Making a case for power-sensitive water modelling: a literature review

Rozemarijn ter Horst[1,2] Rossella Alba[3], Jeroen Vos[1], Maria Rusca[4], Jonatan Godinez-Madrigal[2], Lucie Babel[5], Gert Jan Veldwisch[1], Jean-Philippe Venot[6], Bruno Bonté[7], David W. Walker[1], Tobias Krueger[3]

[1]Water Resources Management Group, Department of Environmental Sciences, Wageningen University and Research, Wageningen, 6708 PB, The Netherlands,
[2]Water Governance Department, IHE Delft Institute for Water Education, Delft, 2611 AX, The Netherlands,
[3]Geography Department and Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Berlin, 10099, Germany
[4]Global Development Institute, University of Manchester, Manchester, M13 9PL, United Kingdom.
[5]Department of Physical Geography, Faculty of Geosciences, Utrecht University, NL-3584 CB Utrecht, The Netherlands
[6]UMR G-EAU, IRD, University Montpellier, 34000 Montpellier, France
[7]UMR G-EAU, INRAE, University Montpellier, 34000 Montpellier, France

Correspondence to: Rozemarijn ter Horst (rozemarijn.terhorst@wur.nl)

Abstract. Models are widely used to research hydrological change and risk. Yet, the power embedded in the modelling process and outcomes are often concealed by claiming their neutrality. Our review shows that in the scientific literature relatively little attention is given to the influence of models on development processes and outcomes in water governance. At the same time, an emerging body of work offering critical insights on the political implications of hydrological models and a nuanced understanding of their application in context has begun to flourish. Drawing on this work, we call for power-sensitive modelling which includes the following considerations: Take a holistic approach to modelling beyond programming and coding; foster accountability; work towards just and equitable water distributions; be transparent on the expectations and choices made; democratise modelling by giving space to, and being mindful of representations of multiple knowledges, multiple stakeholders, and by incorporating marginalised peoples and nature in the modelling process. Our call should not be understood as a suggestion to do away with modelling altogether, but rather as an invitation to interrogate how quantitative models may help to foster transformative pathways towards more just and equitable water distributions.

1 Introduction

Water flows and storages are increasingly researched and governed through quantitative (hydrological, hydrodynamic, socio-hydrological, hydro-economic) models. These models are used with different purposes, including documenting water distribution, exploring causal dynamics, simulating changes, predicting future conditions and informing policy making. Far from being neutral tools, models are shaped by policy projects, institutional backgrounds, specific traditions and practices of modellers, and gendered relations and experiences (Sismondo, 1999; Knorr-Cetina, Lane, 2012; 1999; MacKenzie, 2006; Melsen et al., 2018a; Addor and Melsen, 2019). Since models are complex and the places and people that develop a model may be disconnected from the places and people that use the model, unravelling how and why a model functions, and with what influence, is complicated (Kouw, 2016). Yet, we argue in this paper that this complexity is an often-missed piece of the puzzle in model commission and development, and consciously engaging with it can help to improve the models' fit for purpose or support a modelling process that contributes towards more just and equitable water distributions.

Models are not neutral, and those who commission and develop models do have choices on whether modelling should be done, as well as how. The hydrological modelling community is well aware that any one model could have turned out differently with different assumptions, simplifications, data and if different people had developed it. An iconic example is the study by Hollaender et al. (2014), in which 10 research teams were presented with increasing amounts of data from an artificially constructed catchment in order to model runoff from rainfall, leading to results varying initially by two orders of magnitude. Reflexions about modelling as a social practice and the political consequences of models in the hydrological community have been primarily in terms of how a model could be considered fit for purpose and model adequacy, uncertainty, and subjectivity (Krueger and Alba, 2022).

Beven (2019) distinguishes two kinds of purposes: accurate representation of hydrological processes and mere forecasting of hydrological variables. The latter does not necessarily require any process understanding to develop output, for instance shown recently with the resurgence of machine learning in hydrology (Nearing et al. 2021). Yet, Beven (2019) argues that an accurate process representation is needed if models are to be used for decision making. Addor & Melsen (2019) and Melsen (2022) show that institutional factors play a greater role in modellers choosing models than model adequacy in the sense of fitness for purpose. The question of model adequacy begins to gain an overtly political connotation when Beven (2019, 2022) and Hamilton et al. (2022) consider the possibility of policy makers or stakeholders to be involved in assessing whether a model is fit for purpose. Further developing this point, we would add that the developments, including increasing model complexity, attention for uncertainty, fit for purpose and involvement of stakeholders, will bring the fore ever more clearly the political nature of models, as something to utilise and as something to challenge.

A pitfall could be that discussions remain disconnected from the context the models are used in, while this could improve the modelling practice itself. Naturally, the discussions described above take the model as starting- and end-point, as the aim is to improve a model, but the challenge will be to step out of model-land (Thompson and Smith, 2019). Since hydrological science is inherently bound to societal needs (Lane, 2014), being more explicit about the political influence of models is relevant not only from a science studies perspective but also for hydrology as a discipline and for societies at large. The aim of this article, therefore, is two-fold. First, we research how academic literature discusses the many ways models and modelling processes can gain influence, also beyond their intended reach. We start from the hypothesis that indeed there is still a limited scholarship attending to the influence of models and modelling practices. Second, we draw lessons on how to engage with this political charge of water models, and eventually how to harness the influence of models for progressive transformation. We begin the article by introducing our understanding of what models are. We then describe the methodology of the study and present the findings of our analysis. Based on the results we define and call for a power-sensitive approach towards modelling, and discuss possible methods to facilitate implementing this in practice.

2 Defining models, modelling, and their influence

We are aware that there are different viewpoints on what model are, and subsequently what their influence on development processes looks like, and where accountability lies. It is therefore necessary to clarify the theoretical starting point of this article. First, for the purpose of this article, we adopt a broad definition of models to capture a wide range of modelling practices and that resonates with the representational view many modellers share. This view understands models as simplifications of the world that support the processing of input in various ways, to create output that is informative about the input and process. In other words, the output is influenced by the process and the input (based on Losee, 1997). The simplifications of the world are based on ideas on how the world functions or should function, enabled or limited by technology, and sustained by particular forms of (expert) knowledges, values and understandings (Haas, 1992; MacKenzie and Wajcman, 1999; Krueger and Alba, 2022). An example are the different ways that water is understood, from a purely physical understanding that is often applied in hydrology, taking human influences into account that is common in socio-hydrology, or seeing a deep entanglement of people and water (see Linton, 2009; Sivapalan et al., 2012). Modelling and models are used for different purposes, including to consolidate ideas about what the world is, or to explore unknown parts thereof, for instance through prediction (Morgan and Morrison, 1999; Pielke Jr, 2003; Lane, 2014). Modelling can be done in laboratory- or applied settings, and for narrowly prescribed purposes such as calculating the height of a dam, or to relate to broader questions of whether that same dam should be built, or where, or for whom. These questions have a potential impact (in the case of the dam, a very imminent one) on how modellers and model-users engage with and shape the world around them (King and Kraemer, 1993).

Second, to unpack both how power is inscribed in models and how these might gain influence it is essential to place our analysis in science and technology debates about what knowledge is and how it is produced. This philosophical perspective has significant implications for the way modelling is understood and conceptualised. In this perspective, the modelling process, from problem identification to the development or application of the model to the generation of new information and the support of (policy) decisions, is not linear, although often portrayed or designed to function as such (Macnaghten, 2020; Babel and Vinck, 2022). Different parts of the model development process can run simultaneously or feedback on each other, few processes run exactly as designed on paper, and models are not made in neutral laboratory settings void of funding, norms, values and ideas of what the world is and should be.

The constructivist epistemologies we build on conceptualise scientific knowledge as historically contingent, situated, and socially constructed (Latour, 2003). Science and technology studies have long argued that, scientific knowledge is “primarily as a human product, made with locally situated cultural and material resources, rather than as simply the revelation of a pre-given order of nature” (Golinski, 2005: p. xvii). In contrast to mainstream interpretation of science as neutral and objective, science and technology studies conceptualise environmental knowledge as political and shaped by power relations, which determine what knowledge claims are considered more relevant and usable, how and where research should be published and, in turn, what criteria and norms scientists need to conform with (Demerritt, 2001 and 2006; Law, 2004; Stengers, 2018; Turner, 2011; Zwarteveen et al., 2017). Thus, power is an inevitable component of any piece of scientific investigation. To dedicate attention to what is seen, and how, can be illustrated by the different disciplinary, ontological and epistemological perspectives of socio-hydrology and hydrosocial research (Wesselink et al., 2017). While socio-hydrology takes hydrology as starting point, and adds social components to improve its representation of complex social dynamics (Lane, 2014), hydrosociology takes sociology and the complex interactions between values, significance, power relations as a starting point to explain how water and society interact. An example of this different way of thinking is the hydrosocial cycle in which water is depicted to be able to flow upstream, for instance driven by economic incentives (Linton and Budds, 2014).

All models, including the ‘purely’ physical science-based and quantitative ones, are shaped by people and their norms, values and institutions, and the models shape these in return (Bijker, 2017; Bijker et al., 1987; Latour, 2000; Latour and Woolgar, 1986; MacKenzie and Wajcman, 1999; Krueger and Alba, 2022; Saltelli and Di Fiore, 2023). This societal influence is clearest and most direct through the visual output of models, such as graphs and maps, used in decision making processes. However, there are many clearly recognizable or more hidden ways in which models also interact with social processes. It may be that specific elements of the modelling process have more influence than the final product (Lane et al., 2013), for instance by(re-)producing or challenging discourses, either more or less implicitly (Krueger and Alba, 2022). In this process it matters whose information and knowledge is taken into account, who and what is represented in the process, and how. Information and knowledge enter and exit models at every stage of the development process, so the relation of models with social processes happens throughout the model development chain. Yet, it is important not to essentialize the influence of models in society, and to recognise that their influence might vary from case to case. As Woolgar and Cooper (1999: p. 443) argue on technology more broadly, “technology is good and bad; it is enabling and it is oppressive; it works and it does not; and, as just part of all this, it does and does not have politics”.

Our constructivist theoretical approach and broad definition of models and modelling processes help to make visible that modelling is a process that is susceptible to outside influences and in which different choices are made that shape the process and output (Demeritt, 2006; Lane, 2012). Based on the above, we argue that analysing the potential influence of models requires engaging with questions on why modelling is chosen as method to produce information, what assumptions are included in the problematization phase as well as in the data and model that is used, how available technology enables or excludes, and how the process and output are communicated and questioned, and by whom. The articles that are included in the analysis do not necessarily apply a constructivist approach, but they do discuss one or all of the aforementioned aspects.

3 Methodology

This literature review is primarily based on the ROSES (RepOrting standards for Systematic Evidence Syntheses) method (Haddaway et al., 2018), which is specifically developed for the field of environmental management. It uses a similar approach for systematic reviews that is often used in social sciences (Petticrew and Roberts, 2006). The method provides a three-staged approach that includes searching, screening and critical appraisal, and explicitly allows for additional articles to be included during the screening process to accommodate for the multi-disciplinary nature of environmental research. In our preliminary attempt to define the query, we collected articles that discussed the influence of models. For this selection, we drew on our diverse set of expertise as an interdisciplinary group. In our final inclusion/exclusion strategy we selected papers that engage explicitly with how models gain and have influence, or differently said, have socially and ecologically differentiating effects. Following Petticrew and Roberts (2006) we included doctoral research in addition to published articles, as these often comprise studies that unpack longitudinal modelling processes in detail. This resulted in 136 articles of which 60 discuss water models; we finally identified 30 that reflect on the influence the models have. We formed the first query based on the keywords of these 30 articles. Yet, we were not able to define a comprehensive query that would capture the majority of pre-selected articles in this first selection due to their disciplinary diversity.

To ensure replicability of the study, we defined a query based on words that related to the influence of water models. The final query is defined as TITLE-ABS-KEY (“water model*” OR “hydr* model*” OR “groundwater model*”) AND TITLE-ABS-KEY (justice OR equit* OR politic* OR ethic*). ‘Politic*’ and ‘equit*’ were chosen as keywords because they broadly relate to how models influence issues of distribution, in relation to who gets what, when and how (Lasswell, 1936). ‘Justice’ and ‘ethic*’ were chosen to capture those articles that reflect on why certain actors – including nature – receive or are deprived of water. The query necessarily excludes words such as ‘influence’, ‘power’, ‘values’, ‘reflexivity’, ‘accountability’, and ‘responsibility’; earlier attempts to define a suitable query included these keywords resulted in large quantities of articles that did not reflect on the influence models have due to the multiple meanings of these words.

Results were taken from SCOPUS and Web of Science, based on English language literature for the period January 1993 – December 2023. The query resulted in 408 unique documents. Following the ROSES protocol, we screened the articles to identify those that explicitly addressed or analysed the (potential) influence of water models. A first screening by title excluded 40 documents that had no author listed, were not in English, or did not discuss water or water models. 368 Articles were screened by abstract of which 98 abstracts showed that the article may reflect on the influence of water models and which subsequently were selected for screening the full text. Of the 98 articles, 27 articles were finally selected through the query. In addition, we had pre-selected 30 articles and added four suggested by the HESS community based on the review of this paper. which we included for the critical appraisal stages following the ROSES method, after the elimination of one duplicate. This approach is akin to a mix of a systematic literature review and a narrative review (Cronin et al., 2008). Figure 1 provides a graphic overview of the systematic literature review process and the Appendix provides an overview of the 61 articles included in the literature review.

