



A framework for a joint hydro-meteorological-social analysis of drought

Bettina Lange, Dr. ^{a,*}, Ian Holman, Prof. ^b, John P. Bloomfield, Dr. ^c



^a Centre for Socio-Legal Studies, Manor Road Social Science Building, Manor Road, University of Oxford, OX1 2BU, United Kingdom

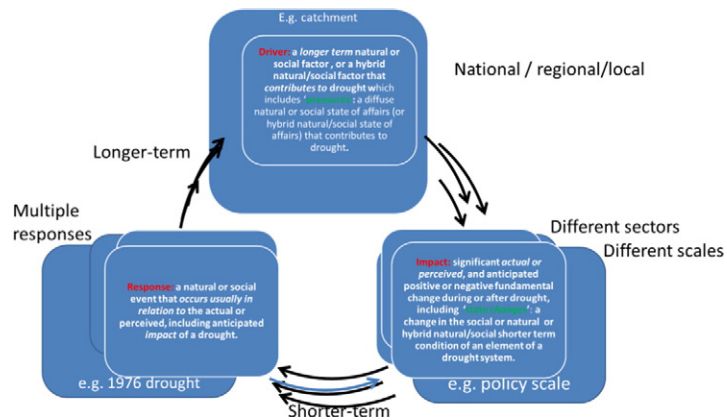
^b Integrated Land and Water Management, Cranfield Water Science Institute, Cranfield University, College Rd, Cranfield MK43 0AL, United Kingdom

^c Groundwater Science Directorate, British Geological Survey, Wallingford, OX10 8BB, United Kingdom

HIGHLIGHTS

- An innovative 'Drivers', 'Responses', 'Impacts' (DRI) framework is proposed.
- Drivers, Responses and Impacts, as well as Pressures and States are defined with reference to linked natural-social worlds.
- A temporal scale and various types of spatial scales are an integral aspect of the DRI framework.
- The framework is applied to the 1976 and 2003–6 drought episodes in the UK.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 25 August 2016
 Received in revised form 18 October 2016
 Accepted 19 October 2016
 Available online 11 November 2016

Editor: D. Barcelo

Keywords:

Drought and water scarcity
 Drivers
 Responses
 Impacts
 Cross-disciplinary research
 Historical analysis

ABSTRACT

This article presents an innovative framework for analysing environmental governance challenges by focusing on their Drivers, Responses and Impacts (DRI). It builds on and modifies the widely applied Drivers, Pressures, States, Impacts and Responses (DPSIR) model. It suggests, firstly and most importantly, that the various temporal and spatial scales at which Drivers, Responses and Impacts operate should be included in the DRI conceptual framework. Secondly, the framework focuses on Drivers, Impacts and Responses in order to provide a parsimonious account of a drought system that can be informed by a range of social science, humanities and science data. 'Pressures' are therefore considered as a sub-category of 'Drivers'. 'States' are a sub-category of 'Impacts'. Thirdly, and most fundamentally in order to facilitate cross-disciplinary research of droughts, the DRI framework defines each of its elements, 'Drivers', 'Pressures', 'States', 'Impacts' and 'Responses' as capable of being shaped by both linked natural and social factors. This is different from existing DPSIR models which often see 'Responses' and 'Impacts' as located mainly in the social world, while 'States' are considered to be states within the natural environment only. The article illustrates this argument through an application of the DRI framework to the 1976 and 2003–6 droughts. The article also starts to address how – in cross-disciplinary research that encompasses physical and social sciences – claims about relationships between Drivers as well as Impacts of and Responses to drought over time can be methodologically justified. While the DRI framework has been inductively developed out of research on droughts we argue that it can be applied to a range of environmental governance challenges.

Crown Copyright © 2016 Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

* Corresponding author.

E-mail addresses: bettina.lange@cs.ox.ac.uk (B. Lange), i.holman@cranfield.ac.uk (I. Holman), jpb@bgs.ac.uk (J.P. Bloomfield).

1. Introduction: cross-disciplinary research about historic droughts

Previous research about past and contemporary droughts, also in the UK, has focused on their hydro-meteorological characteristics, with limited consideration of their socio-economic Drivers, Impact and Responses. When droughts have been analysed with reference to their socio-economic dimensions this has often focused on specific drought events (e.g. Bakker, 2000) rather than a range of droughts over time. Taylor et al.'s (2009) work is an exception. It analyses seven key droughts between 1893 and 2006. The conceptual framework presented in this article seeks to further promote an understanding of the evolution of droughts over time. It also aims to facilitate cross-disciplinary analysis of the evolution of drought systems over time. This draws on data from a range of sectors in which droughts manifest. These are an agricultural, water resource management/legal regulation sector, as well as a meteorological and hydrological sector, including ground- and surface water hydrology. Moreover, the researchⁱ which gave rise to this framework includes data about how droughts affect ecosystems, and how droughts are perceived by those affected, as known through oral histories and media reporting. These 'sectors' capture different dimensions of drought across both a natural and social world, and therefore bring different disciplinary perspectives to bear on an understanding of drought.

The DRI framework presented here is a heuristic device. It builds deductively on existing Drivers, Pressures, States, Impacts and Responses (DPSIR) models discussed in the environmental governance literature. DPSIR models have been applied to water pollution and its regulation (Tscherning et al., 2012), such as most recently the implementation of the European Union Water Framework Directive (EU WFD, 2000, e.g. Borja et al., 2006). They have yet to be applied to the related challenge of drought. The DRI framework also draws on a preliminary collection and analysis of data from a research project on Historic Droughts.

Droughts are a distinct natural hazard. But we suggest that the DRI framework can also be applied to other environmental governance challenges. Droughts are distinct because they are a 'creeping phenomenon' (Wilhite, 2000: 4). In contrast to floods or storms they do not have a sudden beginning or a clear end. Hence, the impacts of drought often only accumulate over a considerable period of time, and, in contrast to other natural hazards, do not necessarily cause structural damage to infrastructure. Moreover, droughts, such as groundwater droughts, are not necessarily very visible, in contrast to floods or snowstorms, but they are still ranked as a very severe hazard in comparison to other natural hazards, such as earthquakes, bush fires or dust storms (Wilhite, 2000: 6). Finally, droughts can spread over a large geographical area, and in comparison to other natural hazard events, are not necessarily confined to a specific locality.

These distinct characteristics of droughts are reflected in the DRI framework since the framework enables to analyse droughts over longer time spans through the emphasis on temporal scales. The fact that droughts can be both large and small-scale is reflected in the DRI framework's emphasis on spatial scale of various magnitude. In light of the sometimes limited visibility of droughts, the DRI framework puts emphasis on combining both a natural and social science perspective in the definition of its key concepts. This ensures that various e.g. socio-economic impacts of drought are captured, even though its physical manifestation may not be very visible.

Hence, the DRI framework reflects distinct features of drought, but it is general and abstract enough to be relevant for the analysis also of

other environmental governance challenges that may consist of more clearly defined specific events and vary less over different spatial scales. The DRI framework thus retains some of the principal features of the well-developed DPSIR model, which has been applied to a range of environmental governance challenges.

2. Key characteristics of the Drivers, Responses, Impacts (DRI) framework

2.1. Why integrate analysis of natural and social dimensions of drought?

The DRI framework presented here is different from existing DPSIR models because it defines its key elements - Drivers, Responses and Impacts - by integrating natural and social dimensions of these. Hence, we also no longer distinguish in this article between 'drought' as the event caused by natural factors, such as lack of rainfall, and 'water scarcity', i.e. water shortages caused by e.g. social factors, such as peaks in demand. Instead we consider drought as caused by both natural and social factors, being a state of too little water for human consumption and the natural environment.

