One Earth

Voices

Stewardship under shifting drought baselines

Climate change is fueling more frequent and severe droughts, with growing consequences for water security, food production, biodiversity, and ecological wellbeing. Yet responses remain too often reactive, fragmented, and tied to past conditions. Building resilience in a drier world will require new approaches to stewardship, restoration, and resource governance under shifting baselines. This Voices asks: what innovations are needed for more proactive, effective, and inclusive management of ecosystems and ecosystem services?

Heidi Kreibich
GFZ Helmholtz Center for Geosciences

Integrated approaches avoid limits of adaptation

Drought risk management must account for unprecedented and cascading drought-flood events in light of the increasingly frequent, severe, and complex hydrological extremes driven by climate change. Cascading drought-flood events can be particularly severe and can lead to substantial economic losses. Unprecedented events—those exceeding historical experience—are particularly difficult to manage, as existing infrastructure and governance systems are not designed for such extremes. For example, an unprecedented drought could surpass available water-storage capacity. Case study evidence indicates that effective governance and high investments in integrated water resources management are critical for managing such events. As flood or drought management measures can also have unintended negative impacts on risk of the opposite hazard, integrated, cross-hazard management approaches are needed, while also needing to avoid long-term unintended consequences. For instance, reservoirs built to mitigate water scarcity can increase demand and thus intensify drought risk. Addressing these dynamics requires sociohydrological or system dynamics modeling to capture human-water co-evolution. Continuous monitoring integrated into the risk management cycle enables the early detection of inefficient risk-management strategies as well as relevant changes in risk, leading to appropriate adaptation. Long-term, integrated, and adaptive approaches are necessary to avoid approaching or exceeding the limits of adaptation under global change.

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Re-thinking resilience in a thirstier atmosphere

The water vapor-holding capacity of air increases rapidly as temperatures warm, raising the ceiling on precipitation intensity and evaporative demand. Widespread increases in "hydroclimate whiplash" over global land areas, driven by more intense but less frequent precipitation amid an overall "thirstier" atmosphere, will yield more severe and faster-onset droughts.

Droughts have shaped human existence. Episodes of severe water scarcity have been responsible for the fall of civilizations, but the imperative to soften their consequences has also motivated ingenious feats of adaptive engineering. Accordingly, drought risk today is a function not only of meteorology but also of water management capacity. Yet the societal benefits derived from advanced water storage and conveyance systems generally don't extend to ecosystems: trees in a forest cannot draw upon water from a distant reservoir; fish downstream of a dam lose access to spawning grounds. Nor do all societies have equal water security, especially when extreme environmental conditions and governance failures converge.

The changing "flavor" of 21st century drought requires urgent re-evaluation of historical assumptions. Predictive models must capture non-mean state changes and move beyond fixed baselines. Enhanced flexibility through drought and flood risk "co-management" should be a priority. Reconnecting rivers to floodplains, proactively re-charging overdrawn groundwater aquifers, operationalizing weather forecast-informed reservoir releases, and scaling water reuse and recycling all comprise elements of a promising drought resilience portfolio that balances human and ecosystem water needs. To minimize looming zero-sum trade-offs, we must rapidly scale up such efforts to keep pace with a rapidly warming climate.

Fi-John Chang
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From rules to adaptive water futures

Droughts are no longer anomalies—they are the new operating condition. Yet water governance remains anchored in static rules and historical baselines, calibrated for a climate that no longer exists. This is not merely an engineering problem; it is a governance failure hiding in plain sight. The deeper challenge is structural. Most AI-driven optimization frameworks still assume known future inflows—useful for planning but misaligned with real-world operations where uncertainty is the rule, not the exception. When droughts intensify and hydrology shifts, systems built on deterministic logic do not adapt. They break quietly, through misallocation, delayed response, and exhausted reserves. A different approach is possible. By training systems on ensembles of optimized scenarios rather than single forecasts, water infrastructure can learn to approximate optimal decisions from observable states alone—responding to evolving conditions and coordinating across interconnected reservoirs and riverine ecosystems. Taiwan's typhoon-to-drought cycles, where reservoir storage can collapse within months once a storm season ends, illustrate precisely why anticipatory, state-aware systems matter. Such systems don't just respond to drought—they learn to see it coming. Resilience in a drier world will not come from refining yesterday's rules. It will require deploying intelligent systems capable of navigating trade-offs among water supply, food production, energy generation, and ecosystem integrity—in real time, under deep uncertainty. The transition from reactive response to anticipatory governance is no longer a research aspiration; it is an operational necessity.

