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

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Abstract. ~~Hydrological models~~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 ~~its~~their neutrality. Our ~~systematic~~ review shows that in the scientific literature relatively little attention is given to the power of models to influence development processes and outcomes in water ~~governance. The review also shows that there is much to learn from those who are willing to be openly reflexive on the influence of models. In agreement with this emerging body of work, we call for power-sensitive modelling, which means that people are critical about how models are made and with what implications, taking into account that: i) The choice for and use of models for water management happens in a political context and has political consequences; ii) Models are the result of choices made by modellers and – since they have political consequences – these need to be made as explicit as possible as opposed to being "blackboxed"; iii) To consider the ethical implications of the choices of modellers, commissioners, and users, and to improve accountability, models and their power need to be understood by connecting the inner workings of a model with a contextual understanding of its development and use, iv) Action is taken upon these implications by democratising modelling processes.~~ 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: Work towards just and equitable water distributions; have a broad take on modelling beyond programming and coding; contextualise water modelling to engage with impact; be transparent on the expectations and choices made; foster accountability; democratise modelling which entails giving space to multiple knowledges, multiple stakeholders, and incorporating marginalised voices of peoples and nature in all stages of 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.

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 aimspurposes, 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). Models are oftenSince 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.

presented or understood as neutral tools, although extensive research exists on how models are shaped by policy projects, institutional backgrounds, and gendered relations and experiences (Sismondo, 1999; Knorr-Cetina, 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 is1999; MacKenzie, 2006; Melsen et al., 2018a; Addor and Melsen, 2019). An additional challenge is that models become increasingly complex and travel easily between places of application, with different elements developed by different people. It complicates the possibility to fully understand how a model shapes world views (Kouw, 2016), and calls for being critical of the applicability of a model

(Beven, 2019). The portrayal of neutrality thus seems ironic, and increasingly so given the societal relevance and aim of tackling water challenges of almost every hydrological modelling paper. And – as evidenced by vibrant discussions – the different modelling communities are well aware that any one model could have turned out differently with different assumptions, simplifications, data and if different people had developed it, even if the nuances of these dynamics and their political charge are not fully recognised.. 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).

Fundamental discussions on the influence of models on decision making processes have been ongoing in scientific and public debates on climate change, the financial sector, and social media (Turnhout, 2007; Pielke Jr., 2007; MacKenzie, 2008; Hulme, 2009). However, these discussions have remained marginal in water research, and are only recently, and slowly, gaining ground. This development occurs in parallel with discussions on how the interplay of water and social relation should be understood and conceptualised, and how hydrology, water management and governance should be approached (Wesselink et al., 2017; Zwarteveen et al., 2017; Rusca and Di Baldassarre, 2019). An important and often overlooked element of how models have influence is the assumptions about water-society relations, which reflect particular visions concerning how the world is and ought to be and which determine important aspects of a model's functioning (MacKenzie and Wajcman, 1999; Krueger and Alba, 2022).

Despite the number of quantitative models developed and used for understanding and managing water, seemingly little seems to have been written on the influence models have in practice. This is interesting not only from a science studies perspective but also for hydrology as a discipline, which one would think would be interested in whether intended impacts of models come true. This article therefore researches how academic literature engages with the influence models have in the water sector, based on a narrative and systematic literature review. 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 power 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 power

ForWe 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). Models are both usedThe 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). This; Lane, 2014). Modelling can be done in laboratory- or applied settings, and for a narrowly prescribed purpose, for example to calculatepurposes 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). Models thus (re)inforce societal influence because they are materialisations of ideas on how the world functions or should function, sustained by particular forms of (expert) knowledges, values and understandings (Haas, 1992; MacKenzie and Wajcman, 1999; Krueger and Alba, 2022).

This societal influenceSecond, to unpack both how power is clearest and most direct through the output of inscribed in models, used in decision making processes. However, models also interact with social processes through (re-)producing or at times challenging discourses, which and how these might happen more or less implicitly (Krueger and Alba, 2022). In this processgain power it matters whose information andis essential to place our analysis in science and technology debates about what knowledge is taken into account.

And information and knowledge enter and exit models at every stage of the model development process, so the relation of models with social processes does not only happen with a final product but throughout the model development chain. This is because the model developmentand 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. It may be that specific elements of the modelling process have more influence than the final product.

We use the term political to capture this broad influence of modelling, or in other words, the mutual shaping of models and society. 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, both have a technical and a social life, which implies that their development isare shaped by people and their norms, values and institutions, as well as thatand 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). There are increasingly calls; 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 this political charge of models,that their influence might vary from non- modellers and modellers alike, for instance to design more transparent and inclusivecase 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 (Maeda, 2021), orhelp 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.

to be explicit about the norms, values and limitations that are embedded in the process and any final model (Puy et al., 2022).

~~3~~ 3 Methodology

This article is based on a literature review that combines a narrative review (Cronin et al., ~~2008) and a systematic review.~~2008) and a systematic review to explore if and how in scientific articles is reflected on how water models have or gain influence. The narrative review was used to support the development of the query for the systematic review, and to include relevant articles that may fall outside of the scope of the query. This includes articles that were suggested by the HESS community and reviewers after the open review of this paper. The systematic part of the review is used to identify a larger set of relevant and representative articles and to examine the articles that discuss the influence of water models. We followed the ROSES (RepOrting standards for Systematic Evidence Syntheses) method (Haddaway et al., 2018), which is specifically designed for the field of environmental management. The method provides a ~~clear~~ three-staged approach that includes searching, screening and critical appraisal. It explicitly allows for additional articles to be included in the screening process to identify the best possible sample of relevant literature. This last step allows a merger with the articles obtained through the narrative review method. Each step is documented and available as additional material to this article.