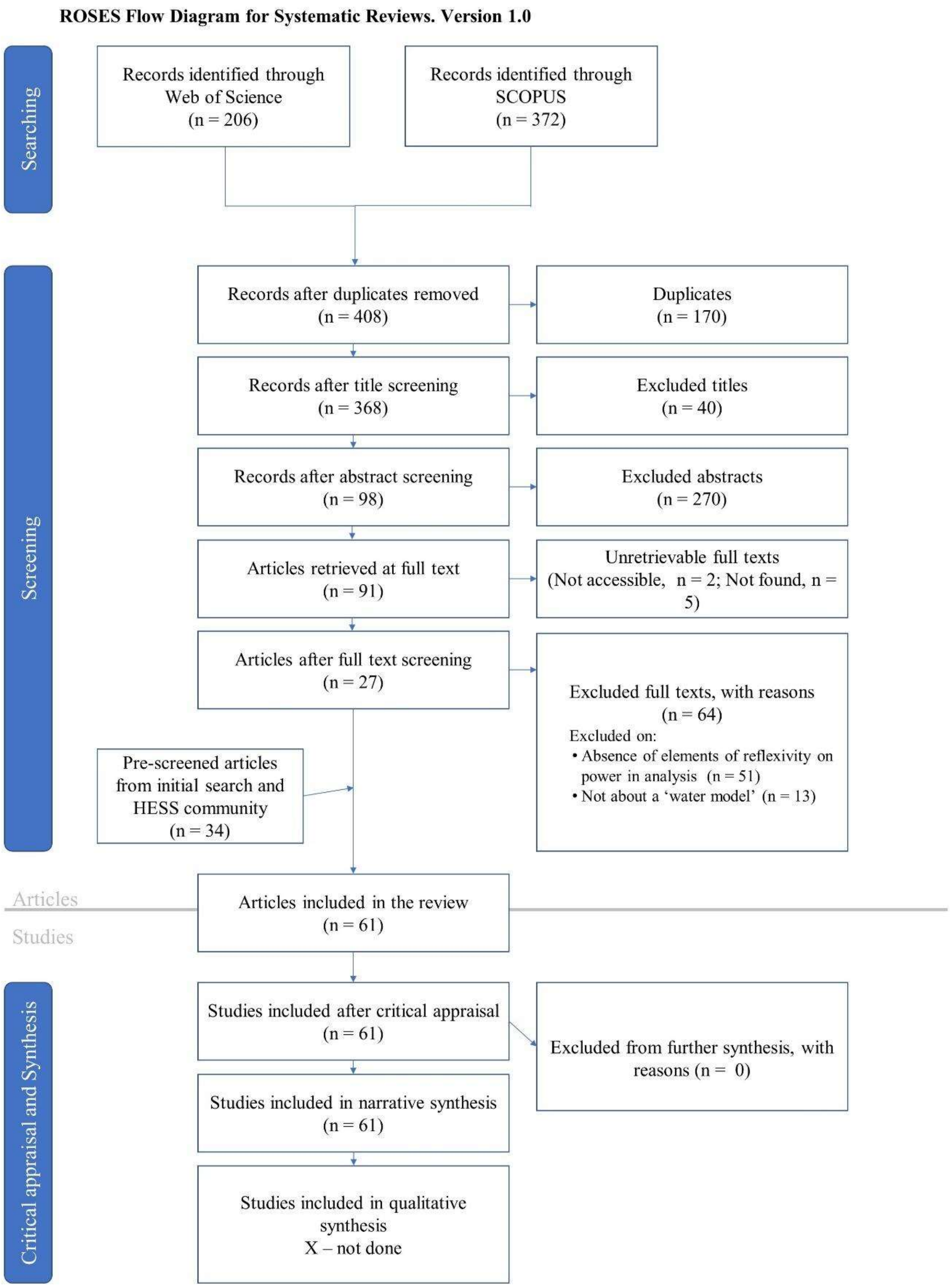

Figure 1: The result of the ROSES systematic literature review process

As the first step of the critical appraisal, we identified shared relationships within and between the reviewed studies (Haddaway et al., 2018). We did this by comparing keywords and by listing common patterns in the included literature, based on our own assessment. By comparing the keywords and main issues, we iteratively identified 13 mechanisms through which models have influence. We identified four overarching themes that represent different phases in a modelling process (see for other ways to represent and structure for instance Refsgaard and Henriksen, 2004; Melsen, Vos and Boelens, 2018). The first three themes unpack different activities of model-making and its relation with the world, from mental models and policy projects, the influence of modellers' choices on the model, and the way models relate to the world around us. The last theme includes studies in which people explicitly apply changes in a modelling process to account for the (potential) influence of models. The four overarching themes form the structure of the narrative synthesis, in which we elaborate how each theme and topic plays out in practice. These themes and related mechanisms of influence we identified are:

- **Mental models and policy projects**
    - Problem framing: Exploration versus consolidation
    - Knowing the world in specific ways
    - Working towards different versions of the world
    - Representation: Mental models translated into, and shaped by, categories
- **The influence of modellers' choices**
    - How modellers' choices matter
    - Familiarity, habits, standardisation of practices and technological requirements
    - Modelling developed through interactions and institutional interests
- **The 'real-world' impact models have**
    - Naturalising and legitimising world views through models
    - Exclusive and inclusive assessments
    - The influence of presentation: colours, maps, and graphs
- **Engaging with non-modellers through models**
    - Connecting to and disconnecting from people and places
    - Stakeholders confronted with different realities of modelling and measuring
    - Representation and fairness
    - Intent: Building in reflection on engaging with the real-world from a modellers perspective

4 Results: narrative synthesis

This review identifies four interrelated dimensions of the modelling process that explain how models gain influence: (a) mental models and policy projects; (b) the influence of modellers' choices; (c) the 'real-world' impact models ; (d) engagement with non-modellers through models (Table 1). We present the main argument of each article reviewed under one of these four dimensions , while being aware that several articles present more than one argument. Appendix A provides more details on the articles reviewed, including the different topics discussed, as well as information on the models and case studies discussed in the articles.

Main themes	Publication (only short reference)
Mental models and policy projects	Alam et al., 2022; Bouleau, 2014; Budds, 2009; Deitrick et al., 2021; Fernandez, 2014; Godinez-Madrigal et al., 2019; Haeffner et al., 2018; Haeffner et al., 2021; Harvey and Chrisman, 1998; Jackson, 2006; Kroepsch, 2018; Krueger and Alba, 2022; Ländstrom et al., 2011; Lane et al., 2011; Meenar et al., 2018; Munk, 2010; Packett et al., 2020; Ramsey, 2009; Sanz et al. 2019; Shrader-Frechette, 1997; Trombley, 2017; Wesselink et al., 2017; Whatmore and Landström, 2010; Wheeler et al., 2018
The influence of modellers' choices	Abbott and Vojinovic, 2014; Addor and Melsen, 2019; Alam et al., 2022; Babel et al., 2019; Bergstrom, 1991; Budds, 2009; Clark, 1998; de Oliveira Ferreira Silva, 2022; Dobson et al., 2019; Godinez-Madrigal et al., 2019; Haeffner et al., 2021; Haines, 2019; Hasala et al., 2020; Holländer et al., 2014; Jackson, 2006; Jenkins and McCauley, 2006; Junier, 2017; Kouw, 2016; Krueger and Alba, 2022; Ländstrom et al., 2011; Lane et al., 2011; Lane et al., 2013; Lane, 2014; Meenar et al., 2018; Melsen, 2022; Melsen et al., 2018; Melsen et al., 2019; Mendoza et al., 2016; Packett et al., 2020; Rainwater et al., 2005; Sanz et al., 2019; Shrader-Frechette, 1997; Srinivasan et al., 2018; Trombley, 2017; Wesselink et al., 2009; Wesselink et al; 2017; Whatmore and Landström, 2010
The 'real-world' impact of models	Bouleau, 2014; Budds, 2009; Cornejo P. and Niewöhner, 2021; de Oliveira Ferreira Silva, 2022; Fernandez, 2014; Godinez-Madrigal et al., 2019; Hasala et al., 2020; Holifield, 2009; Jackson, 2006; Jensen, 2020; Kouw, 2017; Kroepsch, 2018; Krueger and Alba, 2022; Lane, 2011; Meenar et al. 2018; Melsen et al., 2018; Rainwater et al., 2005; Sanz., et al. 2019; Shrader-Frechette, 1997; Wardropper et al., 2017
Engagement with non-modellers through models	Andersson, 2004; Bremer et al., 2020; Budds, 2009; Constanza and Ruth, 1998; Cornejo and Niewöhner, 2021; Falconi and Palmer, 2017; Garcia-Cuerva et al., 2016; Godinez-Madrigal et al., 2019; Haeffner et al., 2018; Holifield, 2009; Jensen, 2020; Kouw, 2017; Krueger and Alba, 2022; Ländstrom et al., 2011; Lane et al., 2011; Melsen et al., 2018; Opitz-Stapleton and MacClune, 2012; Rainwater et al., 2005; Sanz et al., 2019 Wardropper et al., 2017; Wesselink et al., 2009; Wheeler et al., 2018; Wheeler et al., 2018

Table 1: Overview of articles reviewed and related theme

4.1 Mental models and policy projects

We start with discussing the mental model (also called conceptual or perceptual model, Beven 2009; or mental images, Beck, 1999 or framing, see Odoni, N. and Lane, 2010) that underlies any numerical model. Depending on the process, the mental model is not, or less, influenced by limitations posed by data and technology and is more of an 'ideal type' than an actual model, though Krueger et al. (2016) argue that technological possibilities of what can be modelled may already co-shape what can be imagined. We divide the mental model into two elements, with the first being the ideas of how the world works, including any (causal) relations, and the second being the ideas of what this world should look like. Both elements are based on values, norms and ideas about what is important and valid to a society in general and a modelling community in particular (Haas, 1992; Haraway, 1991; Jasanoff and Kim, 2015; Morgan and Morrison, 1999). Mental models are developed based on a multitude of factors, including the common interests, backgrounds, knowledge and skills of those involved. Different communities may have very different ideas of how the world functions (Knorr-Cetina, 1999; Rusca and Di Baldassarre, 2019), or have experience with a particular way of conceptualising linked to an already familiar technology (Addor and Melsen, 2019; Babel et al., 2019; Melsen, 2022). In our systematic literature review, 22 articles dedicated specific attention to mental models. We discuss the main themes, illustrated with examples from the articles reviewed, including 1) problem framing, 2) how different ways of knowing the world influence modelling, 3) how different socio-technical imaginaries influence why a model is made, and 4) how data and categories embody world views and influence what is included and excluded and in what ways.

4.1.1 Problem framing: Exploration versus consolidation

Broadly speaking, there are two very distinct ways to use models. They can be used to explore unknowns, or used to consolidate ideas about reality (Morgan and Morrison, 1999; Pielke Jr, 2003). Several articles put forward how stakeholders that are part of the modelling process may have very different ideas on how the modelling process and outcomes should be used. These articles show that consolidation is often used for decision making processes in which decision makers seek to reduce uncertainty, while exploration is used in processes in which there is disagreement about the issue at hand. We use the article of Ramsey (2009) to highlight how world views, policy projects and technology intertwine based on a case study in which a GIS surface water model was created with the hope of "generating shared understandings" among stakeholders as a key strategy in reducing water allocation conflicts in the Thousand Springs Area in Idaho (USA) (p. 1975-1976). The latter objective led the modellers to try to create a scientifically sound representation of the Thousand Springs Area based on objective and measurable evidence. The model excluded some insights from inhabitants concerning the use of spring water as little measurable data was available on this issue, and the surface water model excluded groundwater from the discussions on water allocation. The exclusion of the experience of spring water users and groundwater prevented a deep exploration of the issues at hand, while this was clearly needed in the process of conflict reduction. The conclusion of the author is to call for dedicated time for exploring 'diverse problem understandings', which entails clearly defining the mental model and modelling vision, before engaging with a modelling effort.

To avoid disconnects between the model and user such as described by Ramsey (2009), Trombley (2017) suggests a multi-model approach to avoid that a model serves one particular policy project at the neglect of others. One of the suggestions they make is to design models for decision making with the aim of facilitating exploration; models becoming mediators that foster a diversity of perspectives. Constanza and Ruth (1998) propose to both engage with the consolidating and exploratory functionality that models can have in the same modelling process by introducing a three-phased modelling approach. The first stage focusses on developing the model structure and 'functional connections between variables' in discussion with stakeholders, the second stage focusses on replicating dynamics of interest realistically, and the third stage focuses on scenarios and management options. Alam et al. (2022) propose a similar approach by calling for an inclusion of positive and negative externalities, specifically in relation to Agent Based Modelling applied to understand the impact of agricultural water management interventions. They propose such an approach as their review shows that there is limited attention for the spatially explicit and inequitable outcomes of interventions.

4.1.2 Knowing the world in specific ways

In the water sector, the way models are developed is often highly influenced by specific 'epistemic communities' that are bound by shared ideas on validity and causality and a way of working that engenders a particular vision of the world (Haas, 1992) or a particular way of doing through communities of practice (Lane, 2012. Bouleau (2014) shows how expertise mixes with political priorities to influence the choice of tools and issues to be addressed, and how this in turn influences the world. In the article Bouleau contrasts the approaches of two different epistemic communities in two different river basins in France. In the Rhône basin, model development was initially mainly guided by geographers and ecologists who focused on the floodplains. As a result, water was conceptualised as a 'hydrosystem' linking hydrological and ecological processes in the river and floodplains. During the same time period in the Seine basin, model development was led by engineers who assessed water quality in relation to economic development of Paris. Water was conceptualised as a condition for economic development that should be closely monitored and modelled. The mental models, differently developed based on different expertise and political priorities on top of the material properties of the two river basins, influenced what was seen and how, and consequently what the aquatic environment looked like (ibid: pp. 253). Another example is provided by Andersson (2004) who confronts a project in which three models (HBV-N, STANK, and SOIL-N) were used to assess options for reducing riverine nitrogen loads in the Upper Svarta Valley in Sweden with opinions of users. The focus of the project on nitrogen, and not on phosphorus as well, for example, was found to be limiting and not reflecting decisions that had to be taken. Despite this limited focus, the overall modelling process was deemed to create a mutual learning environment for modellers, stakeholders and decision makers. A more philosophical reflection is provided by Laborde (2015) who compares their conceptualisation of a lake through MATLAB with the conceptualisation of the same lake by a fisherman. By reflecting deeply on the underlying experiences and expertise that shape a (mental) model, they raise rhetorical questions on why the modelling version of the lake is (better) represented in decision making and the fisherman's not, and whether there is space for complexity that is brought in through lived-experiences as is done by the fisherman.

4.1.3 Working towards different versions of the world

Sociotechnical imaginaries are visions of what the future can become, built on a notion that technology can assist in realising this envisioned future and shaped by values (Haraway, 1985; Jasanoff and Kim, 2009). Working towards a certain envisioned future is also conceptualised as 'policy projects' (Haas, 1992). Making values explicit is therefore useful in understanding what a modelling process aims to achieve. Deitrick et al. (2021) identified and visualised what ethical and epistemological values inspired watershed modellers in the Chesapeake Bay in the USA by surveying and interviewing the modellers involved. To support modellers and those who use or are impacted by models, the authors made visible in a flowchart what kind of choices in the modelling process related to ethics and knowledge production. These choices ranged from questions of funding and model selection, over how environmental processes were to be represented, to how users engaged with the model and how the results were interpreted, while also scoping available alternatives (ibid: pp. 12). The authors call for more openness and more explicitness by modellers when communicating these choices to contribute to transparency in decision making. Rainwater et al. (2005) show how different epistemological values and policy projects influence data collection for groundwater modelling, as well as how local political borders influence how users can engage with modelling results of a shared groundwater body in Texas. Wheeler et al. (2018a, b) also emphasised the importance of making policy projects explicit, and proposed a modelling approach for highly political and conflictual contexts in which intended model-users have very different world views and intended uses of the available water. The authors used the case of the Nile to explore possible future designs and operations of the Grand Ethiopian Renaissance Dam and its relation to operation of the High Aswan Dam in Egypt. The method did not focus on optimisation necessarily, but started with identifying upstream state and downstream state preferences as well as criteria (in this case scenarios based on acceptability and no harm) that guided the modelling exercise.