Markus Reichstein and Vitus Benson
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Forecasting drought—and its consequences

Drought is a slow hazard with fast, systemic consequences across ecosystems, food, and health systems. Predicting drought is difficult because it depends not only on unpredictable precipitation but also on cumulative changes in soils, vegetation, and snowpack. Crucially, predicting weather differs from predicting impacts: anticipating cascading effects in complex systems remains a key scientific and decision-making frontier.

AI is helping close parts of this gap. Machine-learning forecasts boost weather prediction and enable larger ensembles and better uncertainty estimates. Crucially for drought, they can learn long-range interactions across space and time and integrate diverse data sources, while extending predictive horizons remains an active area of research. Paired with Earth observation, this allows forecasting of vegetation stress and food insecurity, linking hazard prediction to impact-based early warning and enabling anticipatory action to mitigate humanitarian impacts.

Yet success also depends on understanding the effects of development and humanitarian interventions. Most AI systems capture correlations, but decisions need causal insight: how ecosystems respond to management, and which actions reduce/amplify risk. For instance, carbon-oriented interventions can raise water demand and inadvertently heighten drought vulnerability.

Advancing drought resilience therefore requires integrated early-warning systems that connect AI-based prediction with impact modeling, causal understanding, and decision making. This shifts the focus from forecasting hazards to holistic models that link impacts and intervention outcomes, and on communicating results effectively to end users, increasingly via AI-based interfaces.

Petra Holden
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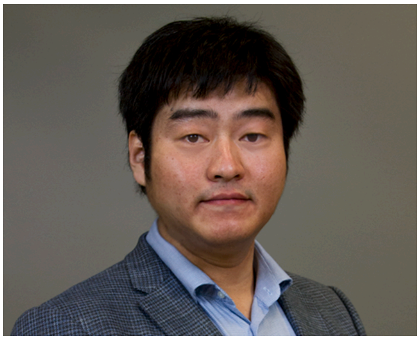
Scaling NbS requires new forms of evidence

Nature-based solutions (NbSs) are frequently described as lacking evidence, yet in many cases reliable evidence exists that they reduce drought risk and improve water security. My research shows that restoring mountain fynbos ecosystems can increase dry-season water supply and reduce drought severity linked to anthropogenic climate change. In Cape Town's "Day Zero" drought, impacts were 12%–29% worse due to climate change but could have been reduced by up to 16% through clearing invasive non-indigenous trees. Yet these invasions persist even as the region becomes drier due to climate change.

The problem is not whether NbSs work, but why available evidence fails to translate into sufficient investment to scale them equitably and effectively. NbSs remain underfunded and reliant on public or grant finance, while mainstream development, adaptation, and mitigation continue to overlook them. The core tension is that the features that make NbSs effective and equitable—site and context specificity, multifunctionality, and low excludability—also make them difficult to finance and scale. NbSs must be site and context specific, and benefits are widely distributed, making replication challenging. As a result, scaling efforts remain inefficient and can produce inequitable or ecologically harmful outcomes.

The innovation required is not technical. It lies in diversifying evidence to align with the incentives and motivations of diverse investors, policymakers, and community groups, and in developing financing models that scale context-specific NbSs without compromising equity or effectiveness. This requires understanding what evidence mobilizes action in financial systems as well as in collective societal and local, community processes.



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Process-aware drought monitoring for agriculture

Agricultural drought is ultimately a soil–plant–atmosphere problem, yet most monitoring systems still lean on meteorological indicators that only indirectly connect to crop stress. This gap matters. Farmers and water managers act on root-zone moisture, crop phenology, and the timing of stress relative to growth stages, not precipitation deficits alone. Closing this gap requires moving beyond static indices toward process-aware, decision-relevant drought assessment.

Recent advances in AI and physics-informed hydrologic modeling offer a new path. Embedding water balance constraints with deep-learning architectures preserves physical consistency while learning complex, nonlinear relationships across scales. We are exploring representations that explicitly capture storage, fluxes, and memory effects to better detect the onset and rapid intensification of flash drought. Integrating satellite observations, i.e., SMAP, and evapotranspiration products, i.e., OpenET, will also provide critical understanding on near-real-time soil moisture dynamics.

