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Over-reliance on water infrastructure can hinder climate resilience in pastoral drylands

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Extreme droughts are affecting millions of livestock farmers in sub-Saharan Africa, causing water shortages, famines, migration and fatalities. The construction of new small water infrastructures (SWIs), such as deep wells and boreholes, is increasingly supported by climate resilience programmes of non-governmental organizations and national governments to improve water availability for agro-pastoralists, especially as an emergency response to extreme droughts. Although the short-term benefits of SWI are clear, their potential cumulative impact and their long-term effects on the resilience of dryland communities remain unclear. Here, building on in-depth anthropological literature from five key African drylands, we model post-drought pastoralists' dynamics related to SWI. We show that while developing new SWI releases water shortages in the short term, it can erode traditional adaptation practices without adequate governance. We further illustrate how our model captures early quantitative signals of resilience loss in dryland Angola. This indicates that poorly governed water development in African drylands can be a limiting factor for the long-term resilience of pastoral communities facing a range of social, demographic, economic and climate challenges.

The year 2022 has been one of the driest years on record, adding to a long period of water scarcity that has affected millions of African smallholders over the past 10 years[1–5]. Climate change is expected to increase drought intensity and frequency in many pastoral regions[6], impacting first and foremost subsistence farmers[7]. According to the latest IPCC report, the global population exposed to exceptionally severe droughts is projected to rise from 3% to 8% in the coming decades[8].

The impacts of climate change and droughts are particularly detrimental in drylands, which are characterized by high precipitation variability and uncertainty[9]. Drylands cover about 40% of global lands and are mostly inhabited by rural communities living on mobile pastoralism[10]. Mobility (that is, seasonal movements of pastoralists and their herd[11]) is the traditional strategy of pastoralists in drylands around the globe to cope with climate variability and water and pasture scarcity[12,13]. Yet it is not to be considered as a mere drought coping mechanism but a whole livelihood strategy that allows pastoralists to navigate uncertainty, change and variability[14]. Depending on drought intensity and sociocultural traditions, herd movements can last a few weeks to years and involve young clan members or entire families. Mobility routes are extremely variable, depending on the health conditions of livestock, pasture, and water resource availability and distribution. During exceptional droughts, water scarcity is a major limiting factor for humans and livestock. Horticulture becomes impracticable, and grass vegetation in areas with natural springs cannot be used as these

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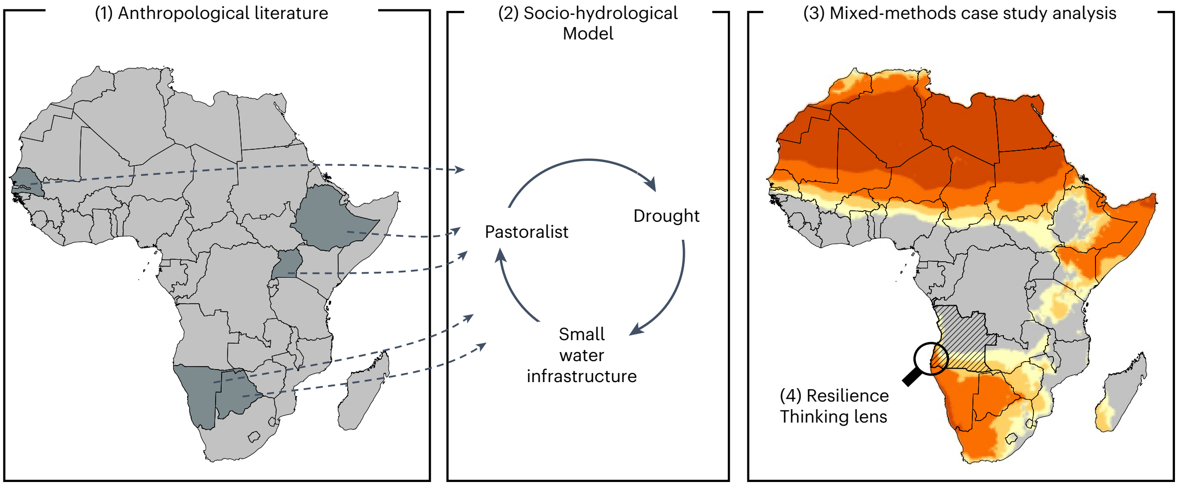

Fig. 1 | Methodological framework. Our approach is based on (1) a literature review of anthropological studies on the effect of water development on mobile pastoralist, (2) qualitative socio-hydrological model of SWI–pastoralist dynamics, (3) mixed-methods case study analysis, linking quantitative trends of socio-hydrological features to local pastoralists behaviour in dryland Angola and (4) resilience thinking lens to interpret socio-hydrological dynamics in a long-term resilience perspective.

water sources usually become dry[15,16]. Hence, these circumstances constitute a serious risk for pastoral livelihoods.

One crucial measure championed by governments and organizations to support pastoralists' resilience to droughts is the construction of small water infrastructures (SWIs), such as deep wells and boreholes. Especially during exceptionally intense droughts, scaling SWIs is considered a priority to achieve the United Nations Sustainable Development Goals[17,18] and placed at the top of national and international agenda for water and agricultural development[11].

A case in point is the recent situation in Angola. The southern part of the country is experiencing the worst drought in the past 40 years[19], if not the worst ever recorded[20], with at least 2.3 million people affected by water and food insecurity[21,22] and about US$244.7 million losses in agriculture from 2012 to 2016[23]. Against this background, the government[24,25], international non-governmental organizations (NGOs) and private companies are pushing investment in small- and large-scale water infrastructures to provide necessary immediate relief to the humanitarian emergency. However, the effects of such short-term fixes on long-term pastoralists' resilience are unknown and mostly ignored by the actors implementing water infrastructure interventions in Angola[26].

Similar situations are common across African drylands hit by exceptional droughts. While representing a necessary emergency response[27,28], a substantial increase in water infrastructure and water supply may also enable a change in pastoral drought-coping strategies, with unforeseen consequences on groundwater availability, rangeland ecologies and overall drought-coping capacity. Given the complexity of pastoral livelihoods and the contextual nature of their drought-coping strategies, driven by cultural, socio-economic, political, demographic and environmental factors[14], understanding the systemic implications of water infrastructure development remains a major barrier for designing resilient development strategies across African drylands.

Drawing from long-term and in-depth anthropological research on the impacts of SWIs on pastoralists' livelihoods, we model pastoralists' dynamics connected to water infrastructure development, especially after exceptional droughts. We specifically focus on the historical precedent of the 1970s–1980s in sub-Saharan Africa[29,30] to better understand the unintended effects of interlinked water development and pastoral adaptation strategies in response to exceptional droughts. We base our modelling framework on the combination of qualitative and quantitative information (Fig. 1). First, we review long-term ethnographic studies describing the effects of SWI in different pastoral drylands across a gradient of agro-climatic conditions of sub-Saharan Africa, including Senegal, Uganda, Ethiopia, Botswana and Namibia. On this basis, we develop a qualitative socio-hydrological model, highlighting links and feedback between water availability, pastoral mobility and drought impacts. Then, we perform correlation analysis (that is, Mann–Kendall test) to check whether trends in drought intensity, SWI and land-cover change support our hypothesis on the possible long-term effects of SWI in Namibe, Southern Angola. Namibe is an instrumental case because of its wide range of hydroclimatic conditions, spanning from hyper-arid to humid subtropical areas, and the ongoing water emergency condition, to which NGOs and the government are reacting by introducing numerous SWIs. We complement the case study analysis with a scoping ethnographic campaign in eight pastoral communities to contextualize the socio-hydrological trends and reveal links with pastoralists' resilience. Finally, we use the resilience thinking lens[31] to identify entry points for sustainable water development strategies supporting long-term pastoralists' resilience.