This goes beyond perspectives that ask e.g. 'where does nature end and society begin?' (Kinzig, 2001: 715), and thus chimes with an approach that considers social and natural dimensions of the environment as closely interwoven (Swyngedouw, 2009: 56–60). This has also been explored through the concept of the Anthropocene, which suggests that human actions have given rise to a new geological epoch which starts with the Industrial Revolution, in England in 1800. It captures that human interactions with the natural environment have now become so significant that they shape earth systems, including the climate (Steffen et al., 2011). Such a shaping of the natural environment by human action can also be observed in the context of water quality. For instance, the Humber riverⁱⁱ and its coastal zone are considered to have been influenced by both the geology in the area that shaped soil type and climatic conditions, as well as past and present socio-economic factors that shaped human activity in the catchment, such as sediments from mining and current farming activity (Cave et al., 2003: 31,32). Linking natural and social dimensions of environmental governance challenges is thus now a crucial aspect of generating 'data' about them. The EU WFD, for instance, requires both socio-economic and natural science data to be considered when regulators assess the state of river basins and develop 'programs of measures' (Preamble 36 and Art. 4 (5) EU WFD).

Finally, understanding social and ecological systems as co-evolving provides the foundation for developing their resilience (Kinzig, 2001: 712). This matters also because resilience is no longer just a general aspiration of environmental management but a legal obligation, e.g. in English and Welsh water law. Achieving resilience of water companies' systems for the supply of water and sewerage services – in the light of environmental pressures, population growth and changes in consumer behaviour – is now a key objective of the regulatory framework (Section 2 (2A) (e) of the Water Industry Act 1991). Current DPSIR models are, however, limited in the extent to which they integrate the 'natural' and 'social' environment in their analysis.

2.2. DPSIR models define their key elements with reference to either 'the natural' or 'the social' environment

DPSIR models are often considered to be a tool for 'holistic' and 'integrated' (Kelble et al., 2013) natural resource management that seeks to incorporate both natural and social science accounts of the state and management of nature. But they frequently replicate in their definition of Drivers, Pressures, States, Impacts and Responses, distinctions

ⁱ We acknowledge financial support from the UK Natural Environment Research Council (NERC) Council [grant number: NE/L010356/1]. BGS staff publish with the Permission of the Director, British Geological Survey, NERC. Data relied upon for this research can be accessed in the public domain. We would like to acknowledge contributions from Lucy Barker, CEH, Rebecca Pearce, University of Exeter, and Carmen Dayrell, University of Lancaster to this article.

ⁱⁱ The river Humber flows into the North Sea on the east coast of England. Its origin lies at the confluence of the Rivers Ouse and Trent. It separates the counties of Yorkshire and Lincolnshire at its widest point.

between natural and social factors in the generation and mitigation of environmental governance challenges. For instance, the precursor to DPSIR was the Pressure-State-Response (PSR) model, that defined Pressures and Responses in anthropocentric terms as pressures and responses generated by humans, and which considered only to a limited extent ‘variability’ in the natural environment (Carr et al., 2007: 544) This trend was attenuated in later versions of the PSR model, which defined pressures not only in terms of social, political, economic and demographic factors, but also as pressures resulting from the condition of the natural environment.

This legacy of differentiating between distinct natural and social factors in order to define key elements is reflected in contemporary DPSIR models. These usually define ‘Responses’ with reference to the social world, as ‘human responses’ (e.g. Karageorgis et al., 2005), concerned with human decision-making (Maxim et al., 2009: 15) or, more generally, as the ‘response of society’ (Rekolainen et al., 2003: 349; Tscherning et al., 2012: 102). Examples of such responses are technical measures, legal regulation, and institutional responses to state changes associated with significant impacts (Carr et al., 2007: 545). For Ness et al. (2010), ‘responses’ are a form of ‘societal feedback’ that can occur at macro, and micro-levels, as well at a level of symbolic transactions.

But not just ‘Responses’, also ‘Drivers’, another key element of DPSIR models, are often defined in anthropocentric terms (Maxim et al., 2009: 13; Gray & Elliott, 2009; Karageorgis et al., 2005). For instance, for Kelble et al. (2013) Drivers reflect ‘human needs and desires’, which manifest themselves in Pressures, which, in turn, impact the State of an ecosystem. An example are rising energy requirements of a growing human population. This Driver manifests itself more specifically in the extraction of oil, which, in turn, has contributed to the acidification of the oceans (Kelble et al., 2013: 2). In addition, also ‘Pressures’ have been defined with reference to human activities. Even where pressures on the environment are captured through indicators of the condition of the environment, it is still human actions that are considered as central to generating or reducing pressures upon the environment (Kelble et al., 2013: 8). Some DPSIR models, however, start to move away from this bifurcated view, for instance by defining ‘Drivers’ as forces which can be located either in the natural or social world (Ness et al., 2010: 479, 480).

In contrast to this parcelling out of different elements of DPSIR to various sectors, such as looking for ‘Drivers’ and ‘Responses’ in the social world, and ‘States’ in the natural world, the DRI conceptual framework presented here identifies ‘Drivers’, including ‘Pressures’, ‘Responses’ and ‘Impacts’, including ‘States’ for each sector included in the analysis. For instance, the framework identifies how the water resource management/legal regulation sector gives rise to all three key elements of a drought system – Drivers, Responses and Impacts. Similarly, the framework identifies how the hydrological sector gives rise to a distinct set of

all three key elements: Drivers, Responses and Impacts of drought, a point that is further illustrated in Figs. 1 and 2 below. Moreover, the DRI framework presented here seeks to go beyond the idea that e.g. ‘Drivers’ may be located either in the natural or social world, by also including hybrid social-natural ‘Drivers’, ‘Responses’ and ‘Impacts’, that is ‘Drivers’, ‘Responses’ and ‘Impacts’ of drought that are each constituted of both natural and social elements. An example of a hybrid natural/social Driver is deficiency in rainfall (natural event) that only turns into a Driver of drought in combination with over-abstraction in some catchments (social event) (see also Pitt Review 2008: 6).

Table 1 thus illustrates that the DRI framework seeks to avoid parceling out ‘Drivers’, ‘Responses’, ‘Impacts’, and the sub-categories of ‘States’ and ‘Pressures’ to either the social or natural world. But why do bifurcated views of the natural and social world persist in DPSIR models?

2.3. An understanding of ‘causality’ as a one-way linear chain as a reason for the persistence of a differentiation between a social and a natural world

DPSIR models often trace causal chains between ‘Drivers’, ‘Pressures’, changes in ‘State’, ‘Impacts’ and finally ‘Responses’. Socio-economic Drivers are considered to create environmental Pressures, which in turn lead to changes in the ambient environmental State, captured by natural science data, which generates Impacts on human welfare, captured by social science data. While this causal logic recognizes that social and natural factors act upon each other, it also reinforces a perception of them as distinct, separate dimensions of ‘the environment’. This is illustrated by Maxim et al.’s (2009:20) statement that ‘natural and anthropogenic factors are interrelated, but the Drivers of main risks for biodiversity are human-made’. This can be contrasted with an approach that perceives the natural world as created also through social relations, and the social world as shaped by the possibilities for and constraints upon human action set by the natural environment. This latter approach understands social and natural worlds as *co-constructed*, not as merely acting upon each other in a one-way causal relationship (Jasanoff, 2006).

3. Moving towards integrated definitions of key DPSIR elements

Fig. 1 below shows how key definitions of the DRI conceptual framework seek to integrate social and natural dimensions of the environment. The arrows indicate that Drivers generate perceived or actual drought Impacts which Responses seek to reduce, for instance in the short-term (indicated through the blue arrow) by acting upon the Impacts. As a consequence, Responses to previous droughts may shape Drivers and Impacts of later droughts.

