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## Modelling Water Worlds

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**ABSTRACT:** Modelling and models influence how water and its flows are understood and governed. It is thus essential to critically explore the roles that models play in producing or addressing uneven water distribution. In this introduction to the Special Issue, we discuss approaches to analysing models and modelling practices. We start by establishing that they deserve special attention because they produce knowledge of another nature than gained from observations and measurements – knowledge that abstracts, generalises and offers access to potential futures and remote places. The paper outlines the ways in which models can appear to have universal relevance because of how they are able to travel between contexts; it also stresses that the rationalisation they offer aligns with the idea of control that underpins the modern water paradigm and related techno-managerial interventions. Despite their widespread appeal and use, this introduction stresses that models remain rather opaque, difficult to understand and navigate for non-experts and even sometimes for experts. The paper goes on to show how, in the context of water research and governance, models derive authority from the networks and discourses that surround them as well as from the epistemic and non-epistemic values that are shared by particular modelling communities. We present three complementary entry points for engaging with models: first, by interrogating their function as tools of representation; second, by exploring how they are produced and operated within constellations of actors, practices, discourses and material artefacts; and third, by analysing how models are deployed to legitimise water governance decisions that are inherently political. We then expand our critical engagement with water modelling, placing it in the broader context of attacks on science and scientists, particularly in the context of rising post-truth politics. Finally, by discussing the papers in this Special Issue, we conclude that models not only contribute to reproducing water inequalities but that they can also be mobilised to understand and address them. We suggest that future critical water research on modelling should continue to ground models and modelling in local realities, while also being invested in models as knowledge practices. Future research would benefit from bringing the diverse approaches that are showcased in this Special Issue into conversation as they enable rich and plural accounts of the worlds of water modelling.

**KEYWORDS:** Models, hydrology, politics, ontologies, practices, post-truth, situated knowledges

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## INTRODUCTION

Whether in research, policy, practice or daily life, it is currently hard to imagine an issue related to water that is not influenced by models and their outputs. Real-time forecasting models, water allocation models, risk assessment models and agent-based models (to name a few) are used to forecast floods and droughts, determine the dimensions of water infrastructures, optimise water resource operations, trace pollution sources, simulate human – water relations, and inform many other areas of science, policy and practice. Models contribute to interventions, policies and visions of the future and, by doing so, they shape how water-related issues are understood and addressed (Melsen et al., 2018; Krueger and Alba, 2022; ter Horst et al., 2024). One can say that models contribute to 'making' or, to use a terminology widely used in the social studies of science, 'enacting' water worlds (Mol, 2002; Law, 2009; Yates et al., 2017).

In the last few years, the editors of this Special Issue have researched how (hydrological) models enact water worlds, with a particular focus on quantitative computational modelling, whether numerical, statistical or data driven. We have done this individually, jointly and with other colleagues. Some of us have delved into the details of coding and uncertainty analysis, others have focused on analysing the practices of modelling and the socio-economic processes that shape them, and yet others have foregrounded the political dimensions of models. Through these engagements, we learned that institutional affiliations, habits and career pathways shape modellers' choices (Addor and Melsen, 2019; Melsen, 2023; Remmers et al., 2024). We uncovered how models embed specific understandings of human – water relations and how these influence the ways in which problems are understood and solutions developed (Krueger and Alba, 2022; Unverzagt et al., in press). We also contributed to protocols (Jakeman et al., 2024), research agendas (ter Horst et al., 2024; Remmers et al., 2025) and novel frameworks (Klein et al., 2024; Alba et al., forthcoming) in order to critically reflect on modelling practices and inspire new routines of modelling. This Special Issue is another modest step in this direction and has the aim of synthesising current scholarship and inviting new perspectives. Our engagement is motivated by two concerns, one is analytical and the other methodological. First, analytically, we are interested in exploring what roles models and modelling play in shaping relations between water and society, particularly in producing and addressing inequalities. Second, methodologically, we are interested in developing approaches to studying how they do so.

Unequal access to enough, affordable and clean water to sustain livelihoods and ecosystems remains a challenge that is global in scale but with a myriad of very local manifestations (WBGU, 2024). As critical water research has solidly demonstrated, water inequalities are the product of uneven power relations where certain groups or individuals are able to exert greater control than others over water resources and their knowledge practices (Rusca, 2023; Mehta, 2025; Wutich, 2025). Tackling inequalities, in turn, requires understanding these unequal power relations and how they shape water flows (Zwarteveen and Boelens, 2017; Sultana, 2018). Models are important in such endeavours. The abstractions, simplifications and predictions that they provide can buttress existing inequalities, but they can also help understand water-related challenges and support the development of possible future pathways towards more just and sustainable water governance.

The transformative potential of models has been discussed by several authors. Rusca et al. (2023) demonstrate that numerical models, when coupled with analyses of uneven power relations, are helpful tools for exploring, for example, future scenarios of vulnerability to floods in urban contexts. Godinez-Madrigal et al. (2022) show how hydrological models can be used by marginalised groups to challenge dominant water governance narratives and influence decisions about more equitable and inclusive water allocation. Venot et al. (2022a) discuss how agent-based models are helpful tools for exploring and speculating about potential alternative scenarios to infrastructure development with diverse stakeholders including, in their case, policymakers, farmers and fishers. Yalew et al. (2024) explore how

justice considerations could be introduced to water allocation models by applying different distributive principles. Engaging with quantification in general, Molle et al. (2024) see in the power of numbers an emancipatory potential and an advocacy tool for activists. Models thus have transformative potential when they help understand specific water-related challenges, especially when they complement other ways of knowing and when they help explore and evaluate pathways for change (Alba et al., forthcoming).

Despite these encouraging developments, engaging models and modelling to support transformative change remains far from straightforward (Saltelli, 2025; Alba et al., forthcoming). First, models remain key tools that are used by a few powerful actors to secure control over water, often to the detriment of other groups (for a review, see ter Horst et al., 2024). Models are mobilised, for instance, by mining companies and state actors to legitimise and support neoliberal governance and extractive projects, often at the expense of Indigenous groups and local communities (Cornejo P. and Niewöhner, 2021; Flores Fernández and Alba, 2023). Second, models, like other forms of quantification (Molle et al., 2024), continue to enjoy a kind of credibility and authority in water research and governance that comes at the expense of other ways of knowing and engaging with water, causing the latter to be seen as less 'true' or important (Zwarteveen et al., 2018; Venot et al., 2022b). The credibility and authority that models and modelling enjoy relate to a stubborn tendency to see them as neutral and objective representations of water states and fluxes, while the responsibility for making decisions that are based on these models is relegated to policymakers. This reflects a modernist treatment of water science and politics as distinct realms, and an understanding of scientific work as a neutral process that is based on the belief that valid knowledge can and should be derived from observable, measurable facts that exist independently of personal values and social contexts. Third, even when a shared commitment to a critical engagement with models and modelling is shared among a group of, for example, researchers, it remains a challenge to develop new modelling practices that are attentive to power relations and local contexts (Alba et al., forthcoming).