Water-supported mobile pastoralism

Mobility is the central mechanism triggering a chain of effects on the availability of local water and pastoral resources. Fewer livestock and people permanently living in an area reduce water demand and pressure on rangeland resources, hence alleviating water and forage shortages for the local communities and their animals (Fig. 2a, balancing loop B1). During exceptional droughts, national governments and international organizations often promote emergency response interventions based on water infrastructure. Being an exogenous strategy for pastoral communities, water infrastructure can have an ambivalent effect on local water and food supply. On the one hand, it increases local water availability, thus reducing water shortage (Fig. 2a,b, pink balancing loop B1). When new SWIs are in waterless rangelands, they can also provide access to new grasslands. On the other hand, higher water availability can motivate sedentism, thus increasing pressure on local water and grazing resources. Reduced mobility can have mixed effects: (1) shift to ranching[31], (2) overgrazing and rangeland degradation around the new water infrastructure[29,30,32,33], and (3) adoption of crop farming[34–36]. All these options might provide opportunities for livelihood diversification, yet at the cost of pastoral mobility—a long-established drought-coping mechanism (Fig. 2b, red reinforcing loop R1). These effects are not an inevitable outcome of water

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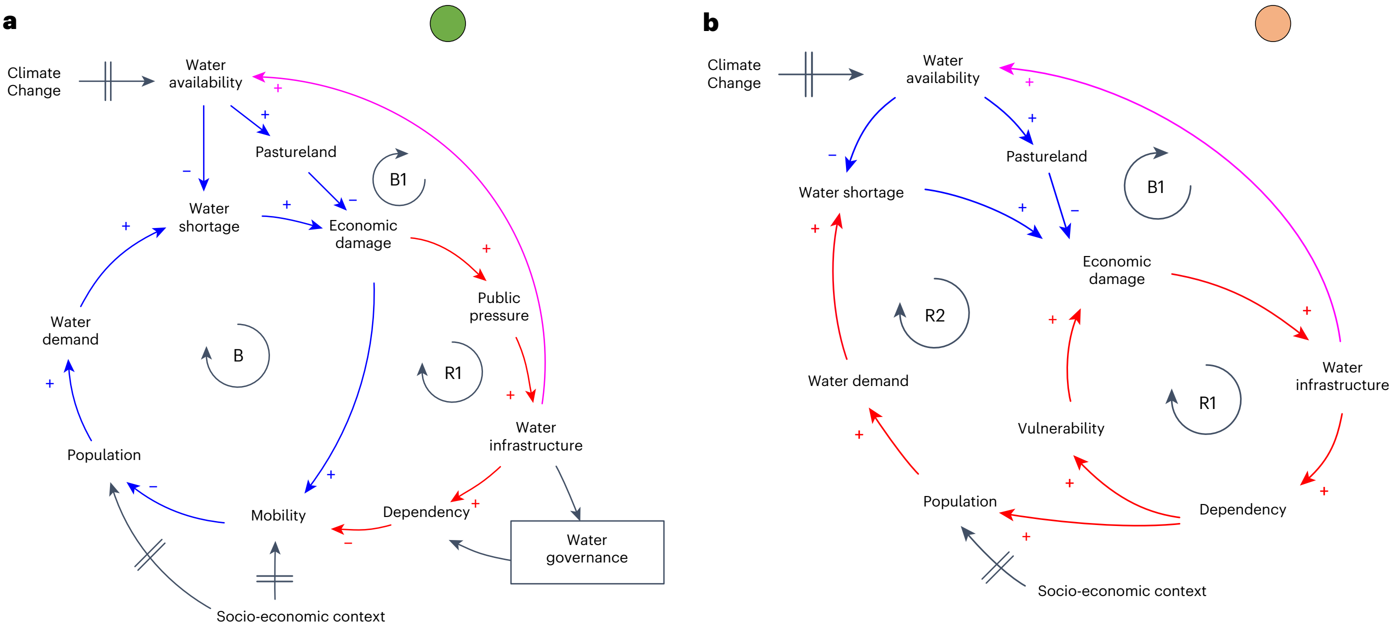

Fig. 2 | Modelling long-term pastoralist–SWI dynamics in drylands. CLDs show the positive (+) and negative (−) relations among variables and the existence of reinforcing (R) or balancing (B) feedback loops. **a**,**b**, Our models illustrate the ambivalent effect of water infrastructure development on water shortage by decreasing mobility (in red) and increasing water availability (in pink) (**a**) and the effect of water infrastructure development on sedentism and transition to highly water-dependent livelihoods (**b**). The green and orange balls in the top-right corners of each panel are introduced to reference the two systems.

infrastructure developments. Pastoralists' sedentism and livelihood options depend on the overall socio-economic context (for example, population growth) and the governance system in place around new SWI, including spatial distribution, use and access institutions at different levels (for example, customary, local and national regulations[37]).

Water-dependent agro-pastoralism

The introduction of SWI is a strategy for short-term drought response that might lead to unintended consequences on local and regional socio-ecological dynamics in the long term. Water infrastructure development can foster a critical transition from mobile pastoralism to more sedentary water-dependent activities if not adequately planned and managed. Consequently, pastoralists might progressively abandon mobility in favour of irrigated agriculture[38] and ranching. Although this condition might increase food security in the short-term, it also raises their water demand while creating dependency on dryland depletable water sources. If sustained for several years, this dependency can slowly transform pastoralists' cultural and socio-economic identity, making them lose their traditional knowledge of the practice of mobility, rangeland and drought management. This new water-dependent livelihood system relies on depletable water sources, although less variable than traditional shallow groundwater, and is thus still vulnerable to water shortage from extreme droughts and human overexploitation[39,40] (Fig. 2b, reinforcing loops R1 and R2). Moreover, within the complex web of interactions in the use of water and land resources, the expansion of small-scale agriculture can significantly increase rangeland fragmentation, reducing the land available for grazing and hampering mobility options for extensive pastoralists[41]. This push to less productive rangelands is often driven or encouraged by population growth[34]. Likewise, the shift from mobile pastoralism to ranching has similar implications to the dynamics described for irrigated agriculture[42–44].

Socio-hydrological dynamics in Angolan pastoral drylands

The 30-year trends of the socio-hydrological features in Namibe (Fig. 3) show signals of a water-dependent pathway due to the current SWI development interventions. Drought conditions, indicated by the standardized precipitation evapotranspiration index (SPEI)[45], show a series of multi-year and intense droughts, culminating in the ongoing drought period that started in 2012. Drought intensity is generally higher in the more arid municipalities of Namibe and Tombwa than in semi-arid Bibala and Camucuio (Fig. 3c,d). Drought intensity and SWI trends exhibit a strong positive correlation in all municipalities (at least $P < 0.01$, Fig. 3b). This trend is well explained by our model, as the main response of national and international agencies has led to the massive construction of SWIs, together with the introduction of irrigated agriculture to increase food and water resilience in the region (loop R1 in Fig. 2a). In fact, an increase in SWI corresponds to a significant ($P < 0.001$) decrease in pastureland in all municipalities, except for the most arid one (Tombwa). Concurrently, cropland trends show varying patterns. Croplands increased in the less arid municipalities (Camucuio and Bibala) until the 2002 drought, keeping a steady or slightly increasing trend despite the long drought conditions. Meanwhile, croplands did not develop much in Namibe and Tombwa municipalities until 2016, when they increased during the driest period. Cropland trends show a very strong and highly significant correlation with SWI in Camucuio with decreasing correlations moving southwards along the aridity gradient (Camucuio, $r = 0.78$, $P < 0.001$; Bibala, $r = 0.51$, $P < 0.001$; Namibe, $r = 0.47$, $P < 0.01$; Tombwa, $P > 0.05$). Population increase is highly correlated with SWI and pasture loss ($r > 0.94$, $P < 0.01$) in all municipalities except for Tombwa, indicating increasing pressure and competition over water and land resources. However, although population shows a ubiquitous and steady increase, the other variables show a varied pattern across the agro-climatic gradient and very steep changes starting from the 2012 drought (Fig. 3 and Supplementary Fig. 2). In particular, cropland expansion and pastureland shrinking are strongly linked with SWI development in dry/sub-humid and semi-arid areas but progressively less so in arid and hyper-arid rangelands, suggesting the influence on SWI number and distribution against the background trend of population growth.