In order to define the query for the systematic literature review, we first selected articles that represented engagement with the different ways in which ~~water models shape water governance.~~models and technology gain or have (potential) influence, resulting in 136 articles of which 60 discuss water models, of which 26 we found are reflexive on the power the models have. For this selection we built on a diverse set of expertise as an interdisciplinary group of academics who are part of a research-collaboration on critical research on water modelling. ~~Based on the~~The keywords and words used in the titles and abstracts of the articles included in this first ~~set of papers,~~selection were compiled, but their diversity did not form a ~~database~~solid basis for a query ~~was constructed.~~. We then turned to identifying words that related to the act of reflecting on influence and power. The final query is defined as TITLE-ABS-KEY ~~(“~~(“water model*” OR “~~hydrolog~~hydr* model*” ~~)~~OR “groundwater model*”) AND TITLE-~~-~~ABS-KEY (~~-~~justice OR equit* OR politic* OR ethic~~*). We selected these keywords as they stand for different ways models influence water governance.~~*). ‘Politic*’ and ‘equit*’ were chosen as keywords because they broadly relate to how models influence issues of distribution~~. Focused on~~, in relation to who gets what, when and how (Lasswell, 1936). ‘Justice’ and ‘ethic*’ were chosen to capture those articles that reflect on ~~the~~ 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’ ~~because the scanning of titles and abstracts showed that~~. Earlier attempts to define a suitable query included these keywords ~~were too broad and yielded many~~ resulted in large quantities of articles ~~most of which~~ 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 – July 2022.December 2023. The query resulted in 293408 unique documents. Following the ROSES protocol, we screened the articles to identify those that explicitly addressed or analysed the power and influence of the modelling process.(potential) influence of models, including a reflection on why modelling was chosen, what assumptions are embedded in the choice for a modelling process, the input, as well as the model, how available technology enables or excludes, and how the process and output are being communicated and questioned, and by whom. We did a first screening by title and thus excluded three articles. 29040 documents that had no author listed, were not in English, or did not discuss water or water models. 368 Articles were screened by abstract fromof which 3398 abstracts showed that the article may reflect on the influence of water models and which subsequently were selected for screening the full text. For three articles, the full text could not be retrieved. Eight articles were excluded as they did not engage with the influence of models, and one did not engage with quantitative modelling. Thus, from the 293 articles, 21Of the 98 articles, 27 articles were finally selected. Following the elimination of four duplicates, 32 pre-screened articles from other sources were added based on our initial set of papers reviewed in the narrative style. From the 54 articles, six articles were omitted as they did not reflect on the ways models can gain or have influence, and 48 articles were through the query. This included inarticles that applied different methods to explore the potential influence of models, including the application of multiple methods for knowledge development, participatory modelling, or actively including vulnerable groups in the analysis, but that did not explicitly reflect on power relations between the model and its environment. In relation to the narrative review, we had pre-selected 30 articles and added four suggested by the HESS community, which we included for the critical appraisals (appraisal stages following the ROSES method, after the elimination of one duplicate. Figure 1). provides a graphic overview of the systematic literature review process and Appendix A provides an overview of the 61 articles included in the literature review. Those marked with "*" were pre-selected through the narrative literature review.

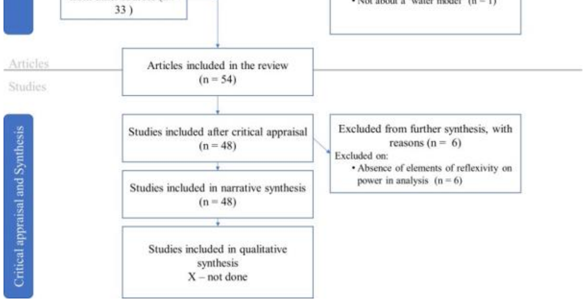

Figure 1: The result of the ROSES systematic literature review process

As the first step of the critical appraisal, the main points made in each of the articles on how models gain and have influence, or differently said, have socially and ecologically differentiating effects were identified and compared as to analyse the relationships within and between studies. Through different iterations of these central points, we finally distinguished 13 main topics that represent different phases of the production process of models, and based on these we identified four overarching themes. The main themes and related topics 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**
  - Modellers' choices matter

~~**4 Results: narrative synthesis**~~

~~The articles were analysed based on what aspects of the modelling process were discussed, the methodologies used, and the insights gained. Four specific aspects stood out: i) the mental models and policy projects that form the basis of a model's development are essential in problem framing and conceptualisation, ii) how modellers' choices influence its development,~~

  - ~~iii) the~~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
  - ~~on decision-making and how water is managed, and iv) engaging~~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

models. We make a note here that these engagements are not necessarily participatory. These four aspectsThe four themes are closely interrelated, and are not linear, and jointly form a model and modelling process. In the following, we use these aspects to structure the review. Table 1 provides an overview of the aspects of the in the modelling process and the articles that discuss these as their main

; thus, the fourteen topics could be seen as different layers of how models have or gain influence. They form the structure of the narrative synthesis, in which we elaborate how each theme. More details are included in Appendix A and topic plays out in practice.

