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Invited perspectives: Advancing knowledge co-creation in drought impact studies

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Abstract. Drought impacts are increasingly recognized as interdisciplinary, socially influenced processes often resulting in uneven outcomes across different social groups, rather than as mere hydro-climatic events. Yet, many drought impact studies do not fully integrate the knowledge and perspectives of those who directly experience the impacts of droughts. While knowledge co-creation represents a promising avenue to address this challenge, there still remains an ample margin of improvement in the depth and breadth of transdisciplinary approaches in drought impact studies: most studies either limit co-creation to specific phases of the research process (breadth) or fail to meaningfully incorporate non-academic knowledge within those phases (depth). Drawing from a diverse body of literature on transdisciplinarity in sustainability science, integrated water resources management, socio-hydrology, science and technology studies, and critical water studies, we delineate five key dimensions which can support broader and deeper knowledge co-creation processes in drought impact studies, including (1) setting up a collaborative space, (2) framing the co-modelling process, (3) shaping a shared knowledge of drought, (4) co-selecting and co-developing models to understand drought impacts, and (5) being aware of power biases and knowledge imbalances. Incorporating all five dimensions promotes broader and more comprehensive studies, while exploring each dimension in greater detail enhances their depth. Together, these dimensions provide conceptual guidance for developing transdisciplinary approaches that are more integrated, power-sensitive, inclusive, situated, and reflexive.

1 Introduction

Droughts are becoming increasingly widespread and impactful, with serious consequences for health, agriculture, societies, and the environment globally (Vicente-Serrano et al., 2021; Wilhite et al., 2007). Socio-economic and environmental impacts of drought have long been studied (e.g. Wilhite and Glantz, 1985) based on drought hazards being primarily assessed as meteorological and/or hydrological processes (Mishra and Singh, 2010, 2011). However, the social dimension of drought is very different from how it is represented in hydro-climatic models (Enenkel et al., 2020; Kchouk et al., 2022). In fact, droughts are increasingly conceptualized as complex socio-hydrological phenomena that affect societies across interdependent sectors and socio-economic groups (AghaKouchak et al., 2021; Mehta, 2007; G. Ribeiro Neto et al., 2023; Van Loon et al., 2016b, a). In parallel, research in climate justice and political ecology has long conceptualized disasters as generated by the interplay of hydro-climatic and historical, socio-political, economic, and institutional dynamics (e.g. Collard et al., 2018; Kallis, 2008). From this standpoint, drought-related impacts, which often escalate into disasters, have been conceptualized as a so-

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cial construction of water scarcity. This perspective highlights how different social groups experience the impacts of drought unevenly due to varying levels of power and influence. It also emphasizes the variable "room for manoeuvre" of different socio-economic groups in responding and adapting to drought events (Alexandra and Rickards, 2021; Eriksen and Lind, 2009). Finally, this perspective draws attention to the underlying political and economic drivers, such as development pathways and policy visions, that shape the vulnerability of different groups and their exposure to hazards (Mehta, 2005; Piemontese et al., 2024; Rachunok and Fletcher, 2023; Rusca et al., 2023; Savelli et al., 2022; Usón et al., 2017).

The multidimensional nature of droughts has been addressed by recent interdisciplinary socio-hydrological research on water-related challenges (Vanelli et al., 2022), which aims at capturing the interplay between natural and social aspects (Rusca and Di Baldassarre, 2019; Wesselink et al., 2017). Yet, there is increasing recognition of the need to include societal perspectives within socio-hydrological studies, such as those of non-academic actors directly experiencing the impacts of drought, through transdisciplinary studies (AghaKouchak et al., 2021; Arheimer et al., 2024; Hadorn et al., 2008; Wheater and Gober, 2015). Transdisciplinary research brings "values, knowledge, know-how, and expertise from non-academic sources" (Klein, 2010) to the knowledge-creation process. This entails fostering mutual learning processes between science and society, reflecting a commitment to a science that collaborates with society rather than simply serving it (Seidl et al., 2013). Transdisciplinarity includes a variety of approaches to knowledge co-creation (Bennich et al., 2022; Brugnach and Özerol, 2019; Norström et al., 2020). In the field of integrated water resources management, knowledge co-creation is often addressed by referring to the concepts of collaborative modelling or co-modelling (Basco-Carrera et al., 2017). This concept involves the collaborative construction of models, which can be physical, conceptual, or computational representations of a system, process, or phenomenon. Co-creation provides the collaborative framework for ideation and value creation, while co-modelling offers the tools and methods to visualize, test, and refine these ideas into actionable solutions, enhancing the effectiveness of co-creation. In this perspective paper, we discuss co-creation in drought impact studies from a broad standpoint and return to co-modelling in Sect. 3.4 to examine its specific role and applications in greater detail, presenting co-modelling as one key dimension of the co-creation process.

Examples of drought or water scarcity studies that include strong participation of non-academic stakeholders embrace co-creation of (i) drought impacts, (ii) water infrastructure planning, and (iii) water use under scarcity conditions. The first body of literature includes studies aimed at increasing stakeholders' participation in drought plans with a variety of approaches. For example, Sodoge et al. (2024) develop individual causal loop diagrams to map cascading drought impacts from different stakeholders, which they ultimately combine to reveal emerging knowledge from multiple perspectives. Cid et al. (2024) use serious games to engage stakeholders in the creation of proactive drought plans while revealing power imbalances and knowledge disparities. Giordano et al. (2013) use cognitive mapping and Bayesian belief networks to collect and analyse stakeholders' perceptions of drought impacts, highlighting the challenges of trust and cooperation in knowledge integration for drought early warning systems. Aldunce et al. (2016) apply the resilience-wheel tool combined with participatory methods to understand key determinants of drought resilience in urban Chile. Streefkerk et al. (2022) integrate farmers' local knowledge with seasonal climate forecasts to select the most relevant indicators for forecasting locally relevant dry conditions in Malawi. The second group of studies focuses on evaluating the feasibility of water infrastructure by integrating knowledge and mediating the values and expectations of different stakeholders (e.g. Coletta et al., 2024; Gil-García et al., 2023; Masi et al., 2024). For example, Gil-García et al. (2023) include experts' knowledge and opinions to co-design scenarios within alternative adaptation strategies and guide policymakers when considering the construction of a dam. The third set of studies uses a variety of methods to provide guidance on mediating the use of water resources under scarcity conditions (e.g. Baker et al., 2015; Gwapedza et al., 2024; Liguori et al., 2021; Mustafa et al., 2021; Ocampo-Melgar et al., 2022; Rojas et al., 2022). For example, Liguori et al. (2021) explore a combination of storytelling and scientific data to guide the development of different co-designed narratives to support the planning of drought adaptation scenarios. The co-creation of adaptation scenarios is also the focus of a co-modelling approach proposed by Mustafa et al. (2021) to improve adaptation to hydrological extremes in the Limpopo River basin. All these approaches attempt to integrate some elements of knowledge co-creation, yet they often limit the transdisciplinary process to specific tasks, usually the definition of adaptation scenarios or the choice of indicators or model parameters (Luetkemeier et al., 2021).