The variables' trends are further clarified by pastoralists' behaviours across the eight communities of Bibala, spread across the aridity

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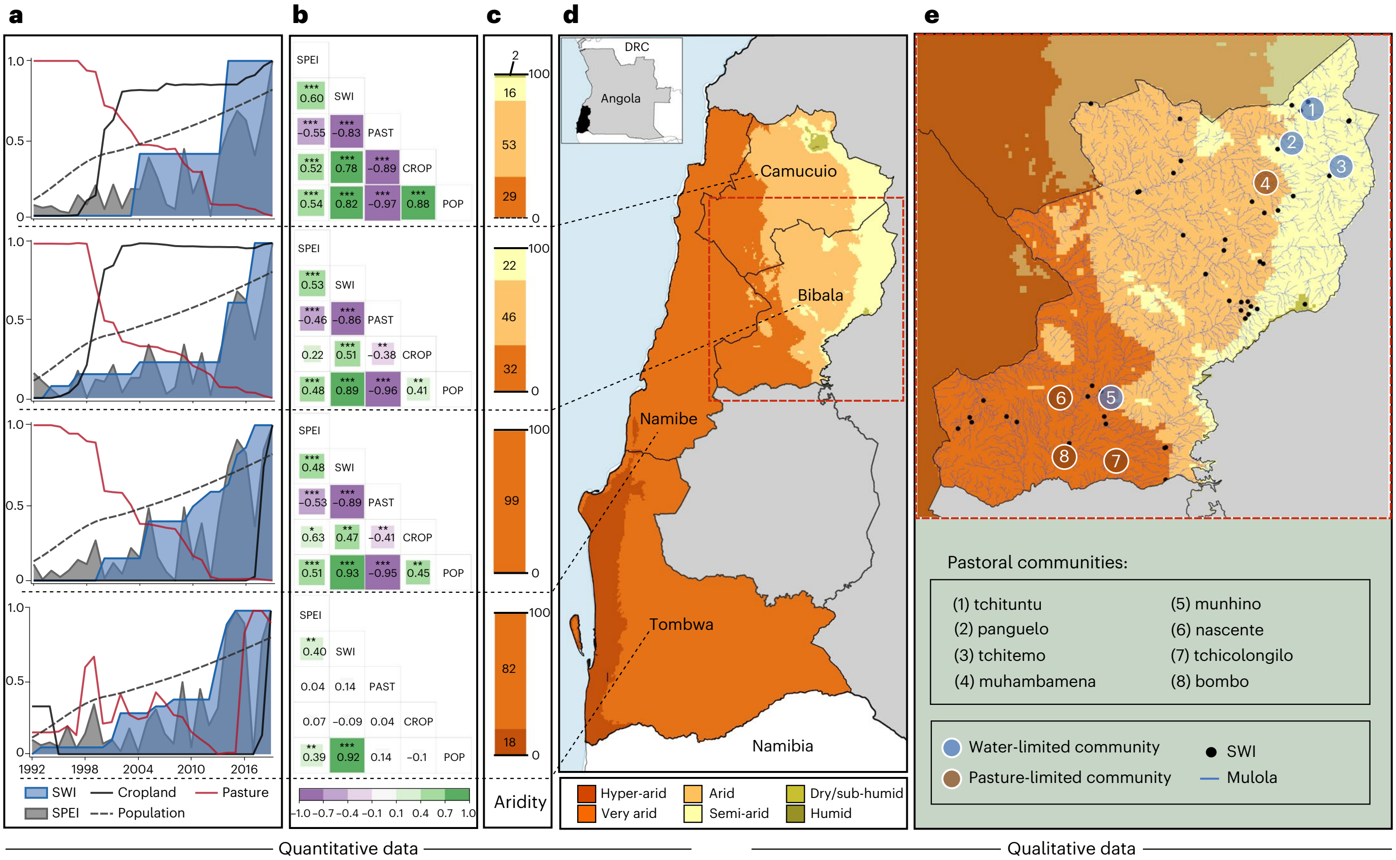

Fig. 3 | Socio-hydrological trends in the pastoral province of Namibe and community-centred water and mobility conditions. a, Trends in normalized values of SWI (blue area), pastureland (PAST, red line), cropland (CROP, black line), population (POP, dotted black line) and drought intensity (SPEI, grey area) from 1992 to 2019. **b**, Correlations (from −1 to 1) between variables and significance: *, ** and *** refer to significant P values ≤ 0.05, ≤ 0.01 and ≤ 0.001, respectively. **c**,**d**, Aridity conditions, from hyper-arid to humid, reported in percentage in the stack plot for all municipalities (**c**) and overview map of the Namibe region (**d**). **e**, Map of the eight pastoral communities across the aridity gradient of the Bibala Municipality and perceived water and mobility needs resulting from the FGDs.

gradient (Fig. 3), which show a clear pattern of water and pasture needs, related mobility mechanisms and aridity conditions. Focus group discussions (FGDs) revealed how pastoralists perceive the construction of new SWIs and their potential effect on local drought-coping strategies. Traditionally, precipitation variability is usually characterized by a pattern of three to four 'good years', two to three 'bad years' and three to four 'normal years'. Mobility is the main drought-coping mechanism in all communities. However, the occurrence and length of transhumance is usually driven by the availability of the limiting resources of water and pasture. For example, pastoral activities in the most arid areas of Bibala municipality (that is, the communities of Nascente, Thcicolongilo and Bombo southwest of Bibala) are primarily limited by pasture. Pastoralists from Thcicolongilo shared that new SWIs in this area would relieve water and food scarcity, enabling crop farming without reducing mobility, which is driven by pasture scarcity. This is particularly important after three 'bad years', which is perceived as a social threshold in most communities, after which the impact of drought becomes unbearable and encourages drastic adaptation measures, such as migration to cities or far-away pasture areas. Communities in the less arid areas (that is, Panguelo, Thcituntu and Tchitemo northeast of Bibala) are primarily limited by water availability, which forces them to travel to distant SWIs. In Tchitemo, families started practicing mobility after the major drought of the early 1970s, learning from Mukubal pastoralists from the hyper-arid south. They also used to access water from SWIs built during the colonial times, but the occasional failure of some of them forces pastoralists to keep moving in search of more reliable water sources. Pastoralists of Tchitemo mentioned that mobility is a tiring practice, which they would not sustain if they had more SWIs. The construction of SWIs in this area would allow them to permanently settle as agro-pastoralists.