Aspect of the modelling process	Publication (only short reference)
Mental models and policy projects	Bouleau, 2014; Budds, 2009; Deitrick et al., 2021; Fernandez, 2014; Godinez-Madrigal et al., 2019; Haeffner et al., 2021; Harvey and Chrisman, 1998; Khiavi et al., 2022; Laborde, 2015; Ländstrom et al., 2011; Munk, 2010; Packett et al., 2020; Ramsey, 2009; Sanz et al., 2019; Trombley, 2017; Wheeler et al., 2018
The influence of modellers' choices	Abbott and Vojinovic, 2014; Addor and Melsen, 2019; Babel et al., 2019; Budds, 2009; Dobson et al., 2019; Godinez-Madrigal et al., 2019; Haeffner et al., 2021; Haines, 2019; Hasala et al., 2020; Holländer et al., 2014; Jenkins and McCauley, 2006; Junier, 2017; Khiavi et al., 2022; Kouw, 2016; Lane et al., 2011; Lane, 2014; Melsen, 2022; Melsen et al., 2018, 2019; Mendoza et al., 2016; Packett et al., 2020; Rainwater et al., 2005; Sanz et al., 2019; Srinivasan et al., 2018; Trombley, 2017
The 'real-world' impact models have	Bouleau, 2014; Budds, 2009; Connor et al., 2008; Cornejo P. and Niewöhner, 2021; Fernandez, 2014; Godinez-Madrigal et al., 2019; Hasala et al., 2020; Jensen, 2020; Kouw, 2017; Kroepsch, 2018; Melsen et al., 2018; Rainwater et al., 2005; Wardropper et al., 2017
Engaging with non-modellers through models	Andersson, 2004; Bremer et al., 2020; Budds, 2009; Connor et al., 2008; Cornejo P. and Niewöhner, 2021; Constanza and Ruth, 1998; Falconi and Palmer, 2017; Garcia-Cuerva et al., 2016; Godinez-Madrigal et al., 2019; Haeffner et al., 2018; Jensen, 2020; Kouw, 2017; Ländstrom et al., 2011; Landström et al., 2011; Melsen et al., 2018; Opitz-Stapleton and MacClune, 2012; Rainwater et al., 2005; Wardropper et al., 2017; Wheeler et al., 2018; Sanz et al., 2019

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; 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 ~~in relation to the aspects of the modelling process they discuss~~reviewed and related theme.

~~4.1~~ 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 ide

as 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, ~~26~~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

~~**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

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

4.1.2 Knowing the world in specific ways

In the

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~~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

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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. (~~2018~~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

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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 ~~towards~~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 Articles discussing 4.2 The influence of modellers' choices

The following set of articles focuses on how a model is developed. 31 OfThirty 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 Modellers' choices matter

4.2.1 Modellers' choices matter

Modellers' choices matter, as they influence both the development and output of a model. HolländerHollaender 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'framings of two models of two water resource systems in the UK, show how these specific representationrepresentations of the systems influenced what 'optimal' 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 4.2.2 Why choices are made: familiarity, habits, and 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 inon 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 typicaltypically 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. ~~These five~~

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~~ ~~Modellers~~4.2.3 Modelling developed through ~~interaction~~interactions and institutional interests

Landström et al. (~~2011~~2011a) draw attention to a wide range of actors that influence modelling by assessing the practices of modelling flood risk ~~of~~, 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~~ 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

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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

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When modelling is presented as a neutral scientific process, a lack of attention to the context and its power-relations can have n e g a t i v e e f f e c t s f o r m a r g i n a l i s e d g r o u ps 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. ~~Also Khiavi et al. (2022) show how modelling results should be used contextually and placed into engagement with other forms of knowledge. In line with this, they combined physical data, hydrological modelling and co- managerial approaches, which consists of apprehending the perspectives of local authorities, technical experts and residents to prioritise sub-watersheds based on flood generation potential in the Cheshmeh-Kileh Watershed in Iran.~~

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~~ 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 ~~and Bousquet,~~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, ~~30~~23 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~~ 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. ~~They~~The authors warn against thinking too much from a modelling and consultant perspective instead of a community perspective~~. For instance, they argue against~~, 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 ~~at~~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

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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. ~~As modelling inhibits more uncertainty than measurements, the~~ 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. (~~2011~~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

~~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 sociohydrological frameworks - including models – that seek to unravel the interplay between water and society. Based on this review, they argue that sociohydrological 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 ~~have~~having shared understandings of the water supply system might lead to an oversimplification of ~~sociohydrological~~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~~

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

There are several authors who reflect on ~~hydroinformatics,~~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~~) discussed how hydroinformatics has changed. It is increasingly argued within the field that its insights can be best developed with stakeholders that 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). The reason this article is discussed in~~ ; Bergstrom, 1991). Clark (1998) also points to the ~~section about modellers' choices is that it emphasises the role~~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 ~~claims that the “quality of the character~~auditing, Clark also points towards the responsibility of the modeller~~, becomes inseparable from~~: “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 ~~quality~~light of their “ethical goodness" or "ethical badness" for the ~~model within~~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 ~~quality~~impact of ~~the total production” (ibid: pp. 528-529).~~its use on society. Also Lane (2014) ~~came to the same conclusion by deconstructing~~ based his suggestions for principles for socio-hydrological modellers on personal experiences with hydrology. Based on a deconstruction of practices of hydrological science, ~~and rethinking hydrology in the context of the societal impact it potentially has.~~ Lane ~~subsequently proposed principles for socio-hydrological modellers, including~~proposes to i) ~~embracing~~embrace conflict and controversy in science, ii) ~~looking~~look for extremes to test knowledge, but doing this in a way that is sensitive to the political and ethical ramifications, iii) ~~using~~use real-life events to think with and step out of ‘model-land’, and iv) co-~~producing~~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 sociohydrological 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.

4.5 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. Themes include: mental models and policy projects, the influence of modellers' choices, 'the real-world' impact models have, and engaging with non-modellers through models. Interestingly, we saw that in the articles reviewed there is a limited attention for the influence of vested interests – including private or academic interests - on the choice of technologies used, as well as limited attention for the way output is presented. Yet, we see that the list of themes and sub-topics forms a starting point of elements to take into account when researching or engaging with the influence of water models. 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?'.

Another observation is that several of the articles that discuss the impact of a model in practice, do not specify the specific 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).

This can be related to the studies on environmental modelling analysing the effects of the modelling process

that can sometimes be more important than the model itself (Étienne, 2011). However, a case can also be made that it would be useful for specific modellers to have such information, for instance through additional material to the article, perhaps especially when it comes to modelling and understanding its societal impact.