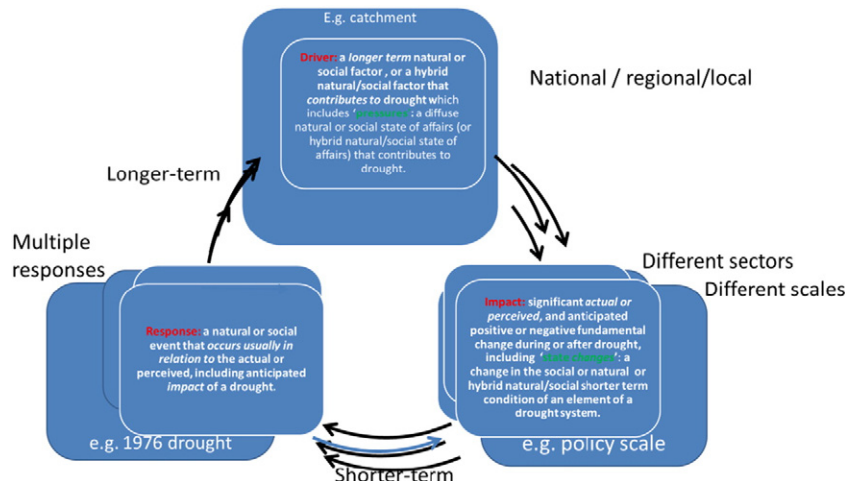


Fig. 1. Definitions of key terms in the DRI framework.

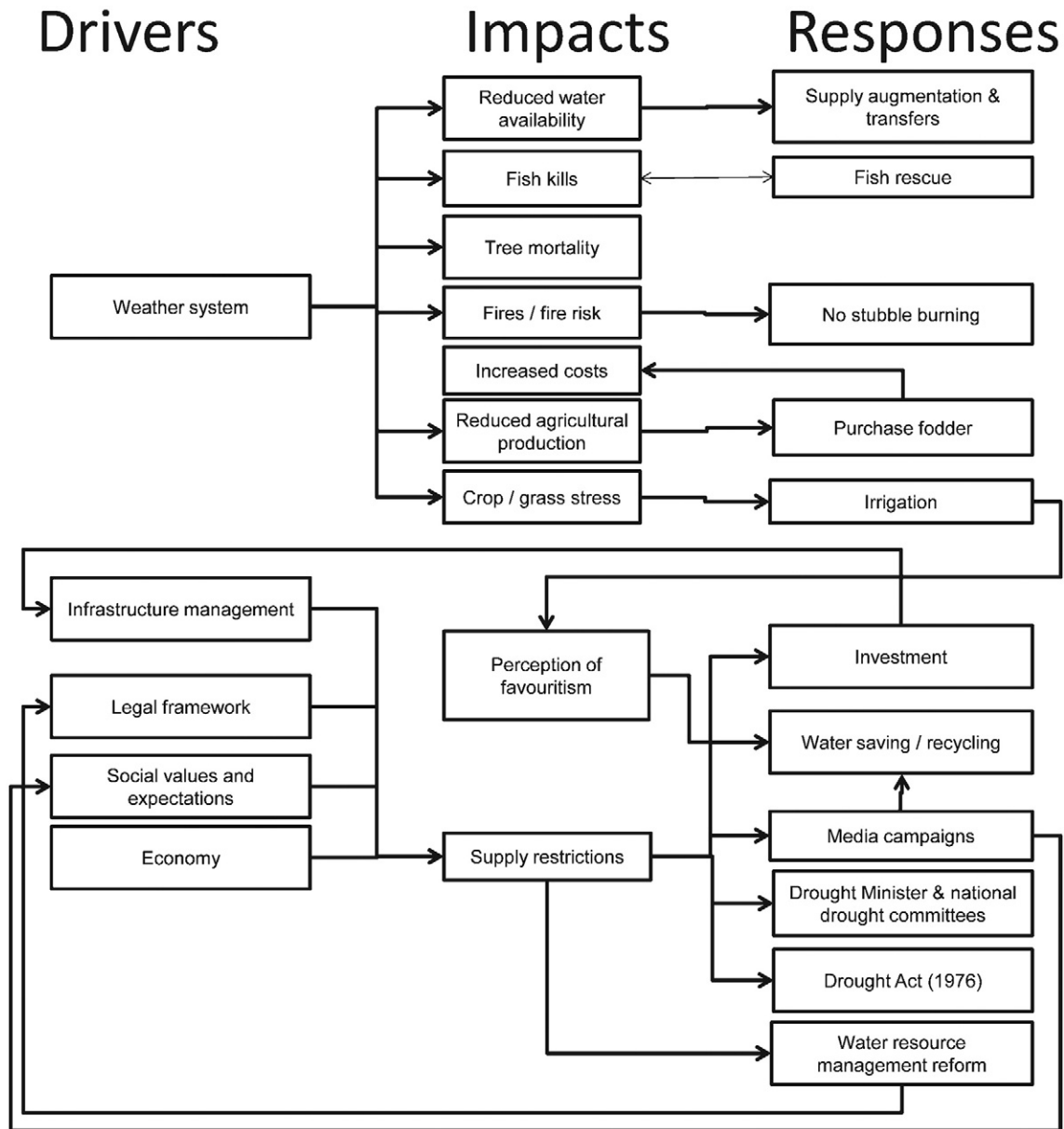


Fig. 2. Applying the DRI framework to the 1976 and 2003–6 droughts.

Examples of Drivers of drought are a significant deficiency in rainfall, or a new housing development. The wide definition of a Driver in Fig. 1 can be further differentiated into Drivers that are exogenous or endogenous to the drought system. For instance, climate can be considered as an exogenous Driver of drought, while lack of rainfall and higher rates of evapotranspiration due to raised temperatures in a particular locality are endogenous Drivers of a drought in that locality. Moreover, the definition of 'Driver' includes what other DPSIR models identify separately as 'Pressures' (Holman et al., 2008: 11). 'Pressures' are considered in the DRI framework as a subcategory of 'Drivers' because they are a *distinct type* of cause, and thus 'Driver' of drought, *not a logically entirely separate concept*. In contrast to 'Drivers', 'Pressures' are more diffuse and less specific causes of drought. It is only by reaching a tipping point or in combination with other factors that 'Pressures' contribute to causing drought. For Maxim et al. (2009:14), for instance, political dynamics contribute to the discursive construction of what becomes considered by whom as a tipping point. Examples of pressures from a groundwater perspective are an increased need for groundwater, compared with surface water, particularly at the start of a drought episode,

to sustain surface water flows and augment public water supplies. Hence, 'Pressures' - as any other key element of the DRI framework - are defined with reference to any of the sectors contributing to the drought system, e.g. water resources management/legal regulation or hydro-meteorological variability within catchments.

'Impacts' are defined as significant and thus more than merely small, transitory changes in linked natural and social dimensions of the environment that can be attributed to a drought. An example is the development of legal standards for water efficient housing developments. In order to facilitate cross-disciplinary research our definition includes what natural scientists understand as the actual impact of a drought in the physical environment, such as increased algae bloom in reservoirs. But it also includes what social scientists understand as the socially constructed, and thus perceived impacts of drought. During a drought various stakeholders generate sometimes contested or even conflicting narratives of such impacts (Svarstad et al., 2008: 117). Moreover, whether impacts can be mitigated also depends on narratives developed by customers of water companies in the UK about the legitimacy of water companies' actions, e.g. to restrict supply during a drought. In

Table 1
Contrasting definitions of key concepts in traditional DPSIR models and the DRI framework.