Improved hydrologic modeling for streamflow simulation remains essential, as agricultural drought often cascades into hydrologic drought and water supply stress. Coupling physically informed AI models with subseasonal-to-seasonal precipitation forecasts can extend predictability and translate early signals of soil moisture deficits into actionable water management insights. The innovation is not prediction alone, but integration. Drought monitoring must feed directly into irrigation decisions, yield sensitivity, and reservoir operations. As climate variability intensifies, the future of agricultural drought assessment lies in hybrid systems: physically grounded, data-rich, and explicitly designed to support proactive decision making.

Farhana Sultana
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Drought is a justice issue

Drought governance is failing along the same fault lines of coloniality and exclusion that shape the accelerating climate crisis. In my research, I have seen how communities bearing the worst of intensifying drought face co-produced crises of water insecurity and livelihood collapse. Poor women provisioning water for households walk longer, Indigenous peoples struggle to steward degraded landscapes, and smallholder farmers experience crop failures as aquifers deplete. They are often excluded from the institutions that manage droughts. This exclusion is structured by colonial legacies of land and water dispossession, extractive capitalism, and hydrosocial inequities that have damaged the ecosystems drought recovery depends on.

Inclusive drought management must confront the coloniality embedded in water governance at different scales. Institutions for drought response privilege large-scale hydraulic infrastructure and market-based water allocation while sidelining place-based ecological knowledge. Addressing accelerating and unexpected droughts requires democratizing water governance such that drought-affected populations co-produce drought policies. Adaptation finance must be safeguarded to reach the communities who need it most. Accountability must address global ecological debt and the racialized, gendered dimensions of water scarcity that colonial and capitalist structures have entrenched over time.

Drought is an intersectional and intergenerational justice issue tied to wider struggles over water and climate. Until drought governance addresses the structural issues, interventions will only manage symptoms.

Chris Funk
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Multi-scale early-warning systems for drought resilience

Droughts are complex multi-scale multi-sector disasters that can cripple economies, weaken ecosystems, and support crippling cycles of poverty. The Climate Hazards Center works with partners to develop complex, rapid, high-resolution multi-scale early-warning systems that support staged interventions. Long before, just before, and during rainy seasons, "interoperable" climate predictions, weather forecasts, and weather observations can inform a sequence of actionable alerts that transition from spatially coarse and relatively uncertain to spatially detailed and certain. For example, in early October 2025 ongoing negative Indian Ocean Dipole and La Niña conditions indicated likely drought in East Africa. This climate information was enhanced by high-resolution weather forecasts, downscaled to match Climate Hazards Center InfraRed Precipitation with Stations data (CHIRPS). Observations, downscaled weather forecasts, and climate analogs were then used to drive a crop model, which correctly anticipated severe crop water deficits. In the middle of the season, CHIRPS data and new 3D-printed automatic weather stations (UCAR 3D PAWS) captured very rapidly the extreme drought in Kenya. Current collaboration with the Kenya Meteorological Services Authority and the Karlsruhe Institute of Technology and Rhiza Research are pushing the forecast horizon forward, increasing the accuracy and resolution of sub-seasonal predictions. In the face of more extreme drought, improved collaboration such as these help make us all more resilient.

Daniel Kobei
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Restoring water resilience via Indigenous governance

The water crisis in the Mau Forest Complex is not just about climate stress; it is about governance exclusion. For the Ogiek, the problem began when fortress conservation displaced them from their ancestral forests in the name of protection, breaking the very systems that sustained water and ecological balance for generations. Displacement opened up fragile catchments to illegal logging, agricultural encroachment, and unsustainable extraction. Today, rivers such as the Mara River and other Mau-origin streams face declining flows, sedimentation, and seasonal drying, deepening drought impacts across ecosystems and downstream communities.

Guided by rich Indigenous knowledge, the Ogiek once safeguarded springs, wetlands, and forest cover through customary laws, sacred sites, seasonal access, and intergenerational ecological practices that kept the watershed alive and resilient. From this lived reality, the Ogiek see fortress conservation as a failed model because it excludes the very custodians who protected these ecosystems for centuries. In response, OPDP supported the community in developing a bio-cultural protocol as a practical pathway toward rights-based co-governance. Co-created with the community, the protocol documents Indigenous knowledge, strengthens customary governance systems, and provides a structured framework for engagement with state and conservation institutions.

The bio-cultural protocol can help restore Ogiek participation in decision-making, strengthen community-led restoration, and revive Indigenous water stewardship. Embedding it in governance can be a pathway to dismantling exclusionary conservation, restore balance, secure water resilience, and promotes a just, inclusive Mau landscape.

DECLARATION OF INTERESTS

The authors declare no competing interests.