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

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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.

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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

35   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

40   (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.

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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

50   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).

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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,

60   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.

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2 Defining models

65 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;

70 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,

75 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.

80 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

85 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

90 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

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

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[Handwritten annotations: "② Not temibly original. Why is your narrative add?" / "text analysis? ③" / "① So, you selected stuff in some syst way and then made sense of it with a narrative?"]

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

100 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.

[Handwritten annotation: "This method description gives me more questions then answers..."]

In order to define the query for the systematic literature review, we first selected articles that represented engagement with the

105 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

110 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

115 the influence models have.

[Handwritten annotation: "→ But how these keywords do link to 'models' is actually a nice comparison?"]

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

120 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

125 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.

[Handwritten annotations: "How could these six have been added?" / "your definition does not do either..." / "So, you selected 21 papers based on key words, and added 34 in another way after reading the 21? How can that be explained?"]

ROSES Flow Diagram for Systematic Reviews. Version 1.0

[Handwritten annotations:]

your method is: "we found some papers and wrote about them". Theme selection is a step, however, that is not explained!

So, first the syst. review and after that the narrative? Why use the two steps in the other order? e.g. on page 9?

?{
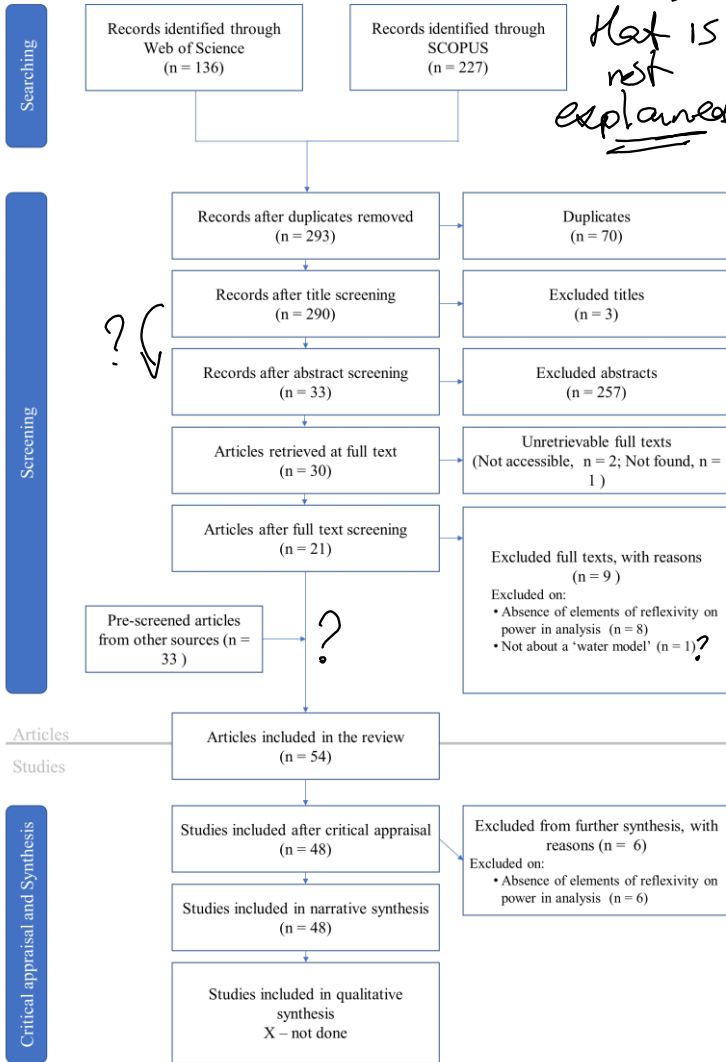
— From 300 to 21 is impressive, but adding more than 30 from other sources may be even more impressive.

?

— How would a next research repeat this process?

— How did your selection process influence the results?

[Flow diagram content:]

Searching:
- Records identified through Web of Science (n = 136)
- Records identified through SCOPUS (n = 227)

Screening:
- Records after duplicates removed (n = 293) → Duplicates (n = 70)
- Records after title screening (n = 290) → Excluded titles (n = 3)
- Records after abstract screening (n = 33) → Excluded abstracts (n = 257)
- Articles retrieved at full text (n = 30) → Unretrievable full texts (Not accessible, n = 2; Not found, n = 1)
- Articles after full text screening (n = 21) → Excluded full texts, with reasons (n = 9). Excluded on: • Absence of elements of reflexivity on power in analysis (n = 8) • Not about a 'water model' (n = 1)
- Pre-screened articles from other sources (n = 33)

Articles:
- Articles included in the review (n = 54)

Studies / Critical appraisal and Synthesis:
- Studies included after critical appraisal (n = 48) → Excluded from further synthesis, with reasons (n = 6). Excluded on: • Absence of elements of reflexivity on power in analysis (n = 6)
- Studies included in narrative synthesis (n = 48)
- Studies included in qualitative synthesis X – not done

130

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

[Handwritten annotations:]
How did papers connect to search terms? your method does not allow to specify that.

Overview of keywords per paper, of journals etc.

after reading or before? How was this decision made? Text analysis?

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

135 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

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

140   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

145   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

150   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

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155 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

160 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

165 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

170 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.

175 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

180 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

185 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

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

190   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

195   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)

200   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

205   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.

210   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

215   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

[handwritten note: → Models support policy or the other way around?]

220 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

[handwritten note: How can models change that?]

Definitions and categories are important mechanisms to translate world views into models. Building on feminist science and

225 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

230 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

235 framing and conceptualisation, model construction, documentation and evaluation, and model interpretation and decision

support.

