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Review article: Co-creating knowledge for drought impact assessment in socio-hydrology

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Abstract. Drought impacts are increasingly recognised as socially influenced processes instead of mere hydro-climatic events. Yet, drought assessments continue to be entrenched in disciplinary boundaries or limited by top-down modelling approaches, excluding those who directly experience the impacts of droughts. Transdisciplinary approaches to knowledge co-creation offer a promising opportunity to advance socio-hydrology by considering the role of politics and power, economic visions, and differential agency in shaping drought outcomes, and the experiences and knowledge of those directly affected by drought events. However, transdisciplinary approaches to drought impact studies are limited to scattered empirical cases and miss coherent theoretical and methodological guidance. Drawing from a diverse body of literature on transdisciplinarity in sustainability science, integrated water resources management, socio-hydrology, science and technology studies, and political ecology, we develop an interdisciplinary conceptual framework to guide knowledge co-creation in drought impact assessment and adaptation. The framework stands on five major dimensions: 1) stakeholder analysis, 2) the scope of the co-modelling process, 3) a shared knowledge of drought, 4) model conceptualisation and implementation, and 5) awareness of power biases and knowledge imbalances. We discuss our framework's applicability space, limitations and contributions for advancing transdisciplinary approaches in future drought impact assessments.

1 Introduction

Drought is an increasingly widespread and impactful disaster globally, with serious consequences for health, agriculture, societies, and the environment (Vicente-Serrano et al., 2021; Wilhite et al., 2007). Drought occurrences and impacts are generally considered as hydrological extreme phenomena and, thus, are conceptualised and modelled with an Earth system process approach (Mishra and Singh, 2010, 2011). However, the social experience of drought is very different from how it is

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represented in hydro-climatic models (Enenkel et al., 2020; Kchouk et al., 2022). Although originating from meteorological, hydrological or soil moisture anomalies, droughts are increasingly understood as complex socio-hydrological phenomena that affect societies across interdependent sectors and socio-economic groups (AghaKouchak et al., 2021; G. Ribeiro Neto et al., 2023; Mehta, 2007; Van Loon et al., 2016b). Merely considering the physical dimension of drought fails to account for its varied and often unequal impacts across socio-economic groups, geographical areas, and urban and rural spaces. A rich geographical scholarship has long theorised the interplay between hazards and the socio-economic processes that make some more vulnerable and exposed than others (Hewitt, 2019). More recently, climate justice and political ecology scholarship have built on this line of inquiry to conceptualise 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)). Drawing on these ideas, drought-related disasters have been conceptualised as a social construction of water scarcity to illuminate the differential agency and power asymmetries that determine highly uneven experiences of drought-related impacts and differential levels of water (in)security, and the underlying political drivers (Mehta, 2005; Rusca et al., 2023; Savelli et al., 2022; Usón et al., 2017). In this perspective, drought impacts are determined by a period of scarce precipitation as much as they are by historical and political water allocation processes and the uneven coping and adaptive capacities of different socio-economic groups and individuals.

The multidimensional nature of drought phenomena highlights the need for interdisciplinary and participatory approaches to drought assessments. Interdisciplinary research on water-related challenges that cross natural and social sciences to capture this complex interplay is often invoked. Yet, studies that bring socio-hydrology into engagement with hydrosocial scholarship remain scant (Rusca and Di Baldassarre, 2019; Wesselink et al., 2017). Additionally, there is an increasing recognition of the need to include societal perspectives, such as those of non-academic actors directly experiencing the impacts of drought, within transdisciplinary studies (Arheimer et al., 2024; Hadorn et al., 2008). The definition of transdisciplinary research and its relationship with other concepts continue to be topics of intense debate. However, there is widespread consensus regarding the significance of including “values, knowledge, know-how and expertise from non-academic sources” (Klein, 2010) in 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 or co-production (Bennich et al., 2022; Brugnach and Özerol, 2019; Norström et al., 2020). The terms "co-creation" and " co-production" are often used interchangeably (Voorberg et al., 2015), but there are subtle differences in the context of research and practice. The key distinction lies in the nature and outcome of the processes: co-creation is more about emergent, iterative interaction leading to a new understanding (Bremer and Meisch, 2017; Roux et al., 2010), while co-production aims at creating specific, practical knowledge through structured collaboration (Lemos et al., 2018; Oliver et al., 2019). According to Mauser et al. (2013), co-production can be seen as the second of the three fundamental steps of the process of co-creation of knowledge, preceded by co-design, and followed by co-dissemination. In the fields of integrated resource management and ecology, knowledge co-production is often addressed by referring to the concepts of collaborative modelling or co-modelling (Basco-Carrera et al., 2017). This concept involves the collaborative