As such, reversing the gaze on models and modelling is not easy, and this supports our second motivation: to explore methodological approaches that go beyond a reified vision of modelling in order to study the diverse practices that it both consists of and affords, that is to engage in a form of constructive critique (Schuurman and Pratt, 2002). In our view, such approaches could help understand how knowledge and politics are entangled in models and modelling, while enabling these issues to be discussed more openly. This, in turn, contributes to resituating scientific work in society and is, we argue, a way to counter the excessive relativism that underpins post-truth claims and rising authoritarian politics. A growing scholarship (including our own work) shows how modelling choices related to computing power, data and uncertainty, to name few, are shaped by historical, geographical and institutional settings, as well as by the values, experiences and practical constraints of the modellers themselves and of other actors who are involved in the modelling process (for a review, see ter Horst et al., 2024). These findings have prompted calls for model commissioners, modellers and model users to assume greater responsibility for how modelling is conducted and how models are used. Many possible pathways have been proposed, including steps towards more responsible (Nabavi, 2022; Remmers et al., 2025) and power-sensitive modelling (ter Horst et al., 2024), and engagements with modelling as a situated knowledge practice (Klein et al., 2024). With this Special Issue, we aim to learn from specific cases of critical engagement with models and modelling and draw insights from the methods these used.

This introduction accompanies five articles that together explore diverse experiences and perspectives on how models and modelling practices can be studied and on how their effects can be explored through a range of methodological approaches. The articles examine models and modelling practices in relation to flooding, watershed management, and forest canopy interception across a diversity of case studies. In the remainder of this introduction, we first clarify what is special about models as knowledge practices in water and environmental governance. We then provide an overview of

different approaches to studying models, showcased by the individual contributions to the Special Issue and by the wider literature on the topic. This is followed by a reflection on the importance of engaging critically in modelling in times of post-truth politics. We argue that opening up scientific practices can serve to counter post-truth claims and their wholesale dismissal of science. We conclude by identifying ways forward in the critical examination of models and modelling.

## **ON MODELS AND WATER WORLDS**

This section first establishes what makes models and the practices of modelling distinct from other modes of scientific knowledge production, such as laboratory or field experimentation, interviews and ethnographies; that is, we look at why models and modelling deserve particular attention. We then discuss how models derive their authority and how they not only represent, but actively 'make', water worlds. We draw on a broad range of scholarship beyond hydrology and water studies, particularly meteorology, climatology, energy policy and economics, all of which are disciplines where models have been subject to philosophical, sociological and ethnographic analyses. There are differences across these fields in terms of types of models, what they are supposed to represent, and their purposes; nonetheless, we can learn from these debates for the study of water.

### **What is special about models?**

We begin by discussing what sets models apart and why they hold a position of authority in water research and governance. We suggest that models are special because they extend beyond observations and measurements: they enable abstraction, generalisation and the simulation of future scenarios. We also highlight the opaque character of models and their capacity to travel between geographical, historical and institutional contexts. These characteristics contribute to making models key to what Linton (2010) calls the "modern water" paradigm.

The first thing that sets models apart is that their quantitative and mathematical foundation facilitates the abstraction of place-based knowledges, that is knowledge derived from experiences or experiments. This lays the ground for generalisation. Generalisation is helpful as it contributes to understanding and comparing phenomena across multiple geographical regions and times, even where and when data are limited. It comes at a cost, however, for instance when experimental hydrological knowledge (such as the storage capacity of the forest canopy) is stitched together in what Van Stan II and Simmons (this Issue) call "geographical chimeras", that is, models that are patched together from disparate, context-specific knowledges that have been derived across different geographies. This has long been a point of contention between experimentalists and modellers in hydrology (Seibert and McDonnell, 2002). Bruun Jensen and Venot (2025) similarly describe the patching together of specific in situ greenhouse gas emission measurements into what they call a "mighty equation" of the IPCC, which is then used globally to assess rice-based emissions. Van der Heide (2020) sees this patching together of model components (that may not have been conceived to work together) as a case of 'bricolage'. The final model receives its authority, epistemically speaking, from the authority of the individual components from which it is built (for summaries of scholarly debates on these characteristics, see Morgan and Morrison, 1999; Frigg and Nguyen, 2020).

Puy and Lankford (2024) demonstrate that this overall scientific authority may not hold when individual model components are abstracted from their contexts. Abstraction entails simplifying, and simplifying, in turn, entails losing detail and being less precise. Matthewson and Weisberg (2009) discuss the trade-off between model precision and model generality, that is, how many phenomena and situations a model can capture. This trade-off is modulated by three factors: first, the variety of model targets (parts of reality) that the model is meant to represent; second, how many, and which aspects of, a target the model is intended to capture (the scope of the model); and third, the evaluative standards

of modellers in terms of how closely the model's predictions are expected to match the data, or how accurately a model represents cause – effect relationships (see also Weisberg, 2013) – two things that do not necessarily go together. Accordingly, a hydrological model that is generally applicable is likely to not be very precise in any one application, and vice versa; that is, a hydrological model that is calibrated for a particular catchment cannot be easily transferred to another catchment.

The second thing that sets models and modelling apart is that their quantitative and mathematical nature and the generalisations they afford allows for rationalisations; that is, they contribute to making complex water systems legible. In this way, models become entangled with modern society's pursuit of logic and organisation, which is also visible in, for instance, cost – benefit analyses in economics and in efforts towards accountable governance (see Nobert et al., 2015, whose specific focus is on flood risk). In water research and management, translating water flows into quantifiable data in and through models rationalises, enables and instrumentalises water regulation and control. This instrumentalization aligns with the modern water paradigm (Linton, 2010) and with the related techno-managerial interventions that are grounded in the idea of control. Critical social science researchers have long discussed these traits, drawing particular attention to the challenges of generalisation and emphasising the importance of context-specific analyses in understanding the relationships between water and society. They questioned the assumed universal applicability of water resource metrics, arguing that such metrics may overlook local complexities and social dynamics (Zwarteveen et al., 2018). They also stressed that not everything can and ought to be measured (Espeland, 1998; Espeland and Stevens, 1998).

The third reason that models are special is because they allow for simulations of target phenomena as a form of virtual experimentation that would not be possible with data alone (Trombley, this Issue). By making predictions, models give access to times and places that may not be accessible through direct observation, for example, the future, the underground, and remote places (Kroepsch and Clifford, 2022). In doing so, models serve the anticipatory function of making the future graspable and eventually subject to control in a way that observations or measurements on their own would not be able (Nobert et al., 2015). The anticipatory possibility offered by models allows for the exploration of, for instance, future water availability under different irrigation development scenarios; this can help make visible how small-scale water users might be affected by large-scale development plans (van der Zaag et al., 2010). Modelling can also be used, as in the case of Rusca et al. (2023), to explore flood impacts in a scenario where transformative policies co-exist with capitalist logics. Using models to extrapolate into the future, however, inevitably constructs specific imaginaries of that future while sidelining others, especially those that resist quantification or are hard to capture with models. Via the projection of future scenarios, models then possess a world-making power through shaping what is deemed relevant, making them politically potent tools (for a discussion of climate modelling, see Beck and Mahony, 2018; Beck and Oomen, 2021).

Fourth, models are special because they tend to be opaque. They are written in specific programming languages that are inaccessible to those unfamiliar with them; they are also meant to formalise, simplify or stylise parts of reality and are based on approximations and assumptions that are not easily comprehended by non-experts, with even experts sometimes struggling to understand them (Silvast et al., 2020). It is also often the case that not all assumptions are made explicit and often receive little more than lip service from the modellers (for documentation of a flood risk case study, see van der Meijden and Melsen, in press). Paired with a dependency on large amounts of data, these features make models particularly opaque, like black boxes (Puy and Lankford, 2024). This opaqueness not only makes it challenging for non-modellers to grasp the complexities of modelling such as coding, parameterisation and uncertainty analysis; it also reinforces modelling as a domain that is reserved for technical experts. Understanding, scrutinising and modifying models indeed requires a certain level of expertise, as does sabotaging them for political ends (Sundberg, 2006; Christley et al., 2013; Aykut et al., 2019).