Early signals of resilience erosion in dryland Angola

Our socio-hydrological model elucidates the province-scale quantitative trends and local-scale pastoralists perceptions in the context of dryland Angola. The steady increase in population has driven the expansion of agriculture in more favourable ecosystems and increased pressure on increasingly marginal pasture, which is a well-described dynamic across modern rangelands[46,47]. However, the population increase (that is, rate of change) is quite flat (Extended Data Fig. 1), suggesting that the peaks of SWI in the most intense drought periods (from 2010 to 2019) can be realistically attributed to drought-response dynamics described by our causal loop diagram (CLD) models (Extended Data Fig. 1) instead of the background water demand increase from population expansion. This dynamic supports the hypothesis of increased dependency of local pastoralists on fixed SWI, which resonates well with Angolan policies supporting irrigated agriculture in the area[24,48]. Although livelihood diversification is a common drought-coping strategy[49], a persistent and prolonged adoption of water-dependent activities might enable a shift in socio-hydrological regimes, especially in less arid areas. A strong push from pastoralism to agriculture in the less arid areas of Bibala and Camucuio has clearly started in the late 1990s because of

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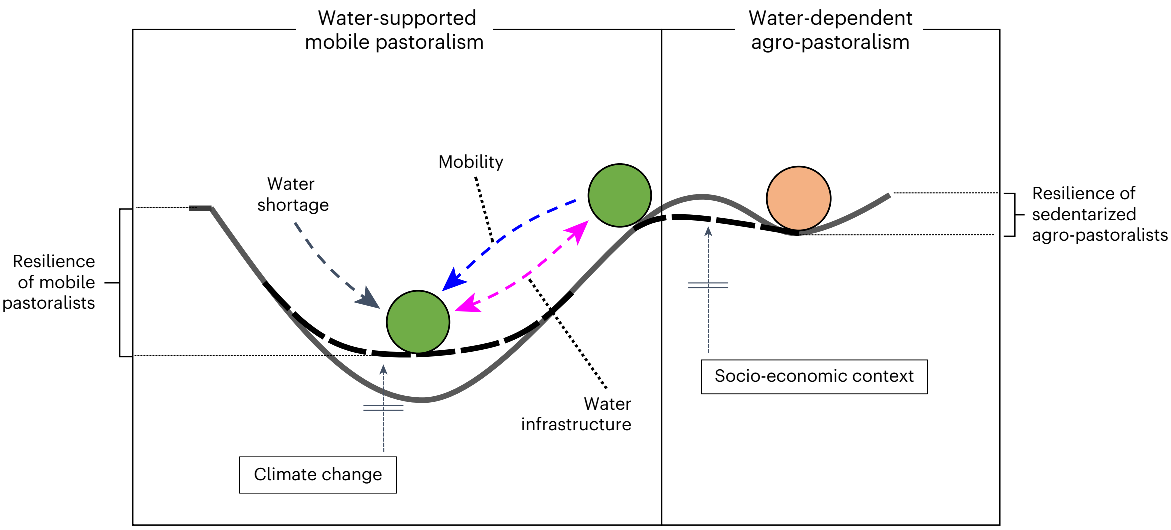

Fig. 4 | Ball-and-cup representation of the socio-hydrological regime shift. Dryland mobile (green ball) and the critical transition to settled agro-pastoralism (orange ball) in the context of SWI development. Climate change and socio-economic trends are external parameters to the system, acting on decreasing the structural resilience of agro-pastoralists. SWI development and mobility are internal variables, contributing respectively to reinforcing and balancing water shortage through feedback internal to the system.

socio-economic development strategies in response to population growth and widespread poverty. SWI development has then been pursued to cope with drought conditions and support agriculture expansion in the past 20 years at the expense of extensive pastoralism. This trend, together with the projected precipitation decrease in the area for the coming decades[50] and further population growth[51], warns of a possible prolonged dependency of pastoralists' livelihood on groundwater supply. Considering that 15–43% of the reported SWIs are currently not functioning (Extended Data Table 2) because of groundwater depletion or broken pumping systems, these policies have already increased communities' vulnerability to drought as mobile pastoralists are better equipped to cope with failing SWIs compared with water-dependent agro-pastoralists. If the current policies do not change, these trends will probably lead to the erosion of mobility as the main drought-coping mechanisms and extreme vulnerability to droughts.

In analogy with social–ecological regime shifts[52,53], giving up mobility, with its cultural implications and opportunistic water and grazing use, would represent a socio-hydrological shift involving a change in the interactions between pastoralists and water[54,55]. Considering resilience as the ability of a socio-hydrological system to endure perturbations[56], a water-supported mobile pastoral system (Figs. 2a and 4) is more resilient in the long-term to extreme droughts than a water-dependent system (Figs. 2b and 4). The high dependency on local water availability binds food security to a fixed and potentially depletable water source, reducing the space of solutions provided by a mobile lifestyle with negative implications for the long-term resilience to extreme droughts.

Our analysis in Namibe also confirms how regime shift is more likely in situations where multiple stable states coexist. In fact, the less arid municipalities, where both agriculture and extensive pastoralism are viable activities, show signals of cropland expansion and pastureland reduction, whereas the most arid ones (such as Tombwa), where crop farming is not viable, do not show any signals of a shift away from mobile pastoralism. Especially in Camucuio, a less arid municipality, this trend is most likely driven by agricultural development policies rather than SWI expansion, although increased water availability reinforces this mechanism. The just-mentioned alternative-stable-states condition in our socio-hydrological system resonates with the analogous concept theorized, modelled and measured for ecological systems. For example, if hydroclimatic conditions of tropical forests get drier (that is, closer to savannah conditions), perturbations, such as wildfires, can trigger a regime shift to the savannah state[57]. Similar conditions can be observed in other ecosystems across the world[58,59]. Although socio-ecological regime shifts are more complex and less mechanistic and thus harder to detect, changes in livelihood systems have been modelled[60] and observed in other pastoral areas, including a shift from pastoralism to agriculture within the Maasai pastoralists in Kenya[61,62] and the transitions from pastoralism to ranching in Central Africa[42]. These cases, unlike the case of Namibe, were driven by explicit sedentarization policies aimed at 'modernizing' traditional dryland pastoral systems. Water infrastructure development was often embedded in broader sedentary policies aimed at better governing mobile communities and managing conflicts between pastoralists and farmers[31,40,43].

Within socio-hydrological enquiry, comparable socio-hydrological dynamics have been previously explored in other contexts. For example, the mechanism of increased vulnerability caused by the dependency on water supply, named the 'reservoir effect', was shown for large dams. In that case, increased water availability enabled the expansion of water-intensive farming, resulting in increased water consumption, that is, the 'supply–demand cycle', in many high-income countries[63]. A similar paradox of increased drought impact associated with increased water supply (and thus consumption) was shown as a possible driver of the Maya collapse[64]. Finally, a recent analysis of the potential impact of unprecedented drought in the African urban context has shown how increased water supply can exacerbate inequalities and worsen the impact of drought on urban communities[65]. This body of socio-hydrological literature, which our work contributes to, helps shift the framing of drought conditions from solely hydro-climatic events to socially influenced water scarcity conditions, reframed as anthropogenic droughts[66]. In simple terms, increasing water supply does not necessarily result in drought palliation as droughts are a result of complex socio-hydrological dynamics. This concept is in tune with the one of 'manufactured' water scarcity[67], which refers to the idea that scarcity can be used as a dialectic construct intended to fuel a simplistic narrative of water scarcity as caused by lack of water supply. This narrative calls for increased construction of expensive water infrastructure, favouring powerful actors (for example, politicians and large irrigation farmers) at the expense of small-scale agro-pastoralists[68]. Further research under this framework could complement the socio-political context and provide interesting insights on the Namibe case in the future.

Insights for resilient water infrastructure development

Despite the negative implications of extensive SWI development highlighted by our study, increasing water availability remains key in supporting drought-stricken pastoralists and sustainable development of drylands, especially considering that water resources development and sustainable irrigation are key to dealing with the effects of climate change[69,70]. Water scarcity can have disastrous effects on food security and human and animal health[71]. It can also trigger conflicts between different user groups, whether pastoralists or farmers[72,73]. Meanwhile, we showed that introducing numerous SWIs can change livelihood strategies, anchoring local communities to the proximity of SWI, especially in places with favourable agro-climatic conditions. Our analysis is not able to discern which and how many SWI have positive or negative implications on the communities or at larger scales. However, our large-scale findings support the position that maintaining mobility is fundamental for pastoralists to cope with drought conditions[74] and for fostering long-term resilience[75,76].