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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 visualise, test, and refine these ideas into actionable solutions, enhancing the effectiveness of co-production (Fig.1).

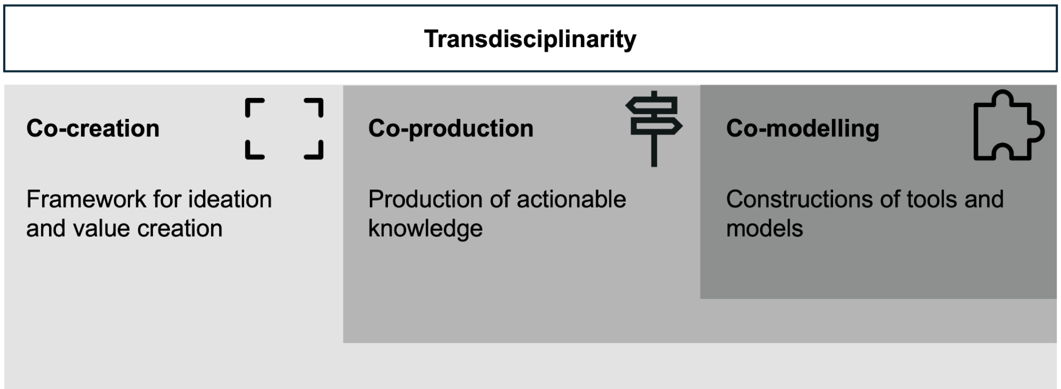

Figure 1: Graphical representation of the relationship between transdisciplinarity and the nested concepts of co-creation, co-production, and co-modelling.

Several definitions are available for transdisciplinarity, co-creation, co-production and co-modelling. Whilst several scholarly definitions are relevant and we are not attempting to choose among them, Table 1 lists some definitions highlighting that co-creation and co-production of knowledge can be intended as an approach for transdisciplinary science and that co-modelling is a form of co-production.

Table 1. Key definitions of transdisciplinarity, co-production, co-creation and co-modelling in human-water systems.

Term	Definition
Transdisciplinarity	Transdisciplinarity involves integrating different methods and knowledge systems, generated by a range of disciplines and through the collaboration between academics and non-academics to address complex development challenges comprehensively (Klein, 2010; Norström et al., 2020). Transdisciplinarity is a research approach required to "define or attempt to solve problems within the boundaries of subjects or disciplines, or where one goes beyond such definitions" (Mittelstrass, 2002, 2011).
Co-creation	Knowledge co-creation is an "iterative, collaborative process where different forms of knowledge are integrated to address complex societal issues" (Norström et al., 2020). It emphasises mutual learning and the integration of various types of knowledge, including scientific, local, and experiential. The collaboration between scientists and stakeholders generates "new, shared knowledge that is both scientifically robust and socially relevant"

