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TOPICAL REVIEW

Does drought management care for nature? Identifying gaps in the consideration of freshwater ecosystems

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Abstract

Growing evidence suggests that freshwater ecosystems incur exacerbated impacts during drought due to anthropogenic activities. This has prompted calls for the development of drought management strategies that more effectively incorporate these ecosystems. Efforts to examine how drought management instruments care for freshwater ecosystems are scarce, limited to a few geographic regions, and do not systematically analyse each of the elements of the drought management process. In this study, we review drought management instruments in 26 countries or regions within countries to assess the extent and the manner with which freshwater ecosystems are considered. We apply an analytical framework integrating knowledge from drought management, ecological risk assessment and ecological drought to extract data from these instruments and identify patterns and gaps. Results indicate that care for freshwater ecosystems in drought management is as yet at an early stage. This is reflected in the limited inclusion of freshwater ecosystems across critical elements of the drought management process, as well as significant shortcomings in how these ecosystems are considered. We synthesise these shortcomings in four gaps. First, the socio-ecological perspective of ecological drought, particularly regarding the combined natural-human causes of drought impacts on freshwater ecosystems, is often lacking in drought definitions, exposure and vulnerability assessments. Second, despite their importance to ecosystems, there is limited consideration of variables related to groundwater, water quality, and aquatic habitats in freshwater ecosystem indicators, exposure assessments and measures. Third, the duration, frequency and timing of drought, which are relevant to the ecology of freshwater ecosystems, are rarely considered in drought indicators and measures. Finally, exposure and vulnerability assessments often lack a comprehensive understanding of ecological drought risk in freshwater ecosystems. We discuss these gaps and provide an outlook towards more integrated and sustainable drought policy and management.

1. Introduction

The resilience of society to drought is inextricably intertwined with the health of freshwater ecosystems and their contributions in the form of intrinsic (e.g. rights of a specific river), relational (e.g. cultural significance of a specific lake) and instrumental (e.g. provision of drinkable water) values (IPBES 2022, Himes *et al* 2024). However, drought entails a critical stress on freshwater ecosystems (Lake 2011), as two main characteristics make them particularly exposed and vulnerable. Firstly, freshwater ecosystems are directly exposed to all the abiotic effects induced by the three main types of drought hazard: precipitation, hydrological and soil moisture deficits (Kovach *et al* 2019). These abiotic effects are often aggravated when coupled with human activities (e.g. water abstraction for irrigation and industry), as shown by a growing body of literature (e.g. Grafton *et al* 2013, Jiang *et al* 2013, AghaKouchak *et al* 2015, Mosley 2015, Lund *et al* 2018, Stewart *et al* 2020, Levy *et al* 2021, Yin *et al* 2022). Secondly, freshwater ecosystems have nowadays a reduced natural capacity to respond and recover from drought (Bond *et al* 2008) due to severe degradation and biodiversity loss (Collen *et al* 2014, WWF, O 2018, Reid *et al* 2019), making them increasingly vulnerable to drought-related disturbances. The magnitude and relevance of drought impacts on ecosystems has led researchers to define the concept of ecological drought as a new drought type. Initially described as 'a water shortage causing stress on ecosystems, and adversely affecting the life of plants and animals' (Lake 2011, p 21, Tallaksen and Lanen 2004), it is more recently referred as 'an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems' (Crausbay *et al* 2017, p 2544). The latter definition makes the socio-ecological dimension of ecological drought explicit, by emphasising that exposure and vulnerability of ecosystems to drought are driven by both natural and anthropic influences, and ecological impacts are transferred to society through ecosystem services (Crausbay *et al* 2017).

The interactions between people, nature and drought are partly regulated by drought risk management instruments (hereafter drought instruments). These are defined here as policy-related documents, with legally binding or non-binding nature (López-Barrero and Iglesias 2009), that establish a clear set of principles or operating practices to govern the management of drought and its impacts (Wilhite 2009). Though specific structure or content may vary, drought instruments are encouraged to integrate a set of elements that enable effective drought management (Wilhite *et al* 1999, Urquijo-Reguera *et al* 2022, Jedd and Smith 2023). These elements can be organised around three pillars (Wilhite *et al* 1999, Hayes *et al* 2004, United Nations Office for Disaster Risk Reduction [UNDRR] 2021, Duel *et al* 2022): (i) drought characterisation, (ii) drought impacts, exposure and vulnerability (or drought impacts and risk, for simplicity), and (iii) mitigation and response planning and measures (or drought planning, for simplicity).

Ecosystems have traditionally been overlooked in drought instruments, largely because drought management stems from the human-centred theory and practice of disaster risk management (Blaikie *et al* 1994, Field *et al* 2012). Nevertheless, ecosystems started to receive greater attention as drought management moved towards proactive approaches. In the European Union (EU), for example, the 2000 Water Framework Directive (European Commission [EC] 2000) set an important milestone by establishing that the good status of water bodies has to be ensured also during drought. A temporary deterioration of water bodies is allowed only under exceptional drought conditions, which are those that cannot be reasonably foreseen, such as prolonged droughts (EC 2000). Despite these advances, the reluctance to protect freshwater ecosystems remains a major barrier to make progress in drought management (Sayers *et al* 2017). This issue is increasingly gaining prominence on the international political agenda. In the EU, a recent review of drought management plans has identified the non-deterioration of the status of water bodies during drought as a key aspect to be strengthened (Schmidt *et al* 2023). More recently, the development of drought management strategies that include ecosystems has been explicitly highlighted as one of the nine recommendations of the Drought Resilience +10 Conference (World Meteorological Organization [WMO] 2024), developed within the framework of the Integrated Drought Management Programme (IDMP) (https://www.droughtmanagement.info/) by the WMO and the Global Water Partnership (GWP).

In light of the need for a policy shift in drought management towards freshwater ecosystems protection, an essential first step includes the understanding of whether current drought instruments, which are the main tools for addressing drought risk as a society, care for nature. Such an understanding would enable gaps in drought management practices to be identified, thereby supporting the development or review of future drought instruments effectively. By *care for* we refer to the conventional definition, which encompasses the consideration for something but also provision of what is necessary for the health, maintenance, and protection of it to avoid damage or risk (Simpson 2008). We deliberately use *care for* rather than *consider* or *integrate* to highlight not only *whether* nature is considered in drought instruments, but also *how* it is considered. This puts the focus on our interaction with nature, and thus on the actions we (can) carry out to protect and conserve something we care for.

Efforts examining how drought policy care for nature, particularly for freshwater ecosystems, are scarce and mainly limited to the Australian and US contexts. In the context of the Millennium Drought in Australia, Bond *et al* (2008) highlight that the main approach consisted of reactive measures aimed at mitigating an ecological crisis. They emphasise the need for a paradigm shift towards a proactive approach through long-term measures that restore the natural resilience of freshwater ecosystems to drought. Mount *et al* (2016) review the current Australian strategy for environmental flow management, including during drought, highlighting its foundation on the ecosystem functional flows approach and the role of water rights for the environment. In the US, McEvoy *et al* (2018) assess how drought instruments incorporate ecological impacts and ecosystems services across various watersheds within the Upper Missouri Headwaters, in Montana. Their findings show that ecological impacts are mainly recorded through fish populations, which are important for the recreational sector in the region, and monitored through ecological indicators based on water temperature and streamflow conditions relevant to fish. Recently, in the EU, Schmidt *et al* (2023) describe the use of exceptions to achieving the good status of water bodies during drought and the management of environmental flows in different Member States.

While these studies offer valuable knowledge on drought management with regards to freshwater ecosystems, there are at least three aspects that warrant further attention in terms of research. First, the existing studies focus on specific locations and cannot be used to draw general conclusions on if and how freshwater ecosystems are included in drought management globally. Second, the recently acknowledged socio-ecological perspective of ecological drought is rarely analysed or has only been considered from the perspective of ecosystem services, with limited attention to how human activities influence exposure and vulnerability in ecological drought. Third, and most importantly, while the literature does examine some of the elements of the drought management process, it barely touches on others. Understanding whether and how freshwater ecosystems are considered in each of the elements of the three pillars of drought management is important, as these inform current decision-making processes for drought planning and management. Here, we recognise that restoration measures that build ecological drought resilience during average climatic conditions are central. However, we stress the need to adapt climate and environmental scientific knowledge to fit into current decision-making processes to enhance its usability (Dilling and Lemos 2011, Kirchhoff *et al* 2015). Moreover, short-term management has a partial yet fundamental role in drought planning (López-Barrero and Iglesias 2009), and this becomes more evident under climate change and non-stationary conditions, where higher variability is expected in the hydrological flow regime (Poff 2018).

