Diagnosing drought for developing reliable and heath-promoting water solutions

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INTRODUCTION

All around the world drought management tends to focus on crisis response rather than addressing underlying vulnerabilities (Walker *et al.* 2022). Incomplete or misdiagnosis of drought typically leads to management strategies that fall short of addressing the main causes of drought impacts. Moreover, flash droughts may cause serious impact on local populations, even though they may go undetected by commonly used drought metrics (Walker and Van Loon 2023). Besides, some drought impacts can linger on long beyond the hydro-meteorologically defined ending of drought events, such as in regions experiencing human-pressure invoked water bankruptcy (Madani 2026). In our **3D Drought Diagnosis** project we developed an approach for conducting comprehensive, collaborative, and contextualized drought diagnosis, aiming to support the development of effective drought management. 3D Drought Diagnosis supports a comprehensive and proactive drought assessment and decision-making for improving intervention effectiveness and strengthening drought resilience (Walker *et al.* 2022), following three related steps:

D1. *Drought Dimensions* – This stage involves an initial diagnostic assessment (anamnesis) of the human impacts (drought symptoms) relevant to a specific drought context, considering local biophysical conditions and the history of drought impacts. Relevant dimensions may include income security, water security, food security, human health, and others.

D2. *Drought Dynamics* – Understanding drought dynamics requires diagnostic testing through data collection and analysis to confirm the diagnosis and identify which human drivers (causes of drought impacts) can be addressed. Methods may include quantitative data analysis, simulation modeling, narrative collection, household surveys, citizen science monitoring, remote sensing, political ecology studies, and participatory research.

D3. *Drought Dialogue* – Translating insights from D1 and D2 into action may require engagement with additional expertise. If diagnostic testing shows that drought impacts are not only driven by water-governance actors, cross-disciplinary perspectives become particularly important. Meaningful dialogue should also incorporate local knowledge and stakeholder participation. Co-producing the diagnosis with relevant actors supports the development of effective drought prevention, mitigation, and preparedness strategies.

This 3D-logic, borrowed from health/medical sciences, guided us in evaluating drought-related impacts, without limiting our scope to a drought-event definition merely based on hydroclimatic anomalies.

LESSONS FROM 3D DROUGHT DIAGNOSIS IN NORTHEAST BRAZIL

Northeast Brazil is a densely populated, largely semi-arid region characterized by highly variable rainfall, high temperatures, and chronic water scarcity (Walker *et al.* 2022).

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D1 *– Drought Dimensions in NE Brazil – context matters*

In Northeast Brazil, adverse drought-related impacts often occur even outside officially defined drought periods and are frequently driven by underlying vulnerabilities rather than extreme weather alone (Walker *et al.* 2024). Analysis of drought-impact monitoring data collected by agricultural extension officers between 2019 and 2022 showed that conventional drought indices do not always reflect impacts experienced by local communities, highlighting the value of continuous impact monitoring for identifying vulnerabilities and improving drought risk management (Walker *et al.* 2024). Comparing these monitoring data with interviews from rural communities revealed important blind spots and mismatches between official information and local experiences (Kchouk *et al.* 2025). Broadening the focus beyond water, food, and income securities further demonstrated the effects of water shortage and poor water quality on human health and their wider societal costs (Costa *et al.* 2025; 2026). These studies underscore that local drought impacts result from interactions between environmental and social factors across multiple scales (Kchouk *et al.* 2023). Yet, drought monitoring systems still rely largely on hydroclimatic indicators and often fail to capture local vulnerabilities and lived experiences, creating a persistent drought monitoring gap (Kchouk et al. 2025).

