https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences
Discussions

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

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

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

Correspondence to: rozemarijn.terhorst@wur.nl

Abstract. Hydrological 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 neutrality. Our systematic review shows that in 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. 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.

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences
Open Access
Discussions
EGU

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 aims, including documenting water distribution, exploring causal dynamics, simulating changes, predicting future conditions and informing policy making. Models are often 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, 1999; 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.

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. 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.

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences Discussions

2 Defining models

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 used 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 can be for a narrowly prescribed purpose, for example to calculate the height of a dam, or 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 influence is clearest and most direct through the output of models, used in decision making processes. However, models also interact with social processes through (re-)producing or at times challenging discourses, which might happen more or less implicitly (Krueger and Alba, 2022). In this process it matters whose information and 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 development process, from problem identification 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. All models, including the 'purely' physical science-based and quantitative ones, both have a technical and a social life, which implies that their development is shaped by people and their norms, values and institutions, as well as that 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 to recognise this political charge of models, from non-modellers and modellers alike, for instance to design more transparent and inclusive modelling processes (Maeda, 2021), or to be explicit about the norms, values and limitations that are embedded in the process and any final model (Puy et al., 2022).

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences Discussions

3 Methodology

This article is based on a literature review that combines a narrative review (Cronin et al., 2008) and a systematic review. 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 narrative review method.

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. 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 keywords and words used in the titles and abstracts of the articles included in this first set of papers, a database query was constructed. The final query is defined as TITLE-ABS-KEY ("water model*" OR "hydrolog* 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 because they broadly relate to how models influence issues of distribution. Focused on 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 excludes words such as 'influence', 'power', 'values', 'reflexivity', 'accountability', and 'responsibility' because the scanning of titles and abstracts showed that these keywords were too broad and yielded many articles most of which did not reflect on the influence models have.

Results were taken from SCOPUS and Web of Science, based on English language literature for the period January 1993 – July 2022. The query resulted in 293 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. We did a first screening by title and thus excluded three articles. 290 Articles were screened by abstract from which 33 abstracts 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, 21 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 included in the critical appraisals (Figure 1). Appendix A provides an overview of the articles included in the literature review. Those marked with "*" were selected through the narrative literature review.