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	(Mauser et al., 2013). The resulting knowledge is often emergent and exploratory, leading to innovative ideas that go beyond traditional boundaries. Co-creation can be viewed as a broader concept compared to co-production. Co-production is a specific stage within the co-creation process, along with other stages such as co-design and co-dissemination (Mauser et al., 2013).
Co-production	Co-production for sustainability science can be defined as "the outcome of iterations between producers and users of knowledge in which both sides are affected and respond to each other's needs, motivations and limitations (in terms of what can be produced and how it can be used in decisions)" (Lemos and Morehouse, 2005). Knowledge co-production focuses on the joint production of actionable knowledge. This process typically involves co-designing, co-implementing, and co-evaluating research or projects, to produce knowledge that is directly applicable to real-world problems and decision-making under uncertainty (Moallemi et al., 2023).
Co-modelling	Basco-Carrera et al. (2017) conceptualise collaborative modelling (i.e. co-modelling) as a form of participatory modelling. Co-modelling approaches are applied to decision-making processes in highly cooperative contexts (collaboration and/or joint action) with high levels of participation for key stakeholders in all the phases of the modelling process, involving them up to the level of collaboration and joint action after the modelling process. In contrast, standard participatory modelling includes stakeholder involvement from discussion to consultation to information sharing.

Traditionally, the fields of application of transdisciplinary research encompass sustainability science (Brandt et al., 2013; Lang et al., 2012) and social-ecological systems (Angelstam et al., 2013; Hummel et al., 2017). Co-creation of knowledge has also been applied to hydrological sciences (Roque et al., 2022), especially socio-hydrology, but with a prominent focus on flood risk and a limited application to drought (Vanelli et al., 2022). Advancing co-created research for drought impact assessment encounters specific barriers related to the different meanings of drought, its context-specific nature, its difficult predictability, as well as the subtle and unclear nature of its indirect impacts (Grainger et al., 2021).

Our paper advances the field of socio-hydrology by developing an interdisciplinary conceptual framework to guide scientists and practitioners in the co-creation of drought impact assessments. Given the limited literature on transdisciplinary approaches specifically focused on drought, we review and integrate knowledge developed in other scientific fields and disciplines. This allows us to identify core aspects that can be transferred and applied effectively in assessing and adapting to drought impacts. This work aims to enhance the understanding of co-creation in drought impact assessment by: (i) identifying key dimensions necessary for ensuring the co-creation of knowledge in drought impact assessment and adaptation modelling through the development of an interdisciplinary framework to guide this process; (ii) analysing the barriers and challenges to implementing co-creation in the context of drought impact assessment. This will support scientists and practitioners in assessing the stage of

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advancement of co-produced drought impact assessment concerning the identified key dimension and directing the development of drought-specific co-creation protocols and tools.

The paper proceeds as follows. In Sect. 2, we discuss the state-of-the-art and the importance of knowledge co-creation in socio-hydrological drought studies. Then, in Sect. 3, we present the interdisciplinary conceptual framework for transdisciplinary drought impact assessment and adaptation, discussing in detail each of the five identified key dimensions. Next, we examine our framework's applicability, limitations, and contributions to advancing transdisciplinary drought research in Sect. 4. Conclusions are reported in Sect. 5.

2 Knowledge co-creation in socio-hydrology of drought

Although socio-hydrology has emerged as a frontier interdisciplinary subject dealing with human-water systems interaction and extremes (Van Loon et al., 2016a), most of the research effort has targeted floods, leaving droughts partially underexplored (Di Baldassarre, 2017; Sivapalan et al., 2012). More recently, however, socio-hydrology of droughts has been advanced with local and global research exploring unequal impacts of droughts across places (Rachunok and Fletcher, 2023; Savelli et al., 2022), and resilience paradoxes of water infrastructure development in drylands (Piemontese et al., 2024). These, and other studies (e.g., Jaeger et al., 2019), aim to provide policy guidance to sustainable water management relying on data analysis and system dynamics modelling, within an academic interdisciplinary research space. An ample margin of investigation remains, especially in understanding the propagation of large-scale droughts or water scarcity into local impacts for an informed design of sustainable development policies (Pande and Sivapalan, 2017), for which transdisciplinary approaches can be pivotal.

Recent studies are exploring collaborative modelling. 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. Although these approaches advance the frontiers of co-modelling in drought research, they often allocate the co-design space to a specific phase of the drought knowledge generation process, usually the adaptation scenarios or the choice of indicators or model parameters (Luetkemeier et al., 2021). A mature knowledge co-creation approach in drought research would require further efforts towards integrating different knowledge domains and fully engaging all actors throughout the knowledge-creation process.