D2 *– Drought Dynamics in NE Brazil – the influence of small reservoirs*

Research in semi-arid Northeast Brazil demonstrates that dense networks of small reservoirs are a key human factor shaping drought dynamics (Rabelo *et al.* 2022; Ribeiro Neto *et al.* 2022). While these reservoirs are widely constructed to enhance drought resilience, support rural livelihoods, and improve local water security, they also modify hydrological processes at the catchment scale (Ribeiro Neto *et al.* 2024). Modeling studies show that dense reservoir networks increase hydrological disconnection, reducing downstream runoff and delaying the recharge of large strategic reservoirs (Colombo *et al.* 2024). As a result, the transition from meteorological to hydrological drought can be accelerated, and hydrological drought conditions may persist longer, particularly during prolonged dry periods. At the same time, small reservoirs provide substantial local benefits. They can increase agricultural production, reduce dependence on emergency water supplies, and alleviate drought impacts for rural communities (Ribeiro Neto *et al.* 2024). These findings highlight important trade-offs between local adaptation benefits and downstream water availability. Beyond their hydrological effects, droughts are also shaped by human behavior, perceptions, and landscape modifications. Applying socio-hydrological approaches and concepts such as downstreamness (Van Oel *et al.* 2018), drought-cycle analysis (Ribeiro Neto *et al.* 2022) and prospect theory (Ribeiro Neto *et al.* 2023) reveals how reservoir networks influence both the physical propagation of drought and the way drought impacts are experienced. Together, these studies show that droughts are co-produced by environmental and social processes, emphasizing the need for integrated drought management strategies that account for both hydrological and human dimensions.

D3 *– Drought Dialogue – increased drought preparedness by fighting and coping*

Research in Northeast Brazil highlights the central role of public policy in shaping drought impacts and strengthening resilience (Cavalcante *et al.* 2020; 2022; 2023; 2025; Walker *et al.* 2022). Studies on cascading drought impacts show that effective policies can prevent water shortages from triggering broader social, economic, and environmental crises (Cavalcante *et al.* 2025). Analysis of continuous drought-impact monitoring data revealed that many potential livelihood impacts are mitigated through development-oriented interventions, although hydrological impacts remain prevalent, partly as an unintended consequence of supply-focused water investments (Cavalcante *et al.* 2025; Walker *et al.* 2024). Over time, Brazilian drought governance has evolved from a reactive "fight-against-drought" paradigm toward a more proactive "cope-with-drought" or drought preparedness approach (Cavalcante *et al.* 2022). This transition was driven by prolonged drought events, growing political attention, and the actions of policy entrepreneurs who promoted preparedness measures. Rather than

a complete paradigm shift, research shows the coexistence and gradual intertwining of both approaches, reflecting incremental policy change (Cavalcante *et al.* 2022). A key element of this evolution has been the adoption of social technologies such as rainwater-harvesting cisterns. Beyond improving water access, these initiatives have enhanced food security, adaptive capacity, and social learning among smallholder farmers, increasing their confidence and ability to cope with future climate variability (Cavalcante *et al.* 2020). More broadly, studies demonstrate a gradual shift from infrastructure-based drought responses toward governance and demand-management approaches (Medeiros and Sivapalan 2020). Together, these findings emphasize that drought resilience depends not only on water infrastructure but also on adaptive institutions, social learning, and policies that strengthen local livelihoods and capacities. Investing in reliable water supply during severe droughts in Northeast Brazil could prevent substantial health-related economic losses, highlighting its importance as a key strategy for both public health protection and economic resilience (Costa *et al.* 2026). Particularly, targeted water supply and public health interventions can reduce hospitalization rates for diarrhea (Costa *et al.* 2025; De Sousa *et al.* 2025).

3D drought diagnosis for developing REliable ALternatives – ***3D4REAL***

Building on the findings of our context-sensitive 3D drought diagnosis approach for Northeast Brazil, the 3D4REAL project seeks to find reliable alternative drinking-water solutions for remote and water-insecure communities in rural areas. Among the solutions explored are health-promoting education, low-cost water filters, and innovative air-to-water technology. These solutions may provide reliable alternatives to the emergency water provision by water trucks. The 3D4REAL project investigates the opportunities and challenges of these possible solutions by evaluating their geographic, financial, and socioeconomic and environmental feasibilities in three selected local communities. By closely monitoring individual households in these communities we aim to increase our understanding on the potential benefits for human health, and overall drought resilience. Through stakeholder engagement (from local to national levels) and interdisciplinary research, the 3D4REAL project generates actionable knowledge, supporting policymakers and practitioners in developing scalable solutions that improve water security, strengthen drought preparedness, and contribute to sustainable development.

CONCLUSIONS

Drought impacts cannot be understood through hydroclimatic indicators alone. In Northeast Brazil, drought impacts often result from interactions between environmental conditions, social vulnerabilities, governance systems, and human behavior, and occur also outside drought periods. Continuous impact monitoring and engagement with local communities are therefore essential for improving drought management.