4.1.4 Representation: Mental models translated into, and shaped by, categories

Definitions and categories are important mechanisms to translate world views into models. Building on feminist science and making gender explicit, two articles in our literature review call for more inclusive modelling. Haeffner et al. (2021) showed that available water data often disfavour women and local communities as few disaggregated data based on these categories are available. Disaggregation, which would entail collecting specific data related for instance to gender, class, and caste, can make differences and inequalities visible. When datasets are not aggregated, or for instance create biases towards male water users who are oftentimes more visible, the modelling exercises based on biased datasets inherit the same biases and knowledge gaps unless these are explicitly acknowledged and addressed. The solution that the authors see to account for the limitations of modelling is to collect data that includes a specification including race, class, and gender, and for results to always be contextualised. This means that in addition to presenting the outputs of the modelling process, the historical and cultural context of what is modelled is described too. Packett et al. (2020) emphasise that it should not only be the input into a model that should be of concern, but that a balanced gender representation should be achieved during the whole modelling process, including problem framing and conceptualisation, model construction, documentation and evaluation, and model interpretation and decision support.

Harvey and Chrisman (1998) unpacked the development of geographical information system (GIS) technology to show how this technology can work inclusively and bring different groups together, but can also work exclusively. Based on a case study on the mapping of wetlands in the USA, the authors argue that an important element that defines who and what is included or excluded is the mental model that underlies the GIS and modelling activities. Their case started with very different ideas on what wetlands are amongst American institutions. How different these understandings can be was highlighted in a 1995 report that compared four different datasets that represent the same wetland. The datasets disagreed on more than ninety percent of the area through different purposes, procedures, sources, definitions, and logics that shaped the different inventory techniques (Shapiro, 1995: p. xiii). To address these discrepancies, one specific system (Cowardin, 1979) was chosen as a standard by the US federal government in 1997 to define wetlands. The authors warn, however, that even though a mental model is standardised to facilitate exchange, the introduction of different modes to collect data, and different approaches to analyse these can again create different interpretations of the same area. In addition, the black-boxed nature of models can obscure these different interpretations, and an effort needs to be made to understand the influence of data collection methods and of model choices.

4.2 The influence of modellers' choices

The following set of articles focuses on how a model is developed. Thirty four off the articles in the review explicitly discuss modeller's choices. This includes the influence of familiarity of the modellers with the models they use, habits, as well as standardisation,

4.2.1 How modellers' choices matter

Modellers' choices matter, as they influence both the development and output of a model. Hollaender et al. (2009) showed through a model comparison experiment that, when provided with the same data-scarce fictive watershed, ten modellers predicted essentially ten different, and some of them very different, discharge time series based on the models of their own choosing. Within the same model, choices also matter greatly. Melsen et al. (2019) systematically demonstrated the impact of modelling decisions for the case of a flood and drought event in the Swiss Thur basin, specifically for decisions on spatial resolution, spatial representation of forcing, calibration period and performance metric. Mendoza et al. (2016) showed how hydrologic modelling decisions can influence evaluations of climate change impacts. When comparing four different modelling structures and parameter estimation strategies applied to three watersheds of the Colorado River Basin, the authors show that calibration decisions may unexpectedly have more impact than the choice of model structure. Dobson et al. (2019), by comparing eight rival framings of two models of two water resource systems in the UK, show how these specific representations of the systems influenced what water management decisions were suggested by the models. The choices of system boundaries and statistical formulation of forcing generators were shown to have the greatest impact. Krueger and Alba (2022) discuss three types of models, a socio-hydrological human-flood model, an export coefficient type model, and a water security model, to showcase the interactions between modelling and policy. These case studies are used to analyse to what extent considerations of uncertainty, subjectivity and fitness for purpose have led the hydrological community to engage with the political consequences of models and the powers inscribed in those models, be they worldviews, omissions or vested interests. The authors especially see an opportunity for both modellers and social scientists to explore and engage the political consequences of models together, in relation to model uncertainty.

4.2.2 Why choices are made: familiarity, habits, standardisation of practices and technological requirements

The choice of the modelling technology or model-type is of great influence on the modelling outcomes. Addor and Melsen (2019) demonstrated, based on a survey of hydrological modellers, how familiarity with a model type is a better indicator of why a model is chosen than whether it is the best fit in terms of representing natural and social dynamics, contrary to what is typically depicted in scientific articles and consultancy reports. Babel et al. (2019) demonstrate that modellers inherit modelling choices from former supervisors and colleagues. This leads to long-lasting and sometimes unquestioned habits in model construction. Jenkins and McCauley (2006) made this visible by unpacking the GIS flow direction algorithm in ESRI products ARC/INFO, ArcView, and ArcGIS, which can seemingly make wetlands disappear from maps. Without understanding why and how the GIS algorithm functions, and without confronting the model-world with the modelled-world, this could mean that decisions are made that are ignorant of what is left invisible. Fernandez (2014) shows through historic research how the development and embedding of an indicator of minimum flow requirements (MFR) is influenced by financial and institutional needs of powerful water users in the Garonne basin in France. Originally introduced in relation to water quality, the MFR indicator later becomes a stand-alone indicator in relation to river health and to define the conditions for the construction and management of hydropower dams to define sector-based water savings. This disconnect, as well as changes in decision making processes for the host institutions of the indicator, led to the indicator to become unquestioned and blackboxed.

Whatmore and Landström (2010) trace the adoption of a formula for calculating the 'velocity or surface inclination of water flowing in an open channel of given dimensions, or Manning's n, first presented in 1889. Although it is criticised as a simplification, the formula allows for simple tuning of a model that has incorporated it, as well as limits the runtime. As such, attempts to replace this formula have failed so far. These six articles show how important the element of expertise is in modelling and warn of certain blind spots, which, once models become accepted and unquestioned tools, may be accepted as the way things are done. This does not mean that modellers are generally not reflexive. Kouw (2016) shows, for the case of hydraulic engineering in the Netherlands, different ways modellers include reflexivity in their modelling practice, including finding a balance between the detail of a model and the time needed to run it, engaging with models as 'sparring partners' instead of 'truth makers', and knowing the basic structure of the model.

4.2.3 Modelling developed through interactions and institutional interests

Landström et al. (2011a) draw attention to a wide range of actors that influence modelling by assessing the practices of modelling flood risk, by consultants for the Environment Agency of England and Wales. The authors show how modelling processes are shaped by environmental managers, decision makers and developers, influenced by standardised modelling processes, including practices to visit the modelled field before and after a modelling exercise, as well as long-term contractual agreements, such as the requirement to use a particular software package. The authors argue that the high level of standardisation limits the space for asking new questions and therefore recommend that the standard practices be routinely compared with new models developed by academics. In a connected paper, Lane et al. (2011) discussed how models are used for predicting floods, taking into account climate change. By unpacking the modelling process, the authors show that a primary assumption in the model was a guideline from the government that estimated peak river flows for the 2080s will increase by 20 per cent compared to 2010. Published as part of the same research project, Lane et al. (2013) show how technology has an influence on the choice for a model. The authors discuss developments from 1D/one dimensional modelling to represent water following a specific path, to 2D/two dimensional modelling in which water can be represented to flow both down and to the sides to mimic a floodplain. A specific event, such as a flood, provided a moment in which such developments and new socio-technological constellations become apparent.

Munk (2010) and Junier (2017) also make visible in their doctoral thesis how models are developed by a multitude of actors and occurrences. In their longitudinal studies based on interviews and observations, they respectively unpacked the development process of the Hydraulic Engineering Center's River Analysis System used for flood risk analysis in the UK, and the WFD (Water Framework Directive) Explorer in the Netherlands. Wesselink et al. (2009) did a similar analysis in a research article, on how models are developed in conjunction with decision making processes. They showcased that in the case of the Dutch Meuse political considerations have an unexpectedly large influence in relation to technical water expertise, especially in relation to transboundary water management.

Jackson (2006) describes in detail the process of how CalSim, a model used by the California Department of Water Resources to estimate and plan water delivery between 2001-2021, became the topic of public controversy. Developed in a sphere of trust based on similar professional expertise, it became apparent that the model was scrutinised based on different requirements in the public sphere. This necessitated changes in the modelling practice towards more open and transparent processes. Jackson calls for a broad take on modelling, not only focusing on the conceptual, mathematical, and computer-based aspects, but also the organizational, political, and broadly sociological, which could lead to decisions to "sacrifice a degree of analytic precision and granularity, but [..] gain in broader stakeholder accessibility and general analytic wieldiness" (ibid: p. 8).

4.3 Modelling and real-world impact

Models are often discussed within the confinement of the model-land they create (Thompson and Smith, 2019), or in other words, in laboratory conditions insulated from the public and disconnected from the world that is being modelled. Whether developed in laboratory conditions, or explicitly to inform (water) governance and management, models can have several unintended impacts. In our systematic literature review, 19 articles have dedicated specific attention to modelling and real-world impact. The articles are all based on case studies and paid particular attention to examine the context in which models are produced and how the model connects with, disconnects from and influences the surrounding environment. The two main themes highlighted in the literature concern how models are mobilised to naturalise and legitimise certain policies and worldviews, and the ways modelling processes can work to conceal or exclude some of the affected groups.

4.3.1 Naturalising and legitimising world views through models

Water governance processes are always contested and political, as stakeholders are likely to hold different worldviews, including contrasting visions about the way water should be managed and allocated, and whose expertise and knowledge should be valued in decision making processes (Zwarteveen et al., 2017). Models, therefore, can have the unintended consequence of legitimising one of these worldviews whilst concealing others. To illustrate, coal mining is a contested process, in which affected stakeholders might have different perceptions on the threats and potential of this development. To illustrate, Connor et al. (2008) analysed the discourses related to a local debate on the development of an opencast coal mine in Murrurundi, a town in the Upper Hunter River basin in New South Wales, Australia. Models formed an integral part of the process by supporting the narrative of both the coalmine exploiter and the government. Despite the multiple distinct perspectives ensued by this project, the models ended up legitimising the worldviews of industry and state, whilst concealing those of many affected groups valorising care of and cultural and spiritual connections to the place and water bodies. The paper thereby highlights two real-world impacts of these models. First, they contribute to policy options grounded on notions of productivity and economic development promoted by state and industry. Second, building on this first point, models also contributed to ground the debates on scientific terminology and concepts, thereby forcing groups contesting these worldviews to draw on the same language and knowledge claims. Cornejo and Niewöhner (2021) exemplified a similar dynamic in the case of mining water abstraction in Tarapacá, Chile. Based on a groundwater model that depicted an aquifer as two separate water basins, it was decided to grant a mining company water rights as it was scientifically proven that water resources would not be affected. Here too, scientific knowledge generated through modelling was prioritised over local knowledge and everyday experiences. The way the modelling process was designed prevented affected groups from questioning assumptions on future impacts of water abstraction. In addition, as the problem was framed in the scientific language generated by the model, local communities were forced to adapt to that language and generate data that speaks to the language and arguments of scientific reports. The authors conclude that in this contested process the model became a 'real' actor, aligned with the interests of private companies and the neoliberal state. Whilst this clearly shows the political nature of models, paradoxically, it is the notion that science is value neutral that makes these models such powerful actors in water-related decision-making processes.

Kroepsch (2018) and Sanz et al. (2019) also discussed how groundwater models can be used to legitimise policies even if there is limited information available. Sanz et al. (2019) showed that despite intrinsic uncertainties, and against advice of the researchers who developed the model, a MODFLOW model was used by a governmental actor to legitimise boundaries drawn that determined which farmers were compensated for refraining from irrigation, and which were not. Kroepsch (2018) questioned how it was decided to optimise space for groundwater abstraction instead of limiting it, even when impacts were unknown due to a long feedback time. Based on the analysis of 10 years of groundwater modelling and governance in the Northern San Juan Basin in Colorado (USA) they argued that in this project in addition to quantitative measures, the 'human values in risk-taking or precaution' should have been prominently included.

4.3.2 Exclusive and inclusive assessments

When modelling is presented as a neutral scientific process, a lack of attention to the context and its power-relations can have negative effects for marginalised groups in society. An example of such a 'desocialised assessment' was provided by Budds (2009) in a case of the La Ligua river basin in Chile. The author questioned the extent to which a hydrogeological model, used to represent the physical diversity in the La Ligua river basin, was representative. The model was based on data mainly available for the main river and not the tributaries, with limited information on actual water use including illegal abstractions, and the modelling process included a limited assessment of the model's validity. Despite this, the model was used to define a generic policy for the additional allocation of water rights that could have led to aquifer depletion. Budds pointed out that this was possible partly due to the legitimacy given to the project by external consultants whose expertise is generally held in high regard. She further argued that the model facilitated the implementation of a policy that reproduced pre-existing water inequalities in the basin. First, the allocation of the additional water rights did not take into consideration that commercial farmers were better placed to acquire them. To illustrate, obtaining legal rights for water abstraction required a lawyer and money, thereby favouring large and smaller commercial farmers over peasant farmers. Second, Budds argues that by excluding knowledge claims from peasant farmers, the model did not account for the fact that the increase in groundwater abstraction by peasant farmers was an adaptive response to the increased water use for agriculture in the valley and the 1996–1997 drought. Not recognising the vulnerability of these farmers by framing their actions as illegal ultimately increased their vulnerability. The author thus concludes that the fact that the water resources agency focused solely on hydrogeological modelling allowed the Chilean state to justify water allocation decisions that reproduced 'unequal patterns of resource use' (Budds, 2009: 418).

Holifield (2009) describes a similar dynamic in the case of groundwater modelling to understand the extent of pollution in St Regis, Minnesota, USA. Modelling by the Champion International Corporation was challenged by a 'counter-network' of local inhabitants and scientists, that had to prove that their representation was more scientifically viable. Holifield shows that this required them to include both disinterested ''outsiders" and interested, locally accountable insiders, and to make connections with ''bigger" centers of power and calculation, which can multiply and amplify the locality's connections with equipment and resources (ibid, pp. 371). Inspired by Holifield (2009, 2012), Meenar et al. (2018) apply an environmental justice perspective as basis to (re)develop flood-mitigation and stormwater management plans in a watershed in southeastern Pennsylvania, USA. Using the Environmental Justice dimension of just distributions, procedure and participation, and recognition as entry points, the authors supported the redrawing of floodplains in a more inclusive way, and in interaction with local inhabitants.