3 Conceptual framework

We performed a critical literature review (Grant and Booth, 2009) to inform the development of a conceptual framework. The framework provides a comprehensive analytical lens to examine multiple dimensions for co-creating knowledge in drought impact assessment and adaptation. It draws from a diverse body of literature on participatory modelling and transdisciplinary

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research in sustainability science, integrated water resources management, socio-hydrology, science and technology studies, and political ecology research fields. The framework is graphically depicted in Fig. 2 and outlines the five key dimensions of participatory drought impact knowledge co-creation. Each dimension is discussed in detail in Sects. 3.1 to 3.5.

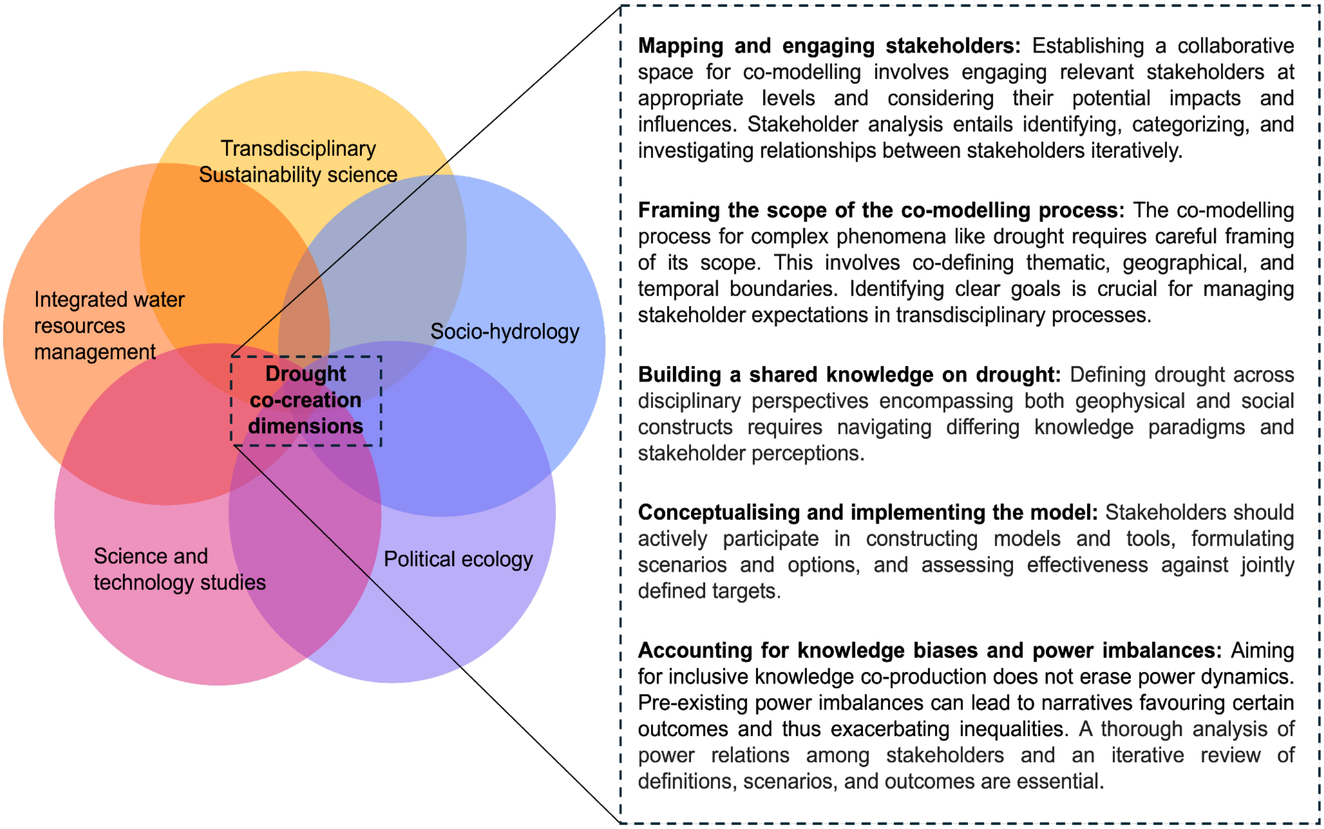

Figure 2: Conceptual framework: graphical representation of the theoretical background (on the left); the five key dimensions of knowledge co-creation for socio-hydrological drought impact assessment and adaptation (on the right).