Our 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. 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. However, the call to address responsibility and accountability of water modellers by Abbott and Vojinovic (2014), Lane, (2014), and Melsen, Vos, and Boelens (2018) suggest and confirm that reflexivity and acting upon it, is not a common practice. Although making space and taking time for reflexivity, including discussions on ethics and accountability, adds further complexity to the modelling process. Yet, it also opens new possibilities to strengthen models and their outcomes. As the review shows, specifically when articles engage with the question of the influence of models on water governance, there are important lessons to be drawn. All authors have in common is that they spent multiple years in engagement with their respective case studies, either through longer research projects or PhD projects. It therefore calls for doing slow science (Stengers, 2017), in which we get out of model-land and take time to deeply engage with the context, the tools and knowledge applied, as well as with each other.

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 shows that models shape the world around them, and the world around models shape them in return in many overt and more covert ways, influencing who is seen or not, and how, and possibly also who gets what, when and how. 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). Of course, a model is never solely responsible, but there are opportunities to consciously engage with the interplay of power imbalances in the setting a model is made and applied in, as well as the influences a model has, for instance through supporting or legitimising certain policy projects, by including or excluding people or things in certain ways. Approaching models as neutral tools may conceal opportunities to do modelling in support of more just and equitable water distributions. 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.

Based on the literature review , the open review discussion process and our own experiences, we identify following considerations that can guide power-sensitive modelling (refined based on Chilvers and Kearnes, 2015; Doorn, 2012; Krueger et al., 2016; Lane, 2014; Saltelli et al., 2020; Venot et al., 2021; Voinov, 2014; Zwarteveen et al., 2017;) :

- **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. We have a 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). This requires consciously defining 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).

- **Have a broad take on modelling:** 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).

- **Contextualise water modelling to engage with impact:** Adapt the development of a water model 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)
- **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).
- **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. (See for example: Bergstrom, 1991, Lane et al., 2011, Meenar et al, 2018).
- **Democratise modelling:** Giving space to multiple knowledges, multiple stakeholders, and incorporating marginalised voices of peoples and nature in all stages of the modelling (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 six 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 ~~in the water sector~~. Driven by ~~on~~ an ~~observation~~hypothesis that there are few scientific articles that critically unpack water models and related modelling processes and impacts, we have conducted both a narrative and systematic literature review to assess whether our assumption is correct, and secondly to identify what lessons we can draw from existing literature. ~~From~~Of the ~~293~~408 articles included in the systematic literature review, ~~21~~27 were finally included in critical appraisal. In addition, ~~28~~30 articles were added to the critical appraisal through the narrative review~~.~~ and four as suggested by the HESS community. The ~~complete~~ literature review ~~shows that most articles do not critically unpack~~ reveals how models~~, nor seek to make their influence explicit. However, we can also confirm that there is a small, yet growing, body of literature that does so. The articles included in the critical appraisal show that the topic of the influence models have on water management clearly finds itself at the crossroads of different scientific fields. The contributions are often based~~

on longitudinal research by people engaged in modelling processes (see for instance Kroepsch, 2018), through PhD projects (Such as Munk, 2010 ; Kouw, 2016; Junier, 2017; Melsen et al., 2018a; Godinez-Madrigal et al., 2019; Cornejo and Niewöhner, 2021;), or as theme within a research department (Landström et al., 2011; Lane et al., 2011; Ländstrom et al., 2011). The case studies included in the review show how rich shape, and diverse modelling processes are, and how they are non-linear and are shaped, by the context they are developed and used in. In this section, we reflect on the insights gained. social and material aspects of the world we live in.

The review also provides insights in the different ways research can be done on the influence of water models. When it comes to mental models and policy projects, it becomes clear from the articles reviewed that models are shaped by values, norms, and ideas on what the world looks like, what it should look like, and how it can be known. Models may be shaped by a group that shares similar values, norms, and ideas of how the world functions (epistemic communities), or through the negotiation between groups with very different worldviews. Developing models that are explicitly grounded in contrasting knowledge claims and worldviews is often argued to be an effective strategy to avoid rejection by users or societal actors with very different worldviews. Furthermore, this approach can place models in the position of a boundary object that allows different people to use it and that facilitates collaboration. The articles also show that a mental, or conceptual, model, as an 'ideal type' of the final model, is quickly influenced and restricted by limitations in technology and data availability, and it is not always identifiable what such an ‘ideal type’, or multiple ideal types, would look like unconstrained by technology and data.

Beyond the mental models and policy choices, other more technical choices influence modelling outcomes. ~~Melsen et al. (2019) and Dobson et al. (2019) quantified the impacts of different modelling choices to show that it is important to make these choices explicit.~~ To further understand how choices are made, several articles analysed modelling processes based on interviews and surveys or based on practice-theoretic research to understand the role of social factors in this process~~.~~ (ref). It is shown that familiarity and habits to a certain extent drive the choice for specific modelling approaches, and that not only the modeller themselves, but also colleagues (Melsen, 2022), as well as managers, decision makers, and developers influence the modelling process. Kouw (2016) showed that reflexivity does happen during modelling processes, such as balancing detail with run-time and considering models as objects to confront rather than accepting them as truth, although opaqueness and black boxing may make this difficult once the model is finished.

When it comes to the impact models have on decision making and shaping the ‘real’ world, the case studies highlighted in section 4.3 all have in common that they are rich in description of the context the modelling practices take place in. The authors dedicated attention to wishes and knowledges of stakeholders, technicalities and limitations of the model and the social consequences the model has, presenting modelling as an intrinsically social process. They also criticise modelling processes that largely overlook socio-political and economic considerations and exclude alternative views on the root-causes and dynamics of, for example, water scarcity problems. ~~All authors have in common is that they spent multiple years in engagement with their respective case studies.~~

Lastly, engaging with non-modellers is an important theme in the articles reviewed, and they show very different approaches on how to engage with non-modellers in processes where modelling is central. All start from the aim of better connecting to a wide range of people, but how this should be done and with what intention differs greatly, ranging from improving the connection between model outcomes and policies, to amplifying the wishes of the population, or to increasing fair and equitable water allocation. In relation to the influence on non-modellers, suggestions are made to address the responsibility for accountability that the modeller has by Abbott and Vojinovic (2014), Lane, (2014), and Melsen, Vos, and Boelens (2018). The authors of these articles draw on personal experiences to suggest how modelling processes can be improved. Instead of taking the model as a starting point, they explicitly call for reflection on the intention of modelling processes, and subsequently who and what is included and excluded. This is a distinctly different approach from the ~~272~~381 articles that were excluded from the critical appraisal. The main reason for exclusion is that most articles 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 as to how the model can achieve these expectations. It shows that not engaging with the potential or actual influence of models is	an ignorance that is persistent.