Similar dynamics were examined by Godinez-Madrigal et al. (2019) who showed how models supported top-down management of water-scarcity issues and related water allocation policies in the Lerma-Chapala Basin, Mexico. Outcomes of one modelling exercise were not accepted when they conflicted with the interest of an important actor, and a second modelling exercise excluded an important out-of-basin user which skewed the results. The decision over water allocation was eventually enforced through influence at the highest political level, the President of Mexico. Jensen (2020) also confirmed that the power of high-level decision makers plays a key role. In the case of the Mekong, the author showed there is a certain saturation in knowledge developed by models, and there is a clear limitation in their impact as governments were unwilling to build on these insights. He argued that "compared with the inventive energy deployed in modelling, moreover, it can also be observed that the efforts made by modellers to make this knowledge travel are rather less creative" (ibid: pp 88). These articles show that a model does not have influence on its own.

The previous examples show how models can work exclusively. The following articles show how pluralising data sources and methods can help to make the excluding nature of models visible, as well as how to mitigate this. Garcia-Cuerva et al. (2016) suggest a participatory modelling method aimed at including marginalised communities in the case of identifying opportunities for stormwater control measures in Walnut Creek watershed in North Carolina (USA). Although not yet tested, the authors opt to first develop a modelled version of the Walnut Creek, and cooperated with an NGO, Partners for Environmental Justice, to facilitate discussions with stakeholders 'to evaluate alternatives and to elicit preferences' (ibid, pp 43). Hasala et al. (2020) followed up on the study of Garcia-Cuerva et al. (2016) and compared the approach of collecting information through modelling with a method that relied on interviews. Specifically looking at identifying possible sites for green roofs in majority-minority neighbourhoods in relation to stormwater control measures, they reported significant differences on what roofs should be greened based on interviews of people living in the area and the model outputs. When used in conjunction, the authors showed how the model could be used as a tool to bring different stakeholders together to discuss what options fit a neighbourhood best.

4.3.3 The influence of presentation: colours, maps and graphs

Interestingly, few articles discuss in-depth what the influence is of specific ways of presenting the modelling results through illustrations such as graphs or maps. Most refer to this in passing. For instance, Bergstrom (1991) also concludes that ethics in modelling is becoming more and more important with the rising popularity of models, and does so based on a review of the development and use of the HBV and PULSE models at the Swedish Meteorological and Hydrological Institute between 1971 and 1990. On illustrations, he calls for "Multi-colour graphical presentations are very useful for illustrative purposes but they should not be used to impress or convince where the scientific foundation is weak" (ibid, pp. 134). Abbott and Vojinovic (2014) discussed illustrations as a way to connect with stakeholders aiming that stakeholders are "challenged-out to exercise and develop their own inherent knowledges, imaginations and judgments, and to exercise these both independently and interactively" (ibid: pp. 528). Also Abbott and Vojinovic point towards the responsibility of the modeller, claiming that the "quality of the character of the modeller, becomes inseparable from the quality of the model within the quality of the total production" (ibid: pp. 528-529).

4.4 Engaging with non-modellers through models

When it comes to modelling, we want to dedicate specific attention to engagement of non-modellers in modelling processes. To counter the exclusionary nature of modelling, a popular approach is to engage those affected by the processes that the models aim to examine. Methods range from taking into account the needs and positions of different stakeholders into the design of, and communication about, the model (Cash et al., 2003; Harmel et al., 2014; Bremer et al., 2020), to different forms of participatory modelling (see for instance Voinov et al., 2010; Venot et al., 2022). Yet, few of these articles discuss power-differences between those involved, account for those who disengage or who and what is excluded, or are mindful of what influences the model can have on decision making processes. In the literature review, 24 of the included articles dedicated specific attention to including people and values in a modelling process. We discern different themes, including i) engagements with how models can create connections and disconnections from the people and places that are being modelled, ii) how non-modellers relate with specific world views and policy projects included in the model, iii) representing who and what is modelled in just and fair ways, and lastly iv) how modellers reflect on engaging with who and what is modelled.

4.4.1 Connecting to and disconnecting from people and places

Lane et al. (2011a) experiment with "doing flood risk science differently" to foster connections between academics and local people for whom flooding is a 'matter of concern, and use this as basis to co-produce knowledge in non-hierarchical ways. The project and approach created a way for local knowledge to be taken into account by the responsible institutions in the case of Pickering, UK, By explicitly confronting modelling results and proposed management options with experiences and opinions of local residents, it became clear that more inclusive and less invasive flood risk management options were possible. Opitz-Stapleton and MacClune (2012) reflected in a book chapter on elements that create disconnects between affected communities and the hydrological and climatological modelling that is used for community-based climate change adaptation and disaster risk reduction. Based on case studies from the edited volume, they identified a number of issues that can create disconnects between the modelling activity and the community for which it is intended. One issue that plays a significant role in communities' (dis)engagement is the degree of complexity of the model. The authors warn against thinking too much from a modelling and consultant perspective instead of a community perspective, and suggest to avoid selecting a model that is overly complex and mal-adapted to situations of data-scarcity, working at scales that are beyond the ones a community is generally thinking at (usually under 10 km), overlooking politics at transboundary and national levels, and not speaking the same language of the communities for whom the model is developed. They conclude that organising modelling activities meets their proposed specifications needs "a rare combination of technical skill, cultural sensitivity, political awareness, and above all, the time to continually engage with and build relationships within the community in order to foster resilient change." (ibid: pp 208).

An often-used framework to analyse the uptake of models is provided by Cash et al. (2003). The framework analyses how a model connects with its environment, based on its acceptance by stakeholders in relation to salience (does it fit), legitimacy (is it fair), and credibility (is it believable). We explain it here as the framework is used in two of the 48 articles included in this review. Bremer et al. (2020) applied the framework to different case studies on watershed management programs in the Atlantic Forest of Brazil. Falconi and Palmer (2017) applied it to assess whether participatory computer models for water resources management in the USA, the Solomon Islands, Senegal and Zimbabwe are indeed effective participatory decision tools based on surveys. They also emphasise that a contextual analysis is first required to gain insights into who, when, how, and why-questions. Both articles highlight that models cannot meet the expectations of each stakeholder, and therefore need to be carefully embedded in decision making processes. Bremer et al. (2020) also emphasised that it is necessary to take power dynamics into account in this process. They conclude that as hydrological modelling can influence larger development projects, it is essential to critically reflect on how and by whom these will be used and to what extent they are grounded in local realities.

4.4.2 Stakeholders confronted with different realities of modelling and measuring

Wardropper et al. (2017) analysed how inherent uncertainty in the Soil and Water Assessment Tool (SWAT) application to the Yahara Watershed in Wisconsin (USA) influenced the development and implementation of a water quality management programme. The programme aimed to reduce phosphorus pollution; modelling was used as a tool to estimate water quality and assign needed pollution reductions to different groups, while monitoring and compliance were based on measurements. An additional challenge in the case study was that results of the policy were not directly visible, as they were most likely to be seen within a ten-year timeframe. The authors questioned how the inherent uncertainty in this approach affected people in the watershed. The authors interviewed policy makers and those who would be subjected to the new policy on how to design such a policy in situations of uncertainty. These deliberations were found to be crucial in designing a policy that was experienced both as fair and effective, although the risk remained that the resulting actions were not influential enough to reduce the pollution. Kouw (2017) also discussed inherent traits of modelling practices that can create disconnects between models and model-users, also emphasising that uncertainty is dealt with differently by engineers, decision makers and users. Subsequently, Kouw calls for more integration of social scientists in the practice of developing and using technical tools for decision making.

Landström et al. (2011b) described in detail a participatory model experiment in which modellers, social scientists, and local residents met on a bimonthly basis over a period of one year to co-produce knowledge about flood risks in Pickering in the UK, using a 'competency group' approach. This approach asked for all participants to join as individuals, not as representatives of a certain group, and for science to be produced based on questions of the group. What was important for the project was that science was disconnected from institutions that had a role in discussions on flood risks, and that scientific questions were not defined in advance, and were open to reframing during the project. Two models were developed as a result of this collaboration; the first was intended to be the final model and ultimately served as a starting point for discussion, and second was designed based on requests and inputs of the participants, and ultimately played a key role in shaping flood management strategy in the area.

4.4.3 Representation and fairness

Haeffner et al. (2018) researched how perceptions and concerns of stakeholders and decision makers were represented in the management of urban water systems in urban areas in Utah, USA. First, the authors undertook a review of socio-hydrological frameworks - including models - that seek to unravel the interplay between water and society. Based on this review, they argue that socio-hydrological studies tend to assume that stakeholders have "roughly equal chances of experiencing, perceiving, and responding" while generally this is not the case (ibid: pp. 666). Drawing on data collected through semi-structured interviews and surveys from city council employees, public utilities, and residents, they conclude that public officials and residents do not share the same concerns about the water supply system. Whilst residents' main concerns relate to shortages and tariffs, public officials are significantly more focused on the deterioration of water supply infrastructures. They also found citizens that were most involved in decision making were also more often shown to agree with the perspectives of water system leaders, Based on these results, they conclude that models assuming that residents are well informed and having shared understandings of the water supply system might lead to an oversimplification of socio-hydrological dynamics in a given location, and that more local involvement could mitigate this.

4.4.4 Intent: Building in reflection on engaging with the real-world from a modellers perspective

There are several authors who reflect on the impact of work in their field, and subsequently call for modellers to take an explicit ethical approach (see for instance Abbott and Vojinovic, 2014; Bergstrom, 1991). Clark (1998) also points to the responsibility of the modeller, and specifically when it comes to improved resolutions in GIS applications as "seemingly omniscient but insensitive systems" (ibid, pp 833). Although it is an old article, its reflections are still valid as technology and resolutions keep improving. Besides meeting standards for data uses and processing, facilitating access for all, and auditing, Clark also points towards the responsibility of the modeller: "Have you personally asked whether what you are doing is beneficial to the business, the customer and society? You cannot transfer this responsibility to someone else" (ibid., pp. 832). Shrader-Frechette, (1997) also call for ethical rationality in hydrogeological modelling, meaning that modelling hypotheses have to be considered in the light of their "ethical goodness" or "ethical badness" for the population on-site. de Oliveira Ferreira Silva (2022) calls for a similar approach to validate models and their hypotheses, especially when it comes to the impact of its use on society. Also Lane (2014) based his suggestions for principles for socio-hydrological modellers on personal experiences with hydrology. Based on a deconstruction of practices of hydrological science, Lane proposes to i) embrace conflict and controversy in science, ii) look for extremes to test knowledge, but doing this in a way that is sensitive to the political and ethical ramifications, iii) use real-life events to think with and step out of ‘model-land’, and iv) co-produce knowledge with affected groups. Lane concludes that hydrologists cannot do this alone, but that it requires both social science and hydrology.

It is this discussion in which Srinivasan et al. (2016; 2018) and Melsen et al. (2018) engaged too in a discussion on how modelling should happen. Melsen et al. (2018) pointed out that models are not value-free and that they carry significant power, which raises questions about the responsibility and accountability of those making and using models. This, the authors suggest, calls for a reflexive approach to modelling, which should incorporate questions about the model’s (potential) impact, who is included and excluded and why, as well as a conscious effort to include less powerful stakeholders. In line with this idea, Srinivasan et al. (2018) proposed a number of practices to improve socio-hydrological modelling, including reflecting critically on model structure and functional form, teaching people to use models as a hypothesis rather than a truth, developing guidelines on how to make modelling choices explicit, soliciting input from stakeholders, and mobilising knowledge brokers or institutions to mediate between modellers and others involved. They warn that educating scientists both in social and natural sciences takes time, and that currently the academic culture does not value interdisciplinarity.

5 Discussion

The literature review provides an overview on the current status of research on the influence of water models. We closely reviewed a total of 61 articles through our methodology, based on the narrative review and query (TITLE-ABS-KEY (“water model*” OR “hydr* model*” OR “groundwater model*”) AND TITLE-ABS-KEY (justice OR equit* OR politic* OR ethic*). The query embodies a particular way of engaging with the influence of models grounded in the idea that modelling processes are not linear and that they shape and are shaped by society in different ways. The articles that are included in the review represent a broad spectrum of theoretical and practical approaches to the influence of water models, as well as a broad range in terms of focus. The four themes, used to order the 13 mechanisms models can influence, include: mental models and policy projects, the influence of modellers’ choices, ‘the real-world’ impact models have, and engaging with non-modellers through models.

We see the list of themes and 13 mechanisms as a starting point for researching the influence of water models, as well as inspiration for the design of modelling processes. Examples from the articles that were reviewed, for instance show that modelling with a particular intention in mind, such as environmental justice or gender equality, does impact the way a modelling process is done (Haeffner et al., 2018; Meenar et al., 2018). It also shows that it is useful to place discussions on the fitness-for-purpose (Beven, 2019), or on salience, credibility legitimacy discussion (Cash et al., 2005), or on a post-audits in a broader and socio-political context. Attending to the influence of models brings up questions such as ‘whose purpose is served?’ and ‘who decided what a model should do?’.

Our systematic and narrative literature review methodology also posed specific challenges. For example, many of the words commonly used to describe the influence of models, (including reflexivity, influence, power, accountability and responsibility) proved to be multiple-meaning words also used to describe specific – yet different – processes in modelling. This made it necessary to specify the query with the risk of missing relevant articles (low sensitivity). Also, it is known that reflexivity on these political aspects of water modelling comes in many forms and often happens in formal and informal meetings (Babel and Vinck, 2022; Melsen, 2022; Kouw, 2016). This also means that modelling processes may have been informed by reflexive practices, without being mentioned in scientific articles. Increasing the sensitivity (obtaining more relevant publications) by broadening the query for the systematic literature review would decrease the specificity, increasing enormously the number of publications to be screened without necessarily providing more papers relevant to the aim of the query.

To complement the systematic literature review we did an initial literature search with a variety of keywords, and we asked the HESS community to suggest relevant literature. These suggestions were very useful and yielded 34 relevant publications that were not retrieved with the systematic literature research. Of course, the selection of these hand-picked publications depended on the set-up of the initial search, and who reacted during the public review process.