[handwritten note: → So, better models need more data?]

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

240 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

245 (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

250 model choices.

[handwritten note: Again, data are mentioned, which is obviously quite important. However, I would argue that data is not that directly translated to discussion on models...]

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

255   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

260   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

265   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

270   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

275   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

280   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

[handwritten: Which is?]

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

285   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

[handwritten: ⌐ Does this input depend on how the study was designed?]

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

290   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

295   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

300   the WFD (Water Framework Directive) Explorer in the Netherlands.

[handwritten: ⟶ so? Rather brief, right? Junier shows actually how certain actors have more influence than others]

[handwritten: blame that!]

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

305   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.

310   ### 4.3.1 Naturalising and legitimising world views through models

[handwritten: ⟶ also with the same]

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

should be valued in decision making processes (Zwarteveen et al., 2017). Models, therefore, can have the unintended

consequence of legitimising one of these worldviews whilst concealing others. To illustrate, coal mining is a contested process,

315   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

320   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

325   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

330   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.

335   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

340   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

345   negative effects for marginalised groups in society. An example of such a 'desocialised assessment' was provided by Budds

(2009) in a case of the La Ligua river basin in Chile. The author questioned the extent to which a hydrogeological model, used to represent the physical diversity in the La Ligua river basin, was representative. The model was based on data mainly available for the main river and not the tributaries, with limited information on actual water use including illegal abstractions, and the modelling process included a limited assessment of the model's validity. Despite this, the model was used to define a

350   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

355   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

360   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

365   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

370   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)

375   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

13

[handwritten note: No evidece. Why would they work in a real world?]

380 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

385 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. *[handwritten note: → in real life or as a thought experiment?]*

4.4 Engaging with non-modellers through models *[handwritten note: → The examples actually show that models are used contextually. The context might be wrong--]*

When it comes to modelling, we want to dedicate specific attention to engagement of non-modellers in modelling processes.

390 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

395 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.

400 **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

405 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

410 their proposed specifications needs "a rare combination of technical skill, cultural sensitivity, political awareness, and above

all, the time to continually engage with and build relationships within the community in order to foster resilient change." (ibid: pp 208).

An often-used framework to analyse the uptake of models is provided by Cash et al. (2003). The framework analyses how a
415 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
420 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.

425 **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
430 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
435 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.

440 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

15

that science was disconnected from institutions that had a role in discussions on flood risks, and that scientific questions were

445 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. *How different were the models in the end?*

4.4.3 Representation and fairness

so, more!

450 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

455 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

460 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. *So, one paper for one paragraph? And then?*

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

465 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

470 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.

So?

Scholars in those groups disagree!

How does this (nice and not very exciting) idea work when social science as much as hydrology is not a very useful category.

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[handwritten note: Is it allowed to compare/use together papers and PhD theses?]

475 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,

480 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.

485 **4.5 Discussion**

[handwritten notes: How? oh? Who is allowed to teach?]

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

490 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

495 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.

[handwritten notes in right margin: No if does not. You simply did not use them!!]

[handwritten note: How do the lines that follow illustrate this remark?]

500

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

505 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

[handwritten notes at bottom: Do they? / your lit selection could only confirm your assumption! / Big word to use. How does your "evidence" support your claim?]

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.

510

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

515 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.

520 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

525 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

530 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

535 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

540 expectations. It shows that not engaging with the potential or actual influence of models is an ignorance that is persistent.

We found a particular set of papers through our methodology, based on the narrative review and query (TITLE-ABS-KEY ("water model*" OR "hydrolog* model*") AND TITLE-ABS-KEY (justice OR equit* OR politic* OR ethic*). The query embodies a particular way of engaging with the influence of models, as we take a broad perspective on the influence of

545 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

550 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

555 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.

560

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

565 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):

570 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

575 contextual understanding of its development and use

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

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

580

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

585   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'.

590   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

595   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

600   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

605   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.

20

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

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Discussions

	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
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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		
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Jensen, C. B. (2020). A flood of models: Mekong ecologies of comparison. *Social Studies of Science*, *50*, 76–93.			X	X

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Junier, S. J. (2017). *Modelling expertise: Experts and expertise in the implementation of the Water Framework Directive in the Netherlands* (Delft University of Technology). Delft University of Technology.	x	X		x
* Khiavi, A. N., Vafakhah, M., and Sadeghi, S. H. (2022). Comparative prioritization of sub-watersheds based on Flood Generation potential using physical, hydrological and co-managerial approaches. *Water Resources Management*, 36, 1897–1917.	X	X		
Kouw, M. (2016). Standing on the Shoulders of Giants—And Then Looking the Other Way? Epistemic Opacity, Immersion, and Modeling in Hydraulic Engineering. *Perspectives on Science*, 24, 206–227.		X		x
Kouw, M. (2017). Risks in the Making: The Mediating Role of Models in Water Management and Civil Engineering in the Netherlands. *Berichte Zur Wissenschaftsgeschichte*, 40, 160–174.			X	X
Kroepsch, A. C. (2018). Groundwater Modeling and Governance: Contesting and Building (Sub)Surface Worlds in Colorado's Northern San Juan Basin. *Engaging Science, Technology, and Society*, 4, 43–66.			X	x
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* 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		

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Earth System
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	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
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Author contribution:

620 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.

625 **Competing interests**

The authors declare that they have no conflict of interest.

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[Handwritten margin notes:]

How did the workshop / method influence the model setup of this paper?

I was here, and am a little disappointed in this text after such a cool workshop...

Can papers be your dataset and regular refs at the same time? Are all?

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