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

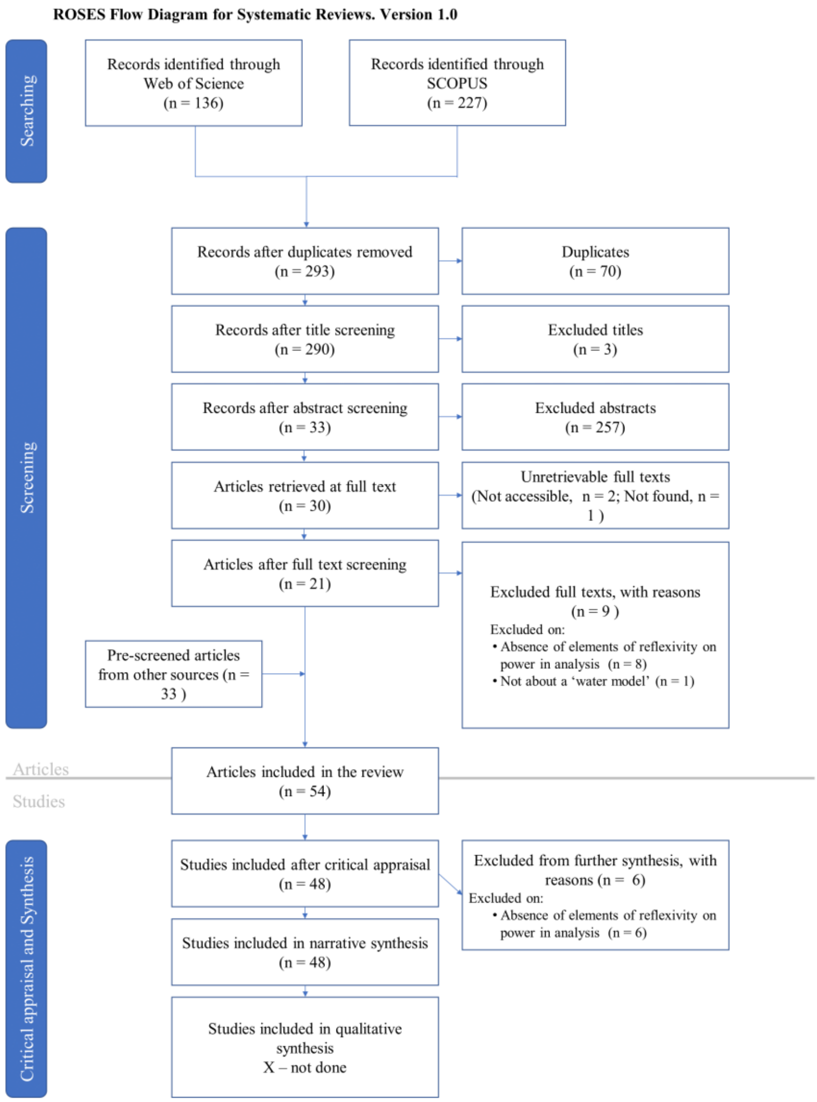

Figure 1: The result of the ROSES systematic literature review process

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 impact models have on decision making and how water is managed, and iv) engaging with non-modellers through

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences Discussions

models. We make a note here that these engagements are not necessarily participatory. These four aspects are closely interrelated, 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 modelling process and the articles that discuss these as their main theme. More details are included in Appendix A.

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

Table 1: Overview of articles in relation to the aspects of the modelling process they discuss.

4.1 Mental models and policy projects

We start with discussing the mental model (also called conceptual or perceptual model, Beven 2009) that underlies any numerical model. Depending on the process, the mental model is not, or less, influenced by limitations posed by data and technology and is more of an 'ideal type' than an actual model, though Krueger et al. (2016) argue that technological possibilities of what can be modelled may already co-shape what can be imagined. We divide the mental model into two elements, with the first being the ideas of how the world works, including any (causal) relations, and the second being the ideas of what this world should look like. Both elements are based on values, norms and ideas about what is important and valid to a society in general and a modelling community in particular (Haas, 1992; Haraway, 1991; Jasanoff and Kim, 2015; Morgan and Morrison, 1999). Mental models are developed based on a multitude of factors, including the common interests, backgrounds, knowledge and skills of those involved. Different communities may have very different ideas of how the world functions (Knorr-Cetina, 1999; Rusca and Di Baldassarre, 2019), or have experience with a particular way of conceptualising linked to an already familiar technology (Addor and Melsen, 2019; Babel et al., 2019; Melsen, 2022). In our systematic literature review, 26 articles dedicated specific attention to mental models. We discuss the main themes, illustrated with examples from the articles reviewed, including 1) problem framing, 2) how different ways of knowing the world influence modelling, 3) how different socio-technical imaginaries influence why a model is made, and 4) how data and categories embody world views and influence what is included and excluded and in what ways.

4.1.1 Problem framing: Exploration versus consolidation

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

To avoid disconnects between the model and user such as described by Ramsey (2009) Trombley (2017) suggests a multi-model approach to avoid that a model serves one particular policy project at the neglect of others. One of the suggestions they make is to design models for decision making with the aim of facilitating exploration; models becoming mediators that foster a diversity of perspectives. Constanza and Ruth (1998) propose to both engage with the consolidating and exploratory functionality that models can have in the same modelling process by introducing a three-phased modelling approach. The first stage focusses on developing the model structure and 'functional connections between variables' in discussion with stakeholders, the second stage focusses on replicating dynamics of interest realistically, and the third stage focuses on scenarios and management options.

4.1.2 Knowing the world in specific ways

In the water sector, the way models are developed is often highly influenced by specific 'epistemic communities' that are bound by shared ideas on validity and causality and a way of working that engenders a particular vision of the world (Haas, 1992). Bouleau (2014) shows how expertise mixes with political priorities to influence the choice of tools and issues to be

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences Discussions

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

4.1.3 Working towards different versions of the world

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

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

Definitions and categories are important mechanisms to translate world views into models. Building on feminist science and making gender explicit, two articles in our literature review call for more inclusive modelling. Haeffner et al. (2021) showed that available water data often disfavour women and local communities as few disaggregated data based on these categories are available. Disaggregation, which would entail collecting specific data related for instance to gender, class, and caste, can make differences and inequalities visible. When datasets are not aggregated, or for instance create biases towards male water users who are oftentimes more visible, the modelling exercises based on biased datasets inherit the same biases and knowledge gaps unless these are explicitly acknowledged and addressed. The solution that the authors see to account for the limitations of modelling is to collect data that includes a specification towards race, class, and, 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.