3.1 Mapping and engaging stakeholders

Establishing a collaborative space is crucial for laying the foundations of a successful co-modelling process (Basco-Carrera et al., 2017). This requires ensuring that all relevant stakeholders are involved and that specific forms of engagement (e.g., communication, consultation, participation) for each group of stakeholders are identified. Stakeholders can be defined as "individuals, groups, and organisations who are affected by or can affect those parts of the phenomenon (this may include non-human and non-living entities and future generations)" (Reed et al., 2009). In transdisciplinary research, involving stakeholders serves multiple purposes (Stirling, 2008). Firstly, it upholds democratic ideals by emphasising 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.

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The stakeholder analysis dimension refers to the activities carried out to identify, categorise and investigate relationships among stakeholders (Reed et al., 2009). 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 would not be too restricted to avoid the unintentional overlooking of some stakeholders, leading to the omission of relevant individuals associated with the phenomenon (Clarkson, 1995). Conversely, the boundaries cannot be too blurred. It is often impractical to include every stakeholder, requiring the establishment of well-founded criteria by the research analyst to determine a cutoff point (Clarke and Clegg, 1998).

Identifying the roles, responsibilities and interests of various stakeholders serves two important purposes. First, a preliminary engagement with stakeholders can generate meaningful conversations about co-creation and can lead to collectively agreeing on a degree of involvement that works for all stakeholders and the assessment (Sect. 3.2). Second, understanding relationships between stakeholders is crucial to capturing power asymmetries that could affect the ability of different groups to meaningfully contribute to the co-modelling process (Sect. 3.5).

3.2 Framing the scope of the co-creation process

Framing the scope of the co-modelling process is crucial, especially when dealing with complex and multifaceted phenomena, such as droughts. First, the driving mechanisms of drought and its impacts as well as drought governance strategies can vary across spatial and temporal scales and sectors (i.e. health, agriculture, energy production, drinking water supply, etc.). Therefore, it is essential to co-define the confines of the co-development study, including thematic, geographical and temporal boundaries (Daré et al., 2018).

The set up of the thematic boundaries refers to the definition of the topics, themes, and areas of focus for a study. This involves identifying the specific sectors, types of impacts, and the 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, organisations, or ecosystems.

The set up of the geographical boundaries refers to the spatial scale in which drought assessment is performed and can vary from local to global. The boundaries can be set considering physical (e.g., hydrological units or ecological systems – (Ballesteros-Olza et al., 2022; Mustafa et al., 2021)) or administrative boundaries (e.g., municipalities, countries, regions – Lillo-Ortega et al. (2019), Nielsen-Gammon et al. (2020)) as well as boundaries related to specific social-cultural-economic systems (e.g., Ayantunde et al. (2015), Pham et al. (2020)). The set up of the temporal boundaries refers to defining the specific period within which the modelling will take place. 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

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change on drought, temporal boundaries could be set to include projections for a future time horizon, such as the next 50 years. For a specific drought event, the temporal boundaries would be set to cover the duration of that specific event, allowing for an analysis of its impacts.

The framing of the scope of a transdisciplinary process also requires performing a so-called 'situation analysis' (Beek and Arriens, 2016), which encompasses (i) the co-analysis of the current situation (e.g. if drought is a current issue or a future concern, if mitigation measures already in place are effective and, if not, why, etc.), (ii) a co-identification of the main problems and issues to be addressed, as well as (iii) the co-definition of the main goals of the study. As an example, some co-modelling processes may aim at learning more about current drought dynamics and impacts to increase awareness. In contrast, others 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.