Interestingly, we saw that in the articles reviewed there is a limited attention to the influence of vested interests – including private or academic interests - on the choice of technologies used, as well as limited attention to the way model outputs are presented. Another observation is that several articles that discuss the impact of models, do not specify the modelling software used. It is clear that choices have to be made, within the limited framework of scientific articles, on what information can be conveyed, and that interactions between specific elements within a model such as a frame or specific representation of the world are prioritised over how a model is developed (see for instance Cornejo and Niewöhner, 2021; Jackson, 2006; Kroepsch, 2018).

Lastly and interestingly, the power disparities between those involved and affected in and through modelling processes, as well as the power of models, are addressed by only a few authors in this literature review (Budds, 2009; Godinez-Madrigal et al., 2019; Haeffner et al. 2021; Harvey and Chrisman, 1998; Holifield, 2009; Connor et al.,2008; Cornejo and Niewöhner, 2021; Meenar et al., 2018). Few of the articles focus on those who disengage from the modelling process or who and what is excluded, and are mindful of what influences the model can have on decision making processes. Exactly those articles, and especially the case studies that describe knowledge controversies, provide opportunities to learn, and bring up questions and examples of how accountability can look like in practice. Hence, we call for a power-sensitive approach towards modelling in the water sector. We argue that this is a crucial endeavour since models are not only influenced by power, but models also have the power to (re)produce particular longlasting social, cultural and technical configurations in the world with more or less desirable social and sustainable outcomes.

6 Towards power-sensitive modelling

This review confirms that models shape the world around them, and the world around models shape them in return. This happens in ways we are aware of, or in more covert or unconscious ways. There are different mechanisms at play that define how a model and modelling process influences what is seen as a 'natural' or legitimate understanding or solution, who and what is concealed or revealed, as well in what ways, and possibly also who gets what, when and how. These mechanisms play in four phases of the model development: the inception and commissioning, the making of the model itself, the use of the model, and during these processes, the engagement with non-modellers. We have shown that it matters that a model is made in a specific context in which a problem frame is defined, and this problem frame can be altered. The literature also shows that we have to be aware of the ways our worldview and expertise influence both the problem framing, the choice to use modelling for a specific purpose, as well as how these are embedded by others in modelling frameworks and databases. The modeller is not the sole responsible in this process, and funders, commissioners, and model-users play important roles.

In section 3 we have argued that this is both applicable to models that are developed for practical applications, as well as those that are developed in laboratory settings (King and Kraemer, 1993). Approaching models as neutral tools may conceal opportunities to do modelling in support of more just and equitable water distributions. The review also shows that modelling can be done differently, for instance by exposing black boxing of decisions; explicitly showcasing the development process of modelling and how modelling decisions affect outcomes; openly questioning modelling decisions and assumptions behind them; foregrounding power relations; calling for particular ethics; and focusing on the process instead of the tool. We therefore call for water modellers, commissioners, funders and model-users to further understand and engage with the power of water models, from ideation to implementation, in an ethical and accountable way. We have identified a few avenues for power-aware water modelling, based on this review and refined these based on other calls related to the politics of modelling (Chilvers and Kearnes, 2015; Doorn, 2012; Krueger et al., 2016; Lane, 2014; Rusca et al., 2023; Saltelli et al., 2020; Venot et al., 2021; Voinov, 2014; Zwarteveen et al., 2017;). We refer to literature reviewed in this article, in which practical examples are given of the points made below:

- **Take a holistic approach to modelling:** A model is more than the final product or output. The modelling process stretches beyond programming and coding, and includes everything that influences model-making and is influenced by it. For instance, it includes the processes of problematisation, defining the purpose of the model, commissioning, implementation decisions based on the modelling, and the co-shaping of discussions. (See for example Jackson, 2006; Junier, 2017; Kroepsch, 2018; Munk, 2010; Trombley, 2017). This holistic approach modelling helps to identify where changes can be made. The development of a water model should be based on a thorough understanding of the interactions with the places a model is developed and applied in (See for example Clark, 1998; Lane et al., 2011).

- **Foster accountability:** Modellers, commissioners and model-users carry an ethical obligation to take possible real-life consequences of a modelling process or use of a model into account, and to change a modelling process accordingly (See for example: Bergstrom, 1991, Lane et al., 2011, Meenar et al, 2018). This also includes reviewing a modelling process after it is concluded.

- **Work towards just and equitable water distributions:** The choice for and use of water models happens in a political context and has political consequences, in a world where some gain and others are overlooked or lose. A first step is to consciously define ethical and epistemic values that underlie the modelling process (See for example Deitrick et al., 2021; Holifield, 2018; Meenar et al, 2018, Packett et al., 2020). There is a joint responsibility to work towards more just and equitable water distributions for people and nature (See for example Abbot and Vojinovic,.2014, Bergstrom, 1991; Lane, 2014).

- **Be transparent:** Increasing transparency throughout the modelling process is a way forward to make explicit and ultimately examine and attend to the multitude of interests shaping the development and use of models and their socio-economic and ecological consequences. Modellers and commissioners can play a pivotal role in fostering such transparency, for instance by explicitly stating the underlying choices, assumptions, normative commitments and expectations as well as and tracking the choices throughout the modelling process, potentially facilitated through protocols (See for example Babel et al., 2019; Addor and Melsen, 2019; Krueger and Alba, 2022).

- **Democratise modelling:** Giving space to multiple knowledges, multiple stakeholders, and incorporating marginalised voices of peoples and nature in all stages of the modelling. This includes questioning who and what is represented, and how, in the data, problem framing, mental model, and decision making process (See for example: Lane et al., 2011; Godinez-Madrigal et al., 2019; Haeffner, 2021; Holifield 2009; Jackson, 2006; Bremer et al., 2020, Voinov, 2016).

We present these five considerations as a starting point for modellers, commissioners and users to think through the potential power-laden effects of modelling processes, and to identify possibilities to alter the design of these processes or to identify alternatives. Our call should not be understood as a suggestion to do away with modelling in the water sector altogether, but as an exploration on how to improve the practice. Although the proposed approach adds further complexity to the modelling process, it also opens new possibilities to strengthen modelling processes, models, and their outcomes.

7 Conclusion

In this article we researched how academic literature engages with the influence water models have. Driven by an hypothesis that there are few scientific articles that critically unpack, or reflexively engage with the socially and ecologically differentiating effects water models and related modelling processes have, we have conducted a literature review based on the ROSES method to assess whether our assumption is correct, and secondly to identify what lessons we can draw from existing literature. To contribute to overcoming disciplinary thinking, we have made use of the open peer-review process of the Hydrology and Earth System Sciences journal, and invited researchers and practitioners from a broad range of disciplines to think with us, share experiences and thoughts, as well as contribute articles which we included in the analysis (Appendix A).

Of the 408 articles included in the systematic literature review, 27 were finally included in critical appraisal. In addition, 30 articles were added to the critical appraisal during the review process and four as suggested by the HESS community. The 61 studies reveal how models shape, and are shaped, by the social and material aspects of the world we live in, and how commissioners, modellers, users, and those affected, engage with this. There is indeed a limited, but over the years a steady number of studies, that engage with the influence of water models. The main reason for exclusion of so many studies from the review is that most of the studies do mention a reflection on the potential impact of the model, or the intention or expectation for the model to contribute to a more equitable and just world, but these statements are mostly brief, disconnected from a specific context, and do not make explicit how the model did, or could, achieve these goals.

The 61 studies that are included in this review highlight different approaches to unpack and critically engage with the influence of water models. The studies show that the shaping of models, and through models, happens in different ways throughout a modelling process and how commissioners, modellers, users and those affected are involved. The studies highlight the way mental models and policy projects become embedded in a modelling process, including through data and categorisation, how modeller's choices – also impacted by familiarity, habits, standardisation or institutional interests - have differentiating effects on the models' outputs and their real-world effects, what impact the models have by legitimising specific understanding of the world and in- or exclusive procedures. A large number of studies also showcases how to intentionally and constructively engage with the potential influence of models, by mindfully connecting to people and places, understanding different realities of stakeholders that are modelled and measured, and by making explicit how the model and modelling process represents people and places in fair ways.

This has led us to define a call for power-sensitive modelling, in which we invite everyone who engages with modelling to work towards just and equitable water distributions, to have a holistic approach to modelling, to contextualise water modelling to engage with impact, to be transparent, to foster a broad accountability, and to democratise modelling. Studying and doing power-sensitive modelling requires a reflexive approach that is grounded and that builds on long-term collaborations and the recognition that modelling is a complex and multifaceted process. To paraphrase Thompson and Smith (2019), this requires making explicit what happens within model-land, but also stepping out of it. As such research finds itself at a crossroads, cooperation across disciplinary boundaries is essential to nurture generative reflexivity and accountability in relation to the power of models (Chilvers and Kearnes, 2015). as well as challenging or enriching modelling results with knowledge from non-modellers and especially those affected by decisions that are related to the modelling exercises (see for instance Wardropper et al., 2017; Hasala et al. 2020). Transdisciplinary research, where both certified and noncertified water experts engage and challenge each other, seems essential (Krueger et al., 2016). This is challenging and seen as a major obstacle in a professional world that does not value complexity but promotes disciplinary thinking (Melsen, Vos, and Boelens, 2018; Srinivasan et al., 2018; Rusca and Di Baldassare, 2019). However, with this interdisciplinary analysis of water models we hope to inspire others to engage in power-sensitive modelling and to consider how quantitative models may help to foster transformative pathways towards more just and equitable water distributions.

Appendix A: Final list of 61 articles included in the review, that explicitly engage and reflect on the power of water models

30 through a general search and personal collection
27 additional articles through the systematic review
4 through the HESS community and reviewers

Based on our assessment, the "X" indicates that an article discusses explicitly i) the mental models and policy projects, ii) the influence of modellers' choices, iii) the impact models have, and/or iv) engaging with non-modellers.
"x" indicates an article discusses one of the abovementioned elements, but not explicitly.

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
				Number of articles that mention a certain element of modelling explicitly	**22**	**34**	**19**	**24**	
Narrative review	Towards a hydroinformatics praxis in the service of social justice	Abbott, M.; Vojinovic, Z.	2014	Journal of Hydroinformatics		**X**	x	x	A general review on hydroinformatics, no model or area defined
Narrative review	Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models	Addor, N.; Melsen, L. A.	2019	Water Resources Research		**X**			Hydrologiska Byråns Vattenbalansavdelning model (HBV), the Variable Infiltration Capacity model (VIC), the mesoscale Hydrological model (mHM), the TOPography-based hydrologic model (TOPMODEL), the Precipitation Runoff Modelling System (PRMS), the Génie Rural model à 4 paramètres Journaliers (GR4J), and the Sacramento soil moisture accounting model
SCOPUS and Web of Science query	Understanding human-water feedbacks of interventions in agricultural systems with agent based models: a review	Alam M.F.; McClain M.; Sikka A.; Pande S.	2022	Environmental Research Letters	**X**	**X**	x		General review, focused on including externalities in modelling Agricultural Water Management interventions, focus on Agent Based Modelling
SCOPUS and Web of Science query	Experiences of the use of riverine nutrient models in stakeholders dialogues	Andersson L.	2004	International Journal of Water Resources Development				**X**	HBV-N, STANK, and SOIL-N, applied in theUpper Svarta Valley in Sweden

Origin	**Title**	**Authors**	**Year**	**Source title**	**i) the mental models and policy projects**	**ii) the influence of modellers' choices**	**iii) the impact models have**	**iv) engaging with non-modellers**	**Model type discussed and Area of study**
Narrative review	Decision-making in model construction: Unveiling habits	Babel, Lucie; Vinck, Dominique; Karssenberg, Derek	2019	Environmental Modelling & Software		**X**			General review, with input of European and North American modelers in a variety of disciplines within Earth and Universe sciences
SCOPUS and Web of Science query	Principles and confidence in hydrological modelling	Bergstrom S.	1991	Nordic Hydrology		**X**		x	HBV and PULSE models at the Swedish Meteorological and Hydrological Institute between 1971 and 1990
Narrative review	The co-production of science and waterscapes: The case of the Seine and the Rhône Rivers, France	Bouleau, Gabrielle	2014	Geoforum	**X**		**X**		Models (undefined) within the PIREN Seine and PIREN Rhône project, France
Narrative review	Who Are we Measuring and Modeling for? Supporting Multilevel Decision-Making in Watershed Management	Bremer, Leah L.; Hamel, Perrine; Ponette-González, Alexandra G.; Pompeu, Patricia V.; Saad, Sandra I.; Brauman, Kate A.	2020	Water Resources Research				**X**	A suite of hydrologic models, such as SWAT, InVEST, and ARIES, as well as proprietary models such as HydroBID, three watershed management programs in the Atlantic Forest of Brazil
SCOPUS and Web of Science query	Contested H2O: Science, policy and politics in water resources management in Chile	Budds J.	2009	Geoforum	**X**	**X**	**X**	**X**	An undefined hydrogeological model by the National Water Directorate, La Ligua basin, Chile
SCOPUS and Web of Science query	Putting water in its place: a perspective on GIS in hydrology and water management	Clark, MJ	1998	Hydrological Processes		**X**	x		General review, no model defined, with reflection on the US and UK.
SCOPUS and Web of Science query	Watercourses and Discourses: Coalmining in the Upper Hunter Valley, New South Wales	Connor, L., Higginbotham, N., Freeman, S., and Albrecht, G	2008	Oceania	x		**X**	**X**	An undefined hydrological model used by the Bickham Coal Company, Upper Hunter Valley, New South Wales
Narrative review	Using Dynamic Modeling to Scope Environmental	Constanza, Robert; Ruth, Matthias	1998	Environmental Management	x	x		**X**	STELLA II modeling environment, Louisiana coastal wetlands

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
	Problems and Build Consensus								
SCOPUS and Web of Science query	How Central Water Management Impacts Local Livelihoods: An Ethnographic Case Study of Mining Water Extraction in Tarapaca, Chile	Cornejo, SM; Niewöhner, J	2021	Water	x		**X**	**X**	Undefined hydrological models, Tarapacá, Chile
SCOPUS and Web of Science query	The Challenge of Model Validation and Its (Hydrogeo)ethical Implications for Water Security	de Oliveira Ferreira Silva C.	2022	Studies in Computational Intelligence		**X**	x	**X**	General review, related to hyrdogeological modelling
SCOPUS and Web of Science query	Investigating the Influence of Ethical and Epistemic Values on Decisions in the Watershed Modeling Process	Deitrick A.R.; Torhan S.A.; Grady C.A.	2021	Water Resources Research	**X**	x		x	a wide array of models, such as the Soil & Water Assessment Tool (SWAT), SPAtially Referenced Regressions on Watershed attributes (SPARROW), and Chesapeake Assessment Scenario Tool (CAST), Chesapeake Bay Watershed
Narrative review	How Important Are Model Structural and Contextual Uncertainties when Estimating the Optimized Performance of Water Resource Systems?	Dobson, Barnaby; Wagener, Thorsten; Pianosi, Francesca	2019	Water Resources Research		**X**			Simulated Water Resources System models, South West of the UK (research on effect of framings in models)
Narrative review	An interdisciplinary framework for participatory modeling design and evaluation—What makes models effective participatory decision tools?	Falconi, Stefanie M.; Palmer, Richard N.	2017	Water Resources Research				**X**	Shared Vision Model (System Dynamic model built on STELLA) for the Tri-State Water Conflict in the ACT-ACF River Basin, USA; System Dynamic Model, Las Vegas, Nevada; Bayesian Network; Solomon Islands