Key concept	Traditional DPSIR model	DRI framework
Driver	An event that contributes to the causation of an environmental governance challenge, usually located in a social sphere	A longer term natural or social factor, or a hybrid natural/social factor that contributes to drought. This includes 'pressures': a diffuse natural or social state of affairs, or hybrid natural/social state of affairs, that contributes to drought.
Pressure States	e.g. variables that quantify Drivers Characteristics of the natural environment	Not a distinct concept Not a distinct concept
Impact	Effect of an environmental governance challenge, located mainly in the social world.	A significant actual or perceived and anticipated positive or negative fundamental change, during or after a drought. This includes 'state changes', i.e. a change in the social or natural or hybrid natural/social shorter term condition of an element of a drought system.
Response	An action taken to address the impact of an environmental governance challenge, usually located in the social world	A natural or social event, or linked natural-social event, that occurs usually in relation to the actual or perceived, including anticipated impact of a drought.

this context customers' perceptions of whether they consider water companies to have sufficiently reduced leakage from their pipes in an old infrastructure network matters:

'credible performance in relation to leakage control is necessary in order to achieve customer co-operation to reduce demand for water during times of drought' (Anglia Drought Plan, 2014).

These narratives can reflect prior assumptions, for instance about where and to whom drought matters. Impacts of drought may thus be amplified, played down or simply be ignored e.g. in social media.

Our definition includes also anticipated impacts, i.e. impacts considered to occur in the future that have not yet materialized, because Responses occur also in relation to these. For example, the Environment Agency may move fish populations because it is anticipating exceptionally low flow in a particular river that would lead to fish kills. We include both negative impacts of drought, such as irreversible deterioration of flora and fauna, and positive impacts of drought, such as increased incomes for farmers due to scarcity of some agricultural products (Gregory et al., 2013: 560).ⁱⁱⁱ Positive and negative impacts can be sometimes closely linked, since droughts are shocks to linked natural and social systems that can generate initially negative effects, which may be a form of 'creative destruction' that – in the long term – may actually enhance, rather than undermine the resilience of linked natural-social systems (Garmestani et al., 2014: 7). Impacts of drought can be further differentiated into 1st, 2nd and 3rd order impacts according to how close in time they are linked to the immediate drought event. First order impacts refer to biophysical impacts, for example loss of agricultural yield. Second order impacts are more indirect and a consequence of first order impacts, such as loss of income for a farmer. Third order impacts are further removed from the initial impact, such as change in crop production or farm closure (Wilhite and Vanyarkho, 2000:247).

'Impact' is defined here as including state changes (Holman et al., 2008: 11). An example of a 'state change' from a groundwater perspective is a change in the baseflow during drought, as well as changes in the quality of surface waters, such as rivers and wetlands which are fed by groundwater. Traditionally the term 'state change' has been defined in DPSIR models from a science perspective as describing only changes in the natural environment (Svarstad et al., 2008: 117; Maxim et al., 2009: 14; for an exception see Rogers and Greenway, 2005). In order to facilitate cross-disciplinary analysis we define the term 'state' as also capturing changes in social states, such as changes in narratives about whether water supply restrictions by a water company are legitimate and thus complied with by customers, which in turn can affect the actual availability of water resources in the natural environment. We

further differentiate state changes according to their severity, e.g. as S1, S2 and S3.

In traditional DPSIR models 'Response' captures in particular societal responses (see e.g. Holman et al., 2008). But the DRI conceptual framework defines Response as also including responses of the natural environment to drought. For instance, during the 2003–6 drought rivers in spring fed, permeable catchments were more affected by the drought than 'responsive' rivers, where sudden floods in a river helped to maintain runoff (Durant, 2015: 32). Moreover, organisms in ecosystems 'respond' to drought, and rates of these responses can be measured. Societal responses to drought can be further differentiated into formal and informal responses with a water company's communication campaign during drought being a formal response, and voluntary household grey water recycling being an informal response. Responses can also be further classified according to the degree to which they alleviate drought. For instance, increased watering of lawns during a drought is a more maladaptive response than greywater re-use for toilet flushing in households. But the DRI framework does not just draw on a more integrated perspective of natural and social dimensions of the environment for the definition of its key elements, it also modifies existing DPSIR models through an explicit inclusion of temporal and various types of spatial scales on which 'Drivers', 'Responses' and 'Impacts' can operate.

4. Time and spatial scale as explicit dimensions of the DRI framework

4.1. Temporal scale in DRI

In contrast to existing DPSIR accounts the DRI framework recognizes time as a key dimension according to which 'Drivers', 'Responses', 'Impacts', and their sub-categories of 'Pressures' and 'States' can vary. Reference to time in existing DPSIR models is usually confined to a temporal dimension of just one of its key elements. For instance, Ness et al. (2010: 482) point out that contemporary eutrophication of the Baltic Sea has been associated with the Pressure of a fourfold increase in the input of nitrogen, and an eightfold increase in phosphorous loads into the sea since the mid-19th century. Some DPSIR models go further and include a time dimension by contrasting data collected about an environmental governance challenge on one temporal scale – such as 'the present', with different future scenarios, that illustrate how the adoption of various management actions may lead to different environmental outcomes (Cave et al., 2003: 47).

In building on this work the DRI framework seeks to go beyond a static snapshot of an environmental governance challenge at a specific moment in time. It seeks to capture the *changing dynamics and thus the evolution* e.g. of drought and water resources systems more generally. For instance, the water resource management/legal regulatory sector in the UK has experienced significant change in its institutional framework by shifting from public water authorities to privatized water suppliers in England and Wales in 1989. But management of the sector is

ⁱⁱⁱ In contrast to this, the Online European Drought Reference (EDR) Database defines 'impact' as the 'negative consequences' to environment, economy and society' (http://www.eu-drought.org/gfx_content/documents/Learning%20from%20the%20past%20-%20An%20Online%20Database%20of%20European%20Drought%20Characteristics%20and%20Impacts.pdf)

also characterized by enduring themes, such as the importance of reducing leakage and continuing debates about how centralized or decentralized regulation of water supply should be (Letter from Peter Shore, 1976, 1–2, the ‘catchment based approach’ in contemporary UK water management: <http://www.catchmentbasedapproach.org>). Moreover, significant impacts of the 2003–6 drought in the UK were associated with a reform of the legal regulatory framework, such as the introduction of a legal duty imposed upon water suppliers under the Water Act 2003 to prepare operational Drought Plans. These Drought Plans require water companies to set out a whole range of specific responses, encompassing both demand management and augmenting supplies.

The inclusion of a temporal scale in the DRI framework thus enables to address questions, such as do some ‘Drivers’, ‘Impacts’ and ‘Responses’ to drought stay the same over time? In which sectors do we see most continuity and in which most change in relation to the key elements of drought? Are those ‘Drivers’ that persist over time really *structural Drivers* that are key to shaping droughts over time, or are they simply enduring, but nevertheless not very significant in shaping drought? Similarly, are there short-lived ‘Drivers’, ‘Responses’ and ‘Impacts’ that introduce significant step changes in the evolution of drought systems over time? Moreover, consideration of a temporal dimension should also contribute to improved drought management. This is now referred to in Guidance in relation to legal provisions for the writing of water companies’ Water Resource Management Plans in England and Wales (EA, *Natural Resources Wales*, 2016: para. 3.1).^{iv} According to this Guidance modelling and forecasting of future droughts and thus their management is to be enhanced through greater knowledge about ‘worst case’ historic drought scenarios, and the ability to place and evaluate these ‘worst case’ scenarios in the context of a wider historical evolution of drought systems over a number of decades. The DRI framework, however, also seeks to capture further variation in the key elements of drought by including various types of spatial scales on which ‘Drivers’, ‘Impacts’ and ‘Responses’ can operate.