Although many studies involve stakeholders with a variety of participatory approaches, the limitation of current transdisciplinary approaches in drought research lies in the depth and breadth of knowledge integration. Most studies either limit co-creation to specific phases of the research process, such as problem definition, scenario development, or result validation (breadth), or fail to meaningfully incorporate non-academic knowledge within those phases, for instance using such knowledge only to validate predefined scientific assumptions rather than to shape core research questions, methodologies, or models (depth). This leaves room for improving knowledge co-creation with the implementation of more "mature" transdisciplinary work, building on a full engagement and integration of different stakeholders (and knowledge holders) in all the phases of the research process. Also, the attention to power dynamics through the process is very important, is largely analysed within social sciences, and can substantially advance socio-hydrological studies within transdisciplinary research.

Our contribution seeks to support hydrological and socio-hydrological modellers and practitioners in developing more structured, power-sensitive, inclusive, situated, and reflexive co-created drought impact studies by providing essential considerations for more effectively integrating diverse knowledge systems and perspectives into the process. In this paper, the term "drought impact studies" is used to refer generically to studies and projects that not only evaluate the hazard dimension of drought but also investigate, describe, or evaluate its impacts and support the identification and planning of drought management or adaptation measures. Moreover, this paper approaches drought from a socio-hydrological perspective, offering a framework tailored for transdisciplinary studies and projects that view drought as a result of feedback between water systems and human activities.

Drawing from five different bodies of literature – socio-hydrology, integrated water resources management (IWRM), sustainability science, critical water studies, and science and technology studies (STS) – we identify and discuss five key dimensions of a comprehensive and structured co-creation process for assessing and adapting to drought impacts. These dimensions address current limitations in both the breadth and the depth of such approaches: incorporating all five promotes more comprehensive and wide-ranging studies, while examining each in greater detail enhances their depth.

The paper proceeds as follows. In Sect. 2, we explore how an interdisciplinary perspective, drawing from five different bodies of literature, contributes to a more comprehensive approach to knowledge co-creation in the context of drought. Then, in Sect. 3 we discuss each of the five identified key dimensions in detail. Next, in Sect. 4, we discuss the limitations of transdisciplinary approaches to drought, related to the five key dimensions. To conclude, Sect. 5 offers insights into how the key dimensions discussed in this paper can help develop more structured and holistic transdisciplinary approaches in the field.

2 An interdisciplinary perspective on knowledge co-creation

To enrich the drought co-creation process from an interdisciplinary perspective, we refer to and integrate knowledge developed in five other scientific fields and disciplines: socio-hydrology, IWRM, sustainability science, critical water studies, and STS.

Socio-hydrology (Di Baldassarre, 2017; Di Baldassarre et al., 2013, 2015; Sivapalan et al., 2012) focuses on the dynamic interactions between hydrological processes and human behaviour, emphasizing how social systems influence water management, which is particularly important in understanding the socio-economic impacts of drought.

IWRM advocates for a holistic approach to managing water resources that considers environmental, social, and economic factors (Rahaman and Varis, 2005; Savenije, 1995; Savenije and Van der Zaag, 2008), fostering collaborative decision-making and stakeholder engagement, which are crucial for effective drought management. Sustainability science (Brandt et al., 2013; Lang et al., 2012), particularly social–ecological systems research (Angelstam et al., 2013; Hummel et al., 2017), supports transdisciplinary approaches and emphasizes integrating knowledge across sectors and disciplines, fostering inclusive participation of non-academic actors to address complex environmental challenges like drought.

Critical water studies offer unique insights into power dynamics, vulnerabilities, and ethical considerations in drought impact studies. For the purpose of drought research, two areas of critical water studies are particularly relevant: hydrosocial studies and critical disaster studies. Hydrosocial studies critique mainstream hydrology for neglecting power dynamics and challenge the reliance on technoscientific solutions to water problems (Boelens et al., 2016; Linton and Budds, 2014). Critical disaster studies argue that vulnerability to natural hazards, such as droughts, is rooted in pre-existing inequalities, with social and economic structures exacerbating exposure and outcomes (Burton et al., 1993; Smith, 2006; White, 1945). Together, these fields highlight that water scarcity and droughts are not merely natural events but the result of deeply embedded power dynamics and social vulnerabilities.

STS provide an insightful self-reflection of the co-production process, challenging the notion of science as unbiased and highlighting that the process of knowledge development is in itself influenced by power relations that determine which knowledge claims are considered valid and actionable (Budds, 2009; Goldman et al., 2019; King and Tadaki, 2018; Turner, 2011; Zwarteveen et al., 2017). This perspective prompts critical reflection on research practices, particularly regarding the inclusivity and legitimacy of knowledge in drought impact studies.