Considering the relevance of these issues and the increasingly large number of drought instruments currently available (Alkadir *et al* 2022, Schmidt *et al* 2023), this study aims at identifying major gaps in drought management in relation to freshwater ecosystem protection by examining how these instruments care for freshwater ecosystems. We conducted a scoping review of drought instruments in 26 case studies worldwide using a protocol to extract and code data. This protocol is based on an analytical framework organised around the three pillars of drought management and associated elements, which are reframed considering concepts from ecological risk assessment theory and recent studies on ecological drought (e.g. Crausbay *et al* 2017, 2020, Sadiqi *et al* 2022).

2. Methods

This section first describes the process for the scoping review of drought instruments, and it then presents the analytical framework used to design the protocol that was applied to the drought instruments to extract and code the relevant information.

2.1. Scoping review of drought instruments

In this study, we applied the PRISMA extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco *et al* 2018). Scoping reviews follow a systematic approach to map evidence of a topic and identify gaps (Tricco *et al* 2018), and usually address broader questions than systematic reviews. The review is structured into four stages (figure 1), which are described in the following subsections.

2.1.1. Identification of potential cases studies

Drought instruments belong to the grey literature—i.e. 'that which is produced on all levels of government, academics, business and industry in print and electronic formats, but which is not controlled by commercial publishers' (Farace and Frantzen 1998, p 5). Therefore, the objective of our search strategy is to identify potential case studies across the globe where governmental institutions (e.g. ministries, agencies and river basin authorities) have published drought instruments. Accordingly, the search strategy combined three different sources:

(i) Two specialised major grey literature sources relevant to drought management; the IDMP website (IDMP 2023), hosted by the WMO and the GWP; and a 2023 outlook report of the state of drought policies, planning and management in the EU Member States developed within the European Drought Observatory for Resilience and Adaptation (EDORA) project (Schmidt *et al* 2023). The IDMP website is regularly updated with a list of countries that have implemented or revised drought risk management strategies (IDMP 2023). For our review, we considered as potential case studies all the countries listed on the IDMP website (IDMP 2023) between 1 November 2022 and 13 March 2023. From the EDORA project report, we considered all the EU Member States that had reported to have a drought management plan

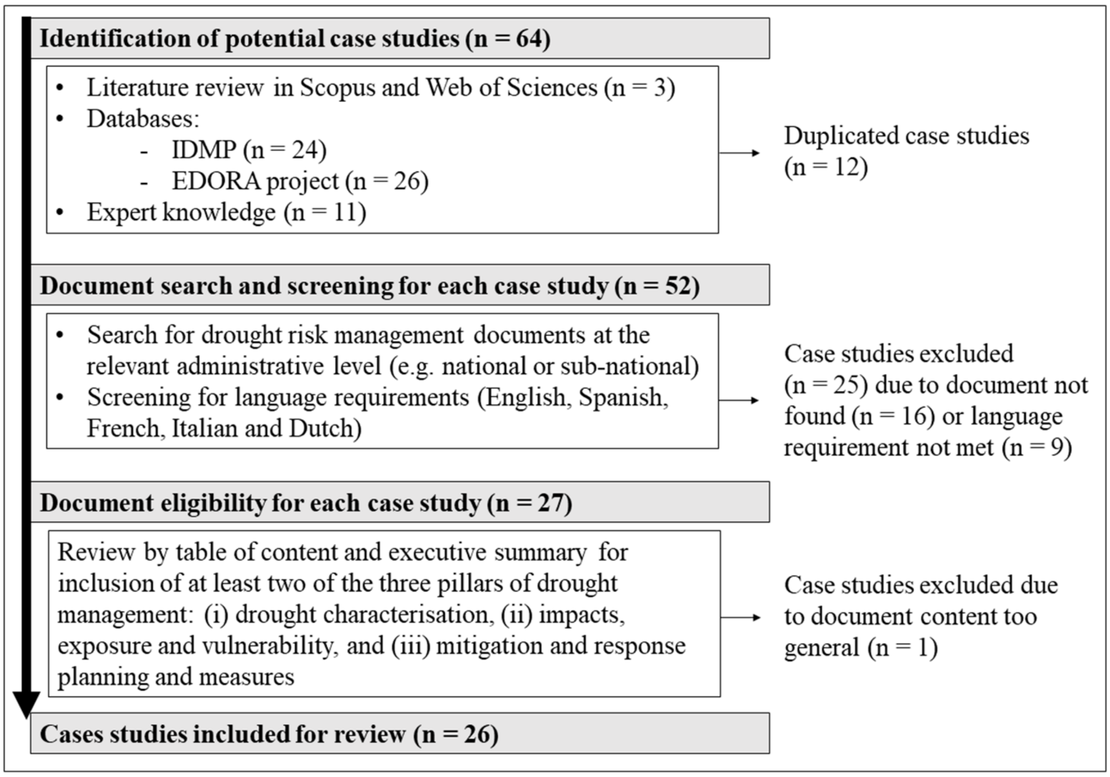


Figure 1. PRISMA flow diagram for the scoping review of drought instruments. n = number of case studies.

or other strategies addressing drought management in place (tables 4 and 5 in Schmidt *et al* 2023).

(ii) The peer-reviewed literature in the Scopus database. The objective was to use the peer-reviewed literature as a means of identifying potential case studies where drought risk management explicitly considers freshwater ecosystems. This targeted search ensured that our analysis included at least some case studies considering freshwater ecosystems during drought management. Additionally, it helped guide case study selection in countries where drought risk management is primarily managed at a sub-national level (e.g. the US). We defined the following search query and, to make it viable in terms of deployed effort, we applied it solely to article titles: *TITLE (drought OR scarc* AND environm* OR ecologic* OR ecosystem AND policy OR manag* OR regul* OR impact* AND water OR aquat* OR hydro* OR freshwater) AND PUBYEAR > 1990.* Resulting papers were first filtered by reading the abstracts to determine whether these contained information on drought risk management from an environmental perspective. Relevant papers were then fully reviewed to identify potential case studies. The search was first conducted on 9 January 2023, and repeated on 10 June 2023, to identify recent updates before finalising the review process.

(iii) Expert knowledge as a complementary source. The authors complemented the identification of potential case studies already found in the previous steps. This is a common approach in reviews of grey literature (Godin *et al* 2015, Yoshida *et al* 2024).

These sources primarily led to identify countries with documented drought instruments. When we found that in a given country drought is managed at a sub-national level, such as at the level of the state or river basin, we selected a single administrative unit within that country based on the criteria described in S1 of the supplementary material.

2.1.2. Document retrieval and screening for each case study

The second step comprises retrieving the documents informing each potential case study, and screening for language requirements. Documents were retrieved primarily from official government websites, links found on the IDMP website (IDMP 2023), or links reported in the EDORA project report (Schmidt *et al* 2023). We excluded case studies where relevant documents could not be found or where documents were not written in English, Spanish, French, Italian or Dutch, given the combined language skills of the authors. For simplicity, when information relevant to drought management in a specific location was found to be contained in more than one document, we refer to the ensemble as 'drought instrument'.

2.1.3. Document eligibility for each case study

As a third step, the documents were reviewed by table of content and executive summary for the eligibility criteria, i.e. inclusion of information related to at least two of the three pillars of drought management. Potential case studies where the documents retrieved did not meet these eligibility criteria, or where these consisted only of slides, schemes, factsheets, etc., were discarded.