4.2. Extending the range and types of spatial scale in DRI

Spatial scale features in various ways in existing DPSIR models with usually a *focus on one, and in particular larger spatial scales, such as state or regional scales* (Carr et al., 2007: 548). A regional scale has been defined as a sub-national scale or encompassing whole continents, such as ‘Europe’ or ‘Asia’ (Tscherning et al., 2012: 106). *Local scales have featured less in DPSIR* (Maxim et al., 2009: 13; but see Tscherning et al. 103, 109). For instance, Borja et al. (2006: 93) focus on the regional level of the Basque Country,^v and Cave et al. (2003) examined the Humber catchment and its coastal area for their research about the implementation of the EU WFD. Some DPSIR models have gone further and have not just focused on one spatial scale, but have included smaller scales as *sub-scales to the main scale focused upon*. For instance, Cave et al. (2003: 47) suggest that it is at the level of the estuary or the wider catchment that responses to potential breaches of the WFD in the UK can be implemented.

In contrast to this, the DRI framework examines ‘Drivers’, ‘Responses’ and ‘Impacts’ on a *range of scales*, extending from the UK national to the regional scale of water supply zones of water companies, to the local, such as particular catchments and communities affected by water supply shortages. This matters because if ‘Drivers’, ‘Pressures’, ‘States’, ‘Impacts’ and ‘Responses’ are only analysed at larger spatial scales, the knowledge, preferences and values of local actors are sidelined, though they can generate a range of effective, sometimes informal

responses (Kelble et al. 2013:2). Moreover, consideration of ‘Drivers’, ‘Responses’ and ‘Impacts’ at a range of scales helps to develop an understanding of the links between them. For instance, the DRI framework can capture scenarios in which local rather than national actors can influence ‘Responses’, but not ‘Drivers’ and ‘Pressures’.

The DRI framework also extends *the types of spatial scales* considered. Usually DPSIR models refer to *generic spatial scales*, such as ‘micro, meso-, macro’ or ‘global scales’ (Ness et al., 2010: 481). In contrast to this, the DRI framework recognizes four different types of spatial scales. First, it takes into account various geographical scales, such as the catchment. This, in turn, can exist at different physical scales, such as those for first order streams and major river basins. In order to develop cross-disciplinary analysis the DRI framework also recognizes that geographical scales can be socially constructed since where the boundaries around a ‘catchment’ are drawn can also be the result of administrative decision-making of environmental regulators. Second, ‘Drivers’, ‘Pressures’ and ‘Impacts’ of drought can also be located on *jurisdictional scales*, such as England and Wales, which are the territory to which key water resource management legislation applies, such as e.g. the Water Industry Act 1991 and the Water Resources Act 1991. *Third, there are policy scales*, which refer to the spatial scales on which political powers in relation to an environmental governance challenge can be exercised. For instance, there is the scale of UK wide national policy, which can be further differentiated into the distinct policy scales of the devolved administrations and separate environmental agencies of Northern Ireland, England, Wales and Scotland. *Fourth, there are social scales which demarcate the territory of various social groups*, such as groups of residents who share water from a standpipe during a drought, including virtual social groups discussing drought e.g. on Twitter.

Differentiating between these four different types of scales matters because often they do not map onto each other. Taking this into account can help to further understand how ‘Drivers’ relate to ‘Impacts’ of and ‘Responses’ to drought beyond one-way linear causal relationships. For instance, ‘Responses’ to drought, such as changes in domestic water consumption practices, may work quite differently depending on what type of scale they are located at. On a jurisdictional scale water companies in England and Wales are under a legal obligation to promote efficient use of water by their customers (S 93A(1) WIA 1991). On the scale of virtual social groups – which are more expansive and fluid in comparison to traditional place based communities e.g. along a river – efficient use of water will also be shaped by social media messages about what is acceptable water consumption, and during drought communication campaigns by water companies and environmental regulators.

4.3. Linking temporal and spatial scales in the DRI framework

A further innovative feature of the DRI framework is that it links an analysis of temporal and spatial variation of ‘Drivers’, ‘Responses’ and ‘Impacts’. For instance, Drivers, Impacts and Responses may vary over time, but this variation may only be observed at a specific spatial scale, with some consistency of Drivers, Responses and Impacts of drought over time at other spatial scales. In the UK water resource management/legal regulation sector, for example, preventative measures in relation to drought at a national scale have varied over time, from reliance on state ‘command and control’ restrictions of abstraction of water from the environment to complementing this through greater control of leakage rates from water supply pipes. But at the local level during drought various types of restrictions on a limited range of domestic and commercial water uses – put in place in specific water resource zones of water companies – have been a consistent response to drought over time, from the 1976 to the 2010–12 droughts. Hence, considering variation of and links between ‘Drivers’, ‘Impacts’ and ‘Responses’ along both a temporal and spatial scale should help to identify what the key spatial scales are for understanding drought systems at a specific point of time and over a longer time span.

^{iv} Attention to a temporal scale also matters for the very definition of drought, with various sectors defining different end and start times for particular drought episodes in the UK. For instance, from a hydrological perspective the ‘1976’ drought lasted from autumn 1975 to November 1976 (Durant, 2015: 18). From a water resource management/legal regulation perspective the drought ended earlier, i.e. on the 6th of October 1976 when restrictions on the use of water were removed (Durant, 2015: 18).

^v The Basque Country is located in the North-East of Spain. Its northern boundary extends to the Bay of Biscay.

5. Results and discussion: applying the DRI framework to the 1976 and 2003–6 droughts

5.1. A cross-sectoral perspective: linking 'Drivers', 'Responses' and 'Impacts' from the water resource management/legal regulation and the hydrological sector

Both the 1976 and the 2003–6 droughts were severe in the UK, and hence generated a range of data about their 'Drivers', 'Impacts' and 'Responses'. The 1976 drought was considered as one of the worst in 250 years (*Western Morning News*, 1976: Front page). Emergency drought orders led to rota cuts and standpipes. Similarly, the 2003–6 drought was one of the most serious in the last 100 years. If there would have been a third dry winter public water supply would have been at risk (EA, *EA South-East Region Drought Plan*, 2012: 19).

Applying the DRI framework to the 1976 drought suggests that from the perspective of the water resources management/legal regulation sector insufficient powers for planning authorities to consider water availability as a criterion for refusing planning permission under the Town and Country Planning Act (TCPA) 1947 were an *exogenous Driver* of the 1976 drought. In fact the TCPA 1947 was intended to facilitate the development of land, rather than to restrict it (S.A. de Smith, 1948). Furthermore the DRI framework highlights that while the link between planning and water law was not well recognized in 1976, it became a theme in the wake of the 2003–6 drought. The framework further captures that there were also *endogenous Drivers* of the 1976 drought that are more directly linked to drought conditions, such as an absence of water grids over the preceding 20 years.

These exogenous and endogenous Drivers of drought from a water resource management/legal regulation perspective operated in conjunction with more diffuse, background 'Pressures' that contributed to the further development of the drought. Insufficient control of leakage from water authorities' and statutory water companies' supply pipes were such a key 'Pressure' not just in relation to the 1976 drought, but also in relation to the 2003–6 drought (*London Assembly* 2006: 4).

Moreover, the 1976 drought generated various Impacts that had a lasting and significant effect on the sector of water resource management/legal regulation. In the wake of the 1976 drought the Water Charges Equalisation Act 1977 was passed which operated at the jurisdictional spatial scale of England and Wales. The key impact of the Act was to enable the Secretary of State to redistribute income from water authorities or statutory water undertakers that incurred less than average costs in financing operations to those water authorities that had higher financing costs, also in relation to ensure water security in their supply zone. This new redistribution measure was intended to address imbalances, such as high water charges in Wales in comparison to average charges in England, a scenario that was considered as unfair also because Wales had provided water to England during the 1976 drought.

The DRI framework can also identify *more short-term changes of different severity in the State of water resource management* during the drought, as a sub-category of 'Impacts'. For example, on the spatial scale of a particular river serious state changes occurred. The Welsh reservoir Llyn Clywedog was depleted to minimum storage levels of 22–23% through substantial releases into the river system, in order to support prescribed river flows and abstraction upstream of the town of Bewdley on the river Severn (EA, *Severn Drought Order, Environmental Report*, 2013: 17, 44).

