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Article

Understanding Hydrologic, Human, and Climate System Feedback Loops: Results of a Participatory Modeling Workshop

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Abstract: Groundwater depletion threatens global freshwater resources, necessitating urgent water management and policies to meet current and future needs. However, existing data-intensive approaches to assessments do not fully account for the complex human, climate, and water interactions within transboundary groundwater systems. Here, we present the design of and findings from a pilot participatory modeling workshop aiming to advance understanding of the hydrologic–human–climate feedback loops underpinning groundwater systems. Using participatory modeling tools and methods from the system dynamics tradition, we captured the mental models of researchers from water, social, data, and systems sciences. A total of 54 feedback loops were identified, demonstrating the potential of this methodology to adequately capture the complexity of groundwater systems. Based on the workshop outcomes, as an illustrative example, we discuss the value of participatory system modeling as a conceptualization tool, bridging perspectives across disciplinary silos. We further discuss how outcomes may inform future research on existing knowledge gaps around groundwater issues, and in doing so, advance interdisciplinary, use-inspired research for water decision-making more broadly.

Keywords: groundwater; transboundary groundwater; water resources; participatory modeling; system dynamics; group model building

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1. Introduction

Groundwater serves as the main source of freshwater for over two billion people globally, and it provides approximately 40% of the world's freshwater for irrigated agriculture [1,2]. Climate change-exacerbated trends of unprecedented groundwater depletion threaten the resilience of communities around the world that rely on these resources [3–6]. Due in part to its invisibility, groundwater remains vastly understudied compared to surface water [7,8]. Challenges associated with understanding and managing these invisible resources are intensified for groundwater systems shared between more than one country, which are referred to as transboundary aquifers. Of the approximately 600 identified transboundary aquifers and groundwater bodies, only one maintains a management agreement that specifies resource allocation between countries [9,10]. Differing scientific assessments, data management approaches, decision-making structures, and political and cultural realities contribute to this complex problem [11].

Water decision-makers implement policies in the present to meet current and future needs. Appropriately assessing these needs, and the ability to meet them, remains critical to the success of a water policy, since changes to the built and natural environment cannot be adjusted instantaneously [12,13]. Existing evaluative approaches, however, lack use-inspired and participatory structures [14,15]. Further, they do not fully account for the complex human, climate, and water interactions within a transboundary groundwater system [16,17]. Understanding these complexities and ensuring that evaluations account for community needs and realities is central to ensuring that decisions can meet their intended outcomes [18]. Even when decisions are made with the best of intentions, they run the risk of producing unintended consequences within these complex and interconnected human and natural systems [13].

However, given the complexity of transboundary groundwater systems, actualizing use-inspired research—or science driven by producing societally beneficial outcomes [19]—that accounts for human, climate, and water interconnections presents challenges. Better understanding the dynamic complexity involved necessitates a "many-model" approach, which incorporates different sets of modeling methods that provide insight into different angles of the problem [20]. The complexity of feedback interactions among the dynamic components of the system represents one of these angles [21].

To address this need, we hosted a two-day online workshop as part of the Transboundary Groundwater Resilience (TGR) Network-of-Networks (NoN) annual workshop in September 2022. We hypothesized that participatory system modeling tools and methodologies could help uniquely capture the foundations of these multi-system interconnections in use-inspired ways. While transboundary groundwater research traditionally takes place within disciplinary silos, the TGR NoN recognizes that these grand challenges cannot be solved within the confines of any single field [16]. As such, the TGR NoN aims to harness the complementary capabilities of water, social, data, and systems sciences to advance transboundary groundwater resilience. The workshop hosted researchers from within the NoN that spanned these academic disciplines. Given this range of backgrounds, not every participant had expertise in all the topics covered during the session. Some participants were well-versed in hydrology, for example, while others had experience primarily related to water policy. We hypothesized that capturing the audience's conceptualizations of the system, or mental models, would provide insight into their perceptions and misperceptions of hydrologic, human, and climate system feedback; perceptions represent a not fully understood component of water decision making [12,22].

Transboundary groundwater research typically takes place at the regional level and focuses on a specific aquifer. Without established mechanisms to share these advances, each region—or even subregions within a single aquifer—must develop their own assessments. Determining how to capture key relationships and feedback loops that exist across multiple systems, rather than determining them on an isolated regional scale, could help facilitate more rapid advancement of our understanding of interconnected hydrologic, human, and climate systems that impact transboundary groundwater resources.