3 Five key dimensions for drought impact knowledge co-creation

We discuss five key dimensions that provide coherent theoretical guidance for advancing transdisciplinary approaches in drought impact studies. These dimensions are derived from the five research fields introduced in Sect. 2 and reflect how insights from these disciplines offer critical perspectives on the role of knowledge integration, power dynamics, and ethical considerations in co-creation approaches for drought impact studies. The dimensions are not sequential and do not need to be addressed in a specific order. Moreover, they are

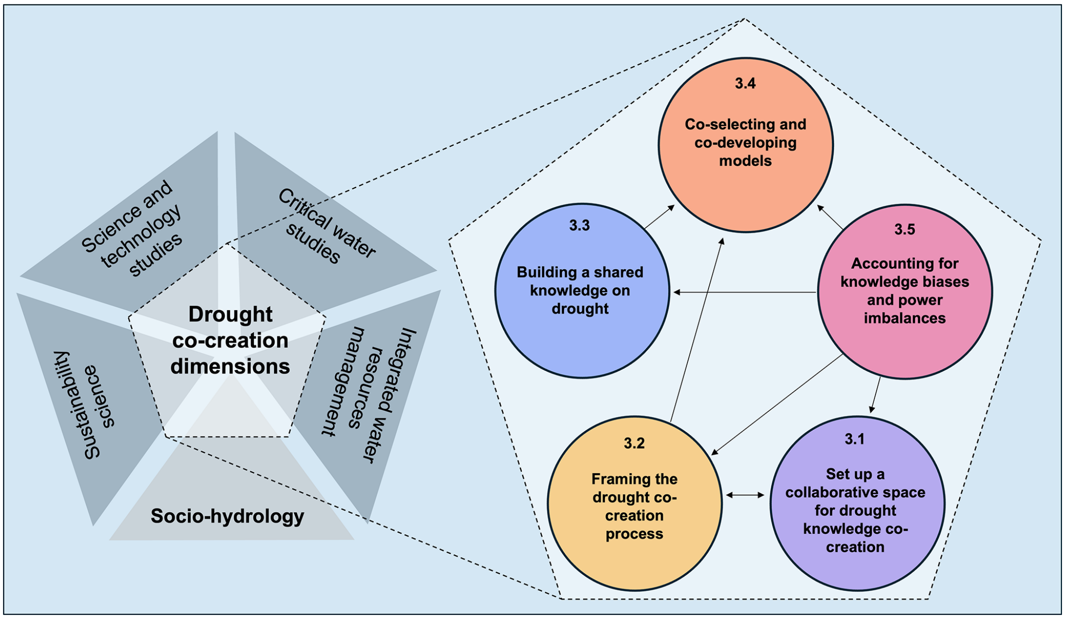

Figure 1. Conceptual framework: a graphical representation of the theoretical background (on the left) and the five key dimensions of knowledge co-creation for socio-hydrological drought impact studies, along with their interconnections (on the right).

highly interconnected, and decisions or actions related to one dimension may iteratively influence others. The five key dimensions, along with their interconnections, are graphically depicted in Fig. 1. They are discussed in detail in Sect. 3.1 to 3.5, with explicit reference to the papers that informed each of them.

3.1 Setting up a collaborative space for drought knowledge co-creation

Setting up a collaborative space includes identifying and establishing relationships among relevant stakeholders in the co-creation process (Reed et al., 2009). It ensures that all the parties that are affected by drought or influence the mitigation process are involved in the decision-making and knowledge generation. Stakeholders' identification is an iterative process where additional stakeholders are incorporated as the analysis unfolds. Setting clear boundaries for the study (Sect. 3.2) facilitates this process. Attention should be paid to verifying that these boundaries will not be too restricted to avoid unintentionally overlooking any relevant individuals associated with the phenomenon (Clarkson, 1995). For example, since the agricultural sector is often the major water consumer, it is typically overrepresented in water-related policy discussions (Paneque et al., 2018). Conversely, the boundaries cannot be too blurred. It is often impractical to include every stakeholder, requiring the establishment of well-founded criteria by the researchers and stakeholders to determine a cutoff point (Clarke and Clegg, 1998). A dynamic interplay between stakeholder identification and boundary setting ensures that the co-creation process remains relevant and comprehensive without excluding important knowledge and perspectives.

In transdisciplinary research, involving stakeholders serves multiple purposes (Stirling, 2008). Firstly, it upholds democratic ideals by emphasizing inclusive processes. Secondly, it taps into stakeholders' insights and risk assessments to improve the quality of process outcomes. Lastly, it enhances the legitimacy of predetermined decisions, ultimately increasing their effectiveness in informing policy processes. However, despite the reported efforts of many drought-related studies, the effective involvement of stakeholders in participatory activities, as well as their contribution to policies, remains limited (Hervás-Gámez and Delgado-Ramos, 2019). In this regard, the direct involvement of public authorities as elicitors of the procedure could facilitate stakeholders' participation (Hervás-Gámez and Delgado-Ramos, 2019; Kim et al., 2019).

When involving stakeholders, drought studies often consider broad categories such as the scientific community, public sector, civil society, and private sector (Aldunce et al., 2016; Lillo-Ortega et al., 2019). While this categorization is certainly useful, it might fall short in fully capturing complex drought dynamics. Some studies have further deepened stakeholder involvement by focusing on specific groups, such as vulnerable residents of informal settlements (Mpofu-Mketwa et al., 2023), or by including historically marginalized actors, such as representatives of the indigenous pueblos as observers in the whole water planning process (Lewis et al., 2005). Rangecroft et al. (2018) differentiated among water users in a rural context by involving, among others, young married mothers, elderly women, and the unemployed, while

Mukherjee and Sundberg (2023) analysed urban water security by contextualizing the opinions of the participants considering their ethnicity, religion, caste, and gender (with a focus also on the perspective of hijra/trans people).

In addressing drought impacts, the failure to include marginalized groups, especially indigenous populations and low-income communities, can significantly hinder effective decision-making. Drought conditions often exacerbate existing inequalities, making it even more crucial to incorporate diverse perspectives and local knowledge into resources management strategies (Rusca et al., 2024). Yet, we argue that available methods remain rooted in a "functionalist orientation and a distinct preference for quantification", limiting their ability to meaningfully integrate stakeholder input (Bachmair et al., 2016; Lemos and Morehouse, 2005; Venot et al., 2022, p. 92). As a result, these methods often lead to decisions that neglect local conditions and reinforce existing power imbalances. A systematic approach to engaging all stakeholders is essential for developing more equitable and effective responses to drought and ensuring that resources management is truly reflective of community needs and experiences (Hargrove and Heyman, 2020), ensuring inclusivity is closely tied to reducing knowledge biases and power imbalances (Sect. 3.5). By actively involving diverse stakeholders, particularly those from historically marginalized groups, the co-creation process can begin to challenge dominant narratives, integrate local knowledge, and ensure that decision-making reflects a broader range of experiences, leading to more balanced and effective outcomes.