Once the list of case studies was finalised, the entire documents were reviewed. Information from the documents was coded using a protocol that is based on the analytical framework described in section 2.2. The protocol consisted of yes/no questions on whether freshwater ecosystems are considered, as well as multiple-choice questions on how these are considered. If freshwater ecosystems were not explicitly mentioned, we coded it as 'not considered', even if terrestrial ecosystems were mentioned (e.g. forests). The first version of the protocol was tested and adjusted iteratively by the authors on 13 drought instruments, until the final version was reached. During this process, two coders independently coded the same documents, and questions and multiple-choice options were refined to ensure these were precise and comprehensive of the full range of casuistic. Discrepancies were resolved by discussion until consensus was reached. Once the final protocol was defined, it was applied to the remainder 13 drought instruments by one author. References supporting each answer were provided, including the page numbers and an explanation and clarification of the answer. The coding of each instrument was then independently reviewed by a second author and discussed where required. The complete version of the protocol, including definitions of concepts can be found in S2.

2.2. Theoretical basis of the analytical framework and protocol

We defined an analytical framework that considers and revisits the three pillars of drought management and associated elements from the perspective of ecological drought and ecological risk assessment theory. The protocol is structured following those three pillars and elements (table 1).

2.2.1. Drought characterisation

Drought characterisation encompasses the definition(s) of drought and drought risk, drought types, and the indicators used to monitor drought and trigger measures (Duel *et al* 2022). Drought definitions and types aim at clarifying its understanding as a phenomenon within a specific context (Wilhite and Glantz 1985), providing insight to its causes and potential impacts (Schmidt *et al* 2023). For definitions and types, we looked at the following aspects (see table 1 for detail): (a) drought definitions refer to impacts on ecosystems; (b) drought definitions acknowledge that the causes of drought and its impacts on ecosystems can be attributed to both natural and human drivers (i.e. inclusion of the socio-ecological perspective) (Van Dijk *et al* 2013); (c) an ecological drought type is considered in the drought instrument using either the definition proposed by Tallaksen and Lanen (2004) or by Crausbay *et al* (2017).

Drought indicators are here defined 'as any variable or computed numerical representation used to describe drought conditions' (WMO and GWP 2016, p 3), including severity levels, and trigger measures (Duel *et al* 2022). Several severity levels, i.e. different stages of drought evolution, may be associated to an indicator based on different drought attributes, namely magnitude, duration, frequency and timing (Zargar *et al* 2011). Ideally, the design of drought indicators should represent drought risk in a specific socio-ecological system (Bachmair *et al* 2016, Duel *et al* 2022). Therefore, the development of ecological drought indicators relevant to freshwater ecosystems requires the use of variables representative of ecological drought exposure, and thresholds representative of ecological drought vulnerability (Park *et al* 2020). For the purpose of this analysis, we examined only those indicators that explicitly consider freshwater ecosystems in their description or that are used to trigger measures related to freshwater ecosystems. We examined the variables through which drought exposure is represented in freshwater ecosystem indicators (e.g. hydrological, water quality, biological, or habitat-related variables), and identified the drought attributes used to define severity levels. We did not set out to identify which method is used to establish the thresholds in the freshwater ecosystem indicators reviewed, as we had to compromise on the detail to which each element of the drought management process was analysed. Moreover, information regarding the method used to establish the indicator threshold in the majority of the reviewed drought instruments was found not to be sufficient to do so.

2.2.2. Drought impacts and risk

From a drought management perspective, drought impacts are often seen as negative consequences derived from the lack of water (Bachmair *et al* 2016). However, from an ecological risk assessment perspective, it is important to distinguish between drought effects on abiotic systems (e.g. water availability deficits) and impacts, which are understood as changes in biotic ecosystem components (Norton *et al* 1992, Crausbay *et al* 2020). Impacts on ecosystems can occur during drought events, or persist after the end of the episode, thus leaving drought

Table 1. Analytical framework applied in the study to examine the three pillars of drought management and associated elements (Hayes *et al* 2004, UNDRR 2021, Wilhite *et al* 1999) from the perspective of ecological drought (Crausbay *et al* 2017, 2020, Sadiqi *et al* 2022) and ecological risk assessment (Norton *et al* 1992, EEA, E 1999). (Source: own elaboration based on the indicated literature).

Pillar of drought management	Element	Questions included in the protocol
I. Drought characterisation	Drought and drought risk definitions. Drought types	— Does the definition of drought or drought risk provided in the drought instrument refer to impacts on ecosystems[a]? — Is the socio-ecological perspective considered in the definition of drought or drought risk? — Does the drought instrument consider the ecological drought as a drought type?
	Drought indicators and associated severity levels	— Does the drought instrument include ecological drought indicators related to freshwater ecosystems? — What variables are used to represent drought risk to freshwater ecosystems in the indicators? — On which drought attributes are the different severity levels of the drought indicators based?
II. Drought impacts and risk	Impacts	- Does the drought instrument include impacts on freshwater ecosystems? - What drought impacts on freshwater ecosystems are considered? Classification based on ecosystem component and impact type. - What level of detail is provided in the reporting of drought impacts on freshwater ecosystems? (i.e. variable, location and time)
	Exposure and vulnerability	- Does the drought instrument include references to the exposure or vulnerability of freshwater ecosystems to ecological drought? - Is there a water balance analysis and are environmental flows considered? - What other stressors or anthropogenic pressures are considered to characterise the ecological exposure? - What species or ecosystems are considered vulnerable to drought or under special protection? - Is the degradation or ecological status of freshwater ecosystems considered to characterise the ecological vulnerability?
III. Drought planning	Principles and objectives	- Does the purpose of the drought instrument include a reference to ecosystems[a]?
	Strategies and measures	- Does the drought instrument include measures directly related to freshwater ecosystems (at least one)? - Classification based on freshwater ecosystem component and measure category.

Note: [a]This question looks at consideration of ecosystems in general, rather than freshwater ecosystems, because the element to which the question refers is too general to assume that freshwater ecosystems should specifically be mentioned.

legacies (Müller and Bahn 2022). For the purpose of this analysis, the negative effects on either abiotic or biotic ecosystem components are considered as drought impacts, and are classified according to biotic components (fauna or flora), and abiotic components (water quantity, quality and other abiotic components). We compiled information on whether actual impacts are reported for past drought events or only as potential impacts of drought, and whether impact variable, location and time were reported.

The assessment of drought risk should be the foundation of drought management (UNDRR 2021). Hence, for the management of ecological drought, the ecological risk perspective should be integrated in each component of drought risk (i.e. hazard, exposure and vulnerability). In ecology, drought hazard, which commonly refers to the possible occurrence of natural deficits of water availability that may impact exposed and vulnerable systems (Wilhite *et al* 1999, Field *et al* 2012), is defined as a natural, abiotic disturbance shaping the components and functions of ecosystems (Humphries and Baldwin 2003).

Exposure relates to the presence of (eco)systems in areas that could be adversely affected by hazard (Field *et al* 2012). From the ecological risk assessment perspective, ecological exposure is determined by stressors (Norton *et al* 1992), which are 'any abiotic or biotic variable of natural or anthropogenic origin that exceeds its range of normal variation and adversely affects individual physiology or population performance in a statistically significant way' (Vinebrooke *et al* 2004, p 451). During drought, these stressors are caused by both anthropogenic pressures on the ecosystem and drought-induced hydro-climatological conditions (Bond *et al* 2008, Lake 2011, Raheem *et al* 2019). Vörösmarty *et al* (2010) categorised stressors of freshwater biodiversity as those induced by catchment disturbance, pollution, water resource development and biotic factors. In the particular case of droughts, the most evident and often recognised stressors are those related to water availability deficits as a consequence of drought itself or due to socio-economic water uses (Van Loon *et al* 2016, 2022, Crausbay *et al* 2017, Di Baldassarre *et al* 2018, Garrick *et al* 2018, Sadiqi *et al* 2022, Alamos *et al* 2023), although other important stressors may occur, including water quality degradation (Mosley 2015, Van Vliet *et al* 2021). As such, the protocol includes specific questions to examine whether environmental flows are considered as a water use potentially affected by drought, as well as what other stressors or anthropogenic pressures are considered.