One technical solution to avoid creating dependency on new water infrastructures is to opt for water harvesting technologies. Water harvesting prolongs water availability during the dry season by collecting and storing sporadic rainfall and runoff water[77]. Moreover, many traditional and innovative water harvesting structures, such as sand dams, subsurface dams and ponds, help increase soil moisture retention, with positive effects on local vegetation and shallow aquifers[78]. Supporting the construction of distributed and temporary water harvesting points can increase water availability while encouraging mobility, especially if placed along traditional transhumance routes[79]. This would also reduce the pressure on groundwater resources, which are expected to be increasingly depleted by future irrigation expansion[69] and relief competition between pastoral and agricultural practices[80].

Nevertheless, more SWIs alone do not necessarily cause sedentism, but they can be an important enabling factor. It is crucial to understand the specific circumstances and objectives underlying the introduction of SWIs and how they are managed afterwards. Our results show how the massive construction of SWIs promoted by recent climate-resilience programmes might enable similar dynamics of mobility erosion and livelihood shift that were forcefully imposed by colonial sedentarization programmes. Water governance is therefore key to ensuring adequate SWI planning and management, alleviating water shortages while avoiding rangeland degradation. Our findings clarify that hyper-arid areas would benefit from increased SWIs without inducing sedentism. Increasing SWIs along pastoral corridors would support transhumance of mobile pastoralists and promote more sustainable rangeland use practices[79]. In addition, expanding SWIs in hyper-arid areas might open new grazing lands, which would otherwise be inaccessible for lack of water resources[31,81]. These strategies would contribute to reducing pressure on less arid areas (that is, semi-arid/sub-humid), easing the competition over water and land among pastoralists and between pastoralists and settled farmers[82]. In semi-arid/sub-humid areas, given the suitable agro-climatic conditions, new SWIs should be developed along with solid rules on water access to discourage sedentism, for example, by restricting their use during the rainy season. Finally, access to SWIs in these areas should also be carefully planned and monitored with the participation of local traditional pastoral leaders to avoid tensions between pastoralist groups and avoid reinforcing power dynamics[31].

In conclusion, our analysis made evident how interventions based on narratives of increasing water supply without effective governance are jeopardizing local climate and water resilience. Such large-scale interventions promoted by the private sector, NGOs and national institutions have been generalized based on sub-Saharan rangelands[83] and described in Angola within the present study. Our results stress that proper infrastructural planning and management are key to regulating construction, access and use of new SWIs to respond to short-term emergency needs while maintaining a sustainable rangeland use based on extensive grazing and enhancing the long-term resilience of pastoralists to droughts.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-01929-z.

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Methods

Resilience thinking within socio-hydrological systems

As a consequence of the rising impact of humans on the water cycle[84] and the increasing effects of hydrological changes (including extremes) on human societies, hydrology research has progressed from analysing the physical processes associated with the natural water cycle to integrated conceptualizations of human–water systems[85]. This new frontier in hydrological sciences has been lately actualized in the concept of socio-hydrology, which aims to model dynamics and feedback between hydrological and social processes and unravel emerging dynamics[85,86]. The complex mutual interactions between society and ecosystems have also been the subject of study in resilience research over the past decades, with the aim of understanding the effects of such interactions on the long-term resilience of social–ecological systems[87,88].

Although resilience thinking and socio-hydrology come from different traditions and have developed within two separate scientific niches, they share the conceptualization of human–nature interaction as part of a complex adaptive system[89]. Using the resilience thinking lens, we can conceptualize the complex interplay of water and society. The resilience thinking lens also allows formalizing the social–ecological relationships within a system and analysing the complex dynamics between different elements and their effect on the system's resilience[56]. In this work, resilience is defined as the ability of the socio-hydrological system to respond to external shocks (droughts) by resisting, adapting or transforming to maintain its characteristics. The system in question is composed by mobile pastoralists and the surrounding institutional and environmental context, which are challenged by the increasing risk posed by droughts in a changing climate.

A traditional representation of resilience is the cup-in-ball model, which shows the system's position (ball) in a cup, which acts as attraction basins. The depth of the cup represents resilience (that is, the amount of disturbance the system can handle while maintaining its structures and functions[90]). A concept central to resilience thinking is the one of regime shift. When a socio-hydrological system (represented by the ball) moves from one basin of attraction to another in response to internal and external changes, it changes its levels of resilience[91]. The shift from one basin of attraction to another represents a 'regime shift' and implies a drastic change in the system's structures and functions[92].

Anthropological literature review

To gain a comprehensive understanding of the complex water–pastoralist dynamics in different sub-Saharan contexts, we used a case-study-oriented review of thick ethnographic descriptions instead of a more conventional extensive literature review. We selected five countries covering the main dryland areas (West Africa, Horn of Africa, and Southern Africa), with a variable presence of pastoral areas and a gradient of aridity conditions, ranging from hyper-arid (that is, Namibia and Botswana) to arid (Senegal and Ethiopia) and moist semi-arid (Uganda). Hereinafter, we review the dynamics from the case-based literature.

The Fulbe of Northern Senegal. The majority of Fulbe pastoralists of the Ferlo valley in Northern Senegal have long practiced mobile pastoralism, involving a marginal component of small-scale agriculture. However, after the drought of 1972, they had considerable herd losses, and pastoralists adopted two different strategies. Some pastoralists did not see rainfed agriculture as a viable option and focused on herd diversification (shifting to sheep and goats) and keeping a mobile life[44,93]. Meanwhile, supported by the state, international donors and NGOs, many pastoralists changed to irrigated agriculture. Settlements flourished around the main ephemeral rivers, and irrigated farms increased from 9,000 ha to 550,000 ha. This expansion of irrigation made livestock rearing increasingly difficult because of the encroachment of good-quality pastureland and blocking of pastoral mobility[34,41]. Ten years after what has been described as a 'borehole revolution' in the Ferlo Valley, over 50% of families who used to practice mobility as the main drought coping strategy gave up mobility[94]. Ten years later, only 10% of pastoralists still practiced transhumance in the area.

At the same time, during the 1980s, the government kept encouraging sedentism by supporting cattle ranching schemes around boreholes and passing on the responsibility of managing boreholes to local pastoralists[43]. The ranching schemes affected the transhumance patterns of these livestock herders. They became accustomed to the new settled grazing method over a decade, so much so that when some boreholes failed in the 1990s, ranchers and their cattle were not accustomed to long and exhausting transhumance anymore, and a large part of their cattle died[43]. In the year 2000, agriculture and ranching encroachment was still growing from the south and the north because of the expansion of irrigated areas along the Senegal River, reducing the space for pastoral mobility[44].

The Ovahimba in northwestern Namibia. Before the South African colonial administration's massive introduction of boreholes in northern Kunene from the 1950s onwards, Ovahimba pastoralists living in the region mostly relied on springs, ephemeral rivers and hand-dug wells for supplying their livestock and households with water. The main homesteads were usually located at more permanent water sources, and outlying grasslands were mainly used during the rainy seasons (that is, when on-site natural pans and rock pools were filled with water) to set up cattle posts[95]. The introduction of water infrastructure in the area was embedded in broader colonial initiatives of 'segregated development', Apartheid, and territorial encapsulation[96]. Throughout the latter part of the 1960s, 1970s and 1980s, boreholes were drilled in large numbers in the by-then Kaokoveld[97].