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
Narrative review	Much Ado About Minimum Flows…Unpacking indicators to reveal water politics	Fernandez, Sara	2014	Geoforum	X	x	X	x	Undefined hydraulic and hydrological models, Garonne system, France
SCOPUS and Web of Science query	Exploring Strategies for LID Implementation in Marginalized Communities and Urbanizing Watersheds	Garcia-Cuerva L.; Berglund E.Z.; Rivers L.	2016	World Environmental And Water Resources Congress 2016: Water, Wastewater, and Stormwater and Urban Watershed Symposium - Papers from Sessions of the Proceedings of the 2016 World Environmental and Water Resources Congress				X	hydrologic/hydraulic stormwater modeling system d using HEC-HMS and SWMM, Walnut Creek Watershed in Raleigh, North Carolina
SCOPUS and Web of Science query	Production of competing water knowledge in the face of water crises: Revisiting the IWRM success story of the Lerma-Chapala Basin, Mexico	Godinez-Madrigal J.; Van Cauwenbergh N.; van der Zaag P.	2019	Geoforum	X	X	X	X	system dynamics models, Lerma-Chapala basin, Mexico
SCOPUS and Web of Science query	Representation justice as a research agenda for socio-hydrology and water governance	Haeffner M.; Hellman D.; Cantor A.; Ajibade I.; Oyanedel-Craver V.; Kelly M.; Schifman L.; Weasel L.	2021	Hydrological Sciences Journal	X	X			General review, for (socio)hydrological modelling
SCOPUS and Web of Science query	Social Position Influencing the Water Perception Gap Between Local Leaders and Constituents in a Socio-Hydrological System	Haeffner, M; Jackson-Smith, D; Flint, CG	2018	Water Resources Research	X			X	Socio-hydrological/coupled system models, WasatchRange Metropolitan Area, Northern Utah
Narrative review	Reckoning Resources: Political Lives of	Haines, Sophie	2019	Technology Studies		X		x	GIS software and the N-SPECT (nonpoint-source pollution and erosion comparison tool), Belize

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
	Anticipation in Belize's Water Sector								
Narrative review	Boundary Objects and the Social Construction of GIS Technology	Harvey, F; Chrisman, N	1998	Environment and Planning A: Economy and Space	**X**				GIS technology, including ATKIS standard database model and A L K / A T K I S - G I A P software, applied to wetlands in the USA
SCOPUS and Web of Science query	Green infrastructure site selection in the Walnut Creek wetland community: A case study from southeast Raleigh, North Carolina	Hasala, D; Supak, S; Rivers, L	2020	Landscape And Urban Planning	x	**X**	**X**		Participatory Geographic Information Systems, Walnut creek, southeast Raleigh, North Carolina
SCOPUS and Web of Science query	How to speak for aquifers and people at the same time: Environmental justice and counter-network formation at a hazardous waste site	Holifield R.	2009	Geoforum			**X**	**X**	Groundwater models:SLAEM (Single-Layer Analytic Element Model), MLAEM (Multi-Layer Analytic Element Model), MODFLOW, St. Regis, Minnesota, USA
Narrative review	Impact of modellers' decisions on hydrological a priori predictions	Holländer, H. M.; Bormann, H.; Blume, T.; Buytaert, W.; Chirico, G. B.; Exbrayat, J.-F.; Gustafsson, D.; Hölzel, H.; Krauße, T.; Kraft, P.; Stoll, S.; Blöschl, G.; Flühler, H.	2014	Hydrology and Earth System Sciences		**X**			DWRSIM, used by the California Department of Water Resources to manage the State Water Project; and PROSIM, used by the Bureau of Reclamation in its Central Valley operations
SCOPUS and Web of Science query	Water models and water politics: Design, deliberation, and virtual accountability	Jackson S.	2006	ACM International Conference Proceeding Series	**X**	**X**	**X**	x	CalSim (generalised model for reservoir analysis, FORTRAN), California, USA
SCOPUS and Web of	GIS, sinks, fill, and disappearing wetlands:	Jenkins D.G.; McCauley L.A.	2006	Proceedings of the ACM Symposium on Applied Computing		**X**			General review, based on ARC/INFO, ArcView, and ArcGIS, applied to wetlands

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
Science query	Unintended consequences in algorithm development and use								
Narrative review	A flood of models: Mekong ecologies of comparison	Jensen, C.B.	2020	Social Studies of Science			X	X	Different models, including MRC SWAT, MIKE, HEC ResSIM, applied to (parts of) the Mekong river
Narrative review	Modelling expertise: Experts and expertise in the implementation of the Water Framework Directive in the Netherlands	Junier, S.J.	2017	PhD dissertation: Delft University of Technology	x	X		x	Water Framework Directive Explorer, the Netherlands
Narrative review	Standing on the shoulders of giants—and then looking the other way? Epistemic opacity, immersion, and modeling in hydraulic engineering	Kouw, M.	2016	Perspectives on Science		X		x	General review, Hydraulic engineering models, The Netherlands
Narrative review	Risks in the Making: The Mediating Role of Models in Water Management and Civil Engineering in the Netherlands	Kouw, M.	2017	Berichte zur Wissenschaftsgeschichte			X	X	General review, Hydraulic engineering models, The Netherlands
Narrative review	Groundwater Modeling and Governance: Contesting and Building (Sub)Surface Worlds in Colorado's Northern San Juan Basin	Kroepsch, A.C.	2018	Engaging Science, Technology, and Society	X		X	x	Groundwater models (by 3M project, CBM, AHA, and Questa), Northern San Juan Basin, USA

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
SCOPUS and Web of Science query	Environmental Research from Here and There: Numerical Modelling Labs as Heterotopias	Laborde, S.	2015	Environment and Planning D: Society and Space	**X**	x			ELCOM, supported by MATLAB, Lake Como, Italy
HESS review	Ontological and epistemological commitments in interdisciplinary water research: Uncertainty as an entry point for reflexion	Krueger, T., & Alba, R.	2022	Frontiers in Water	**X**	**X**	**X**	**X**	socio-hydrological human-flood models, an export coefficient type model, water security model of Dadson et al. (2017)
Narrative review	Virtual engineering: computer simulation modelling for flood risk management in England	Landström, C., Whatmore, S.J., Lane, S.N.,	2011	Science & Technology Studies	**X**				Discussion of different models, including ISIS, HEC-RAS and MIKE11, HEC-RAS, etc. at the Environment Agency of England and Wales
SCOPUS and Web of Science query	Coproducing flood risk knowledge: redistributing expertise in critical 'participatory modelling'	Landström, C; Whatmore, SJ; Lane, SN; Odoni, NA; Ward, N; Bradley, S	2011	Environment And Planning A-Economy And Space	x	x	x	**X**	CRUM2D v 3.1, Pickering, UK and Wales
HESS review	Doing flood risk science differently: an experiment in radical scientific method.	Lane, S. N., Odoni, N., Landström, C., Whatmore, S. J., Ward, N., & Bradley, S	2011	Transactions of the Institute of British Geographers	x	x	**X**	**X**	FEH & ISIS's routing methodology, Pickering, UK and Wales
HESS review	Explaining rapid transitions in the practice of flood risk management.	Lane, S.N., November, V., Landström, C. and Whatmore, S.J.	2013	Annals of the Association of American Geographers		**X**			Flood mapping science (HEC-RAS, ISIS and MIKE-11, RMA2 TELEMAC-2D model)
SCOPUS and Web of Science query	Acting, predicting and intervening in a socio-hydrological world	Lane, S.N.	2014	Hydrology And Earth System Sciences		**X**		x	General overview
Narrative review	Imagining flood futures: risk assessment and	Lane, S.N.; Landström, C.; Whatmore, S.J.	2011	Philosophical Transactions of the Royal Society A: Mathematical, Physical	**X**	**X**			Flood Estimation Handbook based models, UK and Wales

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
	management in practice			and Engineering Sciences					
SCOPUS and Web of Science query	Planning for watershed-wide flood-mitigation and stormwater management using an environmental justice framework	Meenar M.; Fromuth R.; Soro M.	2018	Environmental Practice	**X**	**X**	**X**		ArcGIS, HEC-HMS, HEC-RAS, and HEC-GeoRas software, Pennsylvania, US
SCOPUS and Web of Science query	What is the role of the model in socio-hydrology? Discussion of "Prediction in a socio-hydrological world"*	Melsen L.A.; Vos J.; Boelens R.	2018	Hydrological Sciences Journal		**X**	**X**	**X**	General review
Narrative review	It Takes a Village to Run a Model—The Social Practices of Hydrological Modeling	Melsen, L.A.	2022	Water Resources Research		**X**			Hydrologic modelling, Western Europe
Narrative review	Subjective modeling decisions can significantly impact the simulation of flood and drought events	Melsen, Lieke A.; Teuling, Adriaan J.; Torfs, Paul J.J.F.; Zappa, Massimiliano; Mizukami, Naoki; Mendoza, Pablo A.; Clark, Martyn P.; Uijlenhoet, Remko	2019	Journal of Hydrology		**X**			Three Variable Infiltration Capacity (VIC) models (version 4.1.2.i), Thur Basin, Switzerland
Narrative review	How do hydrologic modeling decisions affect the portrayal of climate change impacts?	Mendoza, Pablo A.; Clark, Martyn P.; Mizukami, Naoki; Gutmann, Ethan D.; Arnold, Jeffrey R.; Brekke, Levi D.; Rajagopalan, Balaji	2016	Hydrological Processes		**X**			Including Weather Research and Forecasting (WRF) regional climate model, Noah-LSM,hompson mixed-phase cloud micro-physics scheme, Colorado River Basin, USA
Narrative review	Risking the flood: Cartographies of things to come	Munk, A.	2010	PhD dissertation: Linacre College, University of Oxford	**X**	x	x	x	HEC-RAS 4.0, UK

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
SCOPUS and Web of Science query	Scientific and social uncertainties in climate change: The Hindu Kush-Himalaya in regional perspective	Opitz-Stapleton S.; MacClune K.	2012	Community, Environment and Disaster Risk Management	x		x	**X**	Different Community Based Modelling inititatives, Hindu Kush-Himalaya
Narrative review	Mainstreaming gender into water management modelling processes	Packett, Evangeline; Grigg, Nicola J.; Wu, Joyce; Cuddy, Susan M.; Wallbrink, Peter J.; Jakeman, Anthony J.	2020	Environmental Modelling & Software	**X**	**X**			Biophysical modelling guidelines, general
SCOPUS and Web of Science query	Impact of political, scientific and non-technical issues on regional groundwater modeling: Case study from Texas, USA	Rainwater K.; Stovall J.; Frailey S.; Urban L.	2003	Developments in Water Science	x	**X**	**X**	**X**	MODFLOW based groundwater model, Texas, USA
Narrative review	GIS, modeling, and politics: On the tensions of collaborative decision support	Ramsey, K.	2009	Journal of Environmental Management	**X**		x	x	GIS Surface water model, Idaho, USA
Narrative review	The social construction and consequences of groundwater modelling: insight from the Mancha Oriental aquifer, Spain	Sanz, David; Vos, Jeroen; Rambags, Femke; Hoogesteger, Jaime; Cassiraga, Eduardo; Gómez-Alday, Juan José	2019	International Journal of Water Resources Development	**X**	**X**	**X**	**X**	A groundwater model, Spain
SCOPUS and Web of Science query	Hydrogeology and framing questions having policy consequences	Shrader-Frechette K.	1997	Philosophy of Science	**X**	**X**	x		USA, the Yucca Mountain in Nevada and Maxey flats, Kentucky
Narrative review	Moving socio-hydrologic modelling forward: unpacking hidden assumptions, values and model	Srinivasan, V.; Sanderson, M.; Garcia, M.; Konar, M.; Blöschl, G.; Sivapalan, M.	2018	Hydrological Sciences Journal	x	**X**			Socio-hydrological models, general overview

Origin	Title	Authors	Year	Source title	i) the mental models and policy projects	ii) the influence of modellers' choices	iii) the impact models have	iv) engaging with non-modellers	Model type discussed and Area of study
	structure by engaging with stakeholders: reply to "What is the role of the model in socio-hydrology?"								
Narrative review	An Environmental Anthropology of Modeling	Trombley, J.M.	2017	PhD dissertation: University of Maryland, College Park	**X**	**X**	x	x	Chesapeake Bay Modelling System, Chesapeake Bay, USA
Narrative review	Uncertain monitoring and modeling in a watershed nonpoint pollution program	Wardropper, Chloe B. , Sean Gillon, Adena R. Rissman	2017	Land Use Policy			**X**	**X**	SWAT, Wisconsin, USA
SCOPUS and Web of Science query	Hydrology and hydraulics expertise in participatory processes for climate change adaptation in the Dutch Meuse	Wesselink A.; De Vriend H.; Barneveld H.; Krol M.; Bijker W.	2009	Water Science and Technology		**X**		**X**	WAQUA, SOBEK, Meuse Basin, The Netherlands
HESS review	Manning's N - Putting roughness to work	Whatmore S.J.; Landström C.	2010	How Well do Facts Travel? The Dissemination of Reliable Knowledge	**X**	**X**			1D floodrisk modelling, TUFLOW, general review
SCOPUS and Web of Science query	Exploring Cooperative Transboundary River Management Strategies for the Eastern Nile Basin	Wheeler K.G.; Hall J.W.; Abdo G.M.; Dadson S.J.; Kasprzyk J.R.; Smith R.; Zagona E.A.	2018	Water Resources Research	**X**			**X**	Eastern Nile RiverWare Model, MOEA = multiobjective evolutionary algorithm, Nile Basin
Narrative review	Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins	Wheeler, K. G.; Robinson, C.J.; Bark, R.H.	2018	Regional Environmental Change			x	**X**	The Colorado River Basin in North America and the Murray-Darling Basin in southeastern Australia

Author contribution:

All authors contributed to the conceptualization and to the narrative review. Rozemarijn ter Horst and Jeroen Vos developed the query for the systematic literature review. Rozemarijn ter Horst and Rossella Alba developed the methodology. Rozemarijn ter Horst did the data collection and analysis for the systematic literature review and wrote the original draft. Jeroen Vos, Rossella Alba, Maria Rusca, David W. Walker and Tobias Krueger reviewed and edited closely, and all authors reviewed.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This article is the follow-up activity of the workshop 'Towards a reflexive approach: Connecting critical research on water modelling', co-organized by the Hydrology and Society group at IRI-THESys, Humboldt University of Berlin and the Water Resources Management Group of Wageningen University on 19 and 20 January 2022. We thank all the participants for sharing their experiences and reflections about modelling waters. We also thank the reviewers and members of the HESS community for their constructive comments and engagement.