Vulnerability, which reflects 'the predisposition to be adversely affected' (Field *et al* 2012, p 564), often relates to the level of susceptibility and coping capacity, and involves the understanding of the underlying causes or drivers of such vulnerability (UNDRR 2021). Ecological vulnerability has diverse definitions and conceptualisations (Gallopín 2006, De Lange *et al* 2010). While recent literature that considers ecological drought defines ecological vulnerability as a combination of exposure, sensitivity and adaptive capacity (e.g. Kovach *et al* 2019, Sadiqi *et al* 2022); in the fields of ecology and biological conservation, it is considered as a function of resistance and resilience (Bogan *et al* 2015, Selwood *et al* 2019). Regardless of the variety of definitions, ecosystem vulnerability depends on physiological and behavioural traits intrinsic to species (e.g. Céréghino *et al* 2020). In addition, there is agreement on the fact that degraded ecosystems are more vulnerable to drought, as they have partially or entirely lost their natural capacity to resist and recover from drought (e.g. Bond *et al* 2008, Müller and Bahn 2022). Thus, the protocol includes questions on what species or ecosystems are identified as vulnerable to drought, as well as whether drought instruments consider the degradation or ecological status of freshwater ecosystems when assessing their vulnerability.

2.2.3. Drought planning

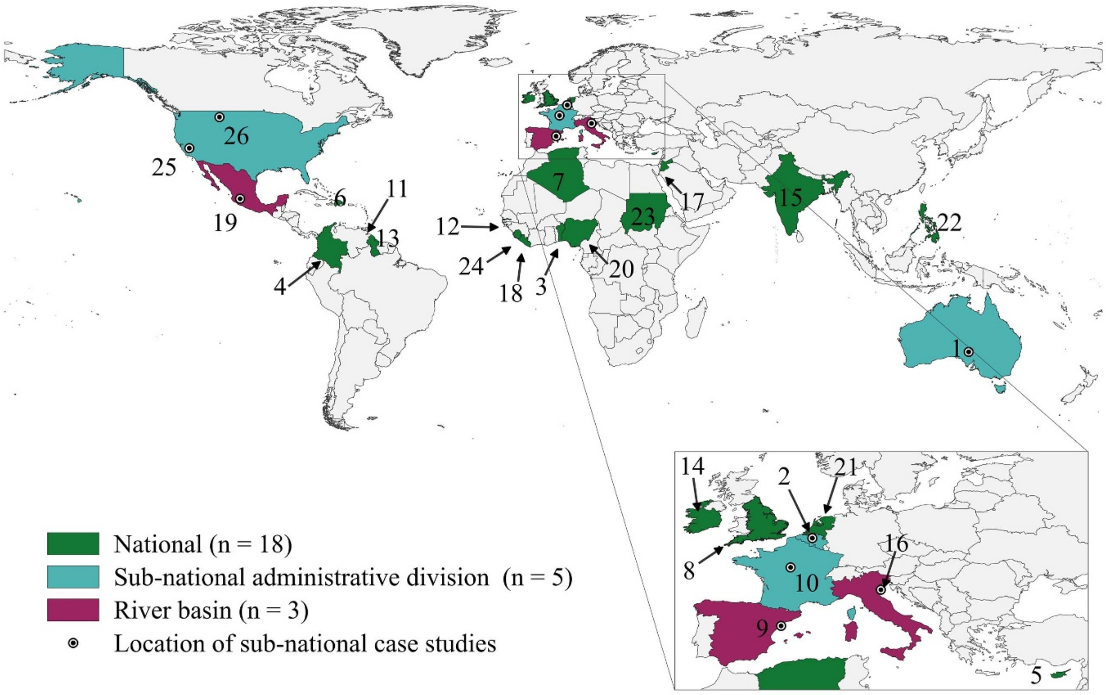
The stated objective of drought instruments is usually to guide the approach of the management strategy and specific interventions for its implementation. Accordingly, the protocol queries whether the purpose of the drought instrument includes the mitigation of impacts on freshwater ecosystems. Moreover, it investigates whether drought management measures consider freshwater ecosystems by examining if there is at least one targeted drought measure or strategy. The identified measures are then classified according to the biotic or abiotic ecosystem component they act on, as well as according to the following measure categories: educational and awareness-raising; infrastructural; knowledge development; monitoring; planning and organisational; regulatory and operational; and surveillance (see S2 for the description of each measure category).

3. Results

After a brief description of the selected case studies, this section presents the extent and the manner in which freshwater ecosystems are considered in the drought instruments reviewed according to the three pillars of drought management and their corresponding elements.

3.1. Description of selected case studies and associated drought instruments

The scoping review yielded 26 eligible case studies in 25 countries. These are predominantly located in Africa ($n = 7$), America ($n = 7$) and Europe ($n = 8$), with fewer cases found in Asia ($n = 3$) and Oceania ($n = 1$) (figure 2). The majority of the case studies were identified through the IDMP database ($n = 18$) or the EDORA project ($n = 7$) (S1). The peer-reviewed literature search in Scopus yielded 64 articles, which led to the identification of three eligible case studies, though these had also been identified through the specialised sources (S1). Expert knowledge added two eligible case studies additional to those identified by other sources (S1).



1. South Australia, Murray-Darling River Basin, Australia
2. Flanders, Belgium
3. Benin
4. Colombia
5. Cyprus
6. Dominican Republic
7. Algeria
8. England
9. Ebro River Basin, Spain
10. Sarthe, Loire-Brittany River Basin, France
11. Grenada
12. Gambia
13. Guyana
14. Ireland
15. India
16. Po River Basin, Italy
17. Jordan
18. Liberia
19. Santiago Watershed, Lerma Santiago Pacific River Basin, Mexico
20. Nigeria
21. The Netherlands
22. Philippines
23. Sudan
24. Sierra Leone
25. California, USA
26. Montana, USA

Figure 2. Geographical distribution of the case studies and the administrative level at which the consideration of freshwater ecosystems in drought instruments is analysed. n = number of case studies.

Figure 2 illustrates the geographical distribution of the case studies and the administrative level considered in the review. Each case study is informed by one or more documents, with drought management plans ($n = 24$) and water resources plans ($n = 6$) being the two most common document types. The majority of the documents reviewed were published after 2016. For an overview of the PRISMA review process, and a complete list of the documents used in each case study, please refer to S1.

3.2. Consideration of freshwater ecosystems in drought characterisation

3.2.1. Drought definition and drought types

Drought impacts on freshwater ecosystems are included in the definitions of drought and drought risk in 17 of the 26 drought instruments evaluated (figure 3). Among these 17, the socio-ecological perspective is included in only five (S3). Therefore, when freshwater ecosystems are mentioned in drought definitions, they are typically considered only in relation to impacts due to stressors induced by drought hazard, without recognising that these impacts may be exacerbated by human activities, and, in turn, negatively affect the contribution nature has to people.

Meteorological drought (n = 21), agricultural drought (n = 21), hydrological drought (n = 19), socio-economic drought ($n = 16$) and water shortage (n = 15) are the types of drought most frequently mentioned (S3), while ecological drought is identified in only five instruments (figure 3). The definition of ecological drought in three of these instruments refers to the effects or stresses caused by a decline in water availability on ecosystems, as defined by Tallaksen and Lanen (2004). In contrast, only two instruments incorporate the most recent definition, which includes the socio-ecological perspective (Crausbay *et al* 2017).

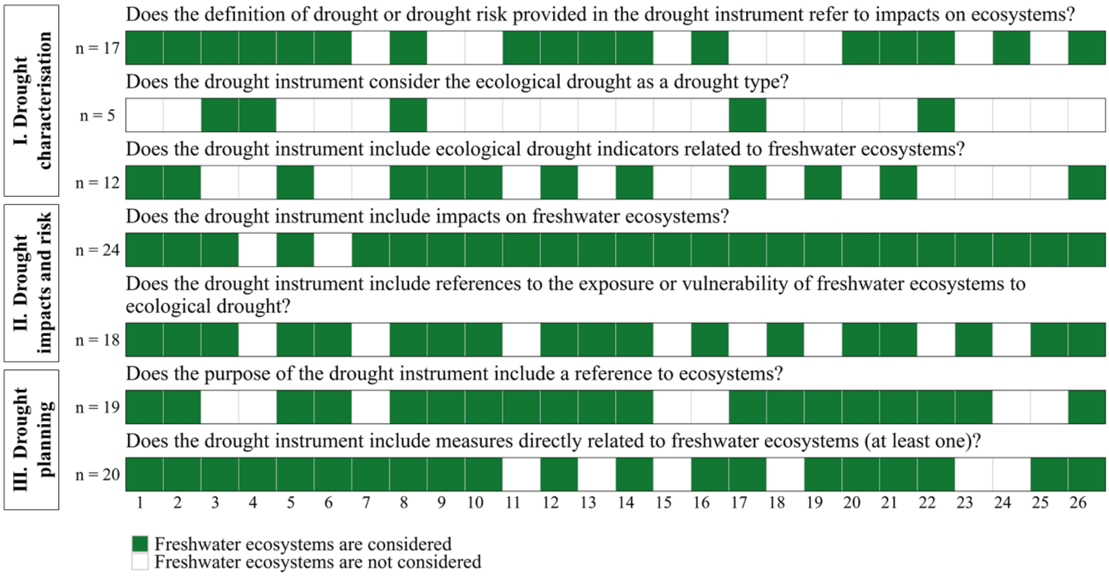


Figure 3. Overall assessment of freshwater ecosystems consideration in the drought instruments reviewed. Numbers on the x-axis correspond to the case study numbers. n = number of drought instruments.