In terms of 'Responses' it became clear that as the drought developed during the spring of 1976 (Durant, 2015: 18) that third party water use had to be restricted. But existing legal powers did not enable to progressively tighten restraints on non-essential uses of water (Letter from John Silkin, 1976: 1), e.g. without standpipes having to be set up (Letter to Prime Minister, 1976: 1). In mid-May 1976 water authorities therefore suggested to the Department of the Environment that they needed further powers to restrict water use. The Drought Act 1976 – a response to the drought – was thus quickly passed by Parliament by the end of July

1976 (Letter to M.W.L. Morris Esq. M.P., 1976: 1). This enabled the Secretary of State – upon applications of water authorities or statutory water companies – to issue drought orders which enabled restrictions of third party use of water, in principle similar to contemporary ordinary drought orders.^{vi}

Applying the DRI framework shows that there are some similarities between the 'Drivers' of the 1976 and the 2003–6 droughts. Climatic conditions were one important exogenous Driver of both droughts, while the resulting endogenous drivers of extreme weather conditions included prolonged periods of below average rainfall and in both cases anomalously high summer temperatures in 1976 and 2006 (Rodda and Marsh, 2011; Marsh et al., 2007). An application of the DRI framework further shows that various 'Pressures' from the water resource management/legal regulation sector, such as an extended period of rapidly increasing groundwater abstraction across England and Wales preceding the 1976 drought as well as limited public acceptance of hosepipe bans during winter (HL Deb., Nov. 2003, Col. 1672) were associated with the 1976 and 2003–6 droughts. But in 2003–6 water companies' supply systems were considered as more resilient than during previous droughts (Durant, 2015: 33).

The DRI framework also captures that impacts of later droughts may be shaped by responses to earlier droughts. For instance, in the run-up to and during the 2003–6 drought Ofwat, the economic regulator of water companies in England and Wales, took further regulatory action in relation to leakage levels by bringing these down to 'economic levels'. Since the 2003–6 drought showed that in practice economic leakage levels were still too high – when combined with a significant lack of rainfall – a stricter standard of 'sustainable leakage levels' was established after the 2003–6 drought, also in order to reduce environmental and social impacts of droughts (Medd and Chappells, 2008: 103).

5.2. Extending the cross-sectoral analysis: linking a meteorological, hydrological, water resource management/legal regulation and agricultural sector perspective

As shown in Figure 2 below, the 1976 drought generated also various impacts for the agricultural sector, such as reduced yields in milk, carrots, potatoes and peas, with these impacts being related to the hydrological impact of 'low water availability'. This, in turn, may have been compounded by changes in the water resource management/legal regulation sector, such as the issuing of drought orders that restrict the amount of water that farmers could abstract. These impacts of the 1976 drought were a consequence of various changes in states at farms, such as reduced soil moisture and reduced vegetation growth (Durant, 2015: 19). Farmers responded in various ways to the 1976 drought, e.g. by purchasing fodder and feed for livestock to compensate for poor grass growth, or by refraining from stubble burning as this was observed during the 1976 drought in Devon (*Western Morning News*, 1976:3). The next section illustrates how a temporal scale can be integrated in the analysis of 'Drivers', 'Responses' and 'Impacts', also with reference to the agricultural sector.

^{vi} In particular an order issued under the Drought Act 1976 could authorize to increase abstraction of water subject to conditions (S. 1 (3) (a) Drought Act 1976), to prohibit or limit the use of water for any purpose specified in the order, with such a purpose prescribed by the Secretary of State in a direction to the water authority or a statutory water company (S. 1 (3) (b) Drought Act 1976), to authorize a water authority to discharge water to any place specified in the order (S. 1 (3) (c) Drought Act 1976), to prohibit or limit abstraction of water by any other person, including a water authority or statutory water company (S. 1 (3) (d), to spend or modify restrictions on abstraction licences (S. 1 (3) (e), and finally, to authorize a water authority to suspend, vary or attach conditions to consents to discharge sewerage or trade effluent (S. 1 (3) (f) Drought Act 1976).

5.3. Linking 'Drivers', 'Pressures', 'Responses', 'Impacts' and 'States' for the 1976 and 2003–6 droughts

For these two key droughts five key Drivers could be identified from the academic and grey literature – atmospheric circulation and weather patterns; water utility infrastructure management; the legal and regulatory framework; social values and expectations affecting water demand and use; and wider economic activity. Fig. 2 provides an overview of how these Drivers, sometimes associated with particular Pressures, led to perceived or actual drought Impacts, that at some times lead to a Response at short (i.e. within drought) to longer (i.e. between different droughts) timescales.

Drought systems are complex, and hence many more connections exist between their various elements than specified in this paragraph. For the sake of clarity not all, but the most salient connections are therefore shown in Figure 2. For instance, poor infrastructure management (Driver) due to lack of investment in the water industry prior to the 1976 drought was associated with insufficient leakage control (Pressure), increasing abstraction requirements (Pressure) that contributed to reduced water levels in rivers, reservoirs and aquifers (State) and therefore water resource availability (Impact) and led to an expectation of progressively severe supply restrictions (Impact). A number of Responses were initiated as a consequence of this, from short term river augmentation, re-circulation and transfers that mitigated the reduced State of river flows; to the passing of the Drought Act (1976) that enabled the imposition of restrictions on short term demand (and thus acted on Pressures) as well as media campaigns by the newly formed national drought committee intended to change public attitudes (State) towards water saving/recycling (Response); and finally longer term water resource management reform that altered the legal framework (Impact on the regulatory framework).

Figure 2 also shows that whilst some responses to drought are direct and their effects are therefore more easily predicted, other responses are affected by actions in other sectors. For example, fish rescues occurred in order to reduce the severity of fish kills. But the efficacy of media campaigns to modify public opinion and encourage water saving/recycling was affected by media reporting of perceived favouritism shown towards other sectors, as irrigation of some agricultural crops (to offset soil moisture stress) and sporting pitches (to mitigate hard dry soils) continued.

Applying the DRI framework also shows that by the time of the 2003–2006 drought, Drivers of drought had changed. Some investment by the privatised water companies in infrastructure management as well as changing social values and expectations towards water use in the home meant that standpipes were now considered as both unnecessary and unacceptable. As a consequence short-term Responses focussed on further media campaigns, so-called hosepipe bans and drought permits, whilst another response – the setting up of the Water Savings Group in October 2005, chaired by Ian Pearson, the Minister for the DoE which also sought to promote efficient use of water in households had the potential to also influence domestic water consumption, as one aspect of drought systems, in future years. Moreover, the DRI framework enables to compare and contrast different Impacts of drought over time as these are captured in the various sectoral perspectives. For instance, from a hydrological perspective the 2003–6 drought generated various impacts which were less severe than those during previous droughts (Durant, 2015: 32). Impacts during 2003–6 included low river flows which, in turn, lead to the death of migratory fish. Also flora was effected, with oak and beech trees dying (Durant, 2015:33).

6. Concluding discussion: integrating different epistemologies in the DRI framework

As illustrated above the DRI conceptual framework (CF) fleshes out its key concepts through reference to data gathered from a range of

different disciplinary perspectives, from the sciences, social sciences and humanities. The CF is thus informed by various approaches to what constitutes valid knowledge that enables to identify 'Drivers', 'Responses' and 'Impacts' of drought as well as their interactions. But how can 'objective facts' about drought from a natural science perspective be reconciled with 'subjective representations', i.e. perceptions of the nature and causes of drought generated by qualitative social science and humanities data? The CF presented here seeks to address this enduring challenge of cross-disciplinary research about environmental governance in two ways.