We found a particular set of papers through our methodology, based on the narrative review and query (TITLE-ABS-KEY ("water model*" OR "hydrolog* 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, as we take a broad perspective on the influence of models, grounded on the idea that modelling processes are not linear and that they shape are shaped by society in different ways. Our approach has influenced the outcomes. For example, many of the words commonly used to describe the influence of models, (including reflexivity, influence, power, accountability and responsibility) proofed to be multiple-meaning words also used to describe specific – yet different – processes in modelling. The value and diversity of the 61 articles that are included in this review, and all differently unpack and critically engage with the influence of models on water governance, demonstrate that there is a merit in adding more case studies. Studying and doing power This made it necessary to specify the query with the risk of missing relevant articles. 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. However, the call to address responsibility and accountability of modellers by Abbott and Vojinovic (2014), Lane, (2014), and Melsen, Vos, and Boelens (2018) suggest and confirm that reflexivity and acting upon it, is not a common practice. Moreover, power disparities between those involved and affected as well as the power of models, are addressed by only a few authors in this literature review (Budds, 2009; Haeffner et al. 2021; Harvey and Chrisman, 1998; Connor et al.,2008; Cornejo and Niewöhner, 2021). 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. This is problematic as it limits opportunities to learn, and in practice also limits accountability. Hence, we call for a power-sensitive approach towards modelling in the water sector.

5. Towards power-sensitive modelling

We call for modellers, model-users, and funders to understand and engage with the power of models, from its ideation to implementation, in an ethical and accountable way. Our review shows that in order to better understand the relation between power and modelling broadly two approaches need to be combined. Firstly, a model needs to be unpacked, including the world views and policy projects embedded in the data and technologies of the model itself. Secondly, we need to understand the way the model is shaped by the context it is developed in, and in turn how it shapes this context. This also entails being mindful of whose discourses are supported and legitimised, and who and what is included and excluded in the model. Based on the literature review, we identify the following considerations that can guide power-sensitive modelling (refined based on Doorn, 2012; Krueger et al., 2016; Venot et al., 2021; Zwarteveen et al., 2017; Chilvers and Kearnes, 2015):

i. The choice for, and use of, models for water management happens in a political context and has political consequences
ii. Models are the result of choices made by modellers and – since they have political consequences – these need to be made as explicit as possible as opposed to being "blackboxed"
iii. To consider the ethical implications of the choices of modellers, commissioners, and users, and to improve

~~accountability, models and their power~~

~~need to be understood by connecting the inner workings of a model with a contextual understanding of its development and use~~

~~iv. Action is taken upon these implications by democratising modelling processes.~~

~~Our call should not be understood as a suggestion to do away with modelling altogether, but as an exploration on how to improve the practice.~~

~~**6. Conclusion**~~

~~The literature review confirms that models shape, and are shaped, by the social and material aspects of the world we live in. The case studies also show that it might be convenient to ignore the influence of models and related responsibilities of those involved. Although the proposed approach adds further complexity to the modelling process, it also opens new possibilities to strengthen models and their outcomes. As the review shows, specifically' when articles engage with the question of the influence of models on water governance, there are important lessons to be drawn. The reviewed literature identifies multiple approaches to explore the influence of modelling on and to do power-sensitive modelling, as described in section 5 'Towards power-sensitive modelling'.~~

~~The value of the articles that unpack, and critically engage with the influence of models on water governance demonstrate that adding more case studies would add further value. 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 showcasing what happens within model-land, but also stepping out of it. As such research finds itself at a ~~crossroad and, we argue~~crossroads, cooperation across disciplinary boundaries is essential to nurture generative reflexivity and accountability in relation to the power of models (Chilvers and Kearnes, 2015). Moreover, several of the articles reviewed show the value of decentralising models, 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~~; Khiavi et al., 2022~~). 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).

To contribute to overcoming disciplinary thinking, we ~~aim to make~~have made use of the open peer-review process of the Hydrology and Earth System Sciences journal, and ~~invite~~invited researchers and practitioners from a broad range of disciplines to think with us, share experiences and thoughts, as well as contribute articles that ~~should be~~have been included in an updated review and in the database of articles in Appendix A. ~~It is an~~The discussions and contributions resulting from this invitation ~~to jointly interrogate~~enabled joint interrogations, now incorporated within this article, on how quantitative models may help to foster transformative pathways towards more just and equitable water distributions.

10

Appendix A: ~~List~~ 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 ~~literature~~ review
4 through the HESS community and reviewers

Articles with * are included based on the SCOPUS and Web of Science query.
Articles with ^ are included based on 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.

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 case study**
Number of articles that mention a certain element of modelling explicitly				~~26~~22	~~31~~34	19	~~30~~23	
~~Abbott, M. B., and Vojinovic, Z. (2014).~~ Towards a hydroinformatics praxis in the service of social justice. ~~Journal of Hydroinformatics, 16, 516–530.~~	Abbott, M.; Vojinovic, Z.	2014	Journal of Hydroinformatics		X	x	x	General review
~~Addor, N., and Melsen, L. A. (2019).~~ Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models. ~~Water Resources Research, 55, 378–390.~~	Addor, N.; Melsen, L. A.	2019	Water Resources Research		X			A general review on hydroinformatics, no model or area defined
*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		Hydrologiska Byråns Vattenbalansavdelning model (HBV), the Variable Infiltration Capacity model (VIC), the mesoscale Hydrological model (mHM), the TOPography-based hydrologic model (TOPMODEL), the