3.2.2. Drought indicators

Approximately half ($n = 12$) of the drought instruments clearly define the link between drought indicators and freshwater ecosystems (figure 3), either through an explicit reference to freshwater ecosystems in the indicator description or because the indicators are used to trigger measures related to freshwater ecosystems. Variables used to represent drought risk in indicators for freshwater ecosystems predominantly focus on surface water ($n = 10$) (e.g. streamflow and water volume). Groundwater, water quality and biological variables are included in only one or two instruments (S3). Drought severity levels in these indicators are typically determined by different magnitude thresholds of a variable over fixed timescales (e.g. cumulative streamflow over several months) or at a specific time (e.g. water level at the start of the hydrological year) (S3). This means that the severity level indicated is not sensitive to the duration, timing or frequency of the drought event, but rather only to changes in the magnitude of drought.

3.3. Consideration of freshwater ecosystems in drought impacts and risk

3.3.1. Drought impacts

The majority of the drought instruments reviewed ($n = 24$) (figure 3) acknowledge the potential impacts of drought on freshwater ecosystems, with approximately half ($n = 11$) detailing specific impacts monitored during past drought events (S3). However, in most cases, the description of these impacts lacks detail regarding their magnitude, location and timing. Nearly all instruments report impacts related to water quantity ($n = 22$) and quality ($n = 21$), while impacts on biotic components are less frequently included (figure 4). Impacts on water quantity are mentioned for both surface and groundwater almost equally, whereas impacts on water quality are more commonly described for surface water ($n = 12$) than for groundwater ($n = 3$) (figure 4). The majority of impacts on freshwater fauna relate to fish communities.

3.3.2. Drought exposure and vulnerability

References to the ecological exposure and vulnerability of freshwater ecosystems to drought were found in 18 drought instruments (figure 3). Exposure is primarily addressed through the consideration of environmental flows ($n = 13$), which are presented either as quantitative estimates ($n = 6$) or as qualitative references ($n = 7$). A small number of instruments ($n = 7$) also mention the exacerbating effects of drought on ecosystems due to human activities (S3).

The vulnerability of freshwater ecosystems to ecological drought is featured diversely, often targeting specific locations: ecosystems within national and or international protected sites ($n = 7$) (e.g. EU Natura2000 sites or wetlands under the Ramsar Convention); wetlands ($n = 4$); degraded freshwater ecosystems ($n = 3$); freshwater refuges ($n = 2$), i.e. locations that foster population resistance and resilience to drought (Selwood *et al* 2019); specific endangered species; pristine freshwater ecosystems ($n = 2$); streams prone to falling dry ($n = 1$) (S3).

The majority of the 18 drought instruments do not describe the ecological exposure and vulnerability of freshwater ecosystems to drought in a systematic way or based on a conceptual or analytical framework. This means that references to exposure and vulnerability are mostly dispersed throughout different sections of the drought instruments, without a clear

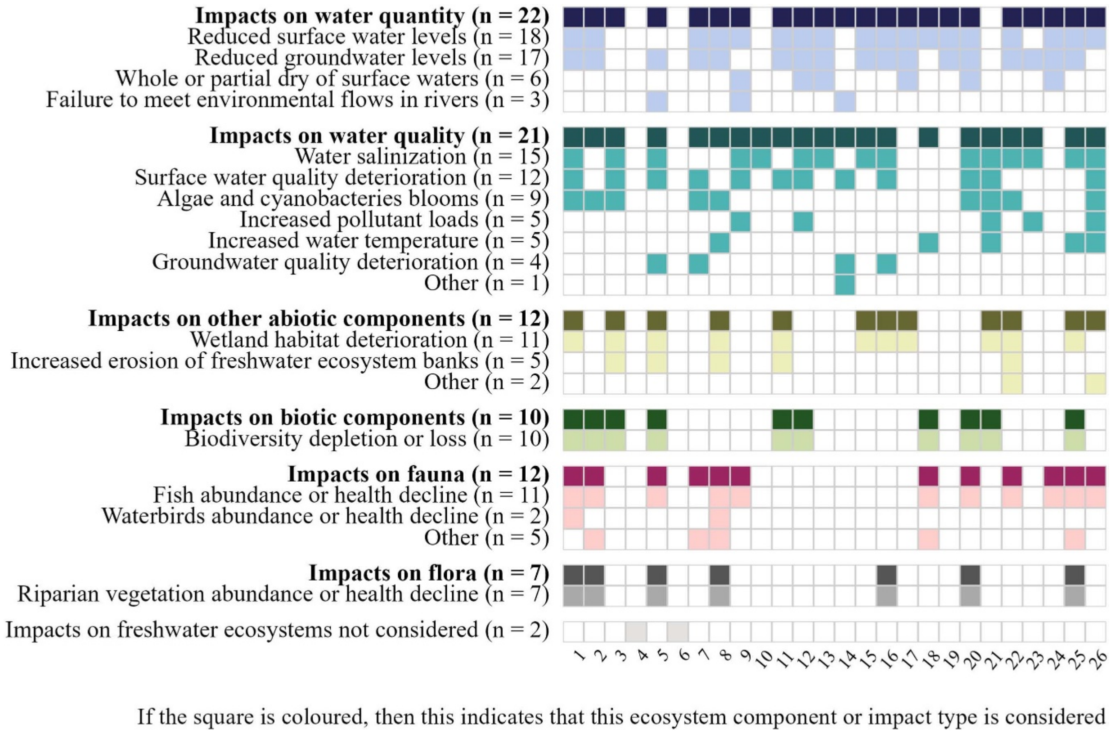


Figure 4. Consideration of drought impacts on freshwater ecosystems in the drought instruments reviewed classified by ecosystem component and impact type. Numbers on the x-axis correspond to the case study numbers. n = number of drought instruments.

distinction between the two concepts, and with little information about their spatial and temporal distribution at different levels of drought hazard.

3.4. Consideration of freshwater ecosystems in the instrument purpose and drought measures

A number of drought instruments ($n = 19$) include the mitigation of the impacts of drought on ecosystems in their stated purpose (figure 3). Most drought instruments ($n = 20$) include at least one measure related to freshwater ecosystems (figure 3). Drought measures aimed at addressing water quantity in freshwater ecosystems are the most common ($n = 16$), while those targeting flora are mentioned the least ($n = 4$) (figure 5(a)). By measure category, the most common measures are regulatory and operational ($n = 13$), and planning and organisational ($n = 11$), while the least common category ($n = 4$) is infrastructural (figure 5(b)).