In this paper, we explore the research foundation for the application of participatory modeling, from the system dynamics tradition, within water resources. This literature informed the development and design of the TGR NoN's participatory modeling workshop. Next, we describe the design of the TGR NoN case study, which includes results from an evaluative survey of the workshop. We then outline the outcomes produced through the interactive workshop sessions in the form of causal loop diagrams. Finally, we discuss the successes, lessons learned, and opportunities identified through this case study. This includes insight into the potential of participatory system modeling to advance use-inspired research that better understands hydrologic, human, and climate interconnections.

2. Methods

2.1. Participatory Modeling

Participatory modeling is an approach for including stakeholders in the modeling process, typically for the co-description of a problem and co-production of a model around that problem. Such an approach has been described as a "purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality" [23] (p. 233). Although there are a variety of tools and methods for modeling with stakeholders, selecting the appropriate design depends on the purpose of the research. For a review of various modeling methodologies with a participatory design, see [23–25]. Of these, we employ the system dynamics method for participatory modeling, which has been formalized as group model building (GMB) within the field [26,27]. System dynamics, more generally, is a methodology for modeling complex systems to understand and address dynamic problem behaviors. System dynamics models focus on the feedback structure of the system under study—i.e., how the various circular causal relationships between interconnected system components (feedback loops) interact to endogenously generate observed problem behaviors.

The feedback loops are typically represented in informal models, stylized in causal loop diagrams (CLD), and/or in formal simulation models, stylized in stock-and-flow diagrams. These stylized visual representations of complex systems have relatively few modeling conventions and, thus, can be easily communicated to and interpreted by (non-technical) audiences outside the field [23,28]. The main conventions relate to the polarities of individual causal links among variables in the feedback loop, which adds up to an overall loop polarity. Each causal link in that chain is assigned a polarity: a positive link when both variables in the dyad vary in the same direction and a negative link when they vary in the opposite direction. The polarity of the feedback loop, however, refers to the net effect of an initial change introduced to a causal link around the loop. Positive feedback loops, also known as reinforcing loops, amplify the change as it goes around the loop (i.e., an initial increase in a variable leads to a further increase in that variable or an initial decline leads to a further decline), whereas negative feedback loops, or balancing loops, dampen changes introduced to the loop (i.e., an initial increase leads to an eventual decline in the variable, or vice versa).

In GMB, more specifically, groups of problem-owners or stakeholders are guided to integrate their diverse knowledge and perspectives and collectively represent their mental model of the problem's underlying system structure in a qualitative causal map using causal loop diagramming [29]. To construct such causal maps, stakeholder participation is facilitated in GMB workshops consisting of both divergent (e.g., variable elicitation) and convergent (e.g., systems mapping, feedback loop and leverage point identification) scripted activities [30,31]. These activities are common to the two main types of GMB, each with their own distinct purpose [32]. The first type of GMB views models as microworlds that aim to empirically represent reality with a dynamic hypothesis that can be tested against observations and real-world data. For that purpose, the co-constructed qualitative causal map (typically a CLD) would be used to conceptualize a quantitative simulation model, which becomes the basis for group learning through experimentations and scenario analyses [27,33]. The second type views models as boundary objects meant to derive "a negotiated view of the group's" collective mental model [32] (pp. 5–6). This approach emphasizes the process of causal mapping for facilitating dialogue and mental model alignment to arrive at a shared understanding of the problem. Given this purpose, it is not necessary to formalize qualitative causal maps into simulation models. In our study, we employ the latter approach to GMB with the explicit purpose of eliciting and aligning mental models regarding transboundary groundwater systems.

2.2. Existing Research

Within the broader participatory modeling framework for transboundary water systems, researchers have utilized surveys and agent-based modeling [34], dialogue and listening sessions [35], and causal statement elicitation ("if X occurs, then Y occurs") of decision makers [36] (p. 6) in their workshop sessions to identify stakeholder beliefs and priorities. Stakeholder engagement in these studies largely focuses on knowledge extraction for the purpose of quantification in formal models or validation of those models. Here, participants are only included in the modeling process indirectly—understandably so, since mathematical modeling commonly poses a high technical barrier to entry. On the other hand, the use of causal loop diagramming in participatory system modeling provides a unified and communicable language for non-technical audiences. Participants are guided to translate their knowledge into concrete visual representations of relationships between two distinct variables (an arrow between a cause and an effect, as well as a positive or negative sign to indicate the polarity of the relationship). As a result, diverse stakeholders can actively contribute to the modeling activities and gain a sense of ownership over the model.