The borehole-drilling programme impacted the regional pastoral system in its mobility patterns enormously. With mechanical boreholes able to supply water throughout the year, herds could remain in the former rainy-season areas during the long dry season as they were no longer dependent on rainwater. The direct consequence was that herds stayed at the permanent SWIs along the rivers during the rainy season and then moved to borehole-equipped outlying pastures during the dry season[98]. This also made more labour investment in cultivation possible: people could now converge close to the rivers during the rainy season while household members set off to various livestock camps at the boreholes[3]. These developments and a sequence of good rain years correlated with increased livestock numbers in the region[98]. Alongside these processes, local communities struggled to develop and effectively implement a series of rules to adapt to the new socio-hydrological system and guarantee equal access and some degree of sustainability. Reasons included territorial disputes between politically dominant figures, lack of effective sanctioning mechanisms (that is, influential elders passed away and difficulties in imposing pressure on culprits) and increasing transaction costs due to population growth in an encapsulated territory to develop new social institutions[99]. The new mobility pattern implied intense stress through grazing during the dry season, which—together with droughts—evidently pushed the rangeland ecosystem in many parts of the region towards an ecological tipping point, implying a switch from perennial to annual grasses, which are more vulnerable to extended dry periods[100].

The Basarwa of Central Botswana. Basarwa communities of Central Botswana have traditionally practiced seasonal migration to deal with climate variability[101]. This adaptive response changed since the mid-nineteenth century with the introduction of boreholes. Pastoralists have started settling around SWIs, also encouraged by government programmes. Settlements and loss of land for other uses has further reduced pastoral mobility and increased their vulnerability to droughts[102].

In the Kgatleng District, boreholes were first dug in the 1920s[37]. Individuals or small exclusive groups of Tswana pastoralists were given the boreholes, making them almost private property. In the following decades, the British colonial governments kept supporting the construction and privatization of boreholes driven by a strong interest in expanding cattle herds and increasing incomes from beef exports[103]. Meanwhile, the colonial administration did not consider the smaller herders demanding SWIs on the arable lands and in residential areas. In the late 1950s and 1960s, the rate of borehole drilling increased, with an ambivalent effect on pastoralists[81]. On the one hand, this opened new territory for grazing; on the other hand, fencing of boreholes and overgrazing led to the degradation of grazing land around boreholes and the need to drill more to create new space for sustaining the cattle, which eventually led to groundwater depletion[104].

When another major drought hit in 1982, the government introduced a grant scheme to support pastoralists in borehole drilling. However, only the wealthiest pastoralists could invest in this scheme, resulting in an indirect concentration of water (and land) resources in the hands of a few[29]. Privatizing land and water reduced the mobility space for the poorer pastoralists, increasing their vulnerability to drought[105].

The Karamojong of Northern Uganda. Karamoja is a semi-arid region of Northern Uganda, with relatively favourable agro-climatic conditions for agriculture, thus hosting both mobile pastoralists and settled agro-pastoralists. During its colonial and post-colonial history, Karamoja has always been an area of political isolation and violent conflicts[106]. Together with the semi-arid agro-climatic conditions, violent inter-tribal and intra-tribal conflicts and the repeated coercive disarmament programmes of the government have been the major drivers of pastoralist mobility in this area since at least the beginning of the 1940s[72]. The focus of the colonial and post-colonial governments was to eliminate the 'problem' of mobile pastoralism by designing farming and ranching schemes for sedentary people[107]. In this context, water development schemes were pursued to enable this livelihood shift. From 1965 to 1971, over 3000 boreholes were drilled by the government, which enabled the settlement policies of the government, increasing the cattle population[107]. Settlement policies created dependence on dryland farming, making farmers more vulnerable to droughts, even under climatic conditions that were previously considered marginally impactful for the mobile pastoral communities[108]. Disarmed communities were also exposed and vulnerable to the heavily armed Turkana and Pokot communities in the neighbouring countries, leaving the Karimojong feeling unprotected. At the same time, the political marginality of Karamojong from the central government and the expensiveness of maintenance interventions compromised the functioning of about 2000 of them in 10 years[107]. Exacerbated by water scarcity, pastoralists' mobility increased, thereby influencing and often intensifying inter-group conflicts and displacement[109], especially between different districts and at the border with the Turkana pastoral region of Kenya[72].

In the following decades, water resources development continued to be promoted under the disarmament programmes. In the early 2000s, a series of donor-funded programmes launched water development projects for pastoralists to strengthen resilience in the face of climate change, supporting small-scale irrigation and other livelihood diversification activities[83]. Disarmament and settling programmes have not ceased, with similar negative consequences on pastoralist drought-coping strategies and impacts on their livelihoods. A recent assessment of water resources in the region found that the concentration of SWIs near settlements has contributed to reduced mobility and increased land degradation[110].

The Borana of Southern Ethiopia. For decades, governments and NGOs have considered drought occurrence to increase in Ethiopian drylands at a level that pastoralism would not have been compatible with anymore[111]. After the drought of 1973–1975, international organizations and state authorities started using water development as the main tool to build services and attract pastoralists to settle[112]. Governments and NGOs have promoted boreholes drilling within a long-term plan to transition pastoralists into small-scale irrigation farming[113]. However, the unexpected consequences of these policies resulted in the impoverishment of farmers, especially women[106], land degradation caused by overgrazing[113] and pastureland fragmentation[114].

Recent policies[115] still carry the long-term vision of settling pastoral and agro-pastoral communities along the perennial riverbanks or securing water resources[116].

The Afar in the Awash valley of North-Eastern Ethiopia. Several dykes and small dams, alongside large irrigation schemes, have been promoted since the 1950s to exploit the water resources along the Awash River. However, this caused the conversion of thousands of hectares of pastureland into irrigated farming, damaging the wetland ecosystem, pastoral mobility and drought-coping capacity[117,118]. Because of these large investments in irrigation schemes and land redistribution policies, a part of mobile pastoralists settled and transitioned to irrigated farming, another large part adopted a mixed agro-pastoral livelihood and some others continued practicing mobility[119]. In fact, contrary to government beliefs and expectations, converting extensive grazing areas into agriculture is not only detrimental for pastoral livelihoods but also less economically profitable[120]. Moreover, the change from extensive pastoralism to irrigated agriculture in almost half of the available land caused salinization of the land to the point that in 1991, over 3,000 ha of cropland were abandoned due to high salinity levels[121]. Only recently have water development strategies shifted away from sedentary policies to address rangeland pastoralism[122].

Qualitative system dynamics

We mapped the socio-hydrological system of pastoralist–water infrastructures by highlighting the main causes and effects of the system's variables using CLD. CLDs are graphical representations of a system made of nodes (representing variables in the system) and connections (representing causal influence between variables). The connections can be either positive when two variables increase or decrease together or negative when they imply the opposite change (for example, one increases when the other decreases, and vice versa). When variables are connected in a circular manner, they create 'feedback loops', which are the focus of CLDs. Feedback loops show the circular effect of complex interactions between variables on the system, thus highlighting the potential counterintuitive effects of distal variables[123,124]. For their simplicity and clarity in representing complex dynamics, CLDs have been used to map socio-hydrological systems and highlight counterintuitive dynamics related to water infrastructure development[63,125].

Mixed-method analysis in the Angolan dryland province of Namibe

Namibe is a dryland province of southwest Angola, with about 1,200,000 people, most of which live in rural areas and depend on mobile pastoralism and agriculture.

We chose the Namibe province in southwestern Angola as an instrumental case to analyse the modelled water–pastoralist dynamics for four main reasons.