Table 2 provides an overview of the types of measures identified in the drought instruments, ordered by measure category. The most common measure is the implementation or modification of environmental flow regimes during drought ($n = 11$, table 3), with the reduction of flows being the prevailing approach ($n = 7$, table 3). Often, the reduction of environmental flows is proposed with certain exceptions. For instance, in Cyprus and in Flanders (Belgium), the drought instrument specifies that environmental flow can be reduced up to the point that no irreversible damage to ecosystems in surface water bodies occurs. Similarly, peatlands in the Netherlands and protected areas in the Ebro River Basin (Spain), the Po River Basin (Italy) and the Santiago Watershed (Mexico) are exempt from reductions in environmental flows. Two drought instruments (table 3) propose to fully safeguard minimum environmental flow regimes, even during drought conditions. Only one drought instrument, that of South Australia (Australia), incorporates a more holistic approach by modifying other flow magnitude components besides the minimum flow (e.g. peak flows) and temporal attributes, as well as considering environmental flows in other parts of the freshwater ecosystem besides instream (e.g. in floodplains). Finally, four other drought instruments (table 3) define specific operations during drought, such as sporadic or scheduled freshwater releases in South Australia (Australia), Ireland, and The Netherlands for water quality purposes, as well as changes to hydropower operations in the Loire-Brittany River Basin (France) and hydraulic infrastructure in Flanders (Belgium). Safeguarding or modifying environmental flows during drought may be implemented either by controlling water levels or streamflow through hydraulic infrastructure (e.g. reservoirs, channels and gates) ($n = 10$, table 2), or by restricting surface and groundwater abstractions and diversions ($n = 9$, table 2).

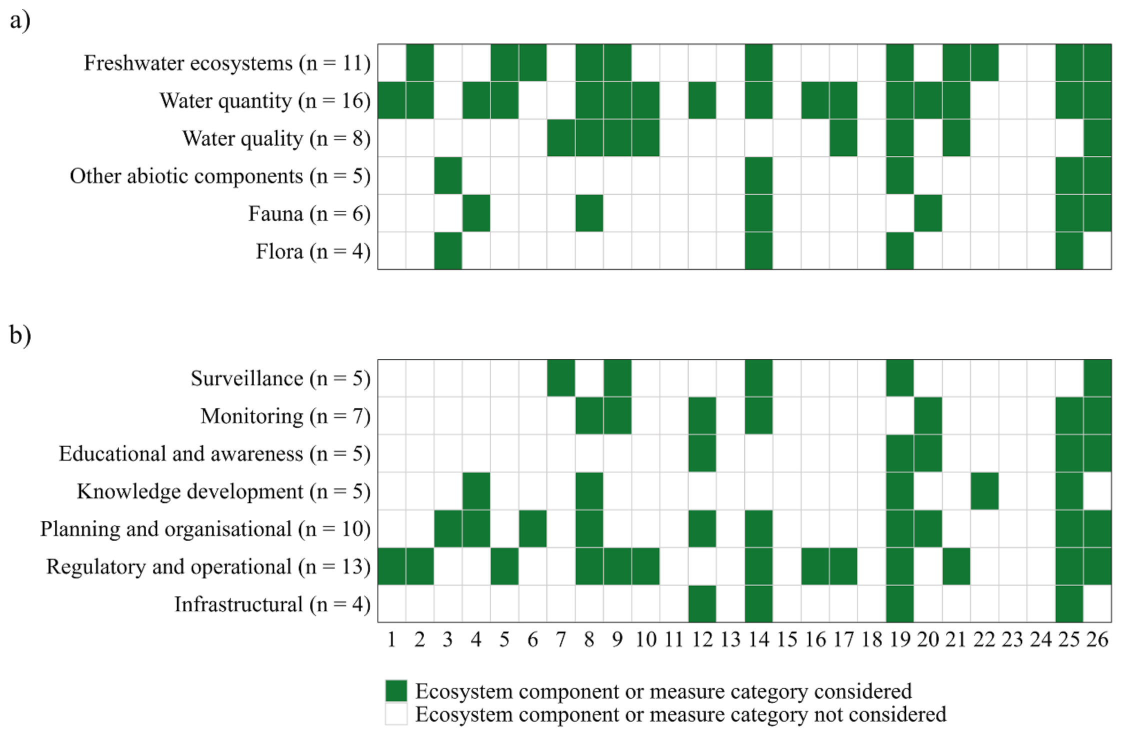


Figure 5. Consideration of drought measures related to freshwater ecosystems in the drought instruments reviewed classified by (a) addressed ecosystem component and (b) measure category. Numbers on the x-axis correspond to the case study numbers. $n =$ number of drought instruments.

Permits and ecological impact assessment requirements specific to drought are included in four drought instruments (table 2). For instance, in England, water supply companies are required to provide an environmental assessment report to determine environmental sensitivity and potential impacts when, due to drought, they need to abstract more water, use alternative water sources or temporarily employ water transfers. Ecological or water quality standards for freshwater ecosystems can be either tightened ($n = 4$) or relaxed ($n = 3$) during drought (table 2). Other specific measures that are mentioned, though to a lesser extent, include but are not limited to: fish rescues, economic penalties, trading of water rights and fishing and navigation restrictions (table 2).

Monitoring ($n = 7$) and surveillance activities ($n = 5$) for the protection of freshwater ecosystems during drought are often focused on specific locations, such as upstream of specific rivers and aquifers (e.g. Ebro River Basin, Spain and Nigeria), stressed freshwater ecosystems (e.g. England and Ireland), sites receiving effluents from wastewater treatment plants (e.g. Ebro River Basin, Spain and Montana, US), or water diversions (e.g. Montana, US). Post-drought impact monitoring, a key measure to control how freshwater ecosystems recover from drought (Stubbington *et al* 2024), was found in only three drought instruments (England, Gambia and Ireland).

Several measure categories also include types of measures related to ordinary management, not necessarily enacted only during drought events (table 2). For example, the drafting of plans, technical rules, and standards for the management of freshwater ecosystems were found in seven drought instruments. Similarly, the development or upgrading of infrastructure to increase the environmental protection of freshwater ecosystems, including sanitation infrastructure, wastewater treatment plants and mechanisms for environmental flows, is foreseen in four drought instruments. Finally, measures related to knowledge development, such as studies to strengthen water resource management and environmental planning, and strategies promoting data availability, accessibility and transparency, were found in three and two drought instruments, respectively.

4. Discussion

In the context of the ongoing freshwater biodiversity crisis, this review investigates to what extent and how drought instruments care for freshwater ecosystems in 26 case studies. The analysis reveals that two-thirds of the instruments reviewed consider freshwater ecosystems in most of the elements of the three pillars of drought management. Nevertheless, several shortcomings emerge. This section summarises these shortcomings into four major scientific and technical

Table 2. Types of drought measures related to freshwater ecosystems organised by measure category. n = number of drought instruments that consider the type of drought measure.

Measure type	n
Educational and awareness	
Public outreach (e.g. announcements in public service media)	4
Outreach to specific users (e.g. sending emails to water users and distributing educational material to water user associations)	2
Technical assistance to specific users (e.g. farmers for water conservation and water quality improvement)	2
Infrastructural	
Build, adapt or remove infrastructure for environmental purposes (e.g. upgrading or building wastewater treatment plants and fish barriers and dam removal)	4
Knowledge development	
Development of studies (e.g. ecological drought risk assessments and optimum habitat of specific species)	3
Data availability, accessibility and transparency (e.g. making available data about the ecological state of freshwater ecosystem to support ecological risk assessments)	2
Monitoring	
E.g. regular or additional monitoring activities; post-drought monitoring and expansion of stream-gauge networks during drought	7
Surveillance	
E.g. surveillance of wastewater effluent quality and inspections in farms to control that diversion mechanism are not harmful for fishes	5
Planning and organisational	
Creation and update of plans, technical rules, and standards to protect and regulate freshwater ecosystems (e.g. plans for delimiting protection zones)	7
Impact assessment and reporting (e.g. freshwater ecosystem impact assessment and reporting and assessment of drought measures effectivity)	3
Stakeholder coordination and engagement (e.g. engagement of environment agencies in drought decision making process)	3
Regulatory and operational	
Implementation or modification of environmental flows (e.g. minimising and safeguarding minimum environmental flows)	10
Reduction or restriction of surface and groundwater abstractions and diversions to protect freshwater ecosystem	9
Tightening of wastewater effluent quality and quantity standards	4
Requirement of permits or ecological impact assessments in freshwater ecosystems to undertake specific activities such as engineering works in water bodies	4
Exemption from ecological or water quality standards	3
Navigation restrictions to protect freshwater ecosystems	3
Economic penalisation (e.g. polluter pays principle and additional abstraction fee from degraded freshwater ecosystems)	2
Water and water rights trade, exchange and lease to protect freshwater ecosystems	2
Response to fish incidents (e.g. fish rescues)	2
Freshwater ecosystem restoration	2
Other measures (e.g. fishing restrictions; proof of wastewater treatment tax payment; making funding available for environmental protection purposes during drought; response to water pollution incidents; conservation facilities for fishes; control of exotic species)	1

Table 3. Environmental flow strategies implemented during drought in the drought instruments reviewed.