Moreover, the feedback perspective of system dynamics allows stakeholders to visualize key system interactions and identify points in the system to intervene in with respect to the anticipated feedback effects. Our study thus focuses on participatory system modeling, using causal loop diagramming and its easy-to-use conventions, to get participants to directly model the feedback structure of the groundwater system. Other participatory modeling approaches, including the ones described above, typically lack this focus on how the system's complex feedback structures interact to influence dynamic behavior.

To date, participatory system modeling has been applied to study water resources in various river basins [37–42], one of which was transboundary [42], and various groundwater systems [37,39,40]. Such studies have included stakeholders for the purpose of building a context-specific quantitative system dynamics simulation model for scenario analyses and policy testing. Our study, on the other hand, focuses on the construction of a generic qualitative model to understand the general dynamics of groundwater systems. To our knowledge, there are no other non-aquifer-specific studies in the literature. Our workshop participants, from various nationalities, are tasked to produce an aggregated generic structure that applies to any aquifer system. This emphasis on a generic structure encourages participants to avoid historical anecdotes and adding detail complexity to the model. The generic structure, with a higher level of aggregation, can then be used to gain an overview of the transboundary groundwater system and build an initial understanding of the complex interactions between system components. Also, historical context and system detail may create or increase tension between groups of stakeholders. Modeling a generic structure, instead, may alleviate tensions and build initial trust and rapport with conflicting groups.

Lastly, the studies outlined above have not reported the design of their participatory modeling and its outcomes. This is understandable, given that their focus is on the quantitative simulation model as a research outcome. The scholarly contribution of our paper is to introduce other water researchers to this qualitative participatory system dynamics methodology. Here, we describe the participatory workshop design and interpret the co-produced qualitative model, serving as an illustrative example for others. We further discuss the utility and potential of participatory system modeling methods for spurring interdisciplinary research in water issues, which is often only briefly discussed in the existing literature.

2.3. Data Collection and Analysis

We organized a two-day online participatory modeling workshop for the TGR NoN's annual workshop, which was held from 28–29 September 2022. A total of 15 registrants participated in the modeling sessions. Participants ranged from senior researchers to students, and they came from diverse disciplinary backgrounds, including hydrology, geology, data science, social sciences, and systems science. The workshop ran for a total of four hours and was evenly split between the two days to prevent Zoom fatigue from sustained online engagement. The purpose of the workshop was to elicit participants' mental models of the interconnected water, human, and climate transboundary groundwater systems in the form of a causal map, and, thus, it did not include quantitative modeling. At the end of the workshop, participants were invited to fill in an online questionnaire to evaluate the modeling process and outcomes of the workshop. The survey was anonymous, and no participant information is linked to any of the responses. Data collection and storage was approved by the Institutional Review Board of New Mexico State University.

After the workshop, the co-designers (J.K.R. and K.B.) analyzed the data collected and the three causal maps developed. A total of 10 workshop participants completed the evaluation form. In general, participants found the modeling process to be useful in broadening their insights on groundwater resilience, and there appears to be some commitment to the conclusions drawn from the process (see Table 1). These results thus indicate that the causal maps generated from the workshop adequately represent the participants' mental models. To represent the collective mental model of all three groups, then, the maps were synthesized into a single CLD ex-post. For the synthesis, each group's causal map was translated into a CLD in Stella Architect version 3.4.0—a system dynamics modeling software—after which, one of the designers (K.B.) merged all the variables and links into a single model file and color-coded the links to identify areas of convergence and divergence in the model.

Table 1. Workshop evaluation results (N = 10; 1 = strongly disagree to 5 = strongly agree).