(1) Namibe is a diverse province, with a wide gradient of social–ecological conditions, and is thus suited for exploring the different effects of water development on a range of social–ecological conditions.
(2) Southwestern Angola is currently suffering the longest and probably the most intense droughts ever recorded[20], hitting in and off from 2012, which severely affect water resources and and-pastoral people[125].
(3) The main strategy in response to such a serious situation is massive construction and rehabilitation of water infrastructures,

especially SWIs, by all actors, including the government, private business and international NGOs.

(4) Angolan pastoralists are understudied, and their historical drought response is not yet understood because of the long civil war (1975–2002). This makes Angolan drylands a suitable location to test the consistency of our model, which was developed based on evidence from more well-known pastoral regions.

Because the water development plan started only a few years ago and potentially unpredictable effects might show up in the future, applying our socio-hydrological model can warn of potential early signals of resilience loss.

Scoping ethnographic campaign. The scoping ethnographic campaign took place from 20 July to 7 September 2021, to complement our understanding of local socio-hydrological conditions and dynamics. We visited eight mobile pastoral communities located in the municipality of Bibala, which has a wide agro-climatic gradient. We held 3 FGDs in each community (a total of 24 FGDs). The NGO COSPE mobilized the members of the communities and offered food to support a large participation and compensate participants for their time. This eased the participation and fostered representativeness in terms of geographical distribution within the communities' territory. As the FGDs were held in communities with common spaces and were open for anyone to participate, it was not possible to provide reliable statistics in terms of number, gender and age of the participants, but roughly 30 to 50 people participated on average, with equal representation of men and women of all ages. The FGDs were centred around the following: (1) local hydrological and hydroclimatic indigenous knowledge, with a group of key informants including the head of the communities (that is, 'soba' in the local language) and the oldest member of the communities; (2) transhumance routes and animal water use, with the group of herders (that is, male members of the communities); and (3) domestic water use and needs, including location of SWI, time to water collection and different water uses, with the group of women of the communities. As the aim of the FGDs was to understand communities' response to droughts and water scarcity, the FGDs were not restricted to specific post-drought coping strategies but rather on the more generic water availability, needs and uses to gain a comprehensive understanding of communities' livelihoods, way of living and indigenous hydrological knowledge. The full list of guiding questions of the FGDs is available in Supplementary Information, and more insights on water-related problems are available in ref. 79.

During the whole campaign, we practiced participant observation and noted observations and personal reflections in a field notebook. We relied on the contacts and connections made by COSPE Onlus within the communities to approach participants and ask for their collaboration for the research project. We held informal discussions with local NGOs, such as COSPE Onlus, FAO and Word Vision, which are all involved in the province's water and agriculture development projects. We also held informal conversations with government authorities at the province and municipal level and donors, especially the FRESAN Program, a large European Union-funded funding programme for 'the reduction of hunger, poverty and vulnerability to food and nutrition insecurity in the southern provinces of the country most affected by climate change'. The informal discussions were functional to grasp the way of thinking of the exogenous actors involved in the construction of SWIs, their motivations and their approach compared with the ones of the pastoral communities.

The notes of the FGDs were then used to isolate the assertions on the following: (1) the underlying motivations of transhumance, (2) the limiting resources (pasture or water) triggering transhumance and (3) the willingness to continue practice transhumance under conditions of increased water availability.

Quantitative data and analysis. The quantitative analysis of Angolan socio-hydrological features included drought conditions (SPEI), SWI, population and land-cover dynamics. The sets of quantitative data are summarized in Extended Data Table 1. We used the time series as they were, apart from SWIs, which we cumulated to represent a proxy of the total water available in the region.

Data on population combines information from the Angolan demographic census[51] spanning from 1992 until 2019 with global data for historical conditions in 1975, 1990 and 2000[126]. We applied a monotone cubic spline interpolation using the Hyman filtering[127] to fill the gap of missing yearly values from 1976 to 1991.

Data on SWIs include boreholes, shallow wells and deep wells, including information on construction date (spanning from 1954 to 2018), type of abstraction method and functionality (Extended Data Tables 2 and 3). Most SWIs are multifunctional and used for domestic, animal and irrigation purposes, depending on the needs of the communities. This information is not included in the SWI dataset, but it comes out from the FGDs.

To compare variables with different magnitudes and units of measurements, we normalized all variables from 0 to 1. We checked all variables for normal distribution using the Shapiro test[128]. As all the variables showed to be non-normally distributed, we selected the non-parametric Mann–Kendall test[129] to assess the correlation between pairs of the four variables, which is reported as a correlation matrix (Fig. 3).

Ethics statement

The research protocol for this study was developed under the guidance of the ethical committee of the University of Florence and following the ethical conduct of the COSPE Onlus (the NGO leading the community engagement process) approved by the General Assembly of COSPE members on 3 July 2021. All members of the research team followed the guidelines and the protocols set by The European Code of Conduct for Research Integrity. The data collection within FGD concerns only aggregated information on non-sensitive topics. We obtained informed consent from all participants after duly notifying them about the context and purpose of the FGDs, expected duration of their participation, funders and lead researchers of the project, data protection, confidentiality and privacy, and duration of storage of personal data. Participants were also informed that they were under no obligation to answer any question and that they could withdraw from the interview at any time.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All quantitative data, except for the number of SWIs, are open source and accessible at the source cited in Table 1. The number of SWIs are available from the Namibe Provincial Government (Governo Provincial Do Namibe), but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. The data are, however, available from the first author upon reasonable request and with the permission of the Namibe Provincial Government. The qualitative data collected in Namibe are not publicly available due to ethical restrictions. These data are available from the leading author (luigi.piemontese@unifi.it) on reasonable request.

Code availability

The codes used to perform the quantitative analysis presented in this study are freely available at https://doi.org/10.5281/zenodo.7849300 (ref. 130).

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Author contributions
L.P. conceived the study, with the support of S.T., G.D.B., G.C. and E.B., performed the fieldwork in Angola, did the literature review, performed the analysis and wrote the paper. S.T. performed the quantitative analysis and substantially contributed to insights and writing. G.D.B., D.A.M.S., G.C. and E.B. contributed insights, discussed the argument and edited the paper.

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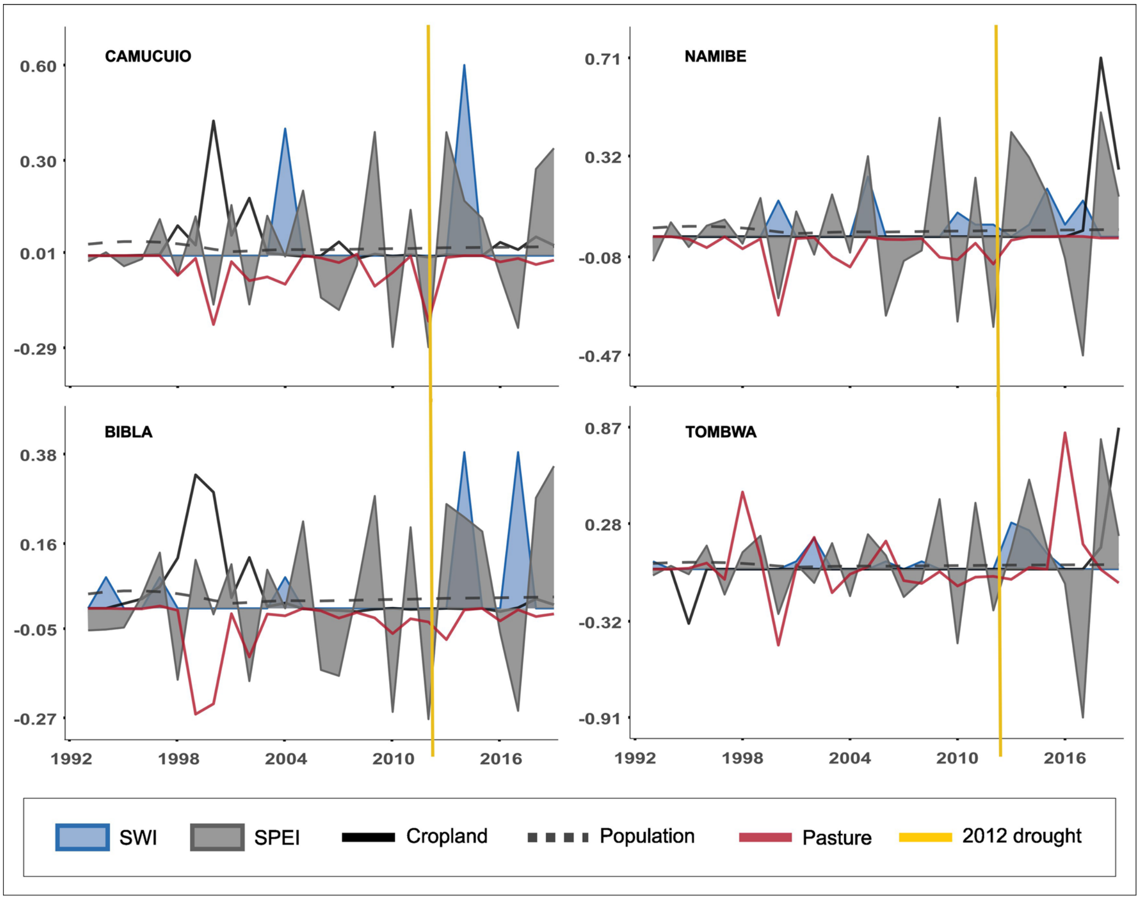