The combined effect of abstraction and generalisation underpins another aspect of models that makes them special: their capacity to travel. Models or model components can be translated from one context to another and from one discipline to another. Model structures from one discipline may be reinterpreted and applied to a problem from another discipline, or a problem may be rearticulated to fit an existing model (for insurance models see, for instance, van der Heide, 2020). Models can play central roles as 'boundary objects', facilitating interactions between multiple discursive spaces such as science, policy and public concerns (Trombley, this Issue); in such cases, models are similar to policy frameworks in that they get reinterpreted and modified in multiple ways as they travel to different geographical contexts (Mehta et al., 2016). In the words of van der Heide (2020: 125), "The terms in which the epistemic problem is described needs to be aligned with the terms that constitute the world within the model, and this requires the re-description of both". Largely overlooked, however, is the conceptual and computational effort that is required to demonstrate that models that had previously been abstracted and assembled in a particular place do indeed perform successfully in other places (Morgan, 2014).

The travelling of models is in part (but not exclusively) facilitated by quantification and mathematics as a common language. Mahony and Hulme (2012) show that, in the case of regional climate models, mobility on a global scale depends on the involvement of diverse and authoritative actors and institutions, each of whom brings their own interests. Despite the potential global reach of models, however, the large amount of computational resources that are needed to run them results in the sites of modelling, at least, to be limited to countries in the Global North. This amplifies a general problem of modernist Western science whereby models provide knowledge about places whose inhabitants have not taken part in that knowledge production (Farbotko et al., 2023).

Taken together, in water management and beyond, models hold a particular epistemic authority (Saltelli and Di Fiore, 2023) even when they are recognised as being incomplete and simplified representations of the world. This authority is derived from the interaction of the aforementioned characteristics of models: their rationalised nature (Aykut, 2019), which they share with other forms of quantification (Molle et al., 2024); their generalising function, which links place-based knowledges in unifying ways (Morgan, 2014) and also facilitates the travelling of models across time and space (Mahony and Hulme, 2012; van der Heide, 2020); and their capacity to 'access' places and times that cannot be directly observed.

### **How do models establish authority?**

The authority of a model is not only linked to its technical features; it also emerges from its acceptance, credibility and use within particular scientific, social and political contexts. Christley et al. (2013) show how, for infectious disease modelling, the authority of models at the science – policy interface is negotiated within the networks and discourses surrounding them. Among their cases are instances where a model had little influence on policy formation because decisions had already been made, and the model was merely used to support these decisions. Van Beek et al. (2022) similarly show how Integrated Assessment Models were aligned with policy commitments to the 1.5°C goal in the Paris Agreement. Demeritt (2001) analyses how climate models derive their authority from the social processes and institutional contexts in which they are developed and utilised. Addor and Melsen (2019) further show how weight is lent to particular models by regulatory guidelines, by the resources invested in model development and maintenance, and by their uptake in professional and consultancy practices.

Modellers, too, confer authority to models; this authority can be based (however implicitly) on both epistemic and non-epistemic values (for energy modelling, see Silvast et al., 2020). Epistemic values include accuracy, simplicity and adequate representation; non-epistemic values, on the other hand, relate to the purposes of a model such as sustainability, reliability and safety of the modelling target, but also to considerations around the practical limits of models and modelling. A common epistemic value in

modelling is the degree to which the inner workings of a model should correspond to empirical knowledge. In practice, however, a lack of agreement with observations may not invalidate models, as a Popperian notion of falsification would suggest (for a case involving meteorological modellers, see Sundberg, 2006). This is partly due to measurements themselves being in error and partly because model simulations and observations relate to different scales than models, and hence are not directly 'commensurate' (for hydrology, see Beven, 1989). What counts as a 'good' model, then, is negotiated in the practices of a particular modelling community (Melsen et al., 2025) and its intersection with other communities such as that of experimentalists (Sundberg, 2006). As such, the epistemic authority assigned by modellers to models is not so much based on strict empirical adequacy as it is on acceptance within a community's shared practices; this results in modellers at times having more confidence in their models than their epistemic grounds would invite them to have (Puy et al., 2025).

The authority that models hold in water governance and beyond (conferred by both model users and modellers themselves) has not gone unchallenged. Research has highlighted how the authority of models is used to present hydrological quantities as impartial and objective (Budds, 2009; ter Horst et al., 2024) and to position modelling as a superior way of understanding water states and fluxes. This has the effect of depoliticising water (Molle et al., 2024); it also tends to sideline and silence other forms of knowing and relating-with water, and to sideline the human and more-than-human actors, values and concerns involved (Zwarteveen et al., 2018). As Wilson et al. (2024) remark, "hegemonic understandings of 'modern water' are enacted in ways that have historically suppressed, and often continue to suppress, Indigenous ontologies, epistemologies and governance systems" (see also Wilson and Inkster, 2018). The significance of attending to, and embracing, epistemological and ontological plurality in water research and governance has already been discussed in the pages of this journal (Vogt and Walsh, 2021) and elsewhere (Barnes and Alatout, 2012; Yates et al., 2017; Venot et al., 2022b; Linton, 2022; Saidani et al., 2024; Rusca et al., 2024; Acevedo-Guerrero et al., 2025). These authors stress that the main issue is not choosing the best conception of, and way-of-relating with, water; rather, it is the establishing of dialogue between a plurality of conceptions, combined with an in-depth understanding of how these are formed through tools and practices such as models and modelling.

### **What does it mean that models 'make' worlds?**

The discussion in the previous sections has already offered a glimpse of how models intervene in the world, that is, how they function as world-making practices. This section develops this idea further through our reading of the relevant literature as social scientists and hydrologists. We examine how models have been conceptualised in terms of both the types of knowledge they produce and the ways in which they contribute to remaking the world they represent.

From a philosophical perspective that resonates with the discipline of hydrology, models are representations of reality, attained through formalising, simplifying or stylising a certain part of reality, and on the basis of which something can be learned about that reality (Silvast et al., 2020). Following this line of thought, models have long been recognised as mediators between theory and experiment, the two classical modes of scientific knowledge production (Morgan and Morrison, 1999). Many scholars, however (including those contributing to Morgan and Morrison, 1999) see modelling neither as a mere extension of theory or experiment nor as a simple link between the two. Building on the work of Michel Foucault, Laborde (2015), for instance, thinks of models as a heterotopia, an entity that is at once "absolutely real" (the computer, the code), "absolutely unreal" (being largely digital), and "absolutely different" from the place it represents. In her words, "a heterotopic numerical (spatial) model acts like a mirror reflecting another place, while also highlighting the differences between the reflected and the reflection, the 'here' and the 'there'" (Laborde, 2015: 275). Modelling then becomes a distinct mode of scientific knowledge production with its own epistemology, with models also serving as mediators

between different domains of science, between science and policy, and between science and various publics (Knuuttila et al., 2018; Trombley, this Issue).