Item	Mean	Std. Dev.
The introduction to systems thinking and to systems mapping was well explained at the beginning of the workshop.	4.5	0.97
The participants in the workshop are the right group of actors to work on this issue.	3.7	1.06
I would be willing to participate in a similar systems mapping activity in the future.	4.4	0.84
The opportunity for open and extensive discussion was useful.	4.6	0.52
The focus on causal relationships was useful.	4.1	0.99
My understanding of groundwater resilience and the underlying feedback processes has increased due to the mapping process.	4.0	0.94
The mapping process aided me in understanding of the opinions of the other participants.	4.2	1.03
I support the conclusions/findings that were drawn during the mapping process, in general terms.	3.8	1.23

The merged model was validated by the other designer (J.K.R), who then began building a synthesized CLD from scratch. He began by first representing the convergent linkages and closing those loops with other unique links where possible. For instance, there was consensus on carbon emissions exacerbating climate change, and therefore affecting rainfall and incidence of droughts. A feedback loop was closed here by including the impact of drought on agricultural irrigation that affects production and carbon emissions, which was identified by Group 1. Once the convergent areas were represented, the model was expanded from there to include all other unique variables and links that formed feedback loops. Exogenous variables not relevant to the feedback structure of the system; for instance, the variable 'beneficiaries' (an exogenous link from water accessibility), were excluded. During the synthesis process, where necessary, some variables were renamed while others were aggregated to better reflect the overall feedback story of the synthesized map. For example, we renamed food demand to production demand in order to aggregate food production and other industrial production into a single variable, Production. Such decisions were made in agreement between both designers. Moreover, additional incidental feedback loops emerged as a result of the synthesis, demonstrating the need for multi-stakeholder and multi-group collaborative efforts to produce a more comprehensive causal map.

3. Results

Here, we present the synthesized CLD of the participants' collective mental model of the complexity surrounding groundwater dynamics. This model reflects their perceptions as well as misperceptions of reality, meaning that the relationships identified are not to be taken as facts, but as artifacts of the participants' deliberation and shared understanding arrived at during the workshop. We identified a total of 54 feedback loops in the model: 28 were reinforcing loops and 26 were balancing loops. These loops can be categorized into three main system-level interactions: hydrologic (see Figure 1 and Table 2), hydrologic–human (see Figure 2 and Table 3), and hydrologic–human–climate feedbacks (see Figure 3 and Table 4).

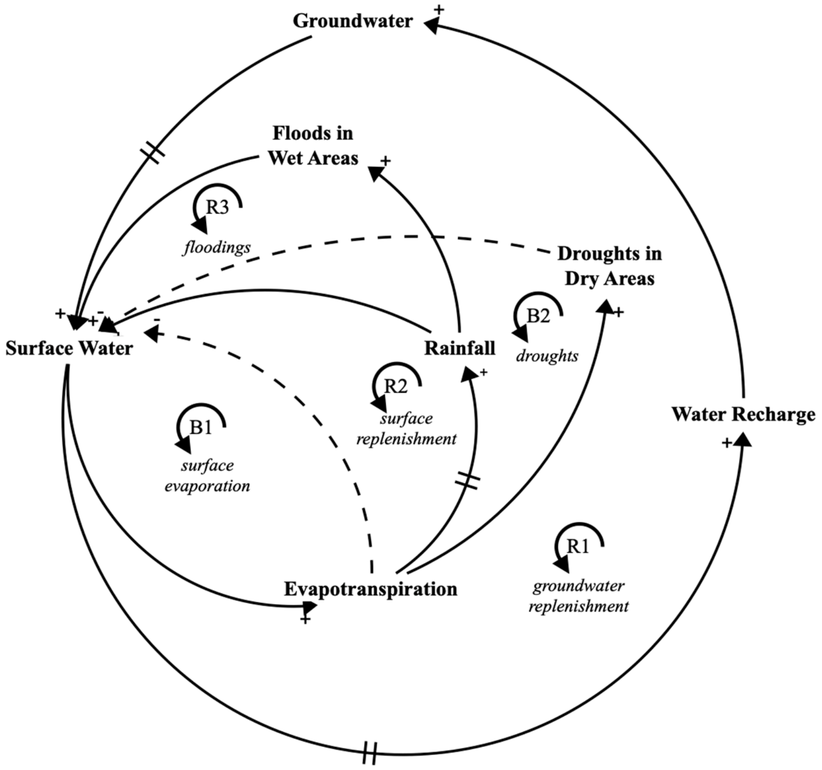

Figure 1. Synthesized causal loop diagram depicting the collective mental model of hydrologic feedback (solid links: positive polarity; dashed links: negative polarity; double stroke on link: significant delay; R: reinforcing loop; B: balancing loop).

Table 2. Description of feedback loops identified in the hydrologic system.