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 case study
								Precipitation Runoff Modelling System (PRMS), the Génie Rural model à 4 paramètres Journaliers (GR4J), and the Sacramento soil moisture accounting model
* Andersson, L. (2004). Experiences of the use of riverine nutrient models in stakeholder stakeholders dialogues. *International Journal of Water Resources Development, 20*, 399–413.	Andersson L.	2004	International Journal of Water Resources Development				X	General review, focused on including externalities in modelling Agricultural Water Management interventions, focus on Agent Based Modelling
Babel, L., Vinck, D., and Karssenberg, D. (2019). Decision-making in model construction: Unveiling habits. *Environmental Modelling and Software, 120*, 104490.	Babel, Lucie; Vinck, Dominique; Karssenberg, Derek	2019	Environmental Modelling & Software		X			HBV-N, STANK, and SOIL-N, applied in theUpper Svarta Valley in Sweden
*Principles and confidence in hydrological modelling	Bergstrom S.	1991	Nordic Hydrology		X		x	General review, with input of European and North American modelers in a variety of disciplines within Earth and Universe sciences
Bouleau, G. (2014). The co-production of science and waterscapes: The case of the Seine and the Rhône Rivers, France. Geoforum, *57*, 248–257.	Bouleau, Gabrielle	2014	Geoforum	X		X		HBV and PULSE models at the Swedish Meteorological and Hydrological Institute between 1971 and 1990

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 case study
~~Bremer, L. L., Hamel, P., Ponette-González, A. G., Pompeu, P. V., Saad, S. I., and Brauman, K. A. (2020).~~ Who Are we Measuring and Modeling for? Supporting Multilevel Decision-Making in Watershed Management~~. *Water Resources Research*, *56*.~~	Bremer, Leah L.; Hamel, Perrine; Ponette-González, Alexandra G.; Pompeu, Patricia V.; Saad, Sandra I.; Brauman, Kate A.	2020	Water Resources Research				X	Models (undefined) within the PIREN Seine and PIREN Rhône project, France
* ~~Budds, J. (2009).~~ Contested H2O: Science, policy and politics in water resources management in Chile~~. Geoforum~~, *40*, 418–430.	Budds J.	2009	Geoforum	X	X	X	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
*Putting water in its place: a perspective on GIS in hydrology and water management	Clark, MJ	1998	Hydrological Processes		X	x		An undefined hydrogeological model by the National Water Directorate, La Ligua basin, Chile
*Watercourses and Discourses: Coalmining in the Upper Hunter Valley, New South Wales	* Connor, L., Higginbotham, N., Freeman, S., and Albrecht, G~~. (2008). Watercourses and Discourses: Coalmining in the Upper Hunter Valley, New South Wales. Oceania, *78*, 76–90.~~	2008	Oceania	x		X	X	General review, no model defined, with reflection on the US and UK.

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 case study
Using Dynamic Modeling to Scope Environmental Problems and Build Consensus	Constanza, Robert; Ruth, Matthias	1998	Environmental Management	x	x		X	An undefined hydrological model used by the Bickham Coal Company, Upper Hunter Valley, New South Wales
* Cornejo P., S. M., and Niewöhner, J. (2021). *How Central Water Management Impacts Local Livelihoods: An Ethnographic Case Study of Mining Water Extraction in TarapacáTarapaca, Chile. *Water*, *13*, 3542.	Cornejo, SM; Niewöhner, J	2021	Water	x		X	X	Undefined hydrological models, Tarapacá, Chile
Constanza, R., and Ruth, M. (1998). Using Dynamic Modeling to Scope Environmental Problems and Build Consensus. *Environmental Management, 22*, 183–195.*The Challenge of Model Validation and Its (Hydrogeo)ethical Implications for Water Security	xde Oliveira Ferreira Silva C.	x2022	Studies in Computational Intelligence	X				General review, related to hyrdogeological modelling
* Deitrick, A. R., Torhan, S. A., and Grady, C. A. (2021). *Investigating the Influence of Ethical and Epistemic Values on Decisions in the Watershed Modeling	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

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 case study
Process. ~~Water Resources Research~~, *57*.								
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)
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
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
*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:				X	hydrologic/hydraulic stormwater modeling system d using HEC-HMS and SWMM, Walnut Creek Watershed in Raleigh, North Carolina
*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

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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 case study
*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
*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
Reckoning Resources: Political Lives of Anticipation in Belize's Water Sector	Haines, Sophie	2019	Technology Studies		X		x	GIS software and the N-SPECT (nonpoint-source pollution and erosion comparison tool), Belize
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
*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
*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

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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
*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
*GIS, sinks, fill, and disappearing wetlands: Unintended consequences in algorithm development and use	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
A flood of models: Mekong ecologies of comparison	Jensen, Casper Bruun	2020	Social Studies of Science			X	X	Different models, including MRC SWAT, MIKE, HEC ResSIM, applied to (parts of) the Mekong river
Modelling expertise: Experts and expertise in the implementation of the Water Framework Directive in the Netherlands	Junier, S.J.	2017	Delft University of Technology	x	X		x	Water Framework Directive Explorer, the Netherlands
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

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Risks in the Making: The Mediating Role of Models in Water Management and Civil Engineering in the Netherlands	Kouw, Matthijs	2017	Berichte zur Wissenschafts geschichte			X	X	General review, Hydraulic engineering models, The Netherlands
Groundwater Modeling and Governance: Contesting and Building (Sub)Surface Worlds in Colorado's Northern San Juan Basin	Kroepsch, Adrianne C.	2018	Engaging Science, Technology, and Society			X	x	Groundwater models (by 3M project, CBM, AHA, and Questa), Northern San Juan Basin, USA
^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		ELCOM, supported by MATLAB, Lake Como, Italy
*Environmental Research from Here and There: Numerical Modelling Labs as Heterotopias	Laborde, S.	2015	Environment and Planning D: Society and Space	X	x			socio-hydrological human-flood models, an export coefficient type model, water security model of Dadson et al. (2017)
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
*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
^Doing flood risk science differently: an experiment in radical scientific method.	Lane, S. N., Odoni, N., Landström, C., Whatmore, S. J.,	2011	Transactions of the Institute of	x	x	X	X	FEH & ISIS's routing methodology, Pickering, UK and Wales