It is debated in philosophical circles how, exactly, models 'represent', that is, how they relate to the world. Frigg and Nguyen (2020) summarise current philosophical arguments; among other features that make models 'represent', they highlight the importance of model descriptions, interpretations, and the keys to translating between models and their targets (see also Weisberg, 2013). Interestingly for a philosophical treatment, the authors see many of these features as being subject to empirical analysis. "Perspectival modelling" (Massimi, 2018) extends this understanding of models as representations by recognising the historically and culturally situated scientific practices of research communities; the theoretical, experimental and technological resources at their disposal; and their methodological – epistemic principles (see also Massimi, 2023). Puy et al. (2023) draw on this concept to see the function of irrigation models to be in exploring spaces of possibilities rather than in being "truthful" representation.

A different perspective, however, is offered by research that argues that models not only describe and represent their targets but also contribute to shaping them. Models, in this sense, are 'performative' (Bamford and Mackenzie, 2018; Aykut, 2019; Krueger and Alba, 2022; Nadaï et al., 2023; Klein et al., 2024). Performative understandings of modelling draw from social studies of science and feminist research where knowledge production is seen as, "specific material engagements that participate in (re)configuring the world" (Barad, 2007: 91). Such a perspective has been developed in relation to modelling in socio-ecological research, including in hydrological modelling. Klein et al. (2024) notably draw on the work of Donna Haraway and Karen Barad to analyse modelling as a situated knowledge practice. Models intervene in the world through the discourses and interventions they afford (Budds, 2009; Krueger and Alba, 2022), and by their assembling and dis-assembling of social networks (Cohen et al., this Issue). This leads van der Heide (2020: 125) to assert that models "shape the conditions of possibility in which action takes place".

Aykut (2019) offers useful empirical entry points to study the social networks, interventions and discourses by which modelling and models enact worlds. Even if the author focuses on energy modelling tightly embedded in the policy-making realm, the same empirical entry points can be used for less overtly policy-facing, seemingly detached research which nevertheless shapes the conditions of possibility in the world (Callon et al., 2011; Klein et al., 2024).

The first way in which models are 'word-shaping' relates to their predictive role and the fact that they are often used in the context of 'anticipatory exercises' that stabilise, unsettle or reconfigure particular social organisations, with political dimensions (Aykut, 2019), as shown in the case of climate (Beck and Mahony, 2018). In the words of Nadaï et al. (2023: 4), "Modelling a future thus contributes to gathering and assembling the know-how, actors and artefacts that might compose this future, if only by orienting policy processes". This social organisation takes place not only between scientists, stakeholders and decision-makers, but also within the scientific community itself. Scientific communities and institutions coalesce around specific models, to the point where it can appear as though the model is shaping the institution rather than the reverse (Trombley, this Issue).

Second, models inform direct interventions in the world by enabling the sharing of practices of prediction and planning among actors (Aykut, 2019). Different models foreground different processes and hence enable particular forms of intervention. In hydrology, this is evident through the long history of using models in water management and in the building of hydraulic infrastructures (Wardropper and Brookfield, 2022), even though scientists emphasise the knowledge generation role of models while engineering and water management practitioners emphasise models' role in prediction and planning

(Landström, 2023). Several papers in this Special Issue engage with this topic. De Tymowski and Hurt (this Issue) make clear how flood models directly inform plans, policies and priorities and eventually the material distribution of funding and flood mitigation measures. Cohen et al. (this Issue) add that global flood risk estimations (and by implication subsequent policies and interventions) will change depending on which vulnerability and exposure datasets are used. Trombley (this Issue) emphasises the pivotal role of the Chesapeake Bay Modelling System (CBMS) in determining how watershed management will take place and how funds will be allocated as a result. When models shape worlds by informing direct interventions, their partiality becomes especially apparent. Westerlaken (2024), for instance, demonstrates how ecological models (in that case digital twins) only enable interventions for species that can be quantified and, for the purpose of data assimilation, captured.

Third, models "influence the *discursive context* of policy-making by reducing the undetermined, 'open' future into an actionable set of 'plausible' development trajectories" (Aykut, 2019: 15, emphasis in the original). The representation of possible futures thereby contributes to defining the spectrum of choices that bring about certain futures and not others (for an analysis of the role of models in energy policy, see Nadaï et al., 2023). This process of futuring is deeply entangled with values and power; it legitimises certain actions in the present while marginalising or delegitimising alternative futures and ways of understanding them (for climate change mitigation and adaptation, see De Jong et al., forthcoming). It is often the very technicalities of modelling that make some matters visible and obscure others (Mahony and Hulme, 2012), starting with the need for model equations to be mathematically solvable (van der Heide, 2020). We now turn to approaches that follow these empirical entry points.

#### **APPROACHES TO STUDYING THE WORLD OF WATER MODELLING AND THE WATER WORLDS THAT MODELS HELP TO BRING ABOUT**

There is a growing recognition of the role of models in shaping how water is understood and managed but the ways in which models and modelling contribute to shaping water worlds have been explored from diverse perspectives. In this section, by again drawing from water-related modelling and beyond, we outline three prevalent approaches: models as representations, modelling as practice and enactment, and the political ecologies of modelling water. These three approaches share similar interests; they differ, however, in their ontological and analytical starting points, in the loci of their research, in their methods, and in their findings. Rather than presenting opposing viewpoints, we suggest viewing them as part of a gradient, each one highlighting a different facet of how models contribute to world-making. It is not uncommon that analyses of modelling draw on multiple approaches simultaneously. The overview below should thus not be seen as a rigid classification, but rather as a useful guide for navigating the diversity of perspectives.

##### **Models as representations**

Models and their consequences are being studied from an 'internal' perspective by those who design and use models on a regular basis, such as hydrologists. By and large, these modellers and model users work with models as representations of reality, however implicitly and however pragmatically (Beven, 2002). Many philosophical accounts of models as representations assert that models do not inherently 'represent', but rather that representation arises through an explicit designation by the modeller or model user (Graebner, 2018; Frigg and Nguyen, 2020). There also seems to be some agreement that the target of any single model is only ever a part of the real world. In hydrology, models are generally seen as hypotheses – that is, conditional and inherently provisional – where multiple competing representations may, or even must, co-exist (Clark et al., 2011).

For modellers, the impossibility of fully accurate representation does not mean that rigour is abandoned (Silvast et al., 2020). Instead, it usually takes the form of sensitivity and uncertainty analyses.

Beven (2002) calls this the "pragmatic realism" of hydrologists. Silvast et al. (2020) show that some of the energy modellers they interviewed admitted to sometimes prioritising the usefulness of a model for policy over the accuracy with which it matched data; in other words, models may not be exactly 'right' but they may still suggest policy that is 'in the right direction'. This echoes George Box, who is well known among hydrological modellers and among researchers who study modelling practices and is famously quoted as saying that, "All models are wrong, but some are useful". In contrast, other modellers who were interviewed by Silvast et al. (2020) were adamant that models should be used by decision-makers in a way that was 'true' to the purpose of the modeller. This emphasises the tension between scientific rigour and the model being pragmatically 'good-enough' for the tasks it was meant to perform.