First, it extends an understanding of *causal relationships* between 'Drivers', 'Responses' and 'Impacts' to also include *perceptions of how these appear to be linked*. These perceptions are voiced by various actors, such as Parliamentarians in Hansard Debate, citizens in local communities, as well as journalists' accounts in newspapers and internet users discussing droughts on social media, including Twitter. This strategy of including both 'objective facts' and 'subjective perceptions' of the key elements of the DRI framework builds on literature about transdisciplinary research which suggests that different ideas about what constitutes valid knowledge, should not be considered as incompatible either/or options, but as capturing different levels of reality, in this case of both the natural and social world (Wickson et al., 2006: 1057). In the context of the DRI CF, e.g. the 'reality' of ecosystems in a river and how their 'State' is affected during drought will be captured through natural science methodologies, while a different level of 'reality', such as the experience of a community in Devon during the 1976 drought will be documented through intensive, in-depth qualitative oral histories.

This approach of the DRI framework can be further illustrated through the following example. In relation to the major 1976 drought in the UK we can observe as a perceived 'Driver' the retreat from a more centralized approach to water resources planning, illustrated through the abolition of the National Water Resources Board by the Water Act 1973 (an endogenous Driver) (HC Deb 24 January 1977, vol. 924, cc 985–1102) and a lack over the past 20 years of an integrated water supply network (an exogenous Driver). This Driver also illustrates linkages between a natural and social world. The absence of a more centralized planning for and administration of water resources in the UK (a Driver from the social world) is associated with a supply infrastructure that keeps water resources in particular localities, rather than moves them around the country (a consequence in the natural world). But these perceived 'Drivers' from the social world of water resource management and regulation^{vii} only turned into 'Drivers' of drought in association with hydrological and meteorological 'Drivers'. For instance, climate forcing from the Atlantic by a series of anticyclonic and easterly weather types was the main Driver of the 1975–6 groundwater drought (Rodda & Marsh, 2011). Groundwater abstractions were a further 'Pressure'. This further illustrates how the DRI framework highlights inter-connections between water resource management practices located in a social world and the actual state of water resources in the natural world. There was an extended period of rapidly increasing groundwater abstraction across England and Wales, from ca. 1,500 M cubic meters Pa in the late 1940s to ca. 2,500 M cubic meters Pa by the mid-1970s which was conducive to the development of drought conditions (Downing, 1993). The groundwater drought then had 'Impacts' on winterbournes and chalk streams (Rodda and Marsh, 2011). These were associated with various State Changes, both in the linked natural and social world. For instance, a number of wells ran dry during June, July and August 1976 (Rodda and Marsh, 2011; Day and Rodda, 1978). But these state changes occurred at different spatial scales. For instance, groundwater levels were particularly low in the southern Chalk (Day and Rodda, 1978), but the northwest and northeast of England were

vii

We see water resource management and legal regulation as forming one 'sector' for the purposes of this paper since we consider the social practices of managing water resources by water suppliers as significantly shaped by legal regulation in the UK.

significantly less affected (Rodda and Marsh, 2011). These changes in the state of the natural environment were associated with state changes in the social world of the regulation of water resources. For instance, various water authorities were now required to provide weekly reports to the government for monitoring the water situation (HC Deb 26 May 1976 vol 912 cc 421–2). The DRI framework then further captures a range of 'Responses' to the impacts of the drought. For instance, oral history accounts tell us that South West Water Authority introduced water saving initiatives, and for mainly political reasons, held back the introduction of standpipes while visitors enjoyed their summer vacation (Pearce, 2016, fieldnotes).

The DRI framework then captures the evolution of droughts by linking earlier droughts in the UK, such as the major 1976 drought to later key droughts, such as the 2003–6 drought. What we can see then is that insufficient leakage control is now being perceived in Parliamentary Debate as a significant endogenous Driver of the 2003–6 drought (HC, 27 June 2006, Col. 26 WH). Despite these new criticisms of water resource management practices, the DRI framework also shows that in terms of 'Responses' water supply systems performed more efficiently than during previous drought periods, and as a result water resource impacts were attenuated (EA, 2011). One of the 'Impacts' of the 2003–6 drought in the water resource management/regulation sector is, however, that the debate moves to demand management. For instance, the House of Lords Select Committee on Science and Technology was set up in July 2005 as a sub-committee to examine water management. This brought into sharper relief domestic water consumption. The sub-committee's June 2006 report, for instance, proposes the labelling of the water efficiency of white goods and grey water recycling (House of Lords, 2006: 84). Hence, the DRI framework helps to structure narratives about the evolution of droughts through emphasis on the key linked concepts of 'Drivers', 'Responses' and 'Impacts' that bridge natural and social dimensions of drought. Where 'Drivers', 'Responses' and 'Impacts' of drought are fleshed out through quantitative data e.g. about the physical state of the environment links between these three concepts may be expressed in causal terms.

But the DRI CF addresses the challenge of cross-disciplinary research also, secondly by recognizing the limits to combining different epistemologies in the definition of 'Impacts', 'Drivers' and 'Responses'. It therefore leaves the definition of these concepts to some degree open because openness of concepts is considered as a pre-condition for further scientific reasoning (Feyerabend, 2010: 287). This seeks to transcend traditional disciplinary specific knowledge that works with 'fixed forms of knowledge' which are then 'applied' to an environmental governance challenge (Ison et al., 2007: 500). Hence, the DRI framework does not assume that there is a pre-given ontological foundation for identifying what constitutes valid knowledge, either in the tradition of objective facts about the environment or subjectively mediated understandings of it. Instead scientific knowledge is considered as shaped also by the particular historical context in which it has been generated (Feyerabend, 2010: xvii), which fits well with the explicit inclusion of a temporal scale in the DRI CF. Hence, this perspective enables to ask what actually is a 'fact'. It recognizes that facts may be constituted by particular belief systems about what valid facts are. Facts then involve 'ideas, interpretations of facts', as well as 'problems created by conflicting interpretations and mistakes' (Feyerabend, 2010:3). It is a perspective that values methodological pluralism and can thereby render visible different ways of understanding how linked natural and social worlds operate, also in order to enable inquiry into *alternative ways of governing natural and social worlds* (Feyerabend 2010: xxix, 5).