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 presents two main challenges. First, there is no single definition of drought across disciplinary perspectives. Second, stakeholders involved in the co-modelling process may work with different definitions of drought (Krueger and Alba, 2022). Specifically to the first challenge, a drought is defined as a geophysical phenomenon within the positivist paradigm (quantifiable based on hydroclimatic thresholds) and as a social construct within the interpretivist paradigm (based on qualitative examinations of the power relations that shape the uneven outcomes of a drought and peoples' perception and experiences of its impacts) (Alharahsheh and Pius, 2020). Underlying these different conceptualisations are fundamentally different knowledge paradigms that can be complex to align and might prevent the development of inclusive and productive collaborations (Wesselink et al., 2017).

Notwithstanding these challenges, promising approaches that embrace and work with epistemological and ontological differences to explore how power relations shape changes in hydrological flows and the distribution of hydrological risk are beginning to emerge (Rusca and Di Baldassarre, 2019). For instance, the social-environmental extreme approach combines climate projections with political-ecological analyses of the social construction of drought and its uneven outcomes to develop an impact-focused understanding of future drought risk beyond what is achievable within disciplinary boundaries (Rusca et al., 2023). On a similar note, although political ecology scholarship tends to define hydrological science as a knowledge project in "search for universally applicable 'laws' of nature based upon practices that guarantee accuracy and lack of political bias" (Forsyth, 2004: 92), the field of hydrology is more heterogeneous and has developed (self)critical analyses on the process of modelling. Beck & Krueger (2016), for instance, draw on science and technology scholarship to argue that depoliticised analyses of hydrological phenomena may reproduce "authoritative representations of dominant perceptions of the world", rather than challenge the status quo. Recognising that scholars within the field of hydrology might hold different

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epistemological or methodological positions is crucial to escaping stereotypical definitions of disciplines and disciplinary boundaries and laying the foundation for interdisciplinary collaborations (Rusca and Di Baldassarre, 2019).

Regarding the second challenge, stakeholders directly experience the impacts of drought and, thus, are likely to have a different way of knowing and defining it based on different "mental models" (Gray et al., 2012). Whilst this diversity might complicate the process of co-creating a shared knowledge of drought and its impacts (Landström et al., 2023), it also carries the potential of generating a richer and more inclusive assessment. Therefore, developing a shared understanding of droughts is about embracing/apprehending different ways of knowing, rather than prioritising one or establishing a hierarchy between them. Models are well placed to act as a boundary object between different ways of knowing socio-climatic phenomena (Garb et al., 2008). In this light, co-modelling can be seen as a way of "redistributing expertise" and transforming knowledge on hydrological processes (Landström et al., 2011) by pluralising it.

3.4 Conceptualising and implementing the model

Co-creating knowledge in drought impact assessments, and even more so in projected adaptation scenarios, very often relies on some levels of hydrological modelling. In this sense, co-modelling integrates non-scientist actors throughout the modelling process, irrespective of its purpose, whether forecasting, prescribing, explaining, describing, learning, or communicating. From a technical standpoint, co-modelling assumes that, 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). Ideally, stakeholders directly engage in constructing models and tools, formulating scenarios and policy options for modelling, and assessing the effectiveness of identified options or solutions against jointly defined performance indicators or targets (Basco-Carrera et al., 2017).

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 for describing the chain of problems and the study goals, or even include computations, algorithms, and dedicated modelling tools and platforms (Smetschka and Gaube, 2020). In this last case, stakeholders can contribute to selecting 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 are preferred over fully co-created ones, setting-up and configuration tasks of the modelling process could include the participation of stakeholders to avoid modellers' pre-assumption and black box implementations (Melsen et al., 2018).

Drought impact co-modelling usually requires the 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-

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modelling. These scenarios can encompass a range of variables, such as climate patterns, land use changes, socio-economic factors, or policy decisions.

