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HESS Opinions: Reflecting and acting on the social aspects of modelling

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Abstract. Within hydrological modelling, a persistent notion exists that a model is a neutral, objective tool. However, this notion has several, potentially harmful, consequences, such as marginalising certain stakeholders. In the critical social sciences, the non-neutrality in methods and research results is an established topic of debate. Thus we propose that in order to deal with it in hydrological modelling, the hydrological modelling network can learn from, and with, critical social sciences. This is a call for responsible modelling – modelling that is accountable, transparent, power-sensitive, situated and reproducible and this responsibility is carried by all actors related to the modelling study. To support our proposition, we have four pillars of arguments, detailing the social aspects in hydrological modelling, insights from the critical social sciences, how to build bridges between sciences, and reflecting on what the hydrological modelling network can learn. We provide several actionable recommendations as a follow-up. The main take-away, from our perspective, is that responsible modelling is a shared responsibility. Therefore, we invite all actors – from the modelling network (from commissioner to modeller to end-user) and society – to take up their share in establishing responsible modelling.

1 Introduction

Within hydrological modelling, a persistent notion exists that a model is a neutral, objective tool (Frigg and Hartmann, 2024; Savenije, 2009; Wesselink et al., 2017). Although it is generally acknowledged that models

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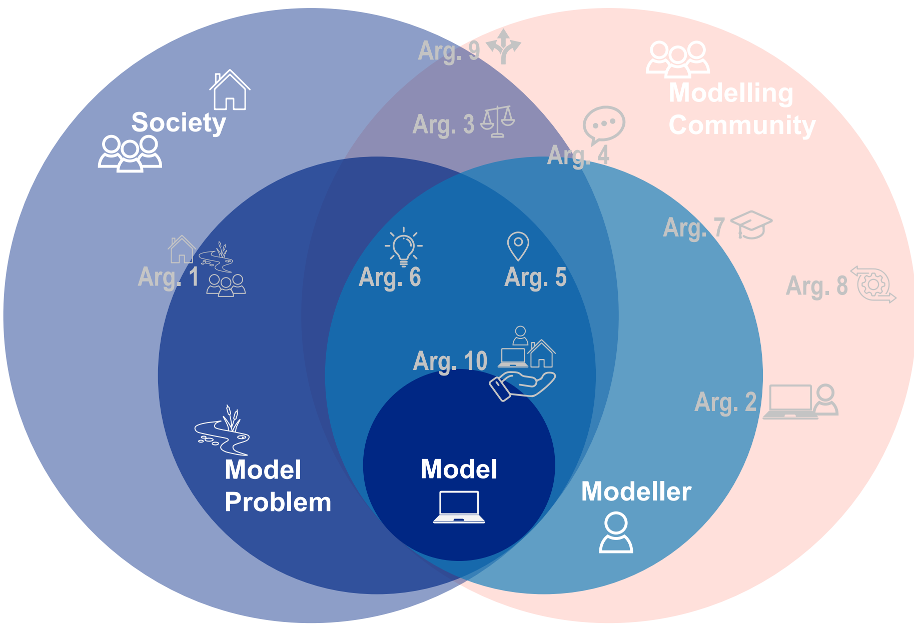

Figure 1. General overview of how the model and its context overlap and where our different arguments are positioned within this. The model problem is the hydrological problem that is being studied and modelled. The argument numbers refer to the arguments numbered in the text. 1) hydrological modelling problems are embedded within society, with all its social processes. 2) the modelling process is a social product. 3) the social aspects of hydrological modelling have ethical implications. 4) vocabulary to express the social aspects in hydrological modelling. 5) reflect on positionality and practice active reflexivity. 6) basic understanding of critical social sciences. 7) education can facilitate the knowledge building. 8) structural changes in the modelling network. 9) new avenues for research. 10) take responsibility for model results.

influence society, for instance through decision-support, this notion of neutrality presumes that the model itself is not influenced by society (Wesselink et al., 2017). Models are deemed to give unbiased information for decision-support. However, we argue that hydrological modelling takes place within a social context (Krueger et al., 2012; Mayer et al., 2017; Melsen, 2022; Packett et al., 2020, , visualised in Fig. 1). The model is influenced by social relations and potentially has differentiating effects on reality; implying that model outcomes might inform policies or infrastructure design that will benefit one group or ecosystem more than others, and will negatively affect different groups or ecosystems in different ways.

https://doi.org/10.5194/egusphere-2025-673
Preprint. Discussion started: 25 February 2025

The notion of neutrality in modelling has several, potentially harmful, consequences. Neutrality implies that all people and aspects are treated equally. This is not the case (Doorn, 2017; Packett et al., 2020). For example, models are always simplifications of reality, and therefore choices are made on what to represent in the model, what not, and how (Frigg and Hartmann, 2024; Refsgaard, 1996; Savenije, 2009). As a result, the unrepresented processes and aspects are marginalised and become invisible. This can result in injustices: some groups being overlooked, some interest being prioritised, or some ways of understanding sidelined (Doorn, 2017; Zwarteveen and Boelens, 2017), which are obfuscated by assumed neutrality. Simultaneously, ignoring the political side of models may impede their potentiality or effectiveness (Beven et al., 2022; ter Horst et al., 2023b; Saltelli and Di Fiore, 2023). Acknowledging the political side of modelling can create opportunities in better connecting to specific needs within the modelled problem.

In the critical social sciences – the sciences dealing with critical questions of power relations, especially oppression and domination (Watts and Hodgson, 2019), the non-neutrality in methods and research results has been a topic of debate for a longer period already (Mendelsohn, 1977; Latour, 1990; Law, 2004; Sismondo, 2011). Different disciplines within the critical social sciences, such as Science and Technology Studies (STS) and political ecology, provide insights into how to analyse and deal with non-neutrality. Thus, in order to take into account the non-neutrality in modelling, we propose that the hydrological modelling network can learn from, and with, critical social sciences. This is a call for responsible modelling – modelling that is accountable, transparent, reproducible, power-sensitive, situated, and inclusive of diverse knowledges and interests – and this responsibility is carried by all actors related to the modelling study.

We are aware that our argument is not new and has been brought up in different terms and ways across the hydrological modelling network. Part of this comes from our own contributions to this debate (ter Horst et al., 2023a; Melsen, 2022; Nabavi, 2022; Remmers et al., 2024), but we also acknowledge active research communities in Australia working on good modelling practices and model governance (Hamilton et al., 2022; Jakeman et al., 2006, 2024), work done in Germany on situated modelling (Klein et al., 2024; Krueger et al., 2012; Krueger and Alba, 2022), ongoing research in France (Molle, 2009; Venot et al., 2014), Post-Normal science (Funtowicz and Ravetz, 1993; Petersen et al., 2011; van der Sluijs, 2002) and sensitivity auditing (e.g. Puy et al., 2023; Saltelli and Di Fiore, 2023), work done in the Chesapeake bay (Deitrick et al., 2021; Lim et al., 2023), and the Open Modelling Foundation initiative (OMF, SA). This list is far from complete, but shows different research groups are working on these topics. That being said, from experience

https://doi.org/10.5194/egusphere-2025-673
Preprint. Discussion started: 25 February 2025

we know that the effects of these studies are often limited in practice, and therefore we provide here a clear overview of arguments to invite the hydrological (modelling) community to join the conversation on the non-neutrality of models, as well as to engage in a constructive way.

To support our proposition, we have four pillars of arguments: the social aspects in hydrological modelling, insights from the critical social sciences, building bridges between sciences, and reflecting on what the hydrological modelling network can learn. Within each of these pillars, we will provide several subarguments. The main points of the subarguments are highlighted in bold. Figure 1 provides an overview of our perspective and where our arguments are positioned in this.

2 Social aspects in hydrological modelling

The first pillar supporting our proposition concerns the social aspects already present in hydrological modelling. Showcasing how hydrological modelling already contains social aspects can highlight the importance for the hydrological modelling network to acknowledge that modelling is not a neutral, purely technical activity. This pillar is underpinned by three arguments.

First, the problems hydrological modellers study are **embedded within society, with all its social processes** (Arg. 1). Water availability in rivers is impacted by land use changes (Teuling et al., 2019; Wamucii et al., 2021). Unsustainable management of groundwater abstraction has social and political consequences (Nabavi, 2018; Sanz et al., 2019). Or sea level rise necessitates societies to adapt to the risks this brings (Irani et al., 2024; Kopp et al., 2019). These examples led to the initiation of the field of socio-hydrology or hydro-sociology (Sivapalan et al., 2012; Krueger et al., 2016; Melsen et al., 2018; Ross and Chang, 2020). These disciplines explore hydrological problems as integrated parts of society and often use stakeholder participation as an approach to include the different perspectives to an hydrological problem (ter Horst et al., 2023a; Xu et al., 2018).

Second, the **modelling process itself is a social product** (Arg. 2), as it inherently contains underdetermined decisions and social processes. Underdetermined decisions arise from equifinality, meaning that certain options are not distinguishable from each other and as such are not ‘objectively better’ compared to each other (Beven and Freer, 2001; Butts et al., 2004; Ward, 2021; Winsberg, 2012). Although equifinality is often explored in the domain of parameter uncertainty, it can be extended to equifinality in methods or approaches, which might still produce different results or conclusions. Proske et al. (2022, 2023) also use the concept of equifinality when evaluating different model complexities. For the case of cloud microphysics, they show that the simplification of the model formulation does not affect the model results substantially – the results are equifinal compared to each other. Such equifinality in modelling decisions are inherently based on social processes, introducing subjectivity and inter-modeller variability (Babel et al., 2019; Krueger et al., 2012; Melsen, 2022; Remmers et al., 2024). For example, certain variables are included and other excluded from the conceptual model, which has large effects on the model outcomes. An example is the modelling of the Ebro River in the north of Spain to design the planned water transfer to the South. As the sediment load was not taken into account in the hydrological model the negative effects of the transfer for the Ebro Delta were not factored in (Gorostiza et al., 2023). Also the choice for model software is often based on legacy and financial constraints – the institute a modeller works at determines which software is used (Addor and Melsen, 2019). Additionally, choices made early on in the modelling process can influence choices later on, creating so-called path dependency (Lahtinen et al., 2017; Lenhard and Winsberg, 2010). For example, the chosen model software limits the possible model settings (Remmers et al., 2024). Furthermore, Lane (2014) argues that the hydrological modeller is not separated from society, and thus is not separated from the problem they study. What these studies show is that the same modelling research question would be answered with a different modelling approach, and therefore likely different model results, at a different time and a different place.

Third, and this is where the previous two arguments come together, **the social aspects of hydrological modelling have political and ethical implications** (Arg. 3), such as questions about who is involved in the modelling and who benefits (Beck and Krueger, 2016). Due to the modelling decisions and assumptions made (from Arg. 2), model results contain a specific perspective of reality (Nabavi, 2022; Saltelli and Di Fiore, 2023). Choosing this perspective means excluding or sidelining other perspectives. Stakeholder engagement has the potential to bring these marginalised perspectives forward again (Packett et al., 2020; Xu et al., 2018), although stakeholder engagement comes again with its own challenges (e.g. **?**Turnhout et al., 2020). As model results have societal implications, injustices can occur (Thaler, 2021; Zwarteveen and Boelens, 2017). For example, models used in flood studies, which obviously can have high societal impact, can cause injustices. They might for instance not consider informal settlements in the floodplains, and as such marginalise inhabitants of those floodplains (Wesselink et al., 2017).

https://doi.org/10.5194/egusphere-2025-673
Preprint. Discussion started: 25 February 2025

3 Insights from critical social sciences

Critical social sciences provide the tools and theoretical frameworks that can address the social aspects of hydrological modelling. Here, we will highlight three.

First, the critical social sciences have the **vocabulary to express the social aspects in hydrological modelling** (Arg. 4). Different disciplines of critical social sciences can provide various suggestions for useful vocabulary. This vocabulary is not (yet) common in the hydrological modelling network, even though similar concepts are addressed in the hydrological modelling network, albeit described more elaborately. For example, when we just described '*model results contain a specific perspective of reality*' in the previous section (in Arg. 3), we could have also used the term 'situated', which is also used in feminist theories (Haraway, 2013). This means that model results are formed in a specific context. Another example is 'ontology', meaning the study of the nature of things (Frigg and Hartmann, 2024; Wesselink et al., 2017). With a model, a researcher studies what a hydrological system looks like. The representations researchers choose are dependent on their ontological view of the system. In more recent literature (e.g. Klein et al., 2024; Wesselink et al., 2017), some of the critical social science vocabulary and concepts are related to the practices of modelling. Knowledge of this vocabulary can enhance our understanding of and facilitate our discussion of the social aspects in hydrological modelling (Laplane et al., 2019).

Second, social scientists **often reflect on their positionality and practice active reflexivity** in their research (Arg. 5). A positionality is written to indicate how they as researcher relate to the subject they study (Lin, 2015; Njeri, 2021; Soedirgo and Glas, 2020). For example, critical social science disciplines using ethnographical methods – observing subjects in their own environment – often include a positionality, since the scientist's background influences the observations and interpretations they make. Hydrological modellers also have a personal perspective/position (from Arg. 2) towards their subject through their own previous experience or the institute they work at or even their own personal interests and hobbies (Deitrick et al., 2021; Melsen, 2022; Packett et al., 2020). Based on these experiences or contextual factors, modellers tend to make decisions (Krueger et al., 2012; Melsen, 2022; Remmers et al., 2024; Sanz et al., 2019). Reflecting on and being transparent about positionality can create more transparency regarding this personal context and assumptions made (Blackett et al., 2024; Klein et al., 2024; Wesselink et al., 2017). For example, Melsen (2022) includes a brief positionality for the interview study she did, highlighting how her

https://doi.org/10.5194/egusphere-2025-673
Preprint. Discussion started: 25 February 2025

own background has influenced the conducted interviews. Besides writing a positionality, active reflexivity – continual questioning of your own assumptions and biases – should also be done throughout the modelling process (Soedirgo and Glas, 2020). This entails documenting assumptions, normalising reflexivity, engaging others in the reflexivity, and publishing the modeller's reflexivity alongside the research. We acknowledge that publishing reflexivity through a positionality means being vulnerable and open. We believe this to be a strength, however, because the vulnerability and transparency can build trust in how models are used. Additionally, it can inspire others to also reflect on or to become more open about their modelling practices and assumptions. As more people start to do this, it could change practices in the whole modelling network.

Third, again combining the previous two arguments, **basic understanding of critical social sciences** is needed to situate research in a broader context, to understand the possible positive and negative consequences of modelling, and to be able to identify who to empower and how (Arg. 6). This context is needed since hydrological modelling addresses societal issues (from Arg. 1), the hydrological modelling process is a social product (from Arg. 2), and model results have political and ethical implications (from Arg. 3). The necessary basic knowledge should entail knowledge to place modelling results in the societal context (from Arg. 1) and reflect on potential ethical consequences of the results (from Arg. 3), for example knowledge on flood warning responses to understand what model results mean. In 1997, the National Weather Service did not include the uncertainties when they issued a flood warning two months in advance for the Red River, North Dakota, USA. Because of this, the administration of a town, Grand Forks, thought it was safe. But, the actual flood reached the upper band of the uncertainty range, resulting in flooding of the town and 75% of the houses were damaged. Currently, the National Weather Service does provide that information (Silver, 2012). Thus, executing an uncertainty analysis or not as a modeller can have ethical implications in society in water management (McMillan et al., 2017; Silver, 2012). Recently, ethics of Artificial Intelligence has gained traction (Doorn, 2021; Maier et al., 2024; Nabavi et al., 2024), and rightly so. This development in ethics of Articficial Intelligence can be used to develop the ethics of numerical (hydrological) modelling. Understanding of certain concepts of critical social sciences can also ease reflecting on the subjectivity in modelling (form Arg. 2). For instance, the vocabulary (from Arg. 4) can help expressing the subjectivity or help initiating reflexivity. Ontology – studying the nature of things – can spark debate on the different perspective people have of a hydrological system (Agrawal et al., 2024). A person living somewhere can define what a system looks like differently than a researcher or tourist.

https://doi.org/10.5194/egusphere-2025-673
Preprint. Discussion started: 25 February 2025

4 Building bridges between sciences

Different researchers have been trying to build bridges between (the social and hydrological) disciplines (Krueger et al., 2016; Pulkkinen et al., 2022; Rödder et al., 2020; Ross and Chang, 2020; Venot et al., 2022; Zwarteveen and Boelens, 2017), but most remain within their own discipline. Hierarchy of sciences – the idea that certain sciences, such as physics, have a higher degree of consensus and scientific advancement than others, such as social sciences – reinforces this way of thinking and acting (Comte, 1855; Cole, 1983; Fanelli, 2010; Simonton, 2006). We propose two ways in which the hydrological modelling network can increase the building of bridges to critical social sciences: firstly, through education, which will instigate structural changes in the long-term, and, secondly, through structural changes that can have an immediate effect.

First, **education can facilitate the knowledge building** necessary to understand the basic critical social science concepts (Arg. 7). Understanding basics of other sciences can increase communication and effectiveness in future work situations, enhancing inter-disciplinary collaborations (from Arg. 6). This teaching of social processes and reflexivity needs to be practical and integrated within hydrological modelling education (Micheletti et al., 2024; Oldfield, 2022; Stefanidou et al., 2014). For example, the curriculum for hydrological modelling education should have reflexivity and responsible modelling integrated in its curriculum: during a modelling course, the students learn to apply reflexivity as they model. Education should extend to working professionals in order to have them keep up with new insights and to also incorporate this knowledge in the current workforce.

Second, although education can help raise a new generation of hydrological modellers, we need **structural changes in the scientific network** to facilitate the incorporation of social aspects in daily modelling practices (Arg. 8). Structural changes can guide and force the hydrological modelling network to adapt practices focusing on taking the social aspects into account (Jakeman et al., 2024). For example, funding requirements can include a positionality statement within the funding application (from Arg. 5) or a research plan that specifically designates time for active reflexivity. Also, journal requirements can be adapted to incorporate social aspects in hydrological modelling more explicitly. Journals might start asking for a positionality statement as well, or they can ask for documentation on assumptions in the modelling process.

https://doi.org/10.5194/egusphere-2025-673
Preprint. Discussion started: 25 February 2025

5 Reflecting on what the hydrological modelling network can learn

Building a bridge to critical social sciences can improve transparency about the social aspects of hydrological modelling. Also, considering and disclosing the uncertainties associated with these aspects potentially creates more reproducibility. Increased transparency and reproducibility can contribute to more constructive scientific progress and more responsible and accountable policy making.

Also, acknowledging social aspects in hydrological modelling can open **new avenues for research** (Arg. 9). Critical social science understanding can move the hydrological modelling network towards more productively working on societal problems (from Arg. 7). Through reflecting, modellers are incentivised to rethink their modelling decisions. This might result in more robust, inclusive and accountable modelling decisions. In turn, this will provide more accountable decision-support. Reflexivity highlights assumptions made. Sharing these assumptions can streamline research where researchers can consciously build on each others methods or findings (Laplane et al., 2019). It is easier to know what has or has not been done before and to have the ability to complement each other because of that knowledge. Additionally, it could be that new research will specifically look for diversity, instead of a universal model (Baldissera Pacchetti et al., 2024; Horton et al., 2022; Savenije, 2009). Different researchers would facilitate diversity in approaches and therefore give a more complete picture (Baldissera Pacchetti et al., 2024). Flexibility can also be introduced through modular modelling frameworks (Clark et al., 2008; Craig et al., 2020; Fenicia et al., 2011). This diversity can encompass the different contexts in which the modelling is shaped or in which the modelling is used.

With more transparency on the social aspects of hydrological modelling, modellers and also funders, commissioners and decision makers can **take responsibility for model results** (Arg. 10). This should be a shared responsibility, not just the modeller's. The interplay between these actors can create dynamics influencing the modelling. This interplay should be made more visible (from Arg. 5). Structural changes in the modelling network (from Arg. 8) can facilitate this. Due to the transparency, modelling results will be more retraceable, and the limitations of a modelling study are more evident for and between different actors in the hydrological modelling network. Reflexivity on ontology can help modellers in their ability to recognize how their model results are partial, and might have looked different with another ontology. The transparency on the interplay influencing the modelling can provide better information for decision/policy makers, contributing to their ability to justify their policy decisions. For instance, after flooding in Brisbane and surrounding, the model

https://doi.org/10.5194/egusphere-2025-673
Preprint. Discussion started: 25 February 2025

results were questioned and the organisations behind them were held responsible (Supreme Court of New South Wales, 2021). This example shows that the organisations using and providing model results need to be able to take responsibility of them. Sharing responsibilities can take many forms, but it starts with curiosity for and openness to knowing, understanding and taking action on the social aspects of hydrological modelling. Another example, outside of hydrology, is that the modellers that simulated the nitrogen emissions for a newly planned airport in the Netherlands were investigated by the Public Prosecution Service, because there were clear indications that all modelling decisions were made such that the nitrogen emission was as low as possible (Adecs Airinfra Consultants, 2021; NOS Nieuws, 2022). Not surprising perhaps, if the executing company sells themselves as "aviation lovers", but also the result of a commissioner that has certain interests. As such it is a clear example of how modellers can be held accountable for their model results, while they also face forces from, for instance, funders.

6 Invitation to start acting

As potential follow-up actions, we suggest:

- If you are a model user (i.e. someone who analyses and uses model results), you can consider asking the modeller for their assumptions
- If you are a modeller, you can consider to start reflecting on your positionality, and consider to include a positionaly statement in your next modelling study. How did your experience and position in society influence how you approached this study?
- If you are teaching the next generation of hydrological modellers, you can consider incorporating reflexivity practices and social science basics in your lecture, computer practical, course, or curriculum.
- If you are a commissioner, you can consider allowing for more time or funding during projects for including reflexivity in the modelling process or writing a positionality statement. You can also consider to change your project requirements to include reflecting on positionality.
- If you are overseeing a modelling team, you can consider having a discussion on internalised assumptions in your way of working, also known as entrenched workflows (Levine and Wilson, 2013).

https://doi.org/10.5194/egusphere-2025-673
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These follow-up actions sound like a recipe. However, in this whole opinion paper, we have advocated and shown that hydrological modelling is context dependent. Therefore, we acknowledge that anyone implementing these potential actions needs to navigate their own working environment. More importantly, this list is not definitive; we invite you to explore and discuss this topic further, and come up with your own ways of incorporating reflexivity.

7 Conclusion

In this opinion paper, we argue why and how we think the hydrological modelling network, which we define as all actors, i.e. funders, commissioner, modellers, users, decision-makers, involved in and influencing the modelling study, can benefit from insights and practices from the critical social sciences. To support this, we have four pillars of arguments: the social aspects in hydrological modelling, insights from critical social sciences, building bridges between sciences, and reflecting on what the hydrological modelling network can learn. Based on these arguments, we provide some tangible follow-up actions targeting the whole modelling network to promote responsible modelling – modelling that is accountable, transparent, inclusive and reproducible. This responsibility is carried by all actors related to the modelling study. Even though we focused on the hydrological modelling network, these lessons are also applicable to other modelling communities.

The main take-away, from our perspective, is that responsible modelling is a shared responsibility. We realise that modellers tend to already bear a lot of the responsibility and are the easiest ones to ask actions from. Substantial change is not possible without also addressing the other actors in modelling studies, such as educators, commissioners, funders or supervisors. Therefore, we address the complete modelling network and society. We invite all actors to take up their share in establishing responsible modelling.

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Preprint. Discussion started: 25 February 2025

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