsson et al., 2016). But the two consecutive hot and dry summers in 2018 and 2019 amplified impacts due to preconditioning from past disturbance legacies (Bastos et al., 2021). The 2018 drought event severely impaired the physiological recovery of trees, making them vulnerable to secondary impacts, such as insect or fungal attacks, with the resulting tree mortality expected to persist for several years. As a consequence, tree mortality rates in Germany spiked in 2020, at values about 10 times higher than in the past decade for needle-leaved trees (BMEL, 2021) and this is likely to continue for several years. Also several ecosystems and specific species in the Netherlands were affected by the accumulated effects of several dry years in a row, combined with other pressures such as pollution (Natuurmonumenten, 2022). This is an example of how ecosystem effects of drought can be creeping and accumulating (Tijdeman et al., 2022).

Social system

Most drought impacts in the Rhine basin were recorded in the years 2003, 2015, and 2018. (Dahlmann et al., 2022) found that these were not evenly spread over the basin, but that more impacts were recorded in downstream parts of the basin, confirming the hypothesis of asymmetric upstream-downstream impacts.

Drought impacts are not always felt by society in the Rhine basin. This is partly because baseline vulnerability is low, partly because effects are compensated economically (for example by higher market prices resulting in a net-zero effect of drought on agricultural or shipping revenue), partly because impacts are passed on in time or passed down to other systems. This passing on of impacts for example happened in 2018-19 in the Netherlands when increased groundwater abstraction for irrigation was increasingly used as adaptation strategy after the 2003 drought (Kreibich et al., 2022a). This reduced the drought impacts in irrigated agriculture, but increased impacts in non-irrigated agriculture and groundwater-dependent ecosystems due to lower levels during the drought. It can also prevent recovery and create more impacts during subsequent drought events (Kreibich et al., 2022a).

A study on the governance of droughts and floods showed that in the Netherlands severe drought events (1976, 2003) resulted in less structural measures than flood events (1953, 1993; Bartholomeus et al. (2023). For example, in the Netherlands drought management is crisis management. Also, during drought often only restrictions on surface water abstraction are implemented, not on groundwater abstraction, which neglects the connections between these parts of the hydrological system and ignores the longer-term impacts that increased groundwater abstraction can have. Using the case study of adaptive water management in the Netherlands, Pot et al. (2023) demonstrate how policy actors can use temporal strategies to navigate dual crises like creeping and acute threats unfoling at the same time, such as extreme weather evens such as drought and flooding and the creeping crisis of climate change. These strategies include strategic coupling of long-term shocks and creeping crises, crafting time horizons, molding the pace of public problem-solving, inter alia.

Climate change makes systems that gradually adapted to a certain state, suddenly not adaptive anymore to the new normal in the future. This is what is currently happening in the Netherlands, a country very well adapted to flooding, but now needing a transformative shift to drought management. Also in other countries in the Rhine basin (Germany, France) and the rest of Europe a change in drought management is happening. For a long time the 1976 drought was the benchmark drought for policy, but only in response to the 2018-2020 drought new policies have been implemented (e.g. Blue Deal in Belgium, Bodem & water sturend in the Netherlands). This shows that the recent droughts have increased awareness.

Management

The different interfacing signals (nival/pluvial, groundwater etc) implies the importance of tracking non-drought conditions (approaching drought) in a drought management context, especially for the more slowly responding rivers and aquifers. Until recently, the Royal Netherlands Meteorological Institute (KNMI) in the Netherlands only monitored drought conditions during the growing season (1 April - 30 September) and the effects of a wet winter were not taken into account (KMNI, 2023). KNMI recently also added continuous SPI monitoring, which the Ministry of Water now includes in their continuous monitoring bulletins of various hydrometeorological variables, including river discharge and groundwater (Rijkswaterstaat, 2023). Nevertheless, the monitoring remains focused on the climatic water balance (precipitation minus potential evapotranspiration) (KMNI, 2023).

The so-called “drought radar” (Deltares, 2023) goes a step further to forecast drought conditions in groundwater. They even include an estimate of water management and groundwater abstraction, but this information is incomplete and not dynamic (Berendrecht et al., 2011). It is rare for these systems to operationally include hydrological drought and dynamics and feedbacks of ecosystems and social systems.

In terms of drought management, increasingly long-term pro-active measures are being implemented in the Rhine basin. For example there are many projects to increase infiltration and decrease drainage, e.g. by reducing drainage density, managed aquifer recharge, etc (Kreibich et al., 2022b, 2022a; Sprenger et al., 2017). In the Netherlands, water boards implement surface water use restrictions during drought, but after multi-year drought there is more awareness that groundwater use should also be restricted with the aim to prevent long-term effects in the hydrological system and potential cascading effects on the social system and ecosystem (Bartholomeus et al., 2023). In Germany, there are different projects which are trying to use agile network control to increase the resilience of water supply infrastructure, by developing a situation-dependent customer (group) specific regulation of water quantities using AI technology, as well as a impelement a (pre-)operation low flow forecasting system for the water levels of Rhine.

There is also discussion on the need of a common drought management strategy within the transboundary Rhine basin, given the different degree of development of drought management and water allocation policies across the riparian states (Blauhut et al., 2022; Dahlmann et al., 2022).

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