3.2 Framing the drought co-creation process

Framing the scope of the co-creation process involves establishing clear boundaries, both for the study itself and for the collaborative process (Daré et al., 2018). Additionally, it requires conducting a "situation analysis" (van Beek and Arriens, 2016), which includes co-analysing the current situation, co-identifying key problems to address, and co-defining the main goals of the study.

The boundaries of the study define the specific aspects of the research that will be investigated. This includes the (a) thematic boundaries, which determine the sectors, types of impacts, and affected units or groups that the study will focus on; (b) geographical boundaries, which define the spatial scale of the study, specifying the region, country, or ecosystem where the research would take place; and (c) temporal boundaries, which specify the period covered by the research, whether it focuses on past events, current conditions, or future projections.

To set up the thematic boundaries, it is essential to co-define the topics, themes, and areas of focus for the study. This involves identifying the specific sectors, types of impacts, and units or groups that will be affected by the study:

- *Sectors.* These are broad categories or fields that the study will address, such as agriculture, health, education, environment, drinking water supply, and energy production.
- *Types of impacts.* This includes the nature of the impacts the study aims to investigate or address, such as economic, social, or environmental impacts, and the distribution thereof across space and socio-economic groups.
- *Impacted units or groups.* These are the specific entities or populations that will be affected by the study. They can be individuals, households, communities, organizations, or ecosystems.

Setting up the geographical boundaries requires the identification of the spatial scale in which drought impacts are investigated, which can vary from local to global. The boundaries are often drawn based on physical (e.g. hydrological units or ecological systems – Ballesteros-Olza et al., 2022; Mustafa et al., 2021), administrative (e.g. municipalities, countries, regions – Lillo-Ortega et al., 2019; Nielsen-Gammon et al., 2020), or socio-cultural and economic criteria (e.g. Ayantunde et al., 2015; Pham et al., 2020). Setting up the temporal boundaries refers to defining the specific period within which the drought impacts and mitigation strategy are studied. To illustrate, examining the impacts of a historical drought requires setting temporal boundaries to focus on a specific range of years or decades in the past. When studying the potential impacts of climate change on drought, temporal boundaries could be set to include projections for a future time horizon, such as the next 50 years (Sampson et al., 2020). Another relevant aspect of a transdisciplinary process for drought impact studies is to perform a "situation analysis" (van Beek and Arriens, 2016), which encompasses (i) the co-analysis of the current situation (if drought is a current issue or a future concern, if mitigation measures already in place are effective and, if not, why, etc.), (ii) the co-identification of the main problems and issues to be addressed, and (iii) the co-definition of the main goals of the study. As an example, some co-creation processes may aim at developing a shared vision of a water management plan (Gwapedza et al., 2024). Other studies might aim to predict future short-term impacts to suggest preventive strategies or quantify current and future drought impacts to define effective drought mitigation measures. Defining goals and outcomes together is essential to ensure transparency and prevent stakeholders' expectations from going unmet at the study's end.

In contrast, the boundaries of the co-creation process are concerned with how the research is conducted collaboratively. These boundaries define how the co-creation team, including both academic and non-academic stakeholders, will engage with the research, how they will contribute, and how their input will influence the research outcomes. This includes setting the rules of engagement, determining how power and influence are distributed among stakeholders, and establishing decision-making processes to guide the collaboration.

Co-creation processes envision the development in partnership with not only the methods, data collection, and interpretation of results, but also the research questions themselves. From a transdisciplinary perspective, a crucial aspect of this step is aligning the research questions with societal knowledge demands (Sarewitz and Pielke, 2007). Thus, framing the scope of the co-creation process is crucial, as societal problems often lack clear boundaries, involve multiple stakeholders, and are deeply interconnected with other challenges, especially when dealing with complex and multifaceted phenomena, such as droughts. This step requires continual interaction and refinement, involving an iterative process of adding new stakeholders and adjusting the scope as the co-creation process evolves.

Although most of these framing elements might be considered somehow during participatory engagements, they are often absent in scientific articles, meaning they can often be overlooked or at least be rarely explicitly reported or discussed. This contributes to lowering the standard of the co-creation process or eventually compromising the soundness of the process. For example, while most studies are explicit about their geographical boundaries (Aldunce et al., 2016; Giordano et al., 2013), they seldom select stakeholders iteratively and dynamically. The iterative nature of co-creation, where stakeholders and research questions evolve over time, can lead to significant expansion, requiring considerable time, effort, and commitment from researchers, stakeholders, and funding bodies. This process can introduce delays and uncertainties into decision-making, particularly when addressing complex issues like droughts, where the intersection of environmental, social, and economic factors demands continuous reassessment. To keep the process manageable and focused, it is crucial to establish clear boundaries that define the limits of time, resources, and engagement, ensuring that co-creation leads to meaningful and actionable outcomes (Thompson et al., 2017).

The framing of the boundaries of the study is particularly important in the context of drought impact studies because the driving mechanisms of drought and its impacts, as well as drought governance strategies, can vary across spatial and temporal scales and among sectors (health, agriculture, energy production, drinking water supply, etc.), with impacts often cascading across sectors and highlighting the interconnected nature of drought (Hagenlocher et al., 2023; Rossi et al., 2023).

The setting of the boundaries for the study itself and for the collaborative process is closely connected to two other dimensions of the co-creation process. To ensure that the research questions and scope align with societal knowledge demands, it is crucial to have a representative group of engaged stakeholders in the process (Sect. 3.1). Framing the problem and setting the research agenda to encompass diverse understandings and perspectives may require expanding the co-creation team to include additional disciplines or engaging with other stakeholders to find the right mix. From a practical perspective, this would lead to an iterative initial phase in which a first set of stakeholders is identified, the scope of the process is framed, and then potential additional stakeholders can be added, requiring further refinement of the scope. Moreover, the setting of the thematic, spatial, and temporal boundaries of the drought impact study would finally influence the development of the co-modelling of the drought impacts (Sect. 3.4). These boundaries help define modelling scenarios that reflect diverse perspectives and align with the study's objectives. By establishing well-defined boundaries from the start, the co-creation process can proceed smoothly and ensure the creation of contextually appropriate models.