Extended Data Fig. 1 | Time series of the first-order derivatives of the normalized socio-hydrological variables in Namibe. Rate of change of the socio-hydrological variable during the 1992–2019 period. For example a flat line in this graph shows a steady increase (that is linear increase) of the variable. SPEI and SWI trends show a clear increase in magnitude after the 2012 drought, while population exhibit a rather flat trend during the whole period.

Extended Data Table 1 | Summary of the input data and sources considered in the quantitative analysis

Variable	Description	Spatial coverage/resolution	Time-range/ resolution	Data source	Open data (yes, no)
SWI	Total number of SWI in the Namibe province	Provincial level, point data	1953-2020, annual	Governo Provincial Do Namibe	no
SPEI	Gridded data of the Standardized Precipitation Evapotranspiration Index (SPEI)	Global, 1°	1955-2023, monthly	Consejo Superior de Investigaciones Científicas	yes
Pastureland and cropland	ESA land cover class data product	Global, 300 m	1992-2019, annual	Copernicus Climate Change Service, Climate Data Store	yes
Aridity index	Global Aridity Index	Global, 30 arc-seconds	Annual average in the period 1970-2000	CGIAR Consortium for Spatial Information (CGIAR-CSI)	yes
Population	Total population	Municipality	1992-2019	Angolan demographic Census, 2016	yes
		Global data, 9 arc second	1975, 1990, 2000	Global Human Settlement Layer (GHSL) Population (POP)	yes

Spatial coverage and resolution, time-range and resolution, source of information and links for open-access data sources.

https://doi.org/10.1038/s41558-024-01929-z

Extended Data Table 2 | Municipal distribution and functioning of SWI

Municipality	Nr of SWI	State of the SWI (%)		
		Good	*Bad*	*No data*
Bibala	194	57.2	41.2	0
Camucuio	119	79.8	19.3	0.8
Namibe	47	61.7	21.3	17
Tombwa	27	85.2	11.1	3.7
TOTAL	387	66,7	30,7	2,6

Summary of the number of SWI and their state of functionality within and across the four municipalities of Namibe considered in this study.

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Extended Data Table 3 | SWI abstraction method and functionality

Municipality	State	SWI abstraction method				TOTAL (by municipality)
		Motorized	*Solar*	*Manual*	*No data*	
Bibala	Good	11	33	65	2	194
	Bad	0	11	69	3	
Camucuio	No data	0	0	0	1	119
	Good	12	9	73	1	
	Bad	0	7	14	2	
Namibe	No data	0	0	0	8	47
	Good	19	3	7	0	
	Bad	3	1	6	0	
Tombwa	No data	0	0	0	1	27
	Good	0	0	0	23	
	Bad	0	0	0	3	
TOTAL (by abstraction method)		45	64	234	44	

Description of SWI abstraction method (that is motorized, solar and manual pumps) and functioning state (that is good or bad) in the four municipalities.

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Software and code

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All quantitative data, except for the number of SWI (original data name "Pequenos Sistemas e Pontos de Agua da Provincia do Namibe"), are open source and accessible at the source cited in table 1. The number of SWI were made available from the Governo Provincial Do Namibe, but restrictions apply to the availability of these data, which were used under licence for the current study and are not publicly available. The data are, however, available from the authors upon reasonable request and with the permission of the Governo Provincial Do Namibe. The qualitative data collected in Namibe are not publicly available due to ethical restrictions. These data are available from the leading author (Luigi.piemontese@unifi.it) on reasonable request.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Since the FGD were held in communities common spaces and open to anyone to participate, it is not possible to provide reliable statistics in terms of number, gender and age of the participants, but roughly 30 to 50 people participated on average, with equal representation of men and women of all ages. This information is reported in the methods section "4.1 Scoping ethnographic campaign".
Population characteristics	Since the FGD were held in communities common spaces and open to anyone to participate, it is not possible to provide reliable statistics in terms of number, gender and age of the participants, but roughly 30 to 50 people participated on average, with equal representation of men and women of all ages. This information is reported in the methods section "4.1 Scoping ethnographic campaign".
Recruitment	All communities' members were invited to join the FGDs. The NGO COSPE has mobilized the members of the communities and offered food to support a large participation and compensate participants for their time.
Ethics oversight	The research protocol for this study was developed under the guidance of the ethical committee of the University of Florence and following the ethical conduct of the COSPE Onlus (the NGO leading the community engagement process) approved by the General Assembly of COSPE Mmembers on July 3rd, 2021. No formal ethical approval was required by the local and national authorities. All members of the research team followed the guidelines and the protocols set by The European Code of Conduct for Research Integrity. The data collection within focus group discussions concerns only aggregated information on non-sensitive topics. We obtained informed consent from all participants after duly notifying them about the context and purpose of the focus group discussions, expected duration of their participation, funders and lead researchers of the project, data protection/confidentiality/privacy and duration of storage of personal data. Participants were also informed that they were under no obligation to answer any question and that they could withdraw from the interview at any time.

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Study description	The study is a mixed-method analysis including modeling from literature an a mixed-method case study application.
Research sample	Both man and women were involved in two out of the three FGD, while one FGD was kept for women only, to allow a safe space for women to express their opinions with us much freedom as possible.
Sampling strategy	The 10 communities involved in the research elicitation were identified under the guidance of the porvincial and municipality authorities as the most vulnerable to water scarcity. Within each community, all families were involved in the focus group discussion (FGD). We provided food for the day of the elicitation to support the participation of the most remote families who often are the most disadvantaged and marginal ones.
Data collection	The focus group discussions were not recorded, but notes were taken in a notebook. This approach was instrumental to the use of the collected information, which were only meant to increase researchers awareness of communities water needs and problems.
Timing	Communities consultations were held between July 20 and September 7, 2021
Data exclusions	No data were excluded from the analysis
Non-participation	The FGD were open and anyone was free to join and leave the discussion at any point. Therefore, we do no have statistics on the exact number of participants dropping the FGDs.
Randomization	All the members of the communities were invited to join the FGD.

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Methods

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☒	☐ ChIP-seq
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