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences Discussions

4.2 Articles discussing modellers' choices

The following set of articles focuses on how a model is developed. 31 Of 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

Modellers' choices matter, as they influence both the development and output of a model. Holländer et al. (2009) showed through a model comparison experiment that, when provided with the same data-scarce fictive watershed, ten modellers predicted essentially ten different, and some of them very different, discharge time series based on the models of their own choosing. Within the same model, choices also matter greatly. Melsen et al. (2019) systematically demonstrated the impact of modelling decisions for the case of a flood and drought event in the Swiss Thur basin, specifically for decisions on spatial resolution, spatial representation of forcing, calibration period and performance metric. Mendoza et al. (2016) showed how hydrologic modelling decisions can influence evaluations of climate change impacts. When comparing four different modelling structures and parameter estimation strategies applied to three watersheds of the Colorado River Basin, the authors show that calibration decisions may unexpectedly have more impact than the choice of model structure. Dobson et al. (2019), by comparing eight 'rival framings' of two models of two water resource systems in the UK, show how these specific representation 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.

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

The choice of the modelling technology or model-type is of great influence on the modelling outcomes. Addor and Melsen (2019) demonstrated, based in 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 typical 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

Hydrology and Earth System Sciences
Open Access
Discussions

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 developed through interaction

Landström et al. (2011) draw attention to a wide range of actors that influence modelling by assessing the practices of modelling flood risk of 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. Munk (2010) and Junier (2017) also make visible 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.

4.3 Modelling and real-world impact

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

4.3.1 Naturalising and legitimising world views through models

Water governance processes are always contested and political, as stakeholders are likely to hold different worldviews, including contrasting visions about the way water should be managed and allocated, and whose expertise and knowledge

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences
Discussions

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

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

4.3.2 Exclusive and inclusive assessments

When modelling is presented as a neutral scientific process, a lack of attention to the context and its power-relations can have negative effects for marginalised groups in society. An example of such a 'desocialised assessment' was provided by Budds

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences
Open Access
EGU
Discussions

(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).

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.

4.4 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, 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 of the included articles dedicated specific attention to including people and values in a modelling process. We discern different themes, including i) engagements with how models can create connections and disconnections from the people and places that are being modelled, ii) how non-modellers relate with specific world views and policy projects included in the model, iii) representing who and what is modelled in just and fair ways, and lastly iv) how modellers reflect on engaging with who and what is modelled.

4.4.1 Connecting to and disconnecting from people and places

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 warn against thinking too much from a modelling and consultant perspective instead of a community perspective. For instance, they argue against 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

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

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 different case studies on watershed management programs in the Atlantic Forest of Brazil. Falconi and Palmer (2017) applied it to assess whether participatory computer models for water resources management in the USA, the Solomon Islands, Senegal and Zimbabwe are indeed effective participatory decision tools based on surveys. They also emphasise that a contextual analysis is first required to gain insights into who, when, how, and why-questions. Both articles highlight that models cannot meet the expectations of each stakeholder, and therefore need to be carefully embedded in decision making processes. Bremer et al. (2020) also emphasised that it is necessary to take power dynamics into account in this process. They conclude that as hydrological modelling can influence larger development projects, it is essential to critically reflect on how and by whom these will be used and to what extent they are grounded in local realities.

4.4.2 Stakeholders confronted with different realities of modelling and measuring

Wardropper et al. (2017) analysed how inherent uncertainty in the Soil and Water Assessment Tool (SWAT) application to the Yahara Watershed in Wisconsin (USA) influenced the development and implementation of a water quality management programme. The programme aimed to reduce phosphorus pollution; modelling was used as a tool to estimate water quality and assign needed pollution reductions to different groups, while monitoring and compliance were based on measurements. An additional challenge in the case study was that results of the policy were not directly visible, as they were most likely to be seen within a ten-year timeframe. As modelling inhibits more uncertainty than measurements, the authors questioned how 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) described in detail a participatory model experiment in which modellers, social scientists, and local residents met on a bimonthly basis over a period of one year to co-produce knowledge about flood risks in Pickering in the UK, using a 'competency group' approach. This approach asked for all participants to join as individuals, not as representatives of a certain group, and for science to be produced based on questions of the group. What was important for the project was that science was disconnected from institutions that had a role in discussions on flood risks, and that scientific questions were not defined in advance, and were open to reframing during the project. Two models were developed as a result of this collaboration; the first was intended to be the final model and ultimately served as a starting point for discussion, and second was designed based on requests and inputs of the participants, and ultimately played a key role in shaping flood management strategy in the area.

4.4.3 Representation and fairness

Haeffner et al. (2018) researched how perceptions and concerns of stakeholders and decision makers were represented in the management of urban water systems in urban areas in Utah, USA. First, the authors undertook a review of 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 shared understandings of the water supply system might lead to an oversimplification of sociohydrological 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 on hydroinformatics, 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 the section about modellers’ choices is that it emphasises the role of the modeller and claims 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). Lane (2014) came to the same conclusion by deconstructing 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 i) embracing conflict and controversy in science, ii) looking for extremes to test knowledge, but doing this in a way that is sensitive to the political and ethical ramifications, iii) using real-life events to think with and step out of ‘model-land’, and iv) co-producing knowledge with affected groups. Lane concludes that hydrologists cannot do this alone, but that it requires both social science and hydrology.