References

- Anglia Drought Plan, 2014. <http://www.anglianwater.co.uk/environment/ourcommitment/our-plans/drought-plan.aspx>.
- Bakker, K., 2000. Privatizing water, producing scarcity: the Yorkshire drought of 1995. *Econ. Geogr.* 76 (1), 4–27.
- Borja, A., Galparsoro, I., Oihana, S., Iñigo, M., Tello, E.M., Ainhize, U., Victoriano, V., 2006. The European Water Framework Directive and the DPSIR, a methodological approach to assess the risk of failing to achieve good ecological status. *Estuar. Coast. Shelf Sci.* 84–96.
- Cave, R.R., Ledoux, L.K., Turner, K., Jickells, T., Andrews, J.E., Davies, H., 2003. The Humber catchment and its coastal area from UK to European perspectives. *Sci. Total Environ.* 314–16, 31–52.
- Carr, E., Wingard, P., Yorty, S., Thompson, M., Jensen, N., Roberson, J., 2007. Applying DPSIR to sustainable development. *Int. J. Sustain. Dev. World Ecol.* 14 (6), 543–555.
- Day, J.B.W., Rodda, J.C., 1978. The effects of the 1975–76 drought on groundwater and aquifers. *Proc. R. Soc. Lond. A Math. Phys. Sci.* 363 (1712), 55–68.
- Downing, R.A., 1993. Groundwater resources, their development and management in the UK: An historical perspective. *Q. J. Eng. Geol.* 26, 335–358.
- Durant, M., 2015. Description of groundwater droughts in the UK: 1890 to 2015, Nottingham, UK. *Brit. Geol. Surv.* 52 pp. BGS Report Number OR/15/007. at: <http://nora.nerc.ac.uk/511707/>.
- EA, EA South-East Region Drought Plan, January 2012. at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/289874/gese0112bvyyie-e.pdf (accessed 17.10.2016).
- EA, Severn Drought Order, 2013. Environmental Report, Version 7. at: <https://www.gov.uk/government/publications/river-severn-drought-order-environmental-report>.
- EA, Natural Resources Wales, May 2016. Final Water Resources Planning Guideline. at: <https://naturalresources.wales/media/678739/ea-nrw-and-defra-wg-ofwat-technical-water-resources-planning-guidelines.pdf> (accessed 17.10.2016).
- EA, 2011. Impact of long droughts on water resources. Environment Agency Report Number SC070079/R5' at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291597/scho1211buvx-e-e.pdf (accessed 17.10.2016).
- EU WFD, 2000. Directive 2000/60/EC of the European Parliament and of the Council Establishing a Framework for the Community Action in the Field of Water Policy. at: http://ec.europa.eu/environment/water/water-framework/index_en.html (accessed 17.10.2016).
- House of Lords, 2006. Science and Technology Committee, 8th Report of Session 2005–6, Vol. I: Report, HL Paper, 191-I. at: <http://www.publications.parliament.uk/pa/ld200506/ldselect/ldstech/191/191i.pdf> (accessed 17.10.2016).
- Gray, J.S., Elliott, M., 2009. *Ecology of Marine Sediments – From Science to Management*. second edition. Oxford University Press, Oxford.
- Feyerabend, P., 2010. *Against Method*. fourth ed. Verso, London.
- Garmestani, A.S., Allen, C., Anthony, C., Arnold, T., Gunderson, L., 2014. Introduction: social-ecological resilience and law. In: Garmestani, A.S., Allen, C.R. (Eds.), *Social-ecological Resilience and Ecological Resilience and Law*. Columbia University Press, New York, pp. 3–13.
- Gregory, A.J., Atkins, J.P., Burdon, D., Elliott, M., 2013. A problem structuring method for ecosystem-based management: the DPSIR modelling process. *Eur. J. Oper. Res.* 227, 558–569.
- Holman, I., et al., 2008. The concepts and development of a participatory regional integrated assessment tool. *Clim. Chang.* 90, 5–30.
- Ison, R., Roling, N., Watson, D., 2007. Challenges to science and society in the sustainable management and use of water: investigating the role of social learning. *Environ. Sci. Pol.* 10 (6), 499–511.
- Jasanoff, S., 2006. *States of Knowledge: The Co-production of Science and the Social Order*. Routledge, London.
- Karageorgis, A., Skourtos, M.S., Kapsimalis, V., Kontogianni, A.D., Skoulikidis, N., Pagou, K., Nikolaidis, N.P., Drakopoulou, P., Zanou, B., Karamanos, H., Levkov, Z., Anagnostou, C.H., 2005. An integrated approach to watershed management within the DPSIR framework: Axios river catchment and Thermaikos Gulf. *Reg. Environ. Chang.* 5, 138–160.
- Kelble, C., Loomis, D., Lovelace, S., Nuttle, W., Ortner, P., Fletcher, P., Look, G., Lorenz, J., Boyer, J., 2013. The EBM –DPSER conceptual model: integrating ecosystem services into the DPSIR framework. *PLoS One* 8 (8), 1–12.
- Kinzig, A., 2001. Bridging disciplinary divides to address environmental and intellectual challenges. *Ecosystems* 4, 709–715.
- Letter from Peter Shore to the Rt. Hon. Michael Foot MP, 1976. National Archives, Kew.
- Letter from John Silkin at the Department of the Environment, to the Rt Hon Michael Foot, MP, Lord President of the Council, 1976n. National Archives, Kew.
- Letter to Prime Minister, 1976. Drought (CP (76) 38), Ref. A02191, National Archives, Kew.
- Letter to M.W.L. Morris Esq. M.P., 1976. To the Prime Minister, National Archives, Kew.
- London Assembly, 2006. Health and Public Services Committee, 'Drought in London', July 2006. at: <http://legacy.london.gov.uk/assembly/reports/health/londons-drought.pdf> (accessed 18.10.2016).
- Marsh, T.J., Cole, G., Wilby, R., 2007. Major droughts in England and Wales, 1800–2006. *Weather* 62 (4), 87–93.
- Maxim, L., Spangenberg, J., O'Connor, M., 2009. An analysis of risks for biodiversity under the DPSIR framework. *Ecol. Econ.* 69, 12–23.
- Medd, W., Chappells, H., 2008. Drought and Demand in 2006: Consumers, Water Companies and Regulators', Final Report, April 2008. at: <http://www.lancaster.ac.uk/lec/sites/cswm/Drought/Drought%20and%20Demand%20Final%20Report%20April%202008.pdf> (accessed 17.10.2016).
- Ness, B., Anderberg, S., Olsson, L., 2010. Structuring problems in sustainability science: the multi-level DPSIR framework. *Geoforum* 41, 479–488.
- Pearce, R., 2016. Fieldnotes for the Historic Droughts Project, on Record with the Authors.
- Pitt Review, 2008. Update of the Foresight Future Flooding 2004 Qualitative Risk Analysis, An Independent Review by Sir Michael Pitt, June 2008, at http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html (accessed 17.10.2016).
- Rekolainen, S., Kamari, J., Hiltunen, M., 2003. A conceptual framework for identifying the need and role of models in the implementation of the WFD. *Int. J. River Basin Manag.* 1 (4), 347–352.

- Rodda, J.C., Marsh, T., 2011. The 1975–76 Drought: a Contemporary and Retrospective Review. at: http://www.ceh.ac.uk/data/nrfa/nhmp/other_reports.html (accessed 17.10.2016).
- Rogers, S.I., Greenway, B., 2005. A UK perspective on the development of marine ecosystem indicators. *Mar. Pollut. Bull.* 50, 9–19.
- de Smith, S.A., 1948. The Town and Country Planning Act 1947. *Modern Law Review.* 11(1) pp. 72–81.
- Steffen, W., Grinevald, J., Crutzen, P., McNeil, J., 2011. The Anthropocene: conceptual and historical perspectives. *Phil. Trans. R. Soc. A* 369, 842–867.
- Svarstad, H., Petersen, L.K., Rothman, D., Siepel, H., Watzold, F., 2008. Discursive biases of the environmental research framework DPSIR. *Land Use Policy* 25, 116–125.
- Swyngedouw, E., 2009. The political economy and political ecology of the hydro-social cycle. *J. Contemporary Water Res. Educ.* 142, 56–60.
- Taylor, et al., 2009. Drought is normal: the socio-technical evolution of drought and water demand in the UK, 1893–2006. *Hist. Geogr.* 35 (3), 568–591.
- Tscherning, K., Helming, K., Krippner, B., Sieber, S., Gomez y Paloma, S., 2012. Does research applying the DPSIR framework support decision-making? *Land Use Policy* 29, 102–110.
- Western Morning News, 1976. Front Page, at British Library: <http://www.bl.uk/eresources/dbstptitles/eresourcesw.html> (accessed 17.10.2016).
- Wilhite, D., 2000. Drought as a natural hazard. In: Wilhite, D. (Ed.), *Drought: A Global Assessment* vol. 1. Routledge, London, pp. 3–18.
- Wilhite, D., Vanyarkho, O., 2000. Drought: Pervasive impacts of a creeping phenomenon. In: Wilhite, D. (Ed.), *Drought: A Global Assessment* vol. 1. Routledge, London, pp. 245–255.
- Wickson, F., Carew, A.L., Russell, A.W., 2006. Transdisciplinary research: characteristics, quandaries and quality. *Futures* 38, 1046–1059.