3.5 Accounting for knowledge biases and power imbalances

Science and knowledge production processes are often framed as neutral, objective, and unbiased. In contrast with this framing, science and technology studies and political ecology scholarship have argued that environmental knowledge is shaped by power relations that ultimately determine what forms of knowledge and expertise are recognised as more valuable, 'scientific' and actionable (Budds, 2009; Goldman et al., 2019; King and Tadaki, 2018; Mukherjee, 2022; Turner, 2011; Zwarteveen et al., 2017). The recognition of the power-laden nature of scientific knowledge carries significant implications for co-modelling. Co-modelling has been argued to foster more inclusive and equitable knowledge and, in turn, water management (Basco-Carrera et al., 2017; Falconi and Palmer, 2017). However, it is essential to recognise that co-modelling does not eliminate these power relations. Co-creation of knowledge often involves stakeholders with a history of relationships and conflicts, and their worldviews and goals, which often influence the direction taken within the co-creation process (Budds, 2009). Embarking in a co-creation process requires engaging with different actors bringing their worldviews and goals. Although differences among stakeholders are likely to persist, the co-creation process can contribute to developing a shared ambition to reduce drought risk and to identify shared goals and strategies. However, any transdisciplinary process involves stakeholders with a history of relationships and conflicts, which often influences the decisions and direction taken within the co-creation process. Elite stakeholders, such as government agencies, international organisations, large NGOs, or scientific communities, typically possess more time and resources to lead participatory processes and negotiate the parameters for participation. Furthermore, their knowledge claims are likely to be deemed more relevant and valuable. As a result, elite actors wield considerable influence in shaping these processes to align with their interests. Within a co-creation framework, these power imbalances are exacerbated by the predominant authority ascribed to scientific expertise over other knowledge systems (Turnhout et al., 2020). Another potential pitfall of power unbalance is represented by narratives or discourses. Multiple narratives can be told about one situation, including drought causes, consequences and potential solutions (Kaika, 2003). Especially powerful actors, like companies or political authorities, can take advantage of a participatory context to legitimise the prevailing narrative of droughts, to support specific outcomes or adaptation strategies which could result in exacerbating the pre-existing power inequalities and creating winners and losers (Alexandra and Rickards, 2023; Mehta, 2001; Swyngedouw, 2009). To avoid such a bias, a drought impact co-creation process must be developed carefully. First, there is a need to analyse power relations among stakeholders and monitor how they evolve and impact the co-creation process. Second, it is crucial to make room and iteratively review the definitions, scenarios and modelling outcomes to ensure that all parties are aware of the potential implications of the process outcomes.

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4. Discussion

4.1 How the framework can help advance drought research

In introducing this framework, we have synthesised key concepts from a diverse body of literature to guide the co-creation of knowledge related to drought. While the conceptual framework is valuable to everyone involved in assessing drought impacts, it is specifically designed to support 'positivist' hydrologists who may find it challenging to navigate the extensive transdisciplinary literature. The proposed framework provides a foundational approach to help hydrologists, and others, effectively utilise transdisciplinary methods in the socio-hydrology of drought in a thorough and informed manner.

Table 2. Core actions that define each of the five key dimensions of knowledge co-creation for socio-hydrological drought impact assessment and adaptation.

Dimension	Core actions
Mapping and engaging stakeholders	• Implementation of a formal stakeholder analysis • Definition of different levels of engagement for each stakeholder group • Definition of clear strategies for stakeholder engagement
Framing the scope of the co-modelling process	• Co-setting of study boundaries (thematic, geographic, temporal) • Co-identification of key problems or criticalities • Co-definition of study goals
Building a shared knowledge of drought	• Co-definition of 'drought' or 'water scarcity' concepts • Co-definition of 'impact' concept • Consideration and integration of different knowledge paradigms
Conceptualising and implementing the model	• Co-identification of the modelling processes • Co-selection and/or co-development of tools and methods
Accounting for knowledge biases and power imbalances	• Explicit consideration of power dynamics among stakeholders • Discussion and agreement upon modelling outcomes • Measure in place to avoid power imbalances or biases among stakeholders