References

Abbott, M. B. and Vojinovic, Z.: Towards a hydroinformatics praxis in the service of social justice, J. Hydroinformatics, 16, 516–530, https://doi.org/10.2166/hydro.2013.198, 2014.

Addor, N. and Melsen, L. A.: Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models, Water Resour. Res., 55, 378–390, https://doi.org/10.1029/2018WR022958, 2019.

Alam, M.F., McClain, M., Sikka, A. and Pande, S.: Understanding human–water feedbacks of interventions in agricultural systems with agent based models: A review. Environ Res Lett, 17(10), 103003, 2022.

Andersson, L.: Experiences of the use of riverine nutrient models in stakeholder dialogues, Int. J. Water Resour. Dev., 20, 399–413, https://doi.org/10.1080/0790062042000248547, 2004.

Babel, L. and Vinck, D.: The "sticky air method" in geodynamics: Modellers dealing with the constraints of numerical modelling, Rev. Anthropol. Connaiss., 16, https://doi.org/10.4000/rac.27795, 2022.

Babel, L., Vinck, D., and Karssenberg, D.: Decision-making in model construction: Unveiling habits, Environ. Model. Softw., 120, 104490, https://doi.org/10.1016/j.envsoft.2019.07.015, 2019.

Bergström, S.: Principles and confidence in hydrological modelling. Hydrol. Research, 22(2),.123-136, https://doi.org/10.2166/nh.1991.0009, 1991.

Beven, K.: Environmental modelling: an uncertain future?, CRC Press, 2009.

Beven K.: How to make advances in hydrological modelling. Hydr. Res., 50(6), 1481-1494 https://doi.org/10.2166/nh.2019.134, 2019.

Bijker, W.: Constructing Worlds: Reflections on Science, Technology and Democracy (and a Plea for Bold Modesty), Engag. Sci. Technol. Soc., 3, 315, https://doi.org/10.17351/ests2017.170, 2017.

Bijker, W. E., Hughes, T. P., and Pinch, T. (Eds.): The Social construction of technological systems: new directions in the sociology and history of technology, MIT Press, Cambridge, Mass, 405 pp., 1987.

Bouleau, G.: The co-production of science and waterscapes: The case of the Seine and the Rhône Rivers, France, Geoforum, 57, 248–257, https://doi.org/10.1016/j.geoforum.2013.01.009, 2014.

Bremer, L. L., Hamel, P., Ponette-González, A. G., Pompeu, P. V., Saad, S. I., and Brauman, K. A.: Who Are we Measuring and Modeling for? Supporting Multilevel Decision-Making in Watershed Management, Water Resour. Res., 56, https://doi.org/10.1029/2019WR026011, 2020.

Budds, J.: Power, Nature and Neoliberalism: The Political Ecology of Water in Chile, Singap. J. Trop. Geogr., 25, 322–342, https://doi.org/10.1111/j.0129-7619.2004.00189.x, 2004.

Cash, D., Clark, W. C., Alcock, F., Dickson, N., Eckley, N., and Jäger, J.: Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making, SSRN Electron. J., https://doi.org/10.2139/ssrn.372280, 2003.

Clark, M.J.: Putting water in its place: A perspective on GIS in hydrology and water management. Hydrological Processes, 12(6), 823-834, https://doi.org/10.1002/(SICI)1099-1085(199805)12:6<823::AID-HYP656>3.0.CO;2-Z, 1998.

Chilvers, J. and Kearnes, M. (Eds.): Remaking participation: towards reflexive engagement, in: Remaking Participation: Science, Environment and Emergent Publics, Routledge, 28, 2015.

Connor, L., Higginbotham, N., Freeman, S., and Albrecht, G.: Watercourses and Discourses: Coalmining in the Upper Hunter Valley, New South Wales, Oceania, 78, 76–90, https://doi.org/10.1002/j.1834-4461.2008.tb00029.x, 2008.

Cornejo P., S. M. and Niewöhner, J.: How Central Water Management Impacts Local Livelihoods: An Ethnographic Case Study of Mining Water Extraction in Tarapacá, Chile, Water, 13, 3542, https://doi.org/10.3390/w13243542, 2021.

Constanza, R. and Ruth, M.: Using Dynamic Modeling to Scope Environmental Problems and Build Consensus, Environ. Manage., 22, 183–195, https://doi.org/10.1007/s002679900095, 1998.

de Oliveira Ferreira Silva, C.: The Challenge of Model Validation and Its (Hydrogeo) ethical Implications for Water Security, In Computational Intelligence for Water and Environmental Sciences, pp. 477-489, Singapore: Springer Nature Singapore, 2022.

Deitrick, A. R., Torhan, S. A., and Grady, C. A.: Investigating the Influence of Ethical and Epistemic Values on Decisions in the Watershed Modeling Process, Water Resour. Res., 57, https://doi.org/10.1029/2021WR030481, 2021.

Demeritt, D. The Construction of Global Warming and the Politics of Science. Ann Am Assoc Geogr, 91(2), 307–337, 2001.

Dobson, B., Wagener, T., and Pianosi, F.: How Important Are Model Structural and Contextual Uncertainties when Estimating the Optimized Performance of Water Resource Systems?, Water Resour. Res., 55, 2170–2193, https://doi.org/10.1029/2018WR024249, 2019.

Doorn, N.: Responsibility Ascriptions in Technology Development and Engineering: Three Perspectives, Sci. Eng. Ethics, 18, 69–90, https://doi.org/10.1007/s11948-009-9189-3, 2012.

Étienne, M.: Companion modelling: a participatory approach to support sustainable development. Editions Quae, 368 p., 2011

Falconi, S. M. and Palmer, R. N.: An interdisciplinary framework for participatory modeling design and evaluation—What makes models effective participatory decision tools?, Water Resour. Res., 53, 1625–1645, https://doi.org/10.1002/2016WR019373, 2017.

Fernandez, S.: Much Ado About Minimum Flows…Unpacking indicators to reveal water politics, Geoforum, 57, 258–271, https://doi.org/10.1016/j.geoforum.2013.04.017, 2014.

Garcia-Cuerva, L., Berglund, E. Z., and Rivers, L.: Exploring Strategies for LID Implementation in Marginalized Communities and Urbanizing Watersheds, in: World Environmental and Water Resources Congress 2016, World Environmental and Water Resources Congress 2016, West Palm Beach, Florida, 41–50, https://doi.org/10.1061/9780784479889.005, 2016.

Giglioli, I. and Swyngedouw, E.: Let's Drink to the Great Thirst! Water and the Politics of Fractured Techno-natures in Sicily: Water and the politics of fractured techno-natures in Sicily, Int. J. Urban Reg. Res., 32, 392–414, https://doi.org/10.1111/j.1468-2427.2008.00789.x, 2008.

Godinez-Madrigal, J., Van Cauwenbergh, N., and van der Zaag, P.: Production of competing water knowledge in the face of water crises: Revisiting the IWRM success story of the Lerma-Chapala Basin, Mexico, Geoforum, 103, 3–15, https://doi.org/10.1016/j.geoforum.2019.02.002, 2019.

Golinski J.:Making Natural Knowledge: Constructivism and the History of Science. Chicago, IL: University of Chicago Press, 2005.

Haas, P. M.: Introduction: Epistemic Communities and International Policy Coordination, 36, 1992.

Haddaway, N.R., Macura, B., Whaley, P. and Pullin, A.S.: ROSES RepOrting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environmental Evidence, 7, 1-8, https://doi.org/10.1186/s13750-018-0121-7, 2018.

Haeffner, M., Jackson-Smith, D., and Flint, C. G.: Social Position Influencing the Water Perception Gap Between Local Leaders and Constituents in a Socio-Hydrological System, Water Resour. Res., 54, 663–679, https://doi.org/10.1002/2017WR021456, 2018.

Haeffner, M., Hellman, D., Cantor, A., Ajibade, I., Oyanedel-Craver, V., Kelly, M., Schifman, L., and Weasel, L.: Representation justice as a research agenda for socio-hydrology and water governance, Hydrol. Sci. J., 66, 1611–1624, https://doi.org/10.1080/02626667.2021.1945609, 2021.

Hamilton, S.H., Pollino, C.A., Stratford, D.S., Fu, B. and Jakeman, A.J.: Fit-for-purpose environmental modeling: Targeting the intersection of usability, reliability and feasibility. Environmental Modelling & Software, 148, p.105278, 2022.

Haines, S.: Reckoning Resources: Political Lives of Anticipation in Belize's Water Sector, Technol. Stud., 32, 22, 2019.

Haraway, D.: Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective, Fem. Stud., 14, 575, https://doi.org/10.2307/3178066, 1988.

Haraway, D. J.: Manifesto for cyborgs: science, technology, and socialist feminism in the 1980s, Social. Rev., 80, 65–108, 1985.

Harmel, R.D., Smith, P.K., Migliaccio, K.W., Chaubey, I., Douglas-Mankin, K.R., Benham, B., Shukla, S., Muñoz-Carpena, R. and Robson, B.J.: Evaluating, interpreting, and communicating performance of hydrologic/water quality models considering intended use: A review and recommendations. Environ Model Softw., 57, 40-51, 2014.

Harvey, F. and Chrisman, N.: Boundary Objects and the Social Construction of GIS Technology, Environ. Plan. Econ. Space, 30, 1683–1694, https://doi.org/10.1068/a301683, 1998.

Hasala, D., Supak, S., and Rivers, L.: Green infrastructure site selection in the Walnut Creek wetland community: A case study from southeast Raleigh, North Carolina, Landsc. Urban Plan., 196, 103743, https://doi.org/10.1016/j.landurbplan.2020.103743, 2020.

Holländer, H. M., Bormann, H., Blume, T., Buytaert, W., Chirico, G. B., Exbrayat, J.-F., Gustafsson, D., Hölzel, H., Krauße, T., Kraft, P., Stoll, S., Blöschl, G., and Flühler, H.: Impact of modellers' decisions on hydrological a priori predictions, Hydrol. Earth Syst. Sci., 18, 2065–2085, https://doi.org/10.5194/hess-18-2065-2014, 2014.

Holifield, R.: How to speak for aquifers and people at the same time: Environmental justice and counter-network formation at a hazardous waste site. Geofor., 40(3), 363-372, 2009.

Holifield R.: Environmental justice as recognition and participation in risk assessment: negotiating and translating health risk at a superfund site in Indian country. Ann Assoc Am Geographers. 102:591–613, 2012.

Hulme, Mike.: Why we disagree about climate change: Understanding controversy, inaction and opportunity. Cambridge University Press, Cambridge, 432 pp., https://doi.org/10.1017/CBO9780511841200, 2009.

Jackson, S.: Water models and water politics: design, deliberation, and virtual accountability, Proc Int Conf Digit Gov Res, 95-104, 2006.

Jasanoff, S. and Kim, S.-H.: Containing the Atom: Sociotechnical Imaginaries and Nuclear Power in the United States and South Korea, Minerva, 47, 119–146, https://doi.org/10.1007/s11024-009-9124-4, 2009.

Jenkins, D. G. and McCauley, L. A.: GIS, SINKS, FILL, and Disappearing Wetlands: Unintended Consequences in Algorithm Development and Use, SAC'06, Dijon, France, 6, 2006.

Jensen, C. B.: A flood of models: Mekong ecologies of comparison, Soc. Stud. Sci., 50, 76–93, https://doi.org/10.1177/0306312719871616, 2020.

Junier, S. J.: Modelling expertise: Experts and expertise in the implementation of the Water Framework Directive in the Netherlands, Delft University of Technology, https://doi.org/10.4233/UUID:EEA8A911-F786-4158-A67E-B99663275BF8, 2017.

King, J. L. and Kraemer, K. L.: Models, Facts, and the Policy Process: The Political Ecology of Estimated Truth, Center for Research on Information Systems and Organizations, Irvine, 1993.

Knorr-Cetina, K.: Epistemic cultures: how the sciences make knowledge, Harvard University Press, Cambridge, Mass, 329 pp., 1999.

Kouw, M.: Standing on the Shoulders of Giants—And Then Looking the Other Way? Epistemic Opacity, Immersion, and Modeling in Hydraulic Engineering, Perspect. Sci., 24, 206–227, https://doi.org/10.1162/POSC_a_00201, 2016.

Kouw, M.: Risks in the Making: The Mediating Role of Models in Water Management and Civil Engineering in the Netherlands, Berichte Zur Wiss., 40, 160–174, https://doi.org/10.1002/bewi.201701823, 2017.

Kroepsch, A. C.: Groundwater Modeling and Governance: Contesting and Building (Sub)Surface Worlds in Colorado's Northern San Juan Basin, Engag. Sci. Technol. Soc., 4, 43–66, https://doi.org/10.17351/ests2018.208, 2018.

Krueger, T. and Alba, R.: Ontological and epistemological commitments in interdisciplinary water research: Uncertainty as an entry point for reflexion. Frontiers in Water, 4, p.1038322, 2022.

Krueger, T., Maynard, C., Carr, G., Bruns, A., Mueller, E. N., and Lane, S.: A transdisciplinary account of water research, WIREs Water, 3, 369–389, https://doi.org/10.1002/wat2.1132, 2016.

Laborde, S.: Environmental Research from Here and There : Numerical Modelling Labs as Heterotopias, Environ. Plan. Soc. Space, 33, 265–280, https://doi.org/10.1068/d14128p, 2015.

Ländstrom, C., Whatmore, S. J., and Lane, S. N.: Virtual engineering: computer simulation modelling for flood risk management in England, Sci. Technol. Stud., 24, 3–22, 2011a.