Description	Label	Causal Pathway
Groundwater replenishment	R1	Groundwater → (+) Surface Water → (+) Water Recharge → (+) Groundwater
Surface evaporation	B1	Surface Water → (+) Evapotranspiration → (−) Surface Water
Surface replenishment	R2	Surface Water → (+) Evapotranspiration → (+) Rainfall → (+) Surface Water
Flooding	R3	Surface Water → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (+) Surface Water
Drought	B2	Surface Water → (+) Evapotranspiration → (+) Drought in Dry Areas → (−) Surface Water

3.1. Hydrologic Feedback Loops

Participants identified surface water quantity as a key variable for explaining groundwater dynamics. R1 describes the participants' generalized perception of the feedback between groundwater and surface water. The effect of this cycle is dampened by B1, since evapotranspiration (ET) represents, in part, the transfer of surface water to the atmosphere, which can reduce groundwater recharge. Precipitation, which participants referred to as rainfall, contributes to participant-perceived increases in surface water quantities (R2). R3 and B2 depict participants' beliefs of the effects of increased ET and how it could impact areas differently through either increased flooding from excess rainfall or increased droughts, respectively. The balance between these loops in the natural water system is perceived to be responsible for maintaining the level of surface water and groundwater, which can be disrupted by interactions between anthropogenic factors from the human system.