Environmental flow strategy during drought	Case study number(s)
Safeguarding minimum environmental flow regimes	8 and 26
Decreasing minimum environmental flow regimes with certain exceptions (e.g. except in protected zones and wetlands)	2, 5, 10, 19, 21, 9 and 16
Considering other flow magnitude components and temporal attributes besides minimum flow components (e.g. peak flow components)	1
Other specific operations (e.g. minimising hydropeaking and water quality issues)	1, 2, 10, 14 and 21

gaps and discusses these to provide insights that can inform policy and decision-making. The section then concludes with a reflection on whether drought management cares for freshwater ecosystems, based on our findings and beyond. Before doing so, a few considerations regarding our methodological approach are worth noting.

Our review process followed a systematic approach, but we acknowledge that two of the sources utilised have limitations in terms of replicability. The IDMP website is an authoritative inventory of countries with drought instruments, but searches in it are not entirely replicable as the webpage undergoes regular updates without tracked changes. Furthermore, expert knowledge is not a systematic or replicable source (Yoshida *et al* 2024), and thus was only utilised as a complementary source, a common practice in grey literature reviews (Godin *et al* 2015, Yoshida *et al* 2024).

Another methodological limitation relates to the peer-reviewed literature search, which yielded no additional country beyond those already found in the IDMP website and EDORA project report. Expanding the search to include abstracts and key words, or to other languages or additional sources, such as programmable search engines (Yoshida *et al* 2024) may have uncovered more relevant cases. However, as it is often the case in scoping reviews (Grant and Booth 2009), our review aimed at being representative, not exhaustive. We believe that the 26 case studies provide a balanced global view of drought management efforts at various management levels, with identified gaps offering insight into the current discussions on ecological drought management.

Finally, we acknowledge that, for each case study, we may not capture all dimensions of how drought events are managed in practice or from all the perspectives. For instance, Australia has water market instruments for environmental water exchange that are also applicable during drought conditions (Mount *et al* 2016). However, these were not identified using the methodology established in this study. This may be because they are not mentioned in the key documents we focused on, namely, drought management plans, and river basin management plans and environmental flow plans that contain specific information about drought. In this context, it is important to recognise that water management policy instruments often do not distinguish between average and drought conditions, making information relevant to drought management difficult to capture (López-Barrero and Iglesias 2009). This presents a significant challenge when investigating drought management.

4.1. The socio-ecological dimension of ecological drought

Despite human–nature interactions being recognised as an essential 'leverage point for achieving sustainability' (Bennett and Reyers 2024, p 402, Dunham *et al* 2018, Sarremejane *et al* 2024), we found that a socio-ecological perspective is often lacking in drought definitions and in the ecological exposure and vulnerability assessments of freshwater ecosystems to drought. This is somewhat surprising, considering that most of the drought instruments reviewed were published after the late 2010s, when the ecological and socio-ecological dimension of drought was already well established in the scholarly literature (e.g. AghaKouchak *et al* 2015, Crausbay *et al* 2017, van Loon *et al* 2016).

The definitions of drought in policy and management instruments provide insights into the overall approach to drought management (Wilhite and Glantz 1985, UNDRR 2021), and influence the application of relevant legislation (López-Barrero and Iglesias 2009). Thus, incorporating an ecological drought type and its socio-ecological dimension into drought definitions is a crucial first step to foster reflection on the nature–human interactions during drought. In this context, we propose expanding the current definition of ecological drought (Crausbay *et al* 2017) to encompass, besides instrumental values (i.e. ecosystem services), intrinsic and relational values.

To turn definitions into effective measures, it is also critical to incorporate the socio-ecological interactions into ecological exposure and vulnerability assessments. This would enable a more precise evaluation of how human actions mediate ecological risk on freshwater ecosystems during droughts, and most importantly, the drivers of this risk (Dunham *et al* 2018). Whilst human pressures are significant contributors to ecological drought risk (Sarremejane *et al*

2024), our findings suggest that sites receiving the most protection during drought (i.e. protected areas) are often those isolated from human actions. Yet, we argue that ecosystems in protected areas are not necessarily the most vulnerable when drought occurs, nor are all drought-vulnerable ecosystems located in protected areas. A recent study found that only 21% of groundwater-dependent ecosystems, which provide key refuges during drought, are located within protected lands or in regions with sustainable management practices (Rohde *et al* 2024a). At the same time, certain drought instruments do include measures aimed at reducing human-induced stressors, such as navigation restrictions. While this is better than no action, such measures should not merely replicate the same protection logic applied under average conditions. During droughts, stressors can exhibit varied environmental change patterns as a result of specific ecological conditions, such as nitrate levels in water, which can increase or decrease depending on whether climates are dry or wet (Van Vliet *et al* 2021), thereby causing different ecosystem responses. In this context, further research is needed to understand how stressor patterns vary across different climatic regions, ecosystems and anthropogenic pressures, and how freshwater ecosystems respond to those stressors.

4.2. Drought monitoring and management beyond surface water quantity

Our review reveals that the consideration of freshwater ecosystems in drought indicators, risk exposure assessments, and drought measures primarily focus on surface water quantity. This contrasts with the results found for drought impacts, which equally recognised water quantity and quality. Impacts on biotic components (fauna and flora) are in contrast mentioned much less frequently. The focus on surface water quantity in drought instruments is likely due to the comparative ease of collecting hydrological data (Dale and Beyeler 2001, Park *et al* 2020), as well as the key role streamflow has in freshwater ecology (Poff *et al* 1997, Poff and Zimmerman 2010). However, the disregard of other abiotic or biotic variables may hinder the protection of freshwater ecosystems during droughts. These variables, including groundwater levels (Davis *et al* 2013, Kaule and Gilfedder 2021, Meyers *et al* 2021, Yin *et al* 2022, Rohde *et al* 2024a), water quality (e.g. Caruso 2001, Kim *et al* 2019, Zhang *et al* 2024) and habitat and geomorphology (Lynch *et al* 2018), have a critical role in the health of freshwater ecosystems during and after drought. Furthermore, drought-induced water deficits may not necessarily be the most significant stressor to freshwater ecosystems, particularly in the presence of human-driven stressors, when interactions between multiple, concurring stressors are likely to occur (Pistocchi *et al* 2017, Fournier and Magoulick 2022).

Diagnosing the most significant stressor in an ecosystem and the interactions across multiple stressors remains challenging and is subject to significant scientific uncertainty (Palmer *et al* 2010, Brown *et al* 2013, Côté *et al* 2016, Reid *et al* 2019), including under drought circumstances (Fournier and Magoulick 2022). In this regard, it is recommended to adopt protection strategies that combine indicators and measures that monitor and address multiple stressors. Figure 5 and table 3 suggest that drought measures addressing stressors related to water quantity as well as quality and other components are rare. Moreover, at times the measures included are meant to relax ordinary ecosystem protection mechanisms (e.g. exemptions from ecological or water quality standards), rather than reinforce them. Currently, drought indicators for freshwater ecosystems that use key abiotic variables such as water quality (e.g. Kim *et al* 2019) and biotic variables such as fish habitat factors (e.g. Park *et al* 2020) do exist, but further efforts are required for their operationalisation. Their implementation to specific regions is often constrained by data scarcity, limited resources and high monitoring costs. Further research on new technologies such as satellite data and others could help address some of these challenges (e.g. Kovach *et al* 2019, Rohde *et al* 2024b).