Hydrological modelling choices are fundamentally underdetermined by empirical evidence. This is captured by the concept of 'equifinality', which highlights that different combinations of model structures and parameter values can produce the same results, making it impossible to differentiate between them on the basis of empirical data (Beven, 2006). Hydrology as a discipline thus has a long-standing history of evaluating these choices using sensitivity analysis (Pianosi et al., 2016), uncertainty analysis (Beven, 2009; Nearing et al., 2016), and (controlled) model inter-comparisons (Clark et al., 2015; Craig et al., 2020; Telteu et al., 2021). These examinations of models critically assess methodological choices in, for instance, data selection, equation formulation, numerical implementation, and parameterisation. The literature on fitness-for-purpose and 'good modelling practices' has further extended such technical analysis to include criteria on model usability, reliability and feasibility (Hamilton et al., 2022; Jakeman et al., 2024).

The notion of objectivity in hydrological modelling has long been challenged (though without necessarily questioning the neutrality of models); it is widely recognised, for instance, that the construction of perceptual models is "partly subjective" (McMillan et al., 2023). Other studies have increasingly emphasised the role of subjectivity in developing underdetermined models, not only in the perceptual phase but also during implementation (Mendoza et al., 2015; Melsen et al., 2019). In this line of work, subjectivity has been framed either as a source of uncertainty or as an integral aspect of expertise (Holländer et al., 2009, 2014; Krueger et al., 2012). While these studies have opened up a broader exploration of subjectivity, a next step is to examine the patterns and structures that shape and sustain it.

The patterned nature of subjectivity is evident in studies that trace how modelling practices are shaped by, among other things, institutional context (Addor and Melsen, 2019), experiences of colleagues (Melsen, 2022), gender-induced choices (Packett et al., 2020), and other path dependencies (Lahtinen et al., 2017). Hydrologists have further identified path-dependent patterns in modelling through historical reconstructions. These showed how certain modelling concepts – such as Manning's roughness coefficient (Lane, 2014), the Nash-Sutcliffe Efficiency coefficient (Melsen et al., 2025), or canopy interception (Van Stan II and Simmons, this Issue), have become entrenched not solely through epistemic merit, but also through inherently social processes. Van Stan II and Simmons (ibid), for example, show how empirical knowledge about leaves and whole trees obtained from particular climates, and sometimes from simple blotting paper, became inscribed in global-level canopy interception models; Bruun Jensen and Venot (2025) documents a similar process whereby global greenhouse gas emission models are supported by specific gas chamber measurements. The authors discuss how this may mislead water management decisions in ecosystems that are very different from the empirical base.

Other scholars who critically examine models as representations engage explicitly with the consequences that modelling choices have in the world. Sanz et al. (2019), for instance, evaluated modelling choices in a participatory modelling context and explicitly discuss their social, economic and environmental implications. In their case, the model functioned as a referee for determining which

farmers were eligible to be compensated for refraining from abstracting groundwater. Puy et al. (2022) investigated choices in irrigation modelling and explored the consequences of ignoring uncertainties in data and process equations. They showed how defining irrigation efficiency only in relation to irrigation hardware in those models renders farmers irrelevant to the management of irrigated agriculture. Puy et al. (ibid) further cite an example (from Johnson, 2020) of the African Risk Capacity model applied in Malawi, which miscalculated the size of the drought-affected population by more than two orders of magnitude for two reasons: first, because the model used a long-cycle maize variety as reference crop instead of the local short-maturing varieties and, second, because they overlooked the importance of when dry spells occurred in relation to crops' growth cycle. Because of these misrepresentations, about six million people in Malawi did not get water insurance payouts.

One response of some hydrological modellers to the contingency and political charge of modelling choices has been to open up these choices to some form of stakeholder or public participation (Krueger et al., 2016). The modes and logics of 'participatory modelling' differ, however, ranging from normative and substantive to instrumental rationales (Voinov and Bousquet, 2010; Tsouvalis and Waterton, 2012). Another response has been to extend traditional sensitivity analysis (which focuses solely on the internal mechanics of a model) to sensitivity auditing that incorporates stakeholder participation and the broader political context (Lo Piano et al., 2022; Saltelli et al., 2023), the latter approach being inspired by what has come to be known as Post-Normal Science (Funtowicz and Ravetz, 1993; van der Sluijs, 2002). Other responses have taken the form of explicit countermodelling, which challenges dominant models and advances alternatives (to which we will return below).

Approaching models as representations can to some extent be seen as critically examining how modelling shapes water states and fluxes; however, such an approach focuses more on the technical details of the model and the dynamics within the modelling community of scientists and consultants, and less on the broader sociopolitical and historico-geographical contexts that shape model demands and implementations (Rusca and Mazzoleni, 2025). Approaches tackling these questions are explored more elaborately in the next two sections.

### **Models, practices and enactments**

A second approach to researching models focuses on deciphering modelling practices. Such a view interrogates how models are being 'done' on a day-to-day basis by following (at times quite literally) the different human and more-than-human actors who are involved in the modelling process. Focusing on 'the social' and demonstrating a deep appreciation for the hard work that goes into modelling, this perspective contributes to the demystifying of models as neutral knowledge practices. The focus is not so much on improving modelling practices to better represent realities (as when approaching models as representations); rather, it is on understanding how modelling and models contribute to the enactment of water worlds, as introduced earlier (Bamford and Mackenzie, 2018; Aykut, 2019; van der Heide, 2020; Krueger and Alba, 2022; Nadaï et al., 2023).

Mobilising Science and Technology Studies (STS) approaches (Mol, 2002; Law, 2009), models are analysed as performative, always within broad material – semiotic constellations of actors, practices, discourses and material artefacts that enact certain worlds and their futures. This take is very much akin to that of Paul Edwards' and its "vast climate machine" (Edwards, 2010). The focus is on tracing how particular knowledges and ways of relating with the world get inscribed in a model and how the technicalities of its implementation interact to afford particular usages of the model while resisting others (Knuuttila et al., 2006).

Modelling as practice is often studied using qualitative research methods (Sundberg, 2006; Silvast et al., 2020); these can include interviews, observations, informal conversations and full-fledged

ethnographies. The focus, in that case, is on tracing the tacit knowledges, routines, improvisations, practical considerations, emotions and values that are involved in seemingly mundane modelling decisions and actions. The objective is to find out how actors construct, commit to, and demarcate a social world, in this case of modelling (Sundberg, 2006). The multi-sited ethnography of Silvast et al. (2020: 3), for example, involved, "going to where energy models are produced and the modelling tools configured as part of daily practice" and examining how these various sites interrelate with each other. In order to trace modelling choices, Babel et al. (2019) conducted face-to-face, semi-directed interviews with modellers. Their research shows how choices – which ultimately became habits – have their roots and motives in the relations modelers have with specific actors such as thesis directors and colleagues and with specific 'schools' or 'fields' within a discipline (see also Melsen, 2022). Trombley (this Issue) also employed extensive, multi-sited ethnographic field work (Trombley, 2017) in his study of the Chesapeake Bay Modelling System (CBMS). The study reconstructs how this modelling system has been instrumental for watershed management in Chesapeake Bay. It shows, among other things, how the model 'assembles' the watershed from disparate pieces (in a way that is similar to that described by Van Stan II and Simmons, this Issue) and, in the process, makes it legible for the development of large-scale policies.

Modelling practices have also been analysed through interdisciplinary collaborations. In an upcoming article, Unverzagt et al. (in press) mobilise a feminist STS perspective to analyse how Bayesian knowledge is 'done' in the context of a model that was developed for understanding pollutant transfers from land to water in a UK watershed. Collaborating as a "heterogeneous collective" (Klein et al., 2024), the authors examined the modelling process by integrating several approaches: analysing existing documentation including published articles and the modeller's personal notes and recordings; reviewing the case through presentations and dialogic inquiry during two interdisciplinary workshops; and conducting content analysis of the entire material, which was carried out by one of the team's ethnographers. Such an approach allowed the authors to single out relevant practices and examine what the modeller and other involved parties reportedly said and did. They asked questions about, for example, the implications of a specific model structure in shaping understanding of the problem at hand; the influence of embodied value-laden assumptions about what is 'good', and the effects of assumptions regarding *where* researchers and policymakers can and should intervene. Another example is provided by De Tymowski and Hurst (this Issue), who analysed flood models through a collaborative discourse analysis. The authors – a flood modeller and a human geographer – first individually and then collaboratively analysed texts and visuals related to flood policy and flood models (policy reports, and model outputs such as maps). They noted that this approach was valuable, first, because it allowed them to discuss the material from two distinctive (disciplinary) perspectives, that is, flood modelling, and housing and land justice; and, second, because it not only enabled them to identify the assumptions about property that were embedded in the flood modelling process, it also revealed to them their own underlying assumptions about property.

STS-inspired approaches have been further used to unpack the practices of participatory and agent-based modelling (represented by, for example, Voinov and Bousquet, 2010; Voinov et al., 2016). These have indeed gained in importance in the field of environmental management research in response to calls for more stakeholder and public involvement in knowledge-making and to other calls for better representation of the complex interplay between nature and society. Venot et al. (2022a), for instance, unpack how researchers' objectives and choices – which they frame as "generous constraints" – shaped forms of participation in the exploration of alternatives to infrastructure development in Cambodia's Mekong Delta. In a similar vein, participatory flood modelling experiments in England have been extensively documented as widening the scope of possible interventions much beyond those usually considered by regulatory authorities (Landström et al., 2011; Lane et al., 2011). Landström et al. (2024) further underscore how the dynamics of 'governance spaces' are key to shaping how and why stakeholders do or do not take up computational models.

As the last example suggests, the focus of STS-inspired approaches often extends beyond the model itself. It can examine the wider modelling paradigms and necessary infrastructures that support it, as well as the wider social, ecological, economic and political context in which models acquire specific meanings and functions. This aspect is exemplified by Yarina (2024), who traces how a diversity of models – first physical and then hydraulic and hydrodynamic – and metrics "reigned supreme" in how water experts read and managed the Dutch Delta at a distance, under the Room for the River programme. The author situates this dominance of models and calculations in a longer tradition of Dutch water management and in efforts to export Dutch expertise. Another contrasting example is provided by Bruun Jensen (2020), who interrogates an "ecology of partially overlapping models" of the Mekong River Basin; the models being of little consequence for the ecology of the Mekong itself, though they may provide the ground for future policy interventions – or so the modellers hope. Trombley (this Issue) emphasises that it is not only the Chesapeake Bay *watershed* that is 'assembled' with the CBMS; it is also (through numerous modelling meetings) the social networks of scientists and management staff that are required for developing and implementing watershed policies. The author further shows how the model "channels" the interests and efforts of numerous organisations towards a common cause, while also "orientating" the activities of various actors in the watershed by defining which of them are (financially) worthwhile (although this orientation has not gone undisputed). In analysing the controversy around a water transfer project in Iran's Zayandeh-Rood River Basin, Nabavi (this Issue) shows how models and modelling become, "a focal point where expertise, political interests, and societal priorities continuously interact and reshape one another".

Lastly, STS approaches have explored how models and modelling contribute to making certain spaces and circulations, such as aquifers, "(in)scrutable", that is opaque to observers and analysts. Kroepsch and Clifford (2022), for instance, mobilise STS and critical physical geography to analyse how the interplay between biophysical, political-economic and epistemic facts contributes to making the Denver Basin Aquifer System (DBAS) inscrutable. The DBAS is a vast and heterogeneous groundwater system whose inner workings are difficult to understand due to limited data, disagreements, and considerable differences in model-based estimates of groundwater depletion. Limited scope for scrutinizing and understanding the DBAS is convenient, as it allows suburban development and groundwater abstraction to continue unchallenged by state authorities; this, in turn, favours residential developers and individual homebuilders.

### **Political ecologies of modelling water**

A third strand of literature has studied models and modelling in relation to wider political-economic processes, with a focus on documenting and analysing how models are used to (re)produce uneven water distributions and also to challenge them, although the latter is less common. Building on political ecology scholarship that is often combined with STS, this work, broadly speaking, engages with the politics of models and modelling; in other words, it analyses how uneven relations of power are (re)produced through models and modelling. This is not to say that the two previous approaches are devoid of politics, but it is not their primary focus.

The entanglement of modelling in broader political-economic processes is studied through qualitative methods such as interviews, policy and discourse analysis, archival research, and ethnographic work. Scholars use a diversity of theoretical frameworks including political-economic analysis, Foucauldian conceptualisations of power and governmentality, and feminist scholarship. The focus is less on the specifics of the models in question (the data, equations and parameters that preoccupy the previous two approaches), and more on the wider processes in which a model – sometimes not even explicitly named – may be entangled.

Overall, this body of work is critical of the dominant role that modelling is given in knowledge-making about water, notably because it comes at the expense of other modes of knowledge (Cornejo and Niewöhner, 2021; Zwarteveen, 2024); it also sees models as contributing to "depoliticising" water governance. Scholars show how the purported neutrality of models can lead to their instrumentalisation, that is, their use in legitimising policy and infrastructural interventions on technical grounds even though these are political decisions about controlling and governing water (Budds, 2009; Fernandez, 2014). These scholars stress that models and modelling provide the backdrop for techno-managerial interventions that are aimed at "solving water issues". In the process, the sociopolitical causes of these issues are pushed into the background and thus not addressed; something that is also characteristic of the recent trend towards digitalisation of water (Walter, 2024). Linton and Saadé (2024) trace attempts to represent and quantify global-scale hydrological phenomena back to late 19th century Russia. They show how these efforts led to the emergence of a concept of 'global water' that, in turn, favoured widespread calls for technical interventions (improved irrigation efficiency) and economic interventions (water markets). In a similar vein, in her analysis of modelling in the context of the La Ligua Valley in Chile, Budds (2009) highlights the problematic nature of undertaking a purely *physical* assessment in response to a situation that was predominantly *sociopolitical*. With a slightly different take, and through archival work and a literature review, Orieschnig and Venot (2024) document knowledge generation on the Mekong River and its floodplains during the French protectorate period, as well as the early efforts of numerical modelling in the 1960s. They unravel a specific vision of the Mekong: that of an unruly river that ought to be controlled so that its waters can be put to productive agricultural use. They show how this vision has infused studies that mixed hydrology and hydraulics, and how these studies, in turn, shaped the landscapes they aimed to represent, through paving the way to the construction of specific water infrastructures. The authors reflect on the fact that the voices and lived experiences of local inhabitants seldom feature in this knowledge generation efforts and the models they documented.

Scholars have also analysed how models are entangled with the politics of water. Kroepsch (2018), for instance, investigated the tensions around groundwater modelling in the western United States. The author focuses on a model that considered interactions between groundwater and surface water. The study portrays how industry players were continuously disputing the model, the reason being that because they were abstracting groundwater, they could be required to compensate senior (surface) water-rights holders if the connection between their abstraction and decreasing water flows was officially recognised. Industry actors repeatedly but unsuccessfully argued for using a different model, one that would consider surface water to be independent of groundwater. Godinez-Madrigal et al. (2020), in a similar vein, focused on Mexico's El-Zapotillo Dam project. Those authors showed how modelling is entangled with knowledge controversies over the construction of large-scale infrastructures and with conflictual politics that have to do with who is to benefit and to lose from these projects. The research team also developed an alternative model that accounted for the interests and claims of grassroots groups that were at risk of being flooded by the reservoir (Godinez-Madrigal et al., 2022).

Such attempts at 'countering' may take different forms. In the case described by Holifield (2009) which focused on a contested groundwater pollution site, it took the form of a 'counter-network' that emerged through the strategic assembling of alternative knowledge practices, actors and representations. This allowed questioning the simplifying assumptions that were made in the officially employed groundwater model. Nabavi (this Issue) describes the countermodelling efforts of an upstream community opposing an interbasin water transfer plan in Iran. The countermodel employed structures, variables and datasets that were different from those used by the model that justified the water transfer. The countermodel challenged the portrayal of upstream water that flowed to the Persian Gulf as 'surplus' or 'wasted'; it achieved this by emphasising other values such as ecology and by calling into question the feasibility of the proposed transfer plan. Eventually, the countermodel became just one element of a broader resistance movement. Participatory modelling, too, may fulfil this role; this is highlighted by Jackson

(2006: 95), who calls for, "broadening the deliberative basis of model design to improve both the technical and political functioning of models".

More recently, interdisciplinary teams of scholars have been experimenting with bringing together political ecology analysis and modelling (Rusca et al., 2024; Rusca and Mazzoleni, 2025). Starting from a recognition of the common interest of hydrology and political ecology in, "examining the nature, scale, distribution of and responses to global water challenges" (Rusca and Mazzoleni, 2025: 247), the studies explore the interplay between floods, vulnerability and sociopolitical transformations in a city characterised by highly uneven development. These studies stand out because they do not stop at unpacking the sociopolitical causes of such inequalities; they go on to explore progressive scenarios for redressing them through system dynamics modelling (Rusca et al., 2024).

### **DEVELOPING A CONSTRUCTIVE CRITIQUE OF MODELS IN TIMES OF POST-TRUTH POLITICS**

We write this introduction at a time when significant areas of science and numerous scientists are increasingly being discredited, dismissed, and even fired, against a background that sees the rise of so-called "alternative facts" that undermine democratic institutions and scholarly research. This happens while we are confronted with the "urgency" (Haraway, 2016) of learning to live with, and respond, to climate-water crises and their profoundly unequal impacts on people and ecosystems (for a critical take on crisis discourses, see Wilson et al., 2024).

In this political climate, developing a constructive critique of models to reveal their contingency on historical, geographical, economic and cultural factors (and problematising the naturalisation of their claims) might be mistaken as supporting a relativisation of facts; this is a criticism that some of us have received from colleagues. In this section, in response to this potential criticism and misinterpretation of our motivations, we draw on work that has grappled with the same dilemma to spell out how critical science – including critiques of models and modelling practices – does not equal the excessive relativism of post-truth politics. We argue that, rather, our research programme sheds light on the realities of knowledge-making and that it thus helps expose the workings of uneven power relations; we argue further that, in the process, it allows revealing the vested interests and instrumentalisations of science that buttress the truth claims of authoritarian politics.

Latour (2004) recognised early on the danger that "critical" projects might be equated with relativism and easily confused with science scepticism, in relations to climate change at that time. The common rebuttal of STS scholars to this suggestion has been that revealing the socially constructed nature of scientific knowledge will demonstrate that this social construction yields knowledge of a particular kind and specific value but that it does not deny the existence of a reality (see also Bijker, 2017). For people who are fixated on a wholesale rejection of science, however, this assertion will not be persuasive. At the first opportunity, they will equate social construction with ideological bias, their aim being to disqualify (all sorts of) science - particularly that which does not align with their ideology or interests.

Schindler (2020) thus sees the task of scientific critique as being twofold: to problematise both the uncritical belief in truth claims and the uncritical relativisation of all truth claims. In the words of Neimark et al. (2019: 617), the aim should be to "[cut] through post-truth to expose it". It is as implausible to claim that knowledge is entirely independent from history, power and perspective (the naturalisation of facts that often underpins modelling efforts) than it is to claim that knowledge is solely the product of history, power and perspective (the relativisation of facts which leaves them detached from the world) (Schindler, 2020). A considerable body of work in STS has shown how the distinction between scientific and non-scientific knowledge is established and maintained (Sismondo, 2017); such methods might thus be especially apt in post-truth times for sorting established facts – however negotiated they are – from claims that are based solely on ideology.

Reflexivity (the awareness of the historical, geographical and cultural contingency of knowledge) is not enough, however, to counter the excessive relativism of post-truth politics (Schindler, 2020); it still runs the risk of leading to a dismissal of scientific endeavours. Schindler calls for digging even deeper into science denial in order to expose some of the underlying emotions that underpin the "post-truth problem"; he calls for taking these emotions seriously. One of them, he argues, is the widespread feeling among individuals that they are being sidelined by elites at "a time when many human beings cannot realise their capacity to relate in an independent, reflexive manner to the world" (ibid: 392). He sees the task of critique, therefore, to be identifying the root causes of such emotions in a society of unleashed competition and helping envision a society in which people are capable of maintaining their own stance rather than giving up and falling for authoritarian politics (Schindler, 2020). This suggests that the sincere scientific critique that we aim for constitutes not only an opposition but is actually a tool for empowering people to respond to the deeper alienation they feel and, with that, to proactively address post-truth scepticism and rising authoritarianism. In a similar vein, Neimark et al. (2019) ask us to go beyond exposing the workings of power in the generation of alternative facts; they call for new ways of knowledge production, policies, institutions and relationships that can counter authoritarian politics with new inclusive, effective and publicly accessible practices. For Bijker (2017: 324), this means putting the "vulnerability of technological cultures centre stage", that is, going beyond technocratic notions of hazard and risk (such as flood risk, as discussed by De Tymowski and Hurt, this Issue; Cohen et al., this Issue).

Feminist scholars, too, foreground a reorientation of how science is performed. Donna Haraway argues against both relativism and universalism, suggesting instead that we embrace embodied, partial or, in her words, situated perspectives (Haraway, 1988, 2016). Haraway insists on the importance of bringing a plurality of perspectives into relations and holding accountable positions – what she calls *respons-ability* (Haraway, 2016: 47). This includes being more explicit about – and accountable to – how, by whom, and for whom knowledge is produced. As Zwarteveen (2024: 67) writes, reflecting on the lessons that water research(ers) can learn from feminist scholarship, and following Haraway's suggestion, "knowledge becomes more credible when admitting and accounting for differences between knowers". "Thinking-with" Haraway, Puig de la Bellacasa suggests "care" as, "both a doing and ethico-political commitment that affects the way we produce knowledge about things" (Puig de la Bellacasa, 2011: 100). The author clarifies that this is more than a moral disposition or wishful thinking, and that care and caring denote affective states, material doings, and ways to take up respons-ability and engagement rather than detachment (Puig de la Bellacasa, 2017). The author further stresses that caring from a feminist standpoint means asking who does the work of caring, how, and for whom, paying attention to who may be harmed and devalued. According to Puig de la Bellacasa, this requires being, as a researcher, invested in the topic.

Following these lines of thought and developing a critique of models and modelling is not about dismissing them or saying that anything goes; rather, it is about contributing to the opening up of scientific practices to societies. Marres (2018) is not the only one to warn us that if scientific knowledge continues to derive its authority from an inaccessible realm beyond the public it will likely remain the target of anti-elite movements. Developing a critique of models and modelling should thus foster public debates about what and who counts and how, as we go about understanding and managing water. Such a critique should bring the messiness of research and governance to the surface (Yarina, 2024) and it should make models and modelled knowledge more openly accessible in order to multiply forms of engagement with models. We thus hope that developing a critique of models and modelling will allow for the emergence of new practices of modelling.

## CONCLUSION

This introduction and the five articles included in the Special Issue are an effort to advance critical engagements with models and how they shape water worlds. In conclusion, we offer a few final reflections on, and lessons from, the two key themes guiding our interest in models: their role in understanding and addressing inequalities, and the methodological approaches required to study them.

While not all of the articles in the Special Issue directly engage with water inequalities and injustices, they offer examples of the ways in which models influence how water is understood and managed and how, in doing so, they are far from neutral because they privilege certain perspectives, interests, scenarios and groups. De Tymowski and Hurst (this Issue) show how flood models are entangled with the wider sociopolitical processes shaping Dublin's urbanisation and how they are situated within an unequal neoliberal property regime. The authors underscore how model outputs are tailored to respond largely to the concerns of real estate actors, to the detriment of lower income residents. Cohen et al. (this Issue) illustrate how global flood models (GFMs) risk being used by states and other powerful actors to privilege the framing of floods primarily as technical problems rather than addressing the political-economic roots of flooding. The authors show how GFMs allow these actors to sideline on-the-ground social and political realities by appealing to global facts about flood risk. GFMs thus contribute to buttressing power and reproducing inequitable and unsustainable development. Nabavi (this Issue) illustrates how, in Iran, the needs of upstream communities were marginalised in favour of the water requirements of the strategic and historically significant city of Isfahan, which was to be served by the BeheshtAbad interbasin water transfer. This project was underpinned by sociocultural narratives dating back centuries that framed the transfer as necessary. In response to such a powerful narrative, an equally strong resistance emerged. It not only challenged the numbers through countermodelling, but also challenged what those simulated numbers symbolised, which was deeply entwined with justice, identity and power. For Van Stan II and Simmons (this Issue), the principal concern is that mosaics of region-specific hydrological evidence, once they are stitched together and elevated to 'global truths', risk concealing the provenance of knowledge. They cite several local studies each of which became a presumed universal, from 'British leaves' for rainwater storage, to 'fresh-cut Idaho conifers' for snow interception, to blotting paper bark for stem evaporation. The authors argue that losing touch with the empirical context of models risks misleading water resource planning when it occurs in places that are very different from that empirical context. Trombley (this Issue) does not speak about inequalities per se, but rather demonstrates how a watershed model assembles both the watershed and the associated social networks as objects of intervention, as well as channels actors' interests and orientates interventions. The Chesapeake Bay Modelling System that is referenced in their work could thus become a model for working out how to address inequalities.

When it comes to methodological approaches, some authors of the papers that make this Special Issue investigate the internal mechanics of modelling in order to enhance models as accurate representations (Van Stan II and Simmons, this Issue). Others privilege an analysis of the mundane social practices involved in modelling and of the practices that modelling allows for (Trombley, this Issue). Yet others examine the politics of modelling and explore how models as devices and techno-political phenomena are embedded in broader efforts to govern water but also society, urban spaces and property (De Tymowski and Hurst, this Issue; Cohen et al., this Issue; Nabavi, this Issue). The articles also offer different methods for achieving their aims. De Tymowski and Hurst (this Issue) carry out a critical discourse analysis of an interdisciplinary dialogue between the two authors and of policy documents. They showcase a novel method of reflexive analysis by recording and preserving the distinct voices of the two authors in the final text, enabling the juxtaposition of disciplinary perspectives. Trombley (this Issue) engaged in ethnographic research with modellers, showing how in-depth engagements are promising venues for studying the roles that computer models play in environmental management. Similarly, Nabavi (this Issue) develops his analysis from extensive ethnographic fieldwork within the Zayandeh-Rood River Basin. Van Stan II and Simmons (this Issue) delve into model equations and their genealogies to analyse the historical and philosophical underpinnings of canopy interception models. Cohen et al.

(this Issue) use a multi-country perspective to demonstrate how global flood models overrule local realities.

As editors, we see three key messages emerging from the articles. First, a common thread across all articles is the emphasis on engaging with local realities in order to ground models, modelling practices, and their critical analysis. To this end, the authors suggest engaging in site-specific campaigns and interrogating the equations and parameters within a model; they also suggest attending to the socio-economic processes that shape the sites where models are developed and in which they are entangled, such as the uneven property regime of Dublin or the limited availability of data along the Akaki River in Addis Ababa. This call for grounding the modelling practice echoes invitations by both hydrologists and critical social scientists to attend to the localised character of water-related challenges, including their hydrological and social roots (Massuel et al., 2018).

Second, if an opportunity still exists for a constructive critique of modelling and models such that they can help address inequalities, then there is a requirement to "[be] invested in the subject" (Schuurman and Pratt, 2002: 291). Each of the articles of the Special Issue is the fruit of close, in-depth engagements with both models *and* local realities. In each article, the authors underscore how they build on several years of experience either by using a specific model, by researching particular places, or by engaging closely with the people inhabiting them. We interpret their critical engagements as different forms of caring for models, for the ways in which models 'make' water worlds, and caring for the water worlds themselves (Domínguez-Guzmán et al., 2022). For us, this offers an important lesson: the responsibility for critically engaging with modelling can be shared among modellers, researchers who study knowledge practices, and the communities that are affected by models.

Lastly, we see value in all of the different perspectives that are represented by the papers in the Special Issue. Analysing the inner workings of a model helps open the black box while also reinforcing the link between empirical phenomena and theoretical representations. Attending to the sociopolitical contexts and consequences of models helps to understand the contingencies of models as well as to identify entry points for structural changes. Engaging with the relations between actors and their practices of model building and model use gives access to seemingly mundane, yet powerful, routines and it also offers insights for collaboration. At the same time, each of these perspectives is partial. We now know how property assumptions may be embedded in flood modelling, but not how they may shape model parameterisation. We also now know how equations and parameters are patched together in a canopy storage model, but not how they end up shaping the use of the model by different actors. We interpret this diversity and partiality as richness. What is largely missing, however, is dialogue across perspectives (Alba and Kanesu, 2024; De Tymowski and Hurst, this Issue), not as a means to force consensus but rather as a way to learn about specific approaches and contexts (Domínguez-Guzmán et al., 2017; Verzijl et al., 2023; see also the dissensus forum in this journal).<sup>2</sup> Dialoguing could take the form of, for example, collaborations with artists that may stimulate reflexive thinking and reopen imaginations (van Beek, 2025). Paraphrasing Zwarteveen et al. (2018), rather than finding the unique 'best' approach to critically and carefully engage with models, the focus should shift to interrogating what and whose concerns a particular approach makes visible, with which aims, in what context, and how this could be otherwise. This Special Issue is a first and modest step in this direction, but there is an urgent need for new venues for dialoguing. How these can be organised at the intersection of critical water research and modelling remains an ongoing challenge.

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<sup>2</sup> <https://www.water-alternatives.org/index.php/blog/models>

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