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	Ward, N., & Bradley, S		British Geographers					
^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)
*Acting, predicting and intervening in a socio-hydrological world	Lane, SN	2014	Hydrology And Earth System Sciences		X		x	General overview
Imagining flood futures: risk assessment and management in practice	Lane, Stuart N.; Landström, Catharina; Whatmore, Sarah J.	2011	Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences	X	X			Flood Estimation Handbook based models, UK and Wales
*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
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
It Takes a Village to Run a Model—The Social Practices of Hydrological Modeling	Melsen, Lieke A.	2022	Water Resources Research		X			Hydrologic modelling, Western Europe
Subjective modeling decisions can significantly impact the	Melsen, Lieke A.; Teuling, Adriaan J.; Torfs, Paul	2019	Journal of Hydrology		X			Three Variable Infiltration Capacity (VIC) models (version

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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 case study
simulation of flood and drought events	J.J.F.; Zappa, Massimiliano; Mizukami, Naoki; Mendoza, Pablo A.; Clark, Martyn P.; Uijlenhoet, Remko							4.1.2.i), Thur Basin, Switzerland
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
Risking the flood: Cartographies of things to come	Munk	2010	PhD dissertation: Linacre College, University of Oxford	X	x	x	x	HEC-RAS 4.0, UK
*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
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
*Impact of political, scientific and non-technical issues on	Rainwater K.; Stovall J.; Frailey S.; Urban L.	2003	Developments in Water Science	x	X	X	X	MODFLOW based groundwater model, Texas, USA

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regional groundwater modeling: Case study from Texas, USA								
GIS, modeling, and politics: On the tensions of collaborative decision support	Ramsey, Kevin	2009	Journal of Environmental Management	X		x	x	GIS Surface water model, Idaho, USA
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
*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
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?"	Srinivasan, V.; Sanderson, M.; Garcia, M.; Konar, M.; Blöschl, G.; Sivapalan, M.	2018	Hydrological Sciences Journal	x	X			Socio-hydrological models, general overview
An Environmental Anthropology of Modeling	Trombley	2017	PhD dissertation: University of Maryland, College Park	X	X	x	x	Chesapeake Bay Modelling System, Chesapeake Bay, USA
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

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*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
^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
*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
Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins	Wheeler, Kevin G.; Robinson, Catherine J.; Bark, Rosalind H.	2018	Regional Environmental Change			x	X	The Colorado River Basin in North America and the Murray-Darling Basin in southeastern Australia

	~~i) the mental models and policy projects~~	~~ii) the influence of modellers' choices~~	~~iii) the impact models have~~	~~iv) engaging with non-modellers~~
~~Dobson, B., Wagener, T., and Pianosi, F. (2019). How Important Are Model Structural and Contextual Uncertainties when Estimating the Optimized Performance of Water Resource Systems? *Water Resources Research*, *55*, 2170–2193.~~		~~X~~		
~~Falconi, S. M., and Palmer, R. N. (2017). An interdisciplinary framework for participatory modeling design and evaluation—What makes models effective participatory decision tools?. Water Resources Research, 53(2), 1625-1645.~~				~~X~~
~~Fernandez, S. (2014). Much Ado About Minimum Flows…Unpacking indicators to reveal water politics. *Geoforum*, *57*, 258–271.~~	~~X~~	~~x~~	~~X~~	~~x~~

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* Garcia-Cuerva, L., Berglund, E. Z., and Rivers, L. (2016). Exploring Strategies for LID Implementation in Marginalized Communities and Urbanizing Watersheds. *World Environmental and Water Resources Congress 2016*, 41–50. West Palm Beach, Florida: American Society of Civil Engineers.				X
* Godinez-Madrigal, J., Van Cauwenbergh, N., and van der Zaag, P. (2019). 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.	X	X	X	X
* Haeffner, M., Hellman, D., Cantor, A., Ajibade, I., Oyanedel-Craver, V., Kelly, M., Schifman, L., \and Weasel, L. (2021). Representation justice as a research agenda for socio-hydrology and water governance. *Hydrological Sciences Journal*, *66*, 1611–1624.		X		
* Haeffner, M., Jackson-Smith, D., and Flint, C. G. (2018). Social Position Influencing the Water Perception Gap Between Local Leaders and Constituents in a Socio-Hydrological System. *Water Resources Research*, *54*, 663–679.	X			X
Haines, S. (2019). Reckoning Resources: Political Lives of Anticipation in Belize's Water Sector. *Technology Studies*, *32*, 22.		X		x
Harvey, F., and Chrisman, N. (1998). Boundary Objects and the Social Construction of GIS Technology. *Environment and Planning A: Economy and Space*, *30*, 1683–1694.	X			
* Hasala, D., Supak, S., and Rivers, L. (2020). Green infrastructure site selection in the Walnut Creek wetland community: A case study from southeast Raleigh, North Carolina. *Landscape and Urban Planning*, *196*, 103743.	x	X	X	
Holländer, H. M., Bormann, H., Blume, T., Buytaert, W., Chirico, G. B., Exbrayat, J.F., Gustafsson, D., Hölzel, H., Krauße, T., Kraft, P. and Stoll, S., Blöschl G., Flühler, H. (2014). Impact of modellers' decisions on hydrological a priori predictions. *Hydrology and Earth System Sciences*, *18*, 2065–2085.		X		
* Jenkins, D. G., and McCauley, L. A. (2006, April 23). *GIS, SINKS, FILL, and Disappearing Wetlands: Unintended Consequences in Algorithm Development and Use*. 6. Dijon, France.		X		
Jensen, C. B. (2020). A flood of models: Mekong ecologies of comparison. *Social Studies of Science*, *50*, 76–93.			X	X