Another critical challenge relates to the spatial distribution of these variables. Kovach *et al* (2019) point out that even hydrological monitoring lacks the spatial coverage necessary to assess ecological drought exposure and vulnerability in freshwater ecosystems comprehensively, as monitoring stations are typically located in human-relevant main rivers and reservoirs. Our results partially align with theirs. While we did not specifically code the locations of the monitoring gauges for the drought indicators reviewed, we did observe that in some case studies (e.g. no. 10), drought monitoring stations are located in main rivers. In others (e.g. nos. 5, 9, 26), stations are also situated in headwaters, smaller rivers, and even in streams prone to falling dry. This suggests that some regions adopt monitoring practices that are more aligned with ecological needs during droughts. However, beyond monitoring, our results also indicate a certain spatial mismatch between current drought measures and ecological requirements. A common pattern observed is that while drought instruments often restrict the reduction of minimum environmental flows in vulnerable areas such as wetlands and refuges, these still allow such reductions in the rest of the river network. Minimum environmental flows, and their reduction, result in suboptimal biophysical conditions for freshwater biota (Stalnaker *et al* 1995), potentially leading to loss of river connectivity or to river stretches with highly degraded water quality. This may hinder freshwater species from accessing refuges, a fundamental need of freshwater biota to resist and recover from disturbances such as drought (Poff 2018).

4.3. The temporal dimension of ecological drought risk

Our analysis reveals a limited representation of the temporal attributes of drought hazard, namely duration, frequency and timing, in relation to freshwater ecology (Richter *et al* 1997, Zargar *et al* 2011). Time-insensitive indicators have limited ability to represent drought risk conditions accurately, and risk to be anthropocentric in their design. For example, we observed that some drought instruments, such as those in the Netherlands and Jordan, incorporate drought indicators that are actively monitored and operational only during the seasons when the greatest risks for agriculture and water supply are expected, with little or reduced monitoring in other seasons, regardless of the impact drought may have on freshwater ecosystems during those seasons.

The duration (Bogan *et al* 2015, Zhang *et al* 2024), timing (e.g. Lear *et al* 2021) and frequency of drought, as well as the alternation of droughts and floods (Van Loon *et al* 2024), significantly influence the degree of impacts on freshwater ecosystems. In this regard, we found that measures related to freshwater ecosystems are often static since the onset of the drought, and ignore these important aspects. For example, we found that only the drought instrument in South Australia describes an environmental flow regime during drought that integrates a specific temporal dynamism by accounting for peak flows and the ecological timings relevant to freshwater biota. The widespread disregard of the temporal dimension of drought highlights a human-centred approach that overlooks the ecological understanding of drought severity. In this context, a key scientific and operational challenge is the design of drought indicators and measures that are dynamic in time.

4.4. Methodological approaches for ecological risk assessments

Results suggest that the risk exposure and vulnerability of freshwater ecosystems are poorly represented. While some common criteria were identified across the drought instruments reviewed, comprehensive methodologies to assess these constituent components of risk are barely utilised. One potential reason for this is that existing frameworks for assessing ecological drought vulnerability (Kim *et al* 2019, Kovach *et al* 2019, Raheem *et al* 2019, Crausbay *et al* 2020, Sadiqi *et al* 2022) are largely conceptual, making them difficult for practitioners to apply. Quantitative methodologies do exist to help elucidate aspects such as the identification of refuges (Yu *et al* 2022), vulnerability thresholds for groundwater management (Rohde *et al* 2024b), and ecological risk induced by drought effects on water quality (Kim *et al* 2019), but these deserve substantially more attention, as highlighted by Kim *et al* (2019). Therefore, there is a need to advance conceptual frameworks towards (semi)quantitative methodologies that can facilitate planners and decision-makers to assess ecological risk in freshwater ecosystems during drought. These methodologies should clearly characterise the relative contributions of ecological exposure and vulnerability to that risk, along with their spatial and temporal dimensions.

To address these gaps, current ecological risk assessment frameworks, such as the Ecological Risk Assessment (Norton *et al* 1992), the Driver-Pressure-State-Impact-Response (European Environment Agency 1999) and variations (e.g. Perujo *et al* 2021), can be adapted and integrated into drought management. Moreover, risk assessments should consider ecosystem-relevant information resulting from ordinary water management. According to our results, this is rarely the case. For instance, the ecological status of water bodies, assessed in EU Member States to inform the design of management measures on surface water bodies, was utilised to assess vulnerability of freshwater ecosystems to drought only in the drought instrument of Cyprus.

4.5. Does drought management care for nature?

Based on our analysis, we conclude that drought instruments provide limited care for nature conservation. This does not appear to stem from a lack of scientific or technical knowledge on ecological drought, as evidenced by the literature supporting the previous sections. Instead, it appears that drought instruments are influenced by the growing environmental trends in overarching policies (e.g. the EU Water Framework Directive), which are typically focused on water resources or agriculture (López-Barrero and Iglesias 2009). While this may have prompted attention to ecosystems in drought instruments, ecosystems are often integrated using the same strategies that are applied under average climatic conditions, and with a human-centred focus. Addressing the gaps identified in this study could lead to drought management strategies that are better aligned with long-term environmental objectives, such as restoring and conserving ecosystem health and resilience to drought (e.g. Bond *et al* 2008, Lake 2011).

While addressing the scientific and technical gaps identified in this study is a crucial step toward a better management of freshwater ecosystems during drought, a transition towards drought strategies that better care for nature can be challenging, particularly due to social perceptions of ecological drought and governance systems. The alignment of the expectations of water users with ecological requirements can give rise to contention and the potential for conflict (Kennen *et al* 2018, Wineland *et al* 2022, Dourado *et al* 2023, Suleymanov 2024), as well as a lack of proportionality in the distribution of impacts across social groups (e.g. Simpson *et al* 2023). In this sense, it is important to note that care for freshwater ecosystems during drought does not imply that the needs of nature take precedence over those of humans. Rather, we advocate for a shift in the purpose of drought instruments from preventing impacts in human and ecological systems to re-distributing these impacts equitably between both. In this regard, fostering multi and transdisciplinary collaboration and engagement between different stakeholders, including experts (e.g. ecologists and social scientists), water users and other social groups that lack formal governance authority to participate in decision-making processes may be required and beneficial (e.g. Reed *et al* 2018, Perrone *et al* 2023). Co-development of drought impact assessments (De Angeli *et al* 2024) and nature valuation frameworks (Berghoefer *et al* 2022) could help achieving consensus, exploring trade-offs and prioritising the allocation of limited resources for freshwater ecosystem monitoring and protection. Some frameworks have recently been created to include stakeholder valuation of nature through ecosystem services (Raheem *et al* 2019), but plural valuation frameworks that account for intrinsic and relational values (Himes *et al* 2024) should also be developed, thereby acknowledging and promoting other forms of care for nature.

5. Conclusions

The present study reviews to what extent drought instruments in 26 case studies worldwide care for freshwater ecosystems across the three pillars of drought risk management. Our results show that drought instruments frequently do incorporate freshwater ecosystems in their stated purpose, as well as in the description of drought impacts and in the planned or implemented measures. However, we find that freshwater ecosystems are rarely considered in other critical elements of the drought management process, including in the definition of drought and the types of drought, in drought indicators, and in the assessment of exposure and vulnerability.

Even when freshwater ecosystems are included in the instruments reviewed, significant shortcomings emerge regarding how they are considered. We synthesise our findings into four major gaps. First, the socio-ecological perspective of ecological drought, which highlights the compounding human influence on drought impacts on freshwater ecosystems, is often lacking in drought definitions and in how exposure and vulnerability are conceptualised. Second, drought instruments are surface water quantity-centred. The negative effects that drought has on groundwater, water quality, habitat integrity and geomorphology are largely missing from the freshwater ecosystem indicators, in the conceptualisation of exposure, and in the measures considered to mitigate the impacts of drought on these ecosystems. Third, the temporal attributes of drought that are relevant to freshwater ecosystems (i.e. duration, frequency and timing) are not well represented in the design of drought indicators and measures, which currently mainly focus on drought magnitude. Fourth, exposure and vulnerability assessments lack a comprehensive understanding of ecological drought risk in freshwater ecosystems, as well as conceptual and analytical frameworks for assessing it. This represent a methodological barrier to identifying vulnerable ecosystems and designing adequate measures, thus hindering risk-based approaches in drought management and planning.

Our analysis confirms that there is still a considerable amount to be done for drought policy to care for nature. While the paucity of long-term and inclusive strategies is frequently cited in the literature as a general limitation of current drought management approaches, addressing these four gaps could provide a concrete way forward to ensure short-term management does not impede long-term sustainability, as well as moving towards a more integrated and sustainable approach to drought management.

Data availability statement

All information supporting the research is publicly accessible in the supplementary materials.

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