Landström, C., Whatmore, S. J., Lane, S. N., Odoni, N., Ward, N., and Bradley, S.: Coproducing flood risk knowledge: redistributing expertise in critical "participatory modelling," Environ. Plan. Econ. Space, 43, 1616–1633, 2011b.

Lane, S.N., Odoni, N., Landström, C., Whatmore, S.J., Ward, N. and Bradley, S.: Doing flood risk science differently: an experiment in radical scientific method. Transactions of the Institute of British Geographers, 36(1),15-36, 2011a.

Lane, S. N., Landström, C., and Whatmore, S. J.: Imagining flood futures: risk assessment and management in practice, Philos. Trans. R. Soc. Math. Phys. Eng. Sci., 369, 1784–1806, https ://doi.org/10.1098/rsta.2010.0346, 2011b.

Lane, S.N., 2012. Making mathematical models perform in geographical space(s). Chapter 17 in Agnew, J. and Livingstone, D. Handbook of Geographical Knowledge. Sage, London

Lane, S.N., November, V., Landström, C. and Whatmore, S.: Explaining rapid transitions in the practice of flood risk management. Annals of the Association of American Geographers, 103(2), 330-342, 2013.

Lane, S. N.: Acting, predicting and intervening in a socio-hydrological world, Hydrol. Earth Syst. Sci., 18, 927–952, https://doi.org/10.5194/hess-18-927-2014, 2014.

Lasswell, Harold. D.: Politics: Who Gets What, When, How, Whittlesey House, Cleveland, New York, 264, https://doi.org/10.1007/978-3-531-90400-9_60, 1936.

Latour, B.: When things strike back: a possible contribution of "science studies" to the social sciences, Br. J. Sociol., 51, 107–123, 2000.

Latour, B.: The promises of constructivism, in Ihde D. (Ed) Chasing Technology : Matrix of Materiality, Indiana Series for the Philosophy of Science, Indiana University Press, 27-46, 2003.

Latour, B. and Woolgar, S.: Laboratory life: the construction of scientific facts, Princeton University Press, Princeton, N.J, 294 pp., 1986.

Law, J., After method: Mess in social science research. Psychology Press, 2004.

Leigh Star, S.: This is Not a Boundary Object: Reflections on the Origin of a Concept, Sci. Technol. Hum. Values, 35, 601–617, https://doi.org/10.1177/0162243910377624, 2010.

Linton, J.: Modern water and its discontents: a history of hydrosocial renewal, WIREs Water, 1, 111–120, https://doi.org/10.1002/wat2.1009, 2014.

Linton, J. and Budds, J.: The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. Geoforum, 57, 170-180, 2014.

Litfin, K. T.: The Gendered Eye in the Sky: A Feminist Perspective on Earth Observation Satellites, Front. J. Women Stud., 18, 26, https://doi.org/10.2307/3346964, 1997.

Losee, R. M.: A discipline independent definition of information, J. Am. Soc. Inf. Sci., 48, 254–269, https://doi.org/10.1002/(SICI)1097-4571(199703)48:3<254::AID-ASI6>3.0.CO;2-W, 1997.

MacKenzie, D. A. and Wajcman, J. (Eds.): The social shaping of technology, 2nd ed., Open University Press, Buckingham [Eng.] ; Philadelphia, 462 pp., 1999.

MacKenzie D.: An engine, not a camera: How financial models shape markets. The MIT Press, Cambridge, 392 pp., 2008.

Macnaghten, P.: Governing Science and Technology: From the Linear Model to Responsible Research and Innovation, in: The Cambridge Handbook of Environmental Sociology, edited by: Legun, K., Keller, J., Bell, M., and Carolan, M., Cambridge University Press, 347–361, https://doi.org/10.1017/9781108554510.023, 2020.

Maeda, E. E., Haapasaari, P., Helle, I., Lehikoinen, A., Voinov, A., and Kuikka, S.: Black Boxes and the Role of Modeling in Environmental Policy Making, Front. Environ. Sci., 9, 629336, https://doi.org/10.3389/fenvs.2021.629336, 2021.

Meenar, M., Fromuth, R. and Soro, M.: Planning for watershed-wide flood-mitigation and stormwater management using an environmental justice framework. Environmental Practice, 20(2-3), 55-67, 2018.

Melsen, L. A.: It Takes a Village to Run a Model—The Social Practices of Hydrological Modeling, Water Resour. Res., 58, https://doi.org/10.1029/2021WR030600, 2022.

Melsen, L. A., Addor, N., Mizukami, N., Newman, A. J., Torfs, P. J. J. F., Clark, M. P., Uijlenhoet, R., and Teuling, A. J.: Mapping (dis)agreement in hydrologic projections, Hydrol. Earth Syst. Sci., 22, 1775–1791, https://doi.org/10.5194/hess-22-1775-2018, 2018a.

Melsen, L. A., Vos, J., and Boelens, R.: What is the role of the model in socio-hydrology? Discussion of "Prediction in a socio-hydrological world," Hydrol. Sci. J., 63, 1435–1443, https://doi.org/10.1080/02626667.2018.1499025, 2018b.

Melsen, L. A., Teuling, A. J., Torfs, P. J. J. F., Zappa, M., Mizukami, N., Mendoza, P. A., Clark, M. P., and Uijlenhoet, R.: Subjective modeling decisions can significantly impact the simulation of flood and drought events, J. Hydrol., 568, 1093–1104, https://doi.org/10.1016/j.jhydrol.2018.11.046, 2019.

Mendoza, P. A., Clark, M. P., Mizukami, N., Gutmann, E. D., Arnold, J. R., Brekke, L. D., and Rajagopalan, B.: How do hydrologic modeling decisions affect the portrayal of climate change impacts?, Hydrol. Process., 30, 1071–1095, https://doi.org/10.1002/hyp.10684, 2016.

Molle, F.: Nirvana Concepts, Narratives and Policy Models: Insights from the Water Sector, 1, 26, 2008.

Morgan, M. S., & Morrison, M. (Eds.): Models as mediators: Perspectives on natural and social science (No. 52). Cambridge University Press, Cambridge. 401 pp., 1999.

Munk, A. K.: Risking the Flood: Cartographies of Things to Come, University of Oxford, Oxford, 268 pp., 2010.

Nearing, G.S., Kratzert, F., Sampson, A.K., Pelissier, C.S., Klotz, D., Frame, J.M., Prieto, C. and Gupta, H.V.: What role does hydrological science play in the age of machine learning?. Water Resources Research, 57(3), p.e2020WR028091, https://doi.org/10.1029/2020WR028091, 2021.

Opitz-Stapleton, S. and MacClune, K.: Chapter 11 Scientific and Social Uncertainties in Climate Change: The Hindu Kush-Himalaya in Regional Perspective, in: Community, Environment and Disaster Risk Management, vol. 11, edited by: Lamadrid, A. and Kelman, I., Emerald Group Publishing Limited, 207–237, https://doi.org/10.1108/S2040-7262(2012)0000011017, 2012.

Packett, E., Grigg, N. J., Wu, J., Cuddy, S. M., Wallbrink, P. J., and Jakeman, A. J.: Mainstreaming gender into water management modelling processes, Environ. Model. Softw., 127, 104683, https://doi.org/10.1016/j.envsoft.2020.104683, 2020.

Petticrew, M., & Roberts, H.: Systematic reviews in the social sciences: A practical guide. Blackwell Publishing Ltd, Malden (USA), 352 pp., 2006.

Pielke Jr. R.A.: The honest broker: making sense of science in policy and politics. Cambridge University Press, New York, 188 pp., https://doi.org/10.1017/CBO9780511818110, 2007.

Puy, A., Sheikholeslami, R., Gupta, H. V., Hall, J. W., Lankford, B., Lo Piano, S., Meier, J., Pappenberger, F., Porporato, A., Vico, G., and Saltelli, A.: The delusive accuracy of global irrigation water withdrawal estimates, Nat. Commun., 13, 3183, https://doi.org/10.1038/s41467-022-30731-8, 2022.

Rainwater, K., Stovall, J., Frailey, S., and Urban, L.: Transboundary Impacts on Regional Ground Water Modeling in Texas, Ground Water, 43, 706–716, https://doi.org/10.1111/j.1745-6584.2005.00068.x, 2005.

Ramsey, K.: GIS, modeling, and politics: On the tensions of collaborative decision support, J. Environ. Manage., 90, 1972–1980, https://doi.org/10.1016/j.jenvman.2007.08.029, 2009.

Refsgaard, J.C. and Henriksen, H.J.: Modelling Guidelines—Terminology and Guiding Principles. Advanc. Water Res., 27, 71-82, http://dx.doi.org/10.1016/j.advwatres.2003.08.006, 2014.

Rusca, M., Mazzoleni, M., Barcena, A., Savelli, E., & Messori, G. (2023). Speculative Political Ecologies:(re) imagining urban futures of climate extremes. Journal of Political Ecology, 30.

Rusca, M. and Di Baldassarre, G.: Interdisciplinary Critical Geographies of Water: Capturing the Mutual Shaping of Society and Hydrological Flows, Water, 11, 1973, https://doi.org/10.3390/w11101973, 2019.

Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Nelson Espeland, W., Kay, J., Lo Piano, S., Mayo, D. and Pielke Jr, R.: Five ways to ensure that models serve society: a manifesto, Nature, 2020.

Saltelli, Andrea, and Monica Di Fiore, eds. The Politics of Modelling: Numbers Between Science and Policy. Oxford University Press, pp. 231, 2023.

Sanz, D., Vos, J., Rambags, F., Hoogesteger, J., Cassiraga, E., and Gómez-Alday, J. J.: The social construction and consequences of groundwater modelling: insight from the Mancha Oriental aquifer, Spain, Int. J. Water Resour. Dev., 35, 808–829, https://doi.org/10.1080/07900627.2018.1495619, 2019.

Shrader-Frechette, K.: Hydrogeology and framing questions having policy consequences, Philosophy of Science, 64(S4), S149-S160, 1997.

Sismondo, S.: Models, Simulations, and Their Objects, Sci. Context, 12, 247–260, https://doi.org/10.1017/S0269889700003409, 1999.

Srinivasan, V., Sanderson, M., Garcia, M., Konar, M., Blöschl, G., and Sivapalan, M.: Prediction in a socio-hydrological world, Hydrol. Sci. J., 1–8, https://doi.org/10.1080/02626667.2016.1253844, 2016.

Srinivasan, V., Sanderson, M., Garcia, M., Konar, M., Blöschl, G., and Sivapalan, M.: Moving socio-hydrologic modelling forward: unpacking hidden assumptions, values and model structure by engaging with stakeholders: reply to "What is the role of the model in socio-hydrology?," Hydrol. Sci. J., 63, 1444–1446, https://doi.org/10.1080/02626667.2018.1499026, 2018.

Star, S. L. and Griesemer, J. R.: Institutional Ecology, `Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39, Soc. Stud. Sci., 19, 387–420, https://doi.org/10.1177/030631289019003001, 1989.

Stengers, I., Another science is possible: A manifesto for slow science. John Wiley & Sons, 2018.

Thompson, E. L. and Smith, L. A.: Escape from model-land, Economics, 13, 20190040, https://doi.org/10.5018/economics-ejournal.ja.2019-40, 2019.

Trombley, J. M.: An Environmental Anthropology of Modeling and Management on the Chesapeake Bay Watershed, University of Maryland, College Park, 2017.

Turnhout, E., Hisschemöller, M., and Eijsackers, H.: Ecological indicators: between the two fires of science and policy. Ecol. Indic., 7(2), 215-228. https://doi.org/10.1016/j.ecolind.2005.12.003, 2007

Turner, M. D. Production of environmental knowledge: Scientists, complex natures, and the question of agency. Knowing Nature: Conversations at the Intersection of Political Ecology and Science Studies. University of Chicago Press, Chicago, 25–29, 2011.

Venot, J.-P., Vos, J., Molle, F., Zwarteveen, M., Veldwisch, G. J., Kuper, M., Mdee, A., Ertsen, M., Boelens, R., Cleaver, F., Lankford, B., Swatuk, L., Linton, J., Harris, L. M., Kemerink-Seyoum, J., Kooy, M., and Schwartz, K.: A bridge over troubled waters, Nat. Sustain., https://doi.org/10.1038/s41893-021-00835-y, 2021.

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P.D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., Ramu, P.: Modelling with stakeholders – Next generation. Environ Model Softw, 77, 196-220. https://doi.org/10.1016/j.envsoft.2015.11.016, 2016.

Voinov, A., Seppelt, R., Reis, S., Nabel, J.E. and Shokravi, S.:Values in socio-environmental modelling: Persuasion for action or excuse for inaction. Environ Model Softw, 53, 207-212, http://dx.doi.org/10.1016/j.envsoft.2013.12.005, 2014.

Wesselink, A., de Vriend, H., Barneveld, H., Krol, M. and Bijker, W.: Hydrology and hydraulics expertise in participatory processes for climate change adaptation in the Dutch Meuse. Water Sci Technol, 60(3), 583-595, 2009.

Wesselink, A., Kooy, M., and Warner, J.: Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. WIREs Water, 4, https://doi.org/10.1002/wat2.1196, 2017.

Whatmore, S.J. and Landström, C.: Manning's N: Putting roughness to work. In Howlett, P. and Morgan, M.S. eds., How well do facts travel?: The dissemination of reliable knowledge. Cambridge University Press, 111-135, 2010.

Wheeler, K. G., Hall, J. W., Abdo, G. M., Dadson, S. J., Kasprzyk, J. R., Smith, R., and Zagona, E. A.: Exploring Cooperative Transboundary River Management Strategies for the Eastern Nile Basin, Water Resour. Res., 54, 9224–9254, https://doi.org/10.1029/2017WR022149, 2018.

Wheeler, K.G., Robinson, C.J. and Bark, R.H.: Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins. Reg Environ Change, 18, 1607-1619, 2018.

Woolgar, S. and Cooper, G., Do artefacts have ambivalence: Moses' bridges, winner's bridges and other urban legends in S&TS. Social studies of science, 29(3), 433-449, 1999.

Zwarteveen, M., Kemerink-Seyoum, J. S., Kooy, M., Evers, J., Guerrero, T. A., Batubara, B., Biza, A., Boakye-Ansah, A., Faber, S., Cabrera Flamini, A., Cuadrado-Quesada, G., Fantini, E., Gupta, J., Hasan, S., ter Horst, R., Jamali, H., Jaspers, F., Obani, P., Schwartz, K., Shubber, Z., Smit, H., Torio, P., Tutusaus, M., and Wesselink, A.: Engaging with the politics of water governance, WIREs Water, 4, https://doi.org/10.1002/wat2.1245, 2017.