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Junier, S. J. (2017). *Modelling expertise: Experts and expertise in the implementation of the Water Framework Directive in the Netherlands* (Delft University of Technology). Delft University of Technology.	x	X		x
* Khiavi, A. N., Vafakhah, M., and Sadeghi, S. H. (2022). Comparative prioritization of sub-watersheds based on Flood Generation potential using physical, hydrological and co-managerial approaches. *Water Resources Management*, *36*, 1897–1917.	X	X		

Kouw, M. (2016). Standing on the Shoulders of Giants—And Then Looking the Other Way? Epistemic Opacity, Immersion, and Modeling in Hydraulic Engineering. *Perspectives on Science*, *24*, 206–227.		X		x
Kouw, M. (2017). Risks in the Making: The Mediating Role of Models in Water Management and Civil Engineering in the Netherlands. *Berichte Zur Wissenschaftsgeschichte*, *40*, 160–174.			X	X
Kroepsch, A. C. (2018). Groundwater Modeling and Governance: Contesting and Building (Sub)Surface Worlds in Colorado's Northern San Juan Basin. *Engaging Science, Technology, and Society*, *4*, 43–66.			X	x
Laborde, S. (2015). Environmental Research from *Here* and *There*: Numerical Modelling Labs as Heterotopias. *Environment and Planning D: Society and Space*, *33*, 265–280.	X	x		
Ländstrom, C., Whatmore, S. J., and Lane, S. N. (2011). Virtual engineering: Computer simulation modelling for flood risk management in England. *Science and Technology Studies*, *24*, 3–22.	X			
* Landström, C., Whatmore, S. J., Lane, S. N., Odoni, N., Ward, N., and Bradley, S. (2011). Coproducing flood risk knowledge: Redistributing expertise in critical "participatory modelling." *Environment and Planning A: Economy and Space*, *43*, 1616–1633.	x	x	x	X
Lane, S. N., Landström, C., and Whatmore, S. J. (2011). Imagining flood futures: Risk assessment and management in practice. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *369*, 1784–1806.	X	X		
* Lane, S. N. (2014). Acting, predicting and intervening in a socio-hydrological world. *Hydrology and Earth System Sciences*, *18*, 927–952.		X		x
Melsen, L. A. (2022). It Takes a Village to Run a Model—The Social Practices of Hydrological Modeling. *Water Resources Research*, *58*.		X		
* Melsen, L. A., Vos, J., and Boelens, R. (2018). What is the role of the model in socio-hydrology? Discussion of "Prediction in a socio-hydrological world." *Hydrological Sciences Journal*, *63*, 1435–1443.		X	X	X
Melsen, L. A., Teuling, A. J., Torfs, P. J. J. F., Zappa, M., Mizukami, N., Mendoza, P. A., Clark, M.P., Uijlenhoet, R. (2019). Subjective modeling decisions can significantly impact the simulation of flood and drought events. *Journal of Hydrology*, *568*, 1093–1104.		X		

	i) the mental models and policy projects	**ii) the influence of modellers' choices**	**iii) the impact models have**	**iv) engaging with non-modellers**
Mendoza, P. A., Clark, M. P., Mizukami, N., Gutmann, E. D., Arnold, J. R., Brekke, L. D., and Rajagopalan, B. (2016). How do hydrologic modeling decisions affect the portrayal of climate change impacts? *Hydrological Processes*, *30*, 1071–1095.		X		

Munk, A. K. (2010). *Risking the Flood: Cartographies of Things to Come* (University of Oxford). University of Oxford, Oxford.	X	x	x	x
* Opitz-Stapleton, S., and MacClune, K. (2012). Scientific and Social Uncertainties in Climate Change: The Hindu Kush-Himalaya in Regional Perspective. In A. Lamadrid and I. Kelman (Eds.), *Community, Environment and Disaster Risk Management* (Vol. 11, pp. 207–237). Emerald Group Publishing Limited.	x		x	X
Packett, E., Grigg, N. J., Wu, J., Cuddy, S. M., Wallbrink, P. J., and Jakeman, A. J. (2020). *Mainstreaming gender into water management modelling processes. Environmental Modelling and Software*, 127, 104683.	X	X		
* Rainwater, K., Stovall, J., Frailey, S., and Urban, L. (2005). Transboundary Impacts on Regional Ground Water Modeling in Texas. *Ground Water*, *43*, 706–716.	x	X	X	X
Ramsey, K. (2009). GIS, modeling, and politics: On the tensions of collaborative decision support. *Journal of Environmental Management*, *90*, 1972–1980.	X		x	x
Sanz, D., Vos, J., Rambags, F., Hoogesteger, J., Cassiraga, E., and Gómez-Alday, J. J. (2019). The social construction and consequences of groundwater modelling: Insight from the Mancha Oriental aquifer, Spain. *International Journal of Water Resources Development*, *35*, 808–829.	X	X	X	X
Srinivasan, V., Sanderson, M., Garcia, M., Konar, M., Blöschl, G., and Sivapalan, M. (2018). 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?" *Hydrological Sciences Journal*, *63*, 1444–1446.	x	X		
Trombley, J. M. (2017). *An Environmental Anthropology of Modeling and Management on the Chesapeake Bay Watershed* (University of Maryland). University of Maryland, College Park.	X	X	x	x
Wardropper, C. B., Gillon, S., and Rissman, A. R. (2017). Uncertain monitoring and modeling in a watershed nonpoint pollution program. *Land Use Policy*, *67*, 690–701.			X	X
* Wheeler, K. G., Hall, J. W., Abdo, G. M., Dadson, S. J., Kasprzyk, J. R., Smith, R., and Zagona, E. A. (2018). Exploring Cooperative Transboundary River Management Strategies for the Eastern Nile Basin. *Water Resources Research*, *54*, 9224–9254.	X			X

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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.

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