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

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 Discussion

In this article we researched how academic literature engages with the influence models have in the water sector. Driven by on an observation 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 the 293 articles included in the systematic literature review, 21 were finally included in critical appraisal. In addition, 28 articles were added to the critical appraisal through the narrative review. The complete literature review shows that most articles do not critically unpack 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 and diverse modelling processes are, and how they are non-linear and shaped by the context they are developed and used in. In this section, we reflect on the insights gained.

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 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. 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, 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 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 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.

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences
Open Access
Discussions

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. 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

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences Discussions

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 it. As such research finds itself at a crossroad and, we argue, 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 use of the open peer-review process of the Hydrology and Earth System Sciences journal, and invite 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 included in an updated review and in the database of articles in Appendix A. It is an invitation to jointly interrogate how quantitative models may help to foster transformative pathways towards more just and equitable water distributions.

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Appendix A: List of articles included in the systematic literature review

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

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.

	i) the mental models and policy projects	**ii) the influence of modellers' choices**	**iii) the impact models have**	**iv) engaging with non-modellers**
Number of articles that mention a certain element of modelling	26	31	19	30
Abbott, M. B., and Vojinovic, Z. (2014). Towards a hydroinformatics praxis in the service of social justice. *Journal of Hydroinformatics*, *16*, 516–530.		**X**		x
Addor, N., and Melsen, L. A. (2019). Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models. *Water Resources Research*, *55*, 378–390.		**X**		
* Andersson, L. (2004). Experiences of the use of riverine nutrient models in stakeholder dialogues. *International Journal of Water Resources Development*, *20*, 399–413.				**X**
Babel, L., Vinck, D., and Karssenberg, D. (2019). Decision-making in model construction: Unveiling habits. *Environmental Modelling and Software*, *120*, 104490.		**X**		
Bouleau, G. (2014). The co-production of science and waterscapes: The case of the Seine and the Rhône Rivers, France. *Geoforum*, *57*, 248–257.	**X**		**X**	
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*.				**X**
* Budds, J. (2009). Contested H2O: Science, policy and politics in water resources management in Chile. *Geoforum*, *40*, 418–430.	**X**	**X**	**X**	**X**
* 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.	x		**X**	**X**
* Cornejo P., S. M., and Niewöhner, J. (2021). How Central Water Management Impacts Local Livelihoods: An Ethnographic Case Study of Mining Water Extraction in Tarapacá, Chile. *Water*, *13*, 3542.	x		**X**	**X**
Constanza, R., and Ruth, M. (1998). Using Dynamic Modeling to Scope Environmental Problems and Build Consensus. *Environmental Management*, *22*, 183–195.	x	x		**X**
* 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 Process. *Water Resources Research*, *57*.	**X**	x		x

	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
***** 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**

	i) the mental models and policy projects	**ii) the influence of modellers' choices**	**iii) the impact models have**	**iv) engaging with non-modellers**
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**		

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences
Open Access
Discussions

	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**

Author contribution:

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

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

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

References

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

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

Khiavi, A. N., Vafakhah, M., and Sadeghi, S. H.: Comparative prioritization of sub-watersheds based on Flood Generation potential using physical, hydrological and co-managerial approaches, Water Resour. Manag., 36, 1897–1917, https://doi.org/10.1007/s11269-022-03114-3, 2022.

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

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

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

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

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

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

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

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

Ländstrom, C., Whatmore, S. J., and Lane, S. N.: Virtual engineering: computer simulation modelling for flood risk management in 28ngland, Sci. Technol. Stud., 24, 3–22, 2011.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Opitz-Stapleton, S. and MacClune, K.: Chapter 11 Scientific and Social Uncertainties in Climate Change: The Hindu Kush-Himalaya in Regional Perspective, in: Community, Environment and Disaster Risk Management, vol. 11, edited by: Lamadrid,

https://doi.org/10.5194/hess-2023-164
Preprint. Discussion started: 30 August 2023

Hydrology and Earth System Sciences Discussions

A. and Kelman, I., Emerald Group Publishing Limited, 207–237, https://doi.org/10.1108/S2040-7262(2012)0000011017, 2012.

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

Pielke Jr, R. A.: The honest broker: making sense of science in policy and politics. 1st ed. Cambridge University Press [Eng.], Cambrigde, 200 pp., 2007.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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