Small reservoir networks enhance local water security but can also intensify downstream water scarcity and prolong hydrological droughts. Drought resilience depends not only on water infrastructure but also on adaptive governance, and proactive preparedness policies.

Investments in reliable drinking water supply can reduce drought impacts, improve public health, and strengthen drought resilience. Building on these insights, the 3D4REAL project moves from diagnosis to action by assessing alternative water solutions, to improve water security and drought preparedness in remote communities through integrated, participatory, and evidence-based approaches.

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REFERENCES

Cavalcante, L., Mesquita, P., and Rodrigues-Filho, S. (2020), '2nd Water Cisterns: Social technologies promoting adaptive capacity to Brazilian family farmers', *Desenvolvimento e Meio Ambiente,* 55, 433-50.

Cavalcante, L., Dewulf, A., and van Oel, P. (2022), 'Fighting against, and coping with, drought in Brazil: two policy paradigms intertwined', *Regional Environmental Change,* 22 (4).

Cavalcante, L., *et al.* (2023), 'From creeping crisis to policy change: The adoption of drought preparedness policy in Brazil', *Water Policy,* 25 (10), 949-65.

Cavalcante, L., *et al.* (2025), 'From insufficient rainfall to livelihoods: Understanding the cascade of drought impacts and policy implications', *Natural Hazards and Earth System Sciences,* 25 (6), 1993-2005.

Colombo, P., *et al.* (2024), 'Modeling the influence of small reservoirs on hydrological drought propagation in space and time', *Journal of Hydrology,* 629.

Costa, A. C., *et al.* (2026), 'Brief communication: Drought economic assessments must include human health impacts', *Natural Hazards and Earth System Sciences,* 26 (6), 2865–2869

Costa, A. C., *et al.* (2025), 'Sharp decline of diarrhea hospitalizations despite historical drought in Brazil: The potential role of local water supply and public health measures', *Journal of water and health,* 23 (6), 743-56.

De Sousa, T. C., *et al.* (2025), 'Groundwater access reduces water insecurity and diarrhea hospitalizations in the drought-affected tropical drylands of Ceará, Brazil', *Hydrogeology Journal*.

Kchouk, S., *et al.* (2023), 'Drought-impacted communities in social-ecological systems: Exploration of different system states in Northeast Brazil', *International Journal of Disaster Risk Reduction,* 97.

Kchouk, S., *et al.* (2025), 'Mind the gap: misalignment between drought monitoring and community realities', *Natural Hazards and Earth System Sciences,* 25 (2), 893-912.

Madani, K. (2026), 'Water Bankruptcy: The Formal Definition', *Water Resources Management,* 40 (2).

Medeiros, P. and Sivapalan, M. (2020), 'From hard-path to soft-path solutions: slow–fast dynamics of human adaptation to droughts in a water scarce environment', *Hydrological Sciences Journal,* 65 (11), 1803-14.

Rabelo, U. P., *et al.* (2022), 'Impact of Dense Networks of Reservoirs on Streamflows at Dryland Catchments', *Sustainability (Switzerland),* 14 (21).

Ribeiro Neto, G., *et al.* (2024), 'Clash of drought narratives: A study on the role of small reservoirs in the emergence of drought impacts', *Earth's Future,* (accepted manuscript).

Ribeiro Neto, G. G., *et al.* (2022), 'Drought Cycle Analysis to Evaluate the Influence of a Dense Network of Small Reservoirs on Drought Evolution', *Water Resources Research,* 58 (1).

Ribeiro Neto, G. G., *et al.* (2023), 'HESS Opinions: Drought impacts as failed prospects', *Hydrology and Earth System Sciences,* 27 (22), 4217-25.

Van Oel, P. R., *et al.* (2018), 'Diagnosing drought using the downstreamness concept: the effect of reservoir networks on drought evolution', *Hydrological Sciences Journal,* 63 (7), 979-90.

Walker, D. W., *et al.* (2024), 'It's not all about drought: What “drought impacts” monitoring can reveal', *International Journal of Disaster Risk Reduction,* 103.

Walker, D. W. and Van Loon, A. F. (2023), 'Droughts are coming on faster', *Science,* 380 (6641), 130-32.

Walker, D. W., *et al.* (2022), 'Drought Diagnosis: What the Medical Sciences Can Teach Us', *Earth's Future,* 10 (4), e2021EF002456.