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The framework outlines crucial core actions across five key dimensions (Table 2), providing a foundation for translating these actions into practical protocols or guidelines for transdisciplinary studies focused on drought impact assessment and adaptation. Moreover, adopting the framework can support the advancement of impact-based drought forecasting by fostering standardised and scientifically sound collaboration with local communities. Incorporating indigenous knowledge addresses a current limitation in understanding exposure, vulnerability, and local coping strategies. This integration is crucial for identifying effective early actions and enhancing the overall response to drought impacts (Shyrokaya et al., 2024). Nevertheless, operationalizing this framework may introduce additional challenges related to the practical application of transdisciplinary approaches, necessitating compromises and potentially suboptimal decisions, which are discussed in the next section.

4.2 Limitations of co-creation – A useful approach, but not a panacea

In this work, we introduce a transdisciplinary approach to knowledge co-creation as a promising means to advance socio-hydrology research on drought. This approach aims to create knowledge that is not only useful and usable but also societally impactful. However, knowledge co-creation involves a series of inherent challenges and limitations that can significantly affect its application, particularly in drought impact assessment research.

Including all the stakeholders impacted by drought in the co-creation process is of paramount importance, but it might be hindered by a lack of economic resources, time, or limited knowledge of the study area. Although highly motivated stakeholders are a prerogative to a successful co-creation approach, some stakeholder categories might not consider drought as an urgent problem or simply might not have enough time or interest in collaborating on the process. In some cases, the local political motivation and capabilities are key to ensuring a successful co-creation process. Vedeld (2022) explains the so-called "co-creation paradox", for 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 drought knowledge co-creation is acknowledging and involving holders of the different types of knowledge to ensure tackling the locally relevant problems and approaches (Brugnach and Ingram, 2012). However, transdisciplinary studies require that goals and methodologies be collaboratively developed with stakeholders to ensure relevance, buy-in, and effectiveness, stakeholders are often only actively engaged after the research has received funding. By this time, 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, either by prioritising some impacts, discipline or sector as well as in the model selection, among other aspects (Melsen, 2022). To propose suitable solutions to these and many other problems, a promising opportunity consists of learning from available case studies that might successfully cover some aspects of our framework when assessing drought impacts.

Co-creating knowledge has great potential to improve drought impact assessments and to promote proactive and effective drought management. Furthermore, many useful synergies can emerge within these transdisciplinary approaches. Co-creation of knowledge is a useful approach but cannot be considered a panacea. Some of the most relevant shortcomings related to co-

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creation are also related to the fact that it is considered an approach which is suitable for any context (Lemos et al., 2018). In particular, it is evident how 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, prioritising 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. Conclusions

In this paper, we have argued that transdisciplinary approaches can advance socio-hydrological drought impact assessments and we proposed a drought-specific framework for knowledge co-creation. Due to the lack of drought-specific literature, we have incorporated knowledge about transdisciplinary approaches developed in other scientific fields and disciplines to identify which core aspects can be transferred and tailored for successful application in drought impact assessment and adaptation. The framework can guide scientists and practitioners in co-creating drought impact assessments, based on five key dimensions: Mapping and engaging stakeholders, Framing the scope of the co-modelling process, Building a shared knowledge of drought, Conceptualising and implementing the model, Accounting for knowledge biases and power imbalances.

The framework is particularly beneficial for "positivist" hydrologists who might struggle with the broad transdisciplinary literature, offering a structured approach for using these methods in drought impact studies. It can represent a basis for the development of practical protocols and guidelines for transdisciplinary studies focused on drought impact assessment and adaptation. Furthermore, the framework aims to foster standard, scientifically sound collaboration with local communities, incorporating indigenous knowledge to improve understanding of exposure and vulnerability and enhance drought response strategies. This can ultimately improve impact-based drought forecasting.

However, co-creation is not without challenges, such as resource limitations, varying stakeholder motivation, and difficulties in achieving consensus. Though not a one-size-fits-all solution, knowledge co-creation, when thoughtfully applied, offers a promising pathway to proactive and effective drought impact assessment and adaptation.

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