3.3 Building a shared knowledge of drought

Successfully co-creating knowledge requires building a shared understanding of drought and its impacts (Grainger et al., 2021). This involves recognizing that drought is conceptualized differently across disciplines, as well as between academics, practitioners, and local communities. It is well recognized that there is no single, universally accepted definition of drought (Krueger and Alba, 2022). While hydrological sciences are often rooted in positivist paradigms, there is growing recognition that drought is a complex phenomenon arising from the interplay between biophysical and socio-economic factors (AghaKouchak et al., 2021; Wilhite and Glantz, 1985). Mpandeli et al. (2015) provide early attempts to include a non-academic perspective in drought impact studies yet build on a top-down quantification of drought from hydro-climatic thresholds. In contrast, the interpretative and critical social sciences focus on the social construction of water insecurity and scarcity, examining the power relations and political economies that shape the uneven outcomes of droughts and the diverse experiences of their impacts (see, for example, Alharahsheh and Pius, 2020; Kaika, 2003; Mehta, 2001; Rusca et al., 2023). These different conceptualizations are underpinned by distinct knowledge paradigms, which may hinder the development of inclusive and productive collaborations (Wesselink et al., 2017). Additionally, stakeholders who directly experience the impacts of drought and who are involved in the co-creation process are likely to have alternative ways of knowing and defining drought, based on their "mental models" (Gray et al., 2012). For example, for urban dwellers in informal settlements, drought may be experienced and conceptualized as water shortages, water insecurity, or waterborne diseases or even as a source of physical and psychological stress, especially for women responsible for domestic water collection, rather than as a large-scale geophysical event (Rusca et al., 2023).

While the diversity of definitions and plural knowledges can complicate the process of co-creating a shared understanding of drought and its impacts (Landström et al., 2023), it also has the potential to generate a richer and more inclusive evaluation. Thus, developing a shared understanding of drought should involve embracing and engaging with these different ways of knowing, rather than privileging one over another or creating a hierarchy between them. Moreover, as noted by Beck and Krueger (2016), depoliticized analyses of hydrological phenomena risk reproducing "authoritative representations of dominant perceptions of the world." Here, interdisciplinary impact evaluations that work through epistemological and ontological differences have the potential to generate more nuanced and power-sensitive understandings of drought, exploring how power relations shape changes in hydrological flows and the distribution of hydrological risk (Rusca and Di Baldassarre, 2019), including drought risk. According to this perspective, drought impact studies can serve as boundary objects between different ways of knowing socio-climatic phenomena (Garb et al., 2008).

The process of developing a shared understanding of drought is closely intertwined with the co-modelling process (Sect. 3.4). On the one hand, co-modelling can serve as a tool to "redistribute expertise" (Landström et al., 2011), incorporating multiple perspectives and frameworks to create a more comprehensive and inclusive understanding of droughts. On the other hand, a shared knowledge of drought provides a crucial starting point for engaging in the co-modelling process. Thus, we view this as an iterative cycle in which building a shared understanding of drought (this section) initiates the co-modelling process (Sect. 3.4), which, in turn, refines and deepens shared understanding. This iterative process also ensures that knowledge generation is dynamic and responsive to evolving perspectives.

Finally, the meaningful development of a shared definition of drought also requires addressing knowledge biases and power imbalances (Sect. 3.5). This involves confronting epistemic injustice by acknowledging that certain forms of knowledge on water, particularly those rooted in physical sciences, are often prioritized over other valuable knowledge systems, such as those held by local communities (Rusca et al., 2024; Zwarteveen et al., 2017). By recognizing and addressing these imbalances, we aim to ensure that all forms of knowledge and actors are treated equitably in the co-creation of drought-related knowledge.

3.4 Co-selecting and co-developing models of drought impacts

Co-creating knowledge in drought impact studies, and even more so in projected adaptation scenarios, very often relies on some levels of modelling (Baumgärtner et al., 2008). From a transdisciplinary perspective, co-modelling integrates non-scientist actors throughout the modelling process, irrespective of its purpose, whether forecasting, prescribing, explaining, describing, learning, or communicating (Srinivasan et al., 2016). With the term "model", we refer to any simplified representation of a real-life situation, thus including the whole range of qualitative conceptual models to predictive hydrological computational models. In transdisciplinary settings, the concept of "constructing models" can take on diverse interpretations. It can result in the co-creation of a conceptual model able to capture all the variables and processes relevant to describing the chain of problems and the study goals or even include computations, algorithms, and dedicated modelling tools and platforms (Smetschka and Gaube, 2020). Whenever the co-modelling involves computations, algorithms, and dedicated modelling tools and platforms, stakeholders might be involved in the co-selection of the most appropriate tool, by considering not only the type of expected outcome but also the skills and background of the people involved in the modelling process, as well as other contextual factors related to the availability of economic resources and other implementation constraints. Even when consolidated models or software is preferred over fully co-created models or software, which is the most common case (Addor and Melsen, 2019), setting up and configuration tasks of the modelling process could include the participation of stakeholders to avoid modellers' pre-assumptions and black-box implementations (Melsen et al., 2018). Through co-modelling, given a suitable interactive environment, non-specialized people can collaboratively produce models that are meaningful to them, fostering valuable discussions and the creation of new knowledge (Biggs et al., 2021).

Drought impact co-modelling might also require a shared definition of modelling scenarios. Essentially, scenarios represent a collection of narratives or stories, which collectively depict various coherent future scenarios for a specific system (Biggs et al., 2021). A fundamental aspect of scenario development involves the co-creation of hypothetical future situations (Iwaniec et al., 2020; Raudsepp-Hearne et al., 2020), as well as conditions of the present or the past, that can be used for the co-modelling. These scenarios can encompass a range of variables, such as climate patterns, land use changes, socio-economic factors, or policy decisions.

