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From prediction to engagement: using technical models to enhance consultation in water management

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ABSTRACT

Technical models are useful tool to address epistemic uncertainties but often fall short of attending to other types of uncertainty that characterize complex water challenges. It is unclear if and how they might be repositioned as a more deliberative tool to help deal with the many uncertainties related to problem framing, uncertain future conditions, and likely intervention effects at various scales. Through the case of a multi-stakeholder water quality project in East Java, Indonesia, this paper explores how technical systems modeling can be used to support consensus-building regarding the characterization of water pollution problems and adjacent policy goals, both in the use of outputs and in the process of model-making and attendant deliberation. The water quality model combines mapped terrestrial pollution source estimates with rainfall-runoff and pollution transport and fate process models to estimate localized, regional, and basin-wide impacts of various source-reduction scenarios on water quality. By visually identifying pollution source concentrations and illustrating estimated impacts of alternative strategies, the model offers a useful visual tool on which to anchor reframing discussions and scenario-building. In this way, the case demonstrates how modeling can be repositioned as an invitation for planners to simultaneously deliberate alternative problem structures alongside interventions to better deal with uncertainties inherent to water resources management.

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Water quality modeling; policy uncertainty; water quality governance; multi-stakeholder consultation; scenario-based decision-making

1. Introduction

Integrated water resource management is conceptualized as a holistic, coordinated approach to balancing social, environmental, and economic demands on water, often across sectors, levels of governance, and geographic regions. Owing to social-ecological system complexities, water managers and planners are challenged with difficult

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choices when tasked with prioritizing water challenges and interventions, particularly when problems and goals are unclear or contested, or when problems can be experienced, applied, and measured at various scales. This is often the case for river water quality management, which involves coordinating water allocation, monitoring, conservation, and control, as well as terrestrial pollution management across sectors. In large basins, particularly, numerous organizations are likely involved in various provisioning and regulatory activities in pursuit of multiple water quality goals expressed at local, regional, and hydrological levels.

Problem structuring and solution-crafting in water quality management are also complicated by the number of system components and complex interactions, along with uncertainty over future physical states, including weather, and choices that govern pollution sources. Uncertainties also arise due to sectoral perspectives and interests. Consequently, water planners and decision makers must navigate shifting objectives and targets that introduce policy ambiguities and limit applicability of traditional optimizing approaches to policy selection, all amidst competing definitions of water quality itself (Houser, Pramana, and Ertsen 2022).

The network of relationships between rainfall, flow regime, and terrestrial pollution, coupled with the intersectoral and multilevel nature of water quality governance creates a tangle of uncertainties, and there is ongoing discourse on both statistical uncertainties inherent to technical-analytical approaches as well as the suitability of such approaches to deal with wicked problems that require inclusion of unquantifiable "uncomfortable knowledge" (Rayner 2016). This paper posits that traditional optimizing decision support tools such as computational systems modeling are, indeed, insufficient to deal with such uncertainties, but that modeling can be re-imagined and repositioned to inform deliberations through and beyond the modeling process.

The benefits of more collaborative modeling have been promoted in several studies on water and water quality management, highlighting advantages such as enhancing understanding and trust, improving decision making, and increasing stakeholder engagement (Hare 2011; Langsdale et al. 2013; Reed 2008; Voinov and Bousquet 2010). Through an empirical case of a multi-stakeholder water quality project in East Java, Indonesia, this paper proposes that computational models can be as useful with respect to questions *prompted* as they are with respect to questions answered, in direct relation to the types of uncertainties at hand.

2. Policy uncertainty and decision making in water environmental policy

Policy uncertainty encompasses various dimensions that limit decision makers' capacities to confidently understand a system and predict impacts of interventions. Policy uncertainties are significant in environmental governance due to the complexities of social-ecological systems and interconnectedness with other spheres (Arlinghaus et al. 2017; DeSarbo et al. 2005; Dewulf and Biesbroek 2018; Klijn and Koppenjan 2015; Nair and Howlett 2017; Sigel, Klauer, and Pahl-Wostl 2008). Moreover, environmental issues often involve long time frames, innumerable unknowns about future choices and physical states, non-linear patterns of change, and irreversible potential damages (Huntjens et al. 2012; Judd, Horne, and Bond 2023; Kandlikar, Risbey, and Dessai 2005; Karantounias 2020; Pindyck 2007; Quiggin 2008). Much attention has been given to dealing with uncertainty in water environmental governance, particularly (Jensen and Wu 2016). Not only are pollution sources and root causes difficult to trace and isolate, predicting overall responses to interventions is difficult due multiple uncertainties at play. Epistemic uncertainty, stemming from lack of knowledge, can theoretically be reduced through additional research and analysis (Isendahl et al. 2009; Kwakkel, Walker, and Marchau 2010). In relation to surface water quality, this may include limited knowledge regarding sources and volumes of pollution, relevant actors, and relationships between terrestrial emissions, rainfall, and pollution transport. Computational models have been developed to accommodate increasingly sophisticated systems (Brugnach et al. 2008), but these, too, involve uncertainties related to specification, parameter estimation, variable selection, assumed functions, input data, and system boundaries (Karantounias 2020; Kwakkel, Walker, and Marchau 2010; Quiggin 2008; Smith and Stern 2011; Walker et al. 2003).