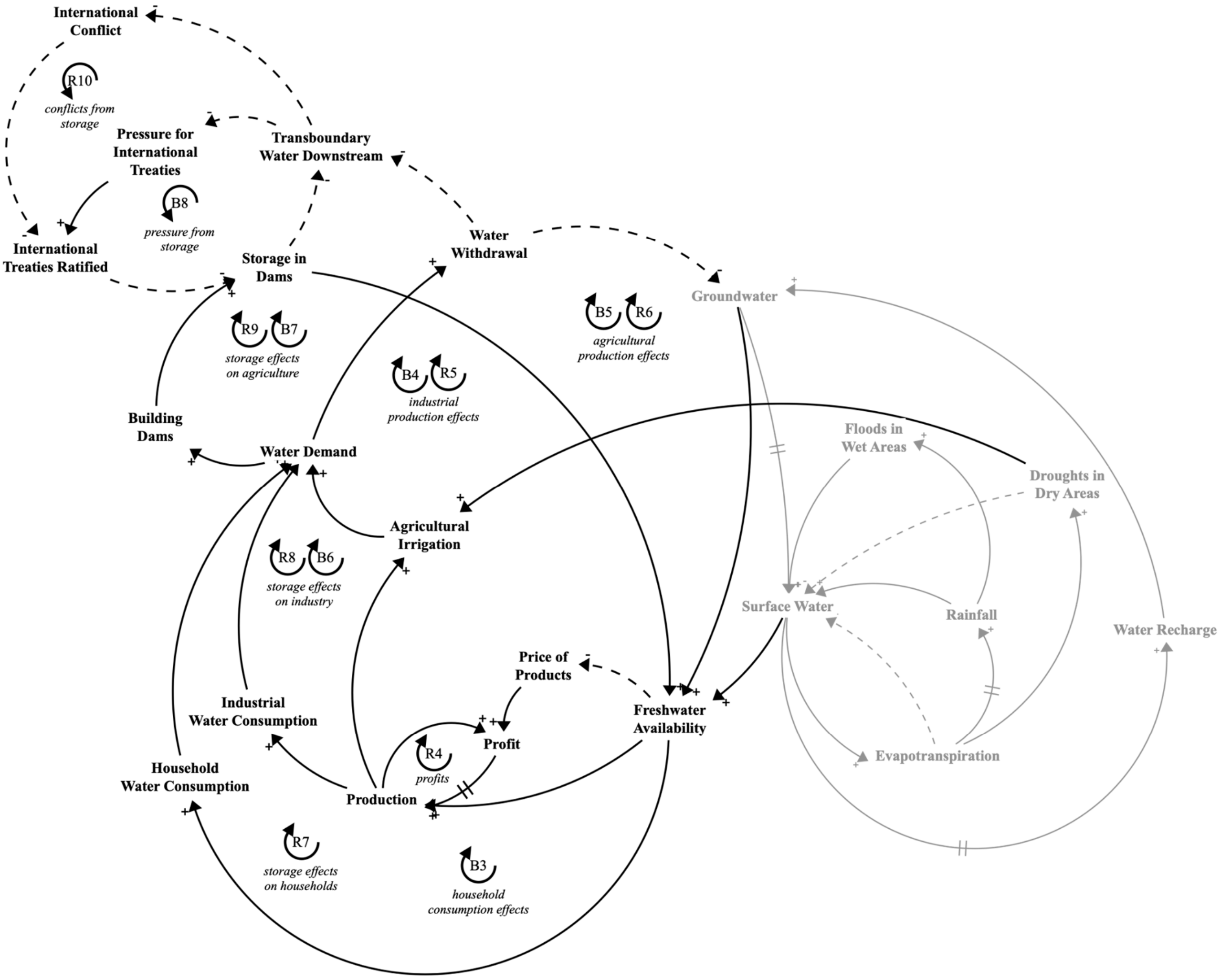

Figure 2. Synthesized causal loop diagram depicting the collective mental model of the hydrologic–human feedback structure (solid links: positive polarity; dashed links: negative polarity; double stroke on link: significant delay; R: reinforcing loop; B: balancing loop; grey areas: structure previously depicted and described).

Table 3. Description of feedback loops identified in the human system.

Description	Label	Causal Pathway
Household consumption effects	B3	Freshwater Availability → (+) Household Water Consumption → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability
Profits	R4	Production → (+) Profits → (+) Production
Industrial production effects	B4	Freshwater Availability → (+) Production → (+) Industrial Water Consumption → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability
	R5	Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Industrial Water Consumption → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability
Agricultural production effects	B5	Freshwater Availability → (+) Production → (+) Agricultural Irrigation → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability
	R6	Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Agricultural Irrigation → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability

Table 3. *Cont.*

Description	Label	Causal Pathway
Storage effects on households	R7	Water demand → (+) Building Dams → (+) Storage in Dams → (+) Freshwater Availability → (+) Household Water Consumption → (+) Water Demand
Storage effects on industry	R8	Water demand → (+) Building Dams → (+) Storage in Dams → (+) Freshwater Availability → (+) Production → (+) Industrial Water Consumption → (+) Water Demand
	B6	Water demand → (+) Building Dams → (+) Storage in Dams → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Industrial Water Consumption → (+) Water Demand
Storage effects on agriculture	R9	Water demand → (+) Building Dams → (+) Storage in Dams → (+) Freshwater Availability → (+) Production → (+) Agricultural Irrigation → (+) Water Demand
	B7	Water demand → (+) Building Dams → (+) Storage in Dams → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Agricultural Irrigation → (+) Water Demand
Pressure from storage	B8	Storage in Dams → (−) Transboundary Water Downstream → (−) Pressure for International Treaties → (+) International Treaties Ratified → (−) Storage in Dams
Conflicts from storage	R10	Storage in Dams → (−) Transboundary Water Downstream → (−) International Conflict → (−) International Treaties Ratified → (−) Storage in Dams

3.2. Hydrologic–Human Feedback Loops

Within the human system, freshwater availability and water demand are identified as key variables that affect several feedback processes related to the water–energy–food nexus. Industrial and agricultural/food production is energy- and water-intensive. When freshwater is more abundant, households (B3), industrial producers (B4), and agricultural producers (B5) can consume more water. As water demand increases, more groundwater is withdrawn. This feeds back to reduce the amount of freshwater available for consumption since groundwater and, by extension, surface water decreases. While these feedback processes could dampen demand as water resources are less readily available, participants expected the profit incentive in production (R4) to compete with these balancing loops. Specifically, they perceived that the reduction in water resources could result in an upward pressure on prices of products (food or other goods), which could incentivize more production and faster rates of groundwater withdrawal through increased industrial water consumption (R5) and agricultural irrigation (R6). In other words, these reinforcing loops could hasten the depletion of water resources. This interplay between the reinforcing and balancing effect is present for all loops that pass through the freshwater availability and production variables, given the alternative pathway through prices and profit incentivization as described. In Figures 2 and 3, we denote this dynamic by coupling loop labels with opposite polarities next to each other (e.g., B4 & R5).

Participants were also concerned with storage of water in dams. They suggested that when a certain country faces increased water demand, they would be motivated to build more dams to store more freshwater, which could then support higher levels of household consumption (R7), industrial production (R8 & B6), and agricultural irrigation (R9 & B7). Increased surface water storage in dams and groundwater withdrawal upstream could consequently reduce the flow of transboundary surface water in downstream areas. Competition for transboundary water resources, in turn, could–as perceived by participants–result in treaties to limit the storage of water to prevent or ease tensions (B8). However, when such treaties are not enforced or ratified, the continued