In water-scarcity- and drought-related research, stakeholders ideally engage in participatory co-modelling by directly constructing models and tools, formulating scenarios and policy options, and assessing the effectiveness of identified solutions against jointly defined performance indicators or targets, often focusing on selecting alternative strategies or refining the application of technical solutions (Basco-Carrera et al., 2017). For example, Masi et al. (2024) applied an extended and highly participatory multi-criteria decision-making analysis to optimize the siting of artificial reservoirs in Central Italy, while Piemontese et al. (2023) included indigenous knowledge to identify the best sites for sand dams in remote Angolan drylands. Wens et al. (2020) integrated an agent-based model with a process-based crop model to simulate alternative adaptation strategies, drawing from information collected through participatory methodologies. While these illustrative studies have the merit of including stakeholders' opinions, the conceptualization, the modelling approaches, and sometimes even the proposed solutions are established by the researchers, often hydrologists (Fischer et al., 2021). An interesting alternative was demonstrated by

Baker et al. (2015), who applied a process-based hydrological model while involving stakeholders in the input generation phase. This approach emphasized the different needs and values of women and men in an Ethiopian catchment. Bayesian networks (e.g. Carmona et al., 2013; Kneier et al., 2023; Singto et al., 2020) and conceptual system dynamics models (e.g. Hossain et al., 2020) are often more suited to performing a transdisciplinary drought impact study because they facilitate the integration of knowledge from multiple disciplines and enable collaboration across sectors by modelling interdependencies. Moreover, Bayesian networks and system dynamics models account for uncertainty, feedback loops, and complex system interactions, making them suitable for implementing adaptive, context-sensitive adaptation strategies and responding to the multifaceted challenges of droughts.

3.5 Accounting for knowledge biases and power imbalances

This dimension focuses on the role of power and differential agency in shaping the co-creation of knowledge. We identify two key areas of influence. Knowledge biases refer to power dynamics within the knowledge production process itself. Mainstream interpretations of science often frame the development of knowledge as neutral, objective, and unbiased, especially in fields that prioritize quantitative methods. However, scholarship in STS and political ecology challenges this view, arguing that knowledge is shaped by power relations that determine which forms of knowledge and expertise are recognized as more scientifically valid and actionable (Budds, 2009; Goldman et al., 2019; King and Tadaki, 2018; Mukherjee, 2022; Rusca et al., 2024; Turner, 2011; Zwarteveen et al., 2017). Power imbalances refer to the unequal influence exerted by different stakeholders. Research in political ecology and critical disaster studies has shown how these power imbalances can generate and perpetuate uneven outcomes, including disparities in water allocations and adaptation to natural hazards across regions, intra-urban spaces, rural–urban populations, identities (e.g. gender, race), and income groups (see, for example, Boelens et al., 2016; Collard et al., 2018; Sultana, 2020; Swyngedouw, 2004, 2009).

Overlooking knowledge biases and power imbalances risks marginalizing certain actors and forms of knowledge and prioritizing dominant, hegemonic ones in processes of knowledge co-creation (Krueger et al., 2016; Macpherson et al., 2024; Reed, 2008; Rusca et al., 2024; Thaler and Levin-Keitel, 2016). This is likely to undermine meaningful co-creation by silencing alternative perspectives and reinforcing existing inequalities, as shown by Cid et al. (2024) in their drought-related serious game, revealing power imbalances and knowledge disparities. Ensuring meaningful co-creation, therefore, requires reflecting on knowledge production itself, recognizing biases in what is deemed legitimate knowledge, and acknowledging that co-creation per se does not inherently eliminate existing power dynamics. First, determining what counts as "scientific" knowledge is particularly relevant in the context of co-creation for drought studies. While co-creation approaches have been argued to foster more inclusive and equitable knowledge, and thereby more just water management (Basco-Carrera et al., 2017; Falconi and Palmer, 2017), the power-laden nature of scientific knowledge can still lead to the dominance of scientific expertise in the co-creation process. Giordano et al. (2013) highlight how mistrust and a lack of cooperation challenge knowledge integration among stakeholders with different perceptions of droughts. Second, power imbalances among stakeholders can further undermine inclusive and equitable knowledge production processes. Dominant actors such as government agencies, international organizations, large NGOs, or scientific communities typically possess more time and resources to lead participatory processes and set the parameters for participation. Their knowledge claims are typically regarded as more credible or valuable (Turnhout et al., 2020).

Co-creation of water knowledge is also shaped by pre-existing relationships and histories of conflict (Budds, 2009), which are likely to influence the process. Embarking on a co-creation process requires engaging with different actors bringing their worldviews and goals. For instance, a drought can be framed differently depending on the actors' histories, interests, and experiences (Kaika, 2003). Powerful actors, like multinationals or political leaders, may exploit the participatory context to legitimize hegemonic drought narratives that support specific outcomes or adaptation strategies, exacerbating the pre-existing power inequalities and benefitting those who are already more powerful (Alexandra and Rickards, 2021; Kallis, 2008, 2010; Mehta, 2001; Savelli, 2023). However, involving powerful stakeholders could be necessary to drive a change towards sustainable adaptation strategies. To that end, powerful stakeholders need to be made aware of the importance of engaging in the co-creation of solutions to drought. In fact, although benefiting from certain power dynamics in the short term, they could face long-term consequences as these dynamics evolve. For example, Gwapedza et al. (2024) show that, if large-scale farmers are made aware of potential long-term drought impacts, they may remain interested in being engaged in the co-creation process and cooperating in a shared drought adaptation plan.

This dimension acts as an ethical compass that fosters a power-sensitive and reflexive approach to the co-creation process. It is inherently relevant to all other dimensions of knowledge co-creation, as it seeks to dismantle the epistemic hegemony of scientific knowledge in drought studies while incorporating diverse perspectives and ways of knowing throughout the co-creation process. First, recognizing power dynamics and epistemic biases is essential for establishing collaborative spaces (Sect. 3.1), which can only be truly inclusive if power imbalances are made explicit and addressed. Similarly, defining the scope of co-creation (Sect. 3.2) and building shared knowledge of drought (Sect. 3.3) often reflect the interests of powerful actors. A reflexive and power-sensitive approach seeks to pluralize narratives by creating space for alternative framings, especially those of marginalized groups. Last, a reflexive and power-sensitive approach is crucial for ensuring that co-modelling practices remain inclusive and equitable. As highlighted by ter Horst et al. (2024), this involves integrating reflexivity into every stage of the modelling process, from co-selecting and co-developing models to iteratively reviewing definitions, scenarios, and outcomes (Sect. 3.4).

4 Limitations of knowledge co-creation approaches

Knowledge co-creation involves a series of inherent challenges and limitations that can significantly affect its application.

Including all relevant stakeholders or their representatives from a given "impacted group" – whether individuals, households, communities, organizations, or ecosystems (Sect. 3.2) – in the co-creation process is crucial. However, in cases where impacts are widely spread over large areas, the implementation of a fully representative co-creation process may be challenging due to the large number of people involved. This represents one of the limitations of applying transdisciplinary approaches.

Furthermore, even when the number of participants is manageable, the process may still face obstacles due to a lack of economic resources, time constraints, or limited knowledge of the study area. Although highly motivated stakeholders are a prerequisite to a successful co-creation approach, some stakeholder categories might not consider drought an urgent problem or simply might not have enough time to collaborate or interest in collaborating on the process. In some cases, local political motivation and capabilities are key to ensuring a successful co-creation process. Vedeld (2022) explains the so-called "co-creation paradox", by which local political institutions that would benefit the most from co-creating solutions with local stakeholders lack the political capacity and leadership to do so.

Another key aspect of knowledge co-creation is acknowledging and involving holders of the different types of knowledge to ensure locally relevant problems and approaches are tackled (Brugnach and Ingram, 2012). Transdisciplinary studies require that goals and methodologies be collaboratively developed with stakeholders to ensure relevance, buy-in, and effectiveness. However, stakeholders are often only actively engaged after the research has received funding. By that point, the researchers have usually already defined key aspects, such as study goals and methodologies, which limits the scope for stakeholder input and collaboration. Donors' expectations might also limit the possibility of fully involving stakeholders in decision-making. Finally, the promoters of the co-creation approach – typically academics, institutions, and NGOs – have a specific background, which inevitably influences the whole process by prioritizing some impacts, disciplines, or sectors as well as influencing the model selection, among other aspects (Melsen, 2022).

Co-creating knowledge has great potential to improve drought impact studies and to promote proactive and effective drought management but cannot be considered a panacea. Some of the most relevant shortcomings related to co-creation are also related to the fact that it is considered an approach that is suitable for any context (Lemos et al., 2018). In particular, it is evident that the involvement of stakeholders in all kinds of research projects has become an indicator and a must-do by many funding agencies, regardless of its suitability for a project (Cleaver, 1999; Spaapen and van Drooge, 2011). This, in turn, may lead to co-creation approaches that, due to time and resource limitations, tend to focus only on the same groups of stakeholders, prioritizing familiarity over diversity, due to the high amount of time needed for building trust and engaged participants in the research approach (Porter and Dessai, 2017). This, in turn, can generate knowledge biases and exacerbate power imbalances (Sect. 3.5).

5 Advancing transdisciplinary drought research

Our five key dimensions offer a comprehensive framework to address the limitations in breadth and depth of current transdisciplinary approaches to drought impact research. They promote the inclusion of a wider range of actors and perspectives across all phases and aspects of the research process, rather than restricting participation to isolated moments (breadth), and support the meaningful, iterative integration of non-academic knowledge within each phase (depth). While these five key dimensions are a valuable reference to everyone involved in studying drought impacts, they are specifically discussed to support hydrologists in effectively utilizing transdisciplinary methods in the socio-hydrology of drought in a thorough and informed manner. Table 1 outlines actions for each dimension's depth across the breadth of the five key dimensions discussed in Sect. 3.1 to 3.5, ensuring the meaningful integration of non-academic knowledge and its influence on every phase of the research process.

From our perspective, two key aspects are crucial to overcoming current gaps in the development of transdisciplinary approaches to drought impact studies. The first is the need to implement iterative processes that incorporate feedback throughout the different phases of the research. For example, most studies seldom continuously adapt and evaluate the stakeholder engagement process, rarely reassess stakeholder involvement, or rarely improve or refine the shared understanding of drought impacts throughout the processes. These feedback mechanisms, identified in each dimension and highlighted in italics in Table 1, are essential for ensuring greater depth and increasing coherence of the study. Period-

Table 1. Matrix for drought impact knowledge co-creation, structured along two axes: breadth (key process dimensions) and depth (practical actions to ensure meaningful inclusion of non-academic knowledge in each dimension). Feedback mechanisms are denoted in italics.

	← BREADTH →				
	Set up a collaborative space for drought knowledge co-creation (Sect. 3.1)	Framing the drought co-creation process (Sect. 3.2)	Building a shared knowledge of drought (Sect. 3.3)	Co-selecting and co-developing models of drought impacts (Sect. 3.4)	Accounting for knowledge biases and power imbalances (Sect. 3.5)
DEPTH ↓	– Implement a stakeholder analysis to identify and map all relevant stakeholders, including those traditionally marginalized or underrepresented. – Develop transparent criteria for stakeholder inclusion, balancing comprehensiveness with practical feasibility. *– Continuously adapt and evaluate the engagement process, regularly reassessing stakeholder involvement to include emerging perspectives and ensure inclusivity and relevance throughout.*	– Engage stakeholders early and iteratively to shape the study's scope and boundaries. – Co-define research questions and themes to ensure alignment with societal knowledge demands. – Identify relevant sectors, impacts, and affected units to guarantee comprehensive coverage. *– Continuously refine the thematic, geographical, and temporal boundaries as the co-creation process progresses, incorporating new insights from stakeholders and ensuring alignment with the study's intended outcomes.*	– Acknowledge multiple knowledge systems (e.g. academic, local, and practitioner knowledge) and work to integrate them into the study, rather than privileging one over another. – Foster interdisciplinary collaboration to integrate geophysical, socio-economic, and political conceptualizations of drought and its impacts. *– Iterate and refine shared understanding through a cyclical process where stakeholder insights inform co-modelling and modelling outcomes, in turn, deepen and challenge that understanding.*	– Define modelling goals and select suitable approaches and tools collaboratively, considering stakeholders' needs, capacities, and available resources. – Co-develop models, integrating diverse knowledge systems to represent relevant variables, processes, and feedback. – Co-define and explore drought impact scenarios, using stakeholder-driven inputs to ensure the selection of plausible futures. *– Iteratively refine the modelling process by discussing and evaluating potential winners and losers of the anticipated impacts and drought mitigation strategies, adjusting the approach or specific aspects, until a consensus is reached.*	– Recognize power dynamics in knowledge production, and ensure that diverse knowledge systems (local, indigenous, experiential) are valued alongside dominant ones. – Create spaces in the co-creation process to openly discuss power dynamics and biases, reflecting on how social and economic factors shape relationships between actors. – Acknowledge the unequal influence of dominant stakeholders, and actively amplify marginalized voices to prevent their exclusion. *– Continuously reflect on and make explicit the power dynamics to prevent the marginalization of alternative perspectives and ensure equitable influence in defining study boundaries, framing drought, integrating dynamics into modelling, and interpreting outcomes.*

ically reassessing the stakeholder engagement (Sect. 3.1) assures that all relevant actors, including marginalized groups, are involved in co-defining and assessing the drought impacts. This inclusive approach ensures that socio-political factors, such as governance structures, power imbalances, and access to resources, are accounted for in the assessment impact evaluation process. Ideally, stakeholder conceptualizations of drought would inform co-modelling efforts (Sect. 3.4), while the modelling outcomes would, in turn, refine and challenge the collective understanding of drought (Sect. 3.3), reinforcing the cyclical nature of the process.

The second essential aspect is the need to acknowledge and address knowledge biases and power imbalances by continuously reflecting on and making explicit the underlying power dynamics. This is crucial to preventing the marginalization of alternative perspectives and ensuring equitable influence in defining study boundaries, framing drought, integrating dynamics into modelling, and interpreting outcomes. To address this, our framework recommends accounting for knowledge biases and power imbalances (Sect. 3.5) and critically examines how power relations influence both the co-creation process and the interpretation of outcomes. This dimension encourages transparency about the political and social influences on knowledge production, ensuring that more powerful stakeholders, such as governments or large institutions, do not dominate the process. Finally, by fostering an inclusive, iterative process through framing the scope of the co-creation process (Sect. 3.2) and iteratively setting up a collaborative space (Sect. 3.1), the framework ensures that all voices, particularly those from marginalized communities, are heard and that knowledge production is not skewed by unequal power relations.

Appendix A: Literature mapping

Table A1. Relationship between the literature in the five analysed bodies of literature and the key dimensions (breadth) they inform. Some studies appear in more than one body of literature due to their interdisciplinary nature.

Dimensions/bodies of literature	Transdisciplinary sustainability science	Socio-hydrology	Critical water studies (hydrosocial studies and critical disaster studies)	Science and technology studies (STS)	Integrated water resources management (IWRM)
Setting up a collaborative space for drought knowledge co-creation (Sect. 3.1)	– Clarke and Clegg (1998) – Clarkson (1995) – Reed et al. (2009) – Aldunce et al. (2016) – Lillo-Ortega et al. (2019)		– Rusca et al. (2024) – Mukherjee and Sundberg (2023) – Mpofu-Mketwa et al. (2023)	– Stirling (2008)	– Hargrove and Heyman (2020) – Rangecroft et al. (2018) – Paneque et al. (2018) – Lewis et al. (2005) – Hervás-Gámez and Delgado-Ramos (2019) – Kim et al. (2019)
Framing the drought co-creation process (Sect. 3.2)	– Lillo-Ortega et al. (2019) – Mustafa et al. (2021) – Pham et al. (2020) – Sampson et al. (2020)	– Mustafa et al. (2021) – Pham et al. (2020) – Gwapedza et al. (2024) – Giordano et al. (2013) – Aldunce et al. (2016) – Hagenlocher et al. (2023) – Rossi et al. (2023)	– Ayantunde et al. (2015) – Thompson et al. (2017)	– Sarewitz and Pielke (2007)	– Ballesteros-Olza et al. (2022) – van Beek and Arriens (2016) - Daré et al. (2018) – Nielsen-Gammon et al. (2020)
Building a shared knowledge of drought (Sect. 3.3)	– Grainger et al. (2021) – Gray et al. (2012)	– Rusca and Di Baldassarre (2019) – Wesselink et al. (2017) – AghaKouchak et al. (2021)	– Beck and Krueger (2016) – Kaika (2003) – Mehta (2001) – Rusca and Di Baldassarre (2019) – Rusca et al. (2023) – Rusca et al. (2024) – Zwarteveen et al. (2017) – Wesselink et al. (2017)	– Alharahsheh and Pius (2020) – Beck and Krueger (2016) – Garb et al. (2008) – Krueger and Alba (2022) – Landström et al. (2011) – Landström et al. (2023)	– Mpandeli et al. (2015) – Wilhite and Glantz (1985)
Co-selecting and co-developing models to understand drought impacts (Sect. 3.4)	– Baumgärtner et al. (2008) – Biggs et al. (2021) – Iwaniec et al. (2020) – Raudsepp-Hearne et al. (2020) – Smetschka and Gaube (2020) – Hossain et al. (2020)	– Melsen et al. (2018) – Srinivasan et al. (2016) – Masi et al. (2024) – Piemontese et al. (2023) – Wens et al. (2020) – Fischer et al. (2021) – Baker et al. (2015) – Addor and Melsen (2019)		– Melsen et al. (2018)	– Basco-Carrera et al. (2017) – Carmona et al. (2013) – Kneier et al. (2023) – Singto et al. (2020)
Accounting for knowledge biases and power imbalances (Sect. 3.5)		– Gwapedza et al. (2024) – Cid et al. (2024) – Giordano et al. (2013)	– Alexandra and Rickards (2021) – Boelens et al. (2016) – Budds (2009) – Collard et al. (2018) – Kallis (2010) – Kallis (2008) – Kaika (2003) – King and Tadaki (2018) – Krueger et al. (2016) – Macpherson et al. (2024) – Mehta (2001) – Mukherjee (2022) – Reed (2008) – Rusca et al. (2024) – Savelli (2023) – Sultana (2020) – Swyngedouw (2004) – Swyngedouw (2009) – Thaler and Levin-Keitel (2016) – Turnhout et al. (2020) – Zwarteveen et al. (2017)	– Goldman et al. (2019) – Turner (2011) – ter Horst et al. (2024)	– Basco-Carrera et al. (2017) – Falconi and Palmer (2017)

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