Additional layers of uncertainty are also at play, including ontological uncertainty, unpredictability that cannot be managed through additional knowledge (Charpentier et al. 2022; Gong et al. 2013; Judd, Horne, and Bond 2023; Smith and Stern 2011). For water quality, this may be derived from unknown futures associated with weather patterns, changes to the built environment, and socio-political shifts. Additionally, ambiguity or frame-related uncertainty arises from the presence of multiple problem perspectives. This is particularly relevant for wicked problems, wherein a large number of stakeholders bring different values, concerns, and interpretations that must be made sense of in order to negotiate shared policy directions (Brugnach and Ingram 2012; Dewulf and Biesbroek 2018; Isendahl et al. 2009; Kwakkel, Walker, and Marchau 2010; Myšiak et al. 2008; Van der Bijl-Brouwer 2019).

In the case of river water quality management, these kinds of uncertainties are also derived from characteristics of the natural, technical, and social systems (Table 1). When such uncertainties are accepted as realistic conditions of decision making, traditional technical-analytical approaches may be deemed inadequate, and water planners must draw on additional tools, including participatory methods, adaptive management, and scenario analysis (Isendahl et al. 2009; Jänicke and Jörgens 2000; Jensen and Wu 2016; Myšiak et al. 2008; Wohlgezogen et al. 2020). Technical approaches like modeling need not be so readily dismissed, however, particularly if the modeling enterprise can be reframed and be made more participatory. Through a case study of the Brantas River basin in East Java, Indonesia, this paper examines the relevance of model-based decision support in a high-uncertainty context and suggests how technical models might be developed and complemented to address different kinds of uncertainty.

3. Brantas water quality model

The Brantas River, a major Indonesian waterway, runs 320 km through 16 municipalities (kotas) and regencies (kabupaten), draining a basin of approximately 14,000 km^2 (Figure 1) (Badan Pusat Statistik Jawa Timur 2021; BBWS Brantas 2020). Recognized for its vital role in national development, it is one of Indonesia's 11

Table 1. Types of uncertainty affecting river water quality management.

	Unpredictability	Incomplete knowledge	Multiple knowledge frames
Natural system	Unpredictable rainfall, temperature, and changes to the built environment that might affect proposed interventions	Incomplete knowledge about water pollution and linkages between emissions and pollution levels; Model uncertainties	Multiple knowledge frames about water quality as a concept at condition
Technical system	Unpredictable behavior of the technical system, including water interventions	Incomplete knowledge about water quality interventions and their impacts	Multiple knowledge frames about pollution problems and available solutions
Social system	Unpredictable behavior of the social system affecting water management, including strategies and choices of agencies, communities, farmers, manufacturers, etc.	Incomplete knowledge about the legal, administrative, political, and social system that govern / are affected by water quality and water interventions	Multiple knowledge frames about the social system governing pollution and affected by water quality

Source: Authors' adaptation of Brugnach et al. (2008).

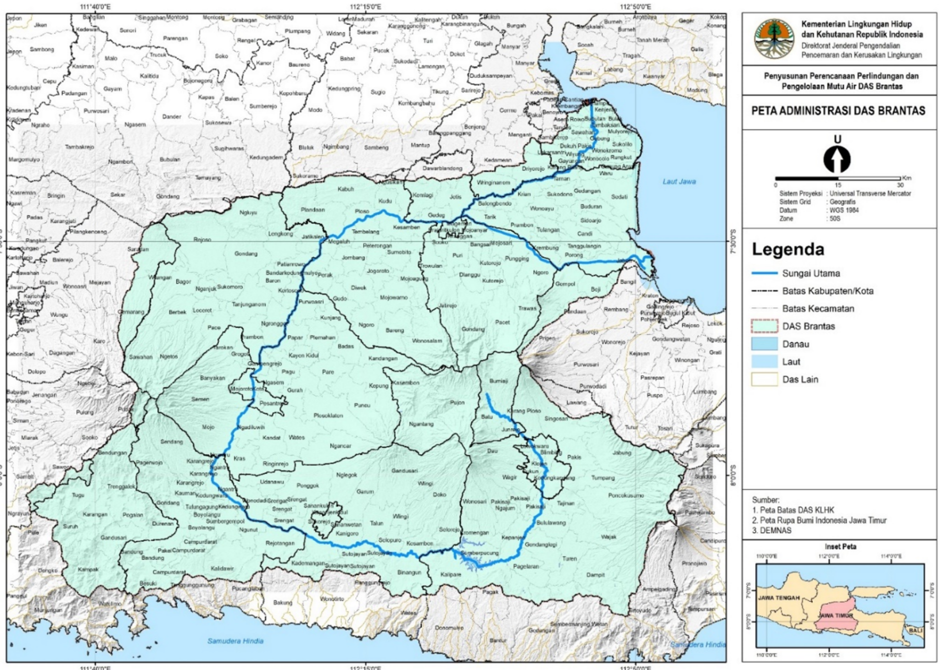

Figure 1. Map of the Brantas River basin (DAS).
Source: Presentation "Perencanaan Perlindungan dan Pengelolaan Mutu Air Sungai Brantas 2023," Ministry of Environment and Forestry, Republic of Indonesia to project team (2023).

National Strategic Rivers. While water pollution has been a longstanding concern, national commitment to sustainable development and strengthened river management has prompted more intensified efforts to improve river health. A 2018–2024 Indonesia-Netherlands multi-stakeholder project, "Fostering inclusive growth, health, and equity by mainstreaming water quality in the Brantas River Basin, Indonesia"

(Brantas Water Quality Project), was initiated to enhance water quality management and brought stakeholders from multiple sectors and levels of government together to analyze issues and develop coordinated management strategies through consultations, reviews, workshops, and technical exercises.

The Brantas water quality problem space is complex, as the river is affected by many terrestrial pollution sources distributed across a large area. While some water quality data was available to support analysis, there was limited data on relative source contributions to pollution. There was also no available approach to consider how weather patterns or sectoral interventions could affect quality. Additionally, water quality is characterized and measured in different ways, and stakeholders held notably different viewpoints and problem frames related to both the concept of water quality and prevailing conditions (Houser, Pramana, and Ertsen 2022). Stakeholders also brought different expressions of quality dependent on their training, mandates, and organizational cultures. Water quality was expressed, for example, in terms of parameter thresholds, indexed values, or qualitative ratings, measured and reported at different time and geographical scales. Moreover, desired states associated with water quality ranged, including parameterized basin-wide targets, reduced microplastics in fish stocks, and reduction of costs of water supply at the municipal level.

Water quality management in the Brantas also involves numerous stakeholders across multiple ministerial lines in a complex multi-level arrangement (Figure 2). Since the river lies entirely within East Java, there is a strong role for the province,

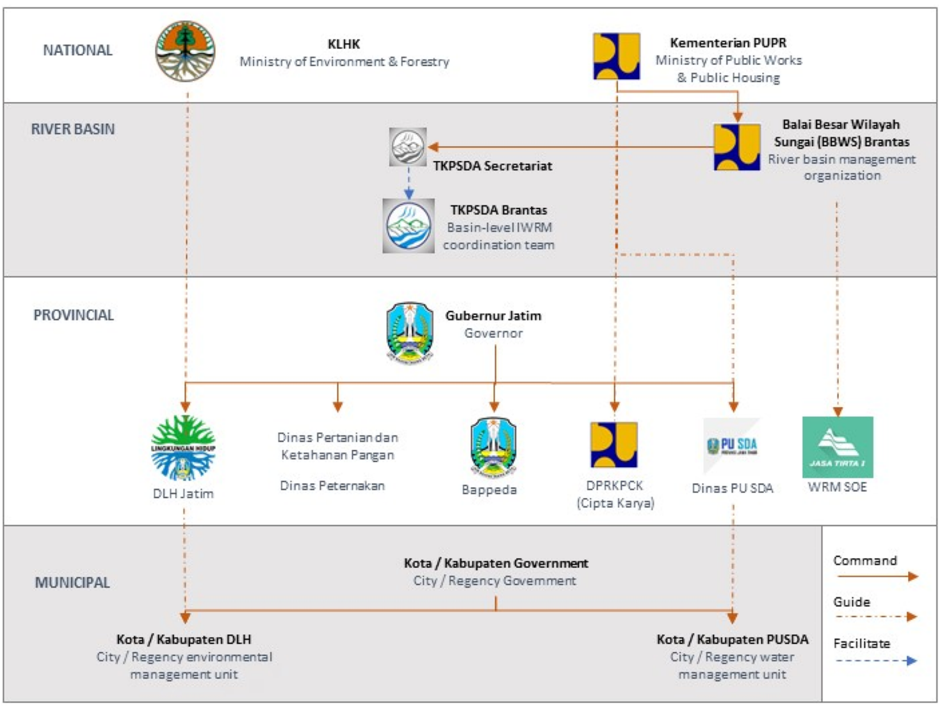

Figure 2. Water quality governance arrangements in the Brantas River basin.

but responsibility for overall management and water quality planning falls with the national government. Moreover, many functions of pollution control and service provision (e.g. sanitation) are local. Agents' problem interests and available interventions are dependent on mandates, jurisdictions, and capacities to coordinate. As such, there was a recognized need to consider differentiated strategies as well as both localized impacts and effects along the full main stem of the river.

In this context, the project team initiated a modeling exercise to support problem analysis and planning. The Brantas Water Quality Model considers pollution sources and hydrological and transport processes to simulate relationships between terrestrial pollution and water conditions. The model (described in detail in Supplementary Material) combines a terrestrial pollution source model, a hydrological rainfall-runoff model, and a pollution fate and transport model to predict water quality under baseline conditions and intervention scenarios.

The emissions model inventories pollution sources (e.g. from domestic wastewater, livestock, agriculture, etc.) by location and volume and estimates leakages to the environment based on management practices. While numerous pollution sources are present, the model accounted only for domestic wastewater and agricultural and livestock runoff due to data limitations – a recognized source of in-model uncertainty. The hydrological model, WFLOW, simulates the catchment's hydrological processes. Static gridded data includes terrestrial features such as elevation, land use, soil characteristics, and water bodies (Figure 3). These inputs are coupled with dynamic inputs such as rainfall, temperature, evapotranspiration, and reservoir data

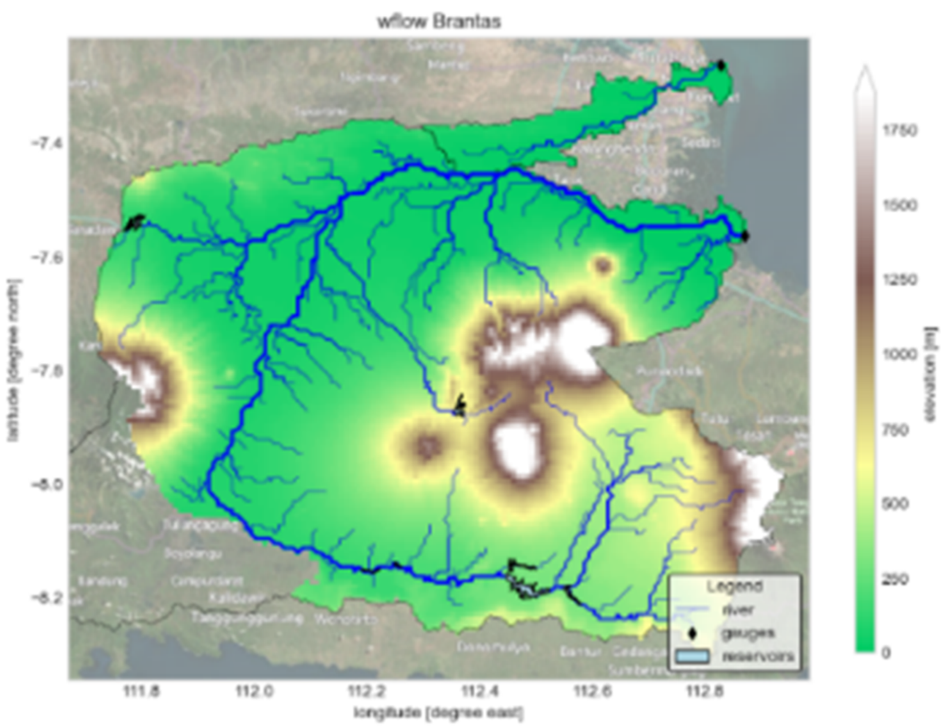

Figure 3. WFLOW rainfall-runoff model.

to calculate runoff, river discharge, and infiltration at a daily time step. These outputs are used, in turn, as inputs to the DELWAQ fate and transport model to simulate spatio-temporally varying pollution concentrations in the river.

Supplementary Materials provide further detail on model set-up, specification, validation, and results. Here, we focus on how both the model and process of model construction prompted and answered important questions with implications for managing uncertainties.

Framing the issue: First, whilst water quality is seemingly straightforward, it may be described, measured, and expressed in myriad ways, resulting in different framings of "the water quality problem" and its root causes. Analysts may take, for example, concentration levels of generalized parameter, an indexed value, or a categorical assessment. Focused interest on a particular type of pollution or high-concern substance would rely on yet another attribute (e.g. pesticide concentration). These choices all yield different perceptions of quality. In a series of consultations with project partner agencies (BBWS Brantas, PJT I, and DLH Jatim) and other key stakeholders (including representatives from the provincial planning agency and river basin management team) in September 2022 through March 2023 (see full list in Supplementary Material) regarding model set-up, this choice of expression was an important subject of consultations. The decision was taken to employ three unit types: a limited set of chemical water quality parameters (herein, biochemical oxygen demand, or BOD); percentage change in BOD associated with an intervention compared to the baseline; and "water class," a categorical classification of water quality defined in law (Table 2) (Peraturan Pemerintah Republik Indonesia Nomor 22 Tahun 2021 tentang Penyelenggaraan Perlindungan dan Pengelolaan Lingkungan Hidup 2021). Class determination is based on acceptable use and concentration limits, and the government designates which classes apply to various river segments (Peraturan Gubernor Jawa Timur Nomor 61 Tahun 2010 tentang Penatapan Kelas Air Pada Air Sungai 2010).

A second set of decisions related to identifying relevant components of the model and the focal points of analysis. With respect to inputs, stakeholders agreed to limit sources under consideration to agriculture, livestock, and domestic wastewater, largely due to data limitations. With respect to scenario-building, the scales and levels of interventions and effects comprised another decision set requiring extensive deliberation about potential interventions and impacts to be considered. Discussions were informed by administrative mandates and policy goals and an extensive policy review of agencies' proposed actions to improve water quality (*Brantas Harmoni* 2024). While the project operated primarily at the basin level, the systems model could be used to examine scenarios differentiated by level and scope of intervention (administrative and geographical) as well as the distribution of effects in response

Table 2. Indonesia water classification system.

Class I	Water that can be used for raw drinking water and/or other uses that require the same quality
Class II	Water that can be used for water recreation, freshwater fish cultivation, animal husbandry, irrigating plants/crops, and/or other usages requiring similar quality
Class III	Water that can be used for freshwater fish cultivation, animal husbandry, water for irrigating plants/crops, and/or other usages requiring similar quality
Class IV	Water that can be used to irrigate plants/crops, and other usages requiring similar quality

to various stakeholders' intervention capacities and policy goals. For example, the provincial government could consider basin-wide reduction strategies and impacts, given their capacity to coordinate and mandate, whereas a municipality facing political pressure to address a particular pollution issue could focus on understanding reductions of a specific source in their local area. Thus, the project team explored both broad sector-wide interventions as well as more targeted approaches to offer anchoring information for negotiating policy goals in subsequent planning discussions.

4. Overview of modeling method and select technical results

The detailed modeling methodology and full results are included in linked Supplementary Material. This section highlights a select set to support reflection on how model-making and model outputs can be positioned to support consensus-driving deliberations. First, mapped pollution source load estimates show baseline (2020) estimations of BOD from each source, offering a visual, geographically relevant overview (Figure 4). Results indicated that, of total estimated BOD load contributions, emissions from domestic wastewater and agriculture are largest and that agricultural emissions are broadly distributed, whereas livestock emissions loads are concentrated. These results inspired discussion regarding the implementation of sectoral versus coordinated interventions (efforts to reduce agricultural emissions

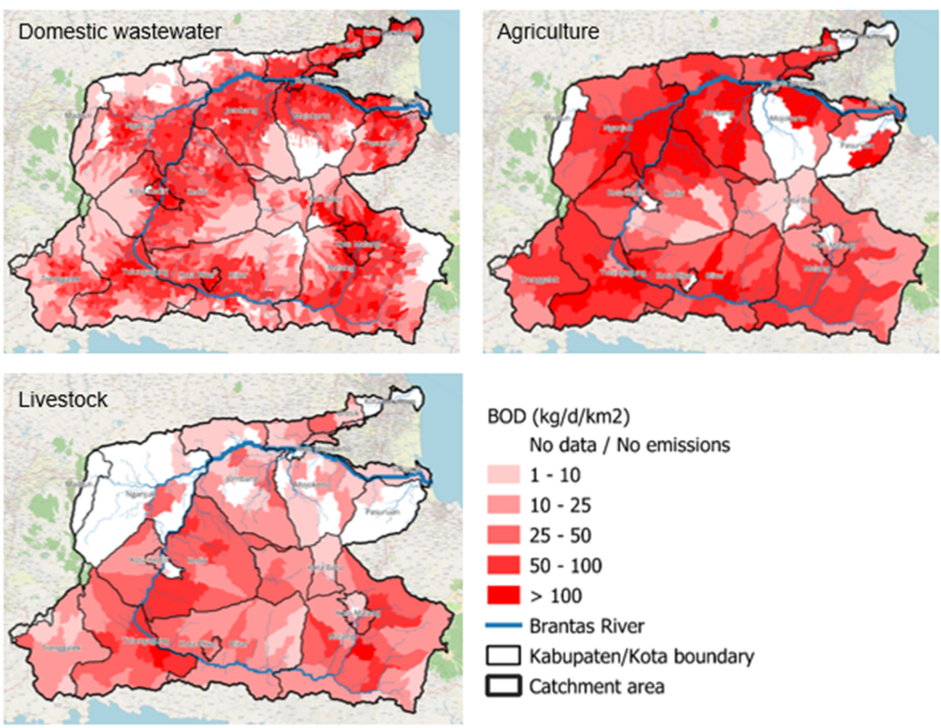

Figure 4. Est. BOD loads by source (kg per day per km^2), showing differentiated levels of source dispersion and concentration.

would require broad implementation, for example, whereas livestock measures could be locally targeted) and attendant considerations of feasibility and capacity to cooperate.

The modeling exercise also allowed for scenario-building to interrogate effects of future hypothesized rainfall patterns, thus attending to some key ontological uncertainties.

The set of modeled interventions was developed by the research team in consultation with government project partners via a series of consultations and workshops (full list in Supplementary Material), designed to explore comparative impacts of strategies and to identify reduction tipping points that would transition river segments from one water class to another. A limited set of results is shared here to demonstrate how the model was used to address prevailing empirical uncertainties regarding contributions of various pollution sources in various locations, as well as the preferability of alternative reduction approaches.

First, broad intervention scenarios targeting each emissions source in isolation predicted limited improvements, whereas combined strategies predicted noticeably greater gains (Figure 5). Reducing emissions for all sources by 30% (scenario 2a), for example, predicts a 20–30% reduction in median BOD concentrations in large segments and shifts from river water Class III to II for the downstream region. This modeling output directly addressed important policy uncertainties regarding the sectoral focus of pollution reduction strategies and need for cross-sector approaches.

The analysis also informed more granular considerations regarding sectoral distribution of reduction targets. Scenario analysis of combined agriculture-domestic

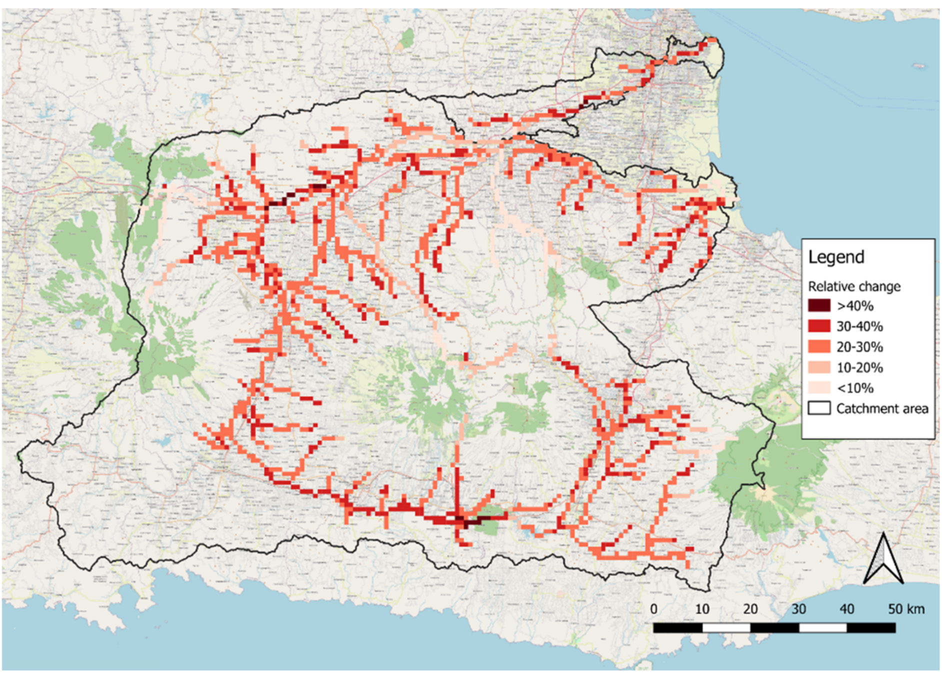

Figure 5. Predicted % reduction BOD, scenario 2a, symmetric 30% reduction of emissions from domestic wastewater, agriculture, and livestock.

strategies suggested that combined strategies could produce significant effects (Scenario 3a in Figure 6), particularly when weighted toward greater domestic wastewater reductions (Scenario 3c).

These results closed an important empirical gap – namely, missing knowledge regarding the relative importance of both pollution sources and potential sectoral strategies – but they also supported reframing of preferred administrative and geographical settings for reduction strategies. The important role of domestic wastewater was noted especially around cities and suggested that urban surface water standards would only be met with immediate upstream interventions. For example, when domestic wastewater from the city of Malang was isolated as a separate source in Scenario 4, which assumed 100% safe management in the city, results showed no change to water class in the river overall, but high relative reductions in Malang

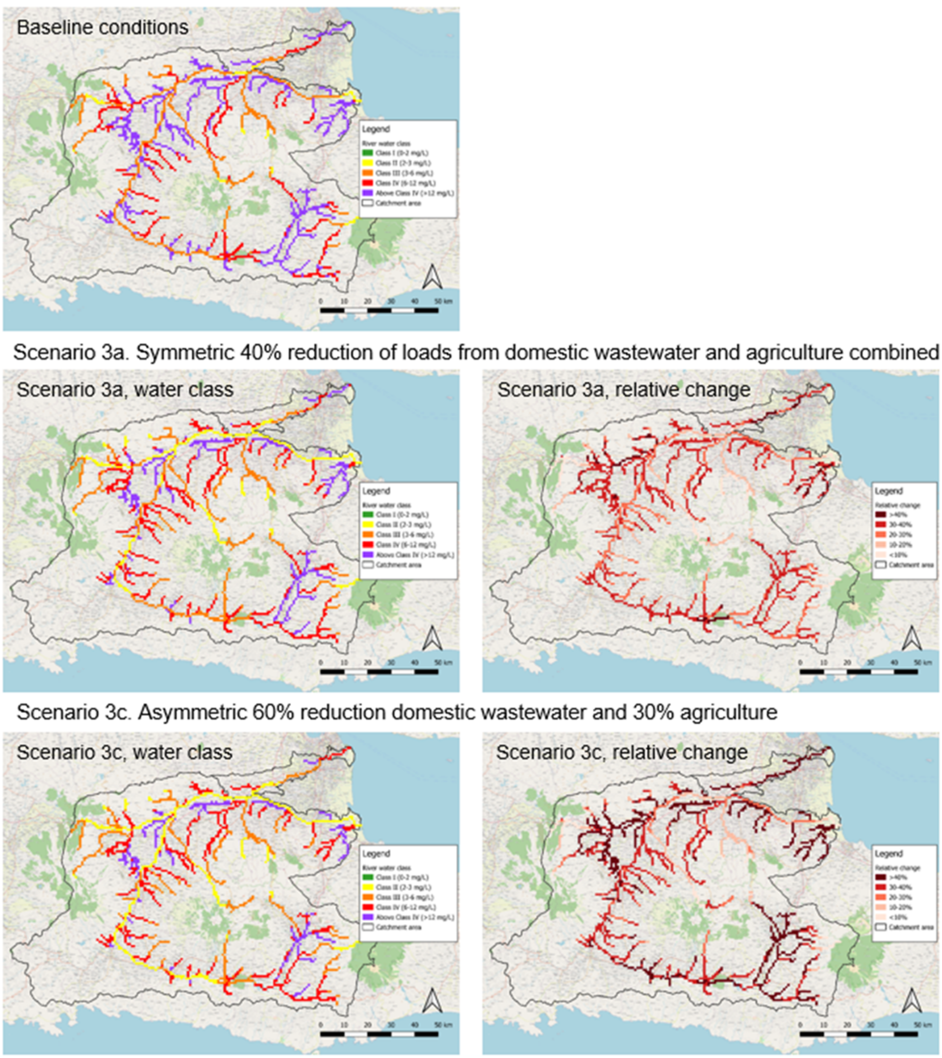

Figure 6. Predicted water class (BOD) and relative change (% reduction BOD), Scenarios 3a, 3c.

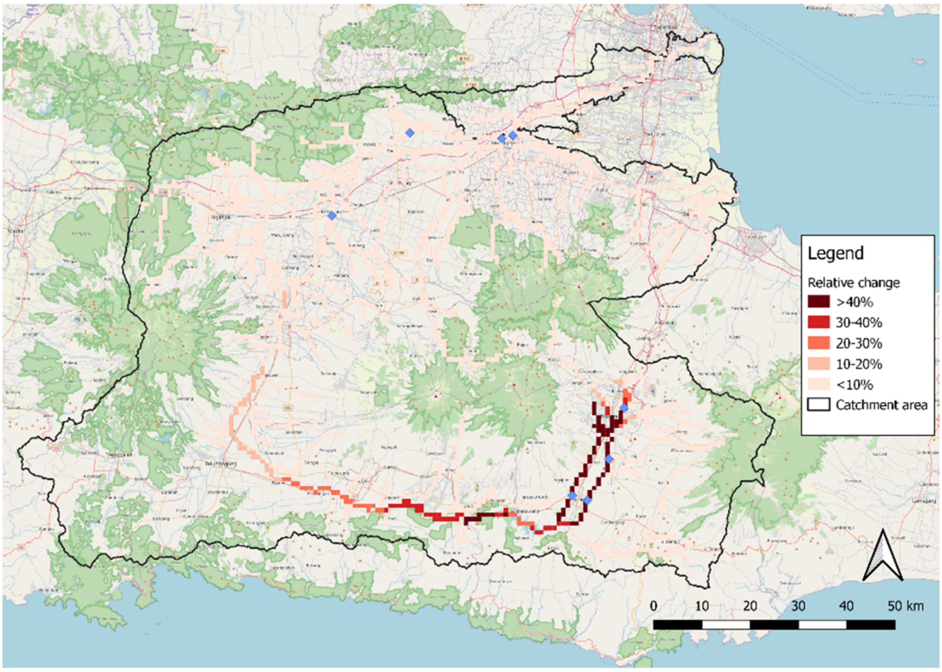

Figure 7. Estimated % reduction of median BOD, 100% safely managed Malang wastewater.

and for some 100 kilometers downstream (Figure 7). Similarly, livestock emissions reductions, which failed to produce significant overall impacts, still had significant local impacts in select areas (Figure 8).

5. Repositioning modeling as a consensus-building tool

By allowing decision makers to link localized and basin-wide pollution sources, water conditions, and predicted impacts of pollution reduction strategies, the Brantas model mitigates some of the epistemic uncertainties that hamper policy and prioritization of both problems and solutions. That said, the model is certainly not a panacea to all questions water quality, nor is it devoid of inherent uncertainties. The model itself is subject to parameter, data, and computational uncertainties arising from various sources, including missing and other data limitations, uncertainties regarding linkages between emissions, interventions, and water conditions, and assumptions regarding source contributions, the built environment, and emissions factors. While partially addressed by validation and verification, they are impossible to eliminate.

Accepting these, the Brantas model nevertheless reduces knowledge gaps and, as a discussion anchor, helped deal with both indeterminacy and ambiguity. Related to the first, the Brantas case reiterates ontological uncertainties of water management, including difficulties predicting uncertain futures with respect to weather, the built environment, and social choices of waste management. But the model does foster

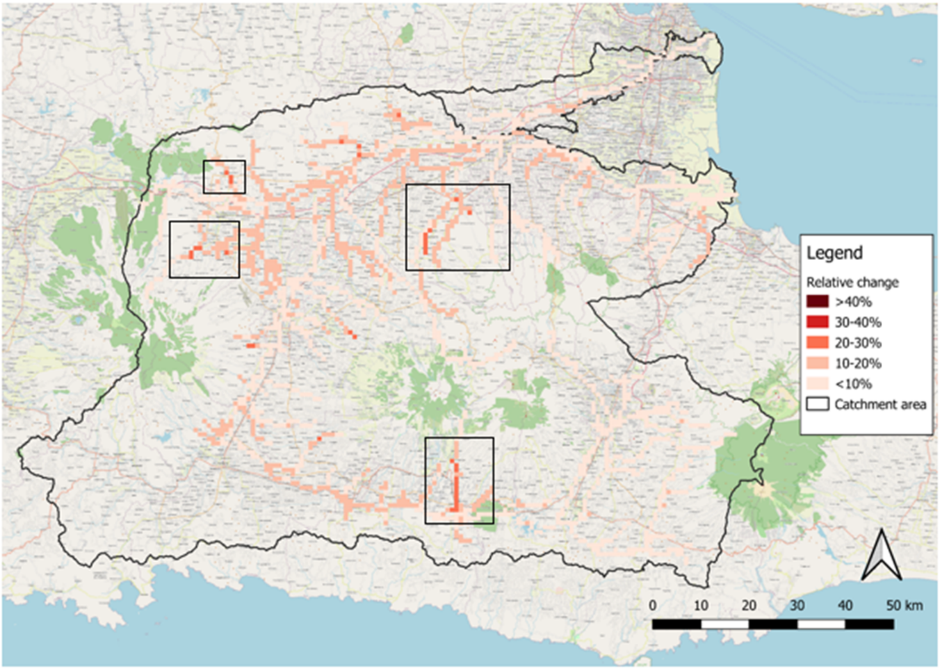

Figure 8. Localized reductions in BOD due to 30% livestock emissions reduction.

scenario-building to consider such futures, particularly with respect to temperature, rainfall, and land use.

While the Brantas exercise involved consultations with water planners and bureaucrats from agencies involved in the project (BBWS Brantas, DLH Jatim, Perum Jasa Tirta I) and representatives from the provincial water authority, planning agency, and river basin coordination team (see full list of consultations in Supplementary Material), wider participation in model set-up and scenario selection could also provide an important opportunity to gather variant knowledge bases to improve problem specification and flexible responses. As Smith and Stern point out, scientists need not focus wholly on reducing uncertainties. Rather, the contribution of science for policy is to engage in “deep conversations with policymakers” in an effort to better classify and communicate uncertainties and their potential implications (Smith and Stern 2011). Assuming this more relational lens, the Brantas case shows that such models can support key analytical tasks in policy design, but that the *process* of modeling can also work to deal with ambiguities and identify important administrative considerations.

6. Observations on systems modeling for framing

Effective policy design for water quality, particularly considering the many stakeholders involved, depends in part on resolving contradictory problem viewpoints. The Brantas case reaffirms recognized difficulties in characterizing and defining water quality as a policy problem. In set-up, the notion of water quality itself was extensively discussed, driving agreement on a parameterized version of “good water quality" that mirrors the language of national water law. The process of model-building revealed more ambiguities to be framed and reframed in discussions regarding scenarios, boundaries, relevant interventions, and key pollution sources. Such differences related to the relevance of components, system boundaries, and the focus of attention for analysis and intervention.

A consultative approach also helps meet some important policy design principles that relate to managing uncertainty in policy design laid out in other studies (Bali and Ramesh 2018; Giordano, Brugnach, and Pluchinotta 2017; Huntjens et al. 2012; Mukherjee, Coban, and Bali 2021; Pluchinotta, Salvia, and Zimmermann 2022). For one, the Brantas model serves important analytical functions by conceptualizing water quality problems and their component elements and, to follow, visually demonstrating root causes to be attended to in intervention scenario-building. The visual outputs allow planners to consider relative effects of geographically targeted versus dispersed interventions, impacts of alternatives based on different goals at various scales, and results of isolated or coordinated strategies. The model set-up and mapped outputs also prompted important discussions about scale, scope, and capacity, including the distribution of costs and potential gains to regional stakeholders, the appropriate administrative levels of interventions, coordination required for various strategies, and capacities or barriers to collaborate (workshop proceedings, 2023).

While the model offers little to directly inform key considerations such as costs associated with interventions or administrative and political feasibility, participation in the process of model-building provides important opportunities for such issues to arise and be addressed in attendant discussion. In this way, the modeling process itself can serve as an anchor for a deliberative system that both answers key questions but also facilitates structured dialogue to identify new dimensions of the problem at hand. As such, the case demonstrates how such models can be employed to both support decisions and spur deliberation to address all three kinds of uncertainty. Drawing on the linkages made by Brugnach et al. (2008) between uncertainty and "objects of knowledge" in water governance systems, we summarize the uncertainties and example questions the Brantas model dealt either directly or by prompting discussion (Table 3).

In prompting important framing discussions, particularly in relation to the concept of water quality and the relevant components to be included (or excluded) from analysis, the Brantas modeling exercise shows how a highly technical tool can be used both to inform decisions and to enhance consensus regarding the system. Consultations also improved model relevance with respect to real policy concerns and operating conditions and facilitate deeper discussions regarding the goals and experienced conditions related to water resources.

That said, the modeling process and its outcomes could have been improved with the involvement of an even wider stakeholder group in both construction and in the deliberation over modeled outcomes. This could have, for example, introduced a wider set of perspectives into model construction and lessen the acknowledged risk that technical models, in their simplified representations, can exclude important problem perspectives. A richer stakeholder involvement could also reposition the

Table 3. Uncertainties and example questions informed by modeling or prompted by the modeling process, adapted from Brugnach et al. (2008).

	Use	Unpredictability	Incomplete knowledge	Multiple knowledge frames
Natural system		Unpredictable rainfall, temperature, and changes to the built environment that might affect proposed interventions	Incomplete knowledge about water pollution and linkages between emissions and pollution levels; Model uncertainties	Multiple knowledge frames about water quality as a concept at condition
	Inform	*How might future rainfall affect water quality? What are tipping points with respect to runoff and pollution loads? (scenario analysis)*	*How do hydrological processes and terrestrial emissions affect water quality?*	*What are the relevant pollution problems? How serious are they*
	Prompt	*What other potential future conditions need be considered?*	*What water quality, hydrological, and pollution source data is missing?*	*What is "good water quality"? How is it measured? How is it relevant?*
Technical system		Unpredictable behavior of the technical system, including water interventions	Incomplete knowledge about water quality interventions and their impacts	Multiple knowledge frames about pollution problems and available solutions
	Inform	*How might future land use change affect water quality? (scenario analysis)*	*How can sector interventions reduce pollution? Where and for whom?*	*What scales of intervention are relevant (basin or local)? What sectors should be prioritized (agriculture or wastewater)? What interventions are needed?*
	Prompt	–	What interventions are feasible?	*Who is responsible (local or provincial, environmental or water)?*
Social system		Unpredictable behavior of the social system affecting water management, including strategies and choices of agencies, communities, farmers, manufacturers, etc.	Incomplete knowledge about the legal, administrative, political, and social system that govern / are affected by water quality and water interventions	Multiple knowledge frames about the social system governing pollution and affected by water quality
	Inform	*What are tipping points with respect to human choices regarding pollution control? (scenario analysis)*	*How would pollution control strategies (including non-action) affect conditions? What are differentiated impacts for stakeholders across the basin (upstream-downstream, rural-urban)?*	*Who is affected by poor water quality? Who is producing pollution that affects water quality? Do upstream or downstream communities pay the price of poor water quality? Are root causes concentrated in rural or urban areas?*
	Prompt	*What is the policy direction for water and the environment in Indonesia? How would rural citizens and government respond to an agricultural emissions strategy?*	*At what administrative level (or degree of coordination) should solutions be implemented?*	*What are the policy goals at hand? What interventions are administratively and politically feasible? Whose responsibility is water quality?*

Source: Authors' adaptation of Brugnach et al. (2008).

modeling as a form of prototyping to be subject to deliberation, revision, and redesign to better address a greater set of objectives, concerns, and intervention possibilities.

7. Conclusion

The Brantas model demonstrates the potential of integrating modeling tools with deliberative approaches in environmental planning, not only to improve the applicability of models to real-world policy concerns but also promote deeper and more inclusive cross-sectoral participation in environmental management. The contribution of this paper is to more explicitly demonstrate how water models and model-making can address different types of uncertainty, both directly through analysis and indirectly by prompting important questions and anchor points for deliberation. In particular, the case demonstrates how systems models can help deal with ambiguities in complex policy spaces when they are re-couched as interactive consultative tools and invitations for policymakers to simultaneously explore alternative problem structures alongside interventions at multiple geographic and administrative scales.

The visual, geospatial nature of the Brantas model's outputs also directly informed discussions of who wins or loses, where, and at what costs to whom, offering a relevant and relatable starting point for further deliberation regarding layered objectives of water policy and the capacities and barriers to coordinate across sectors and levels. Looking ahead, more guidance is needed in the science-for-policy field to help modelers and policymakers effectively couple systems modeling with structured stakeholder dialogue. While hydrological models are valuable for their analytical rigor and ability to simulate complex environmental processes, they often fall short of capturing the multifaceted nature of water issues that require deeper stakeholder engagement.

Integrating deliberative methods with systems modeling can enhance the relevance, legitimacy, and effectiveness of policy interventions, but only if the process of integration deals supports both modelers and decision makers. There is a gap in science-for-policy literature and training with respect to offering clear frameworks and methodologies by which policy communities can combine modeling and deliberative practices, structuring discussions on important issues that arise in model-making, particularly related to ambiguity, and guiding use of models for problem framing. There is also a need for more research and guidance on how modelers can identify and communicate various cascading uncertainties and how policymakers are to deal with these in decision making. Guidance that emphasizes the complementary roles of systems modeling and participatory methods is crucial for preparing researchers and policymakers to tackle complex and "wicked" problems in environmental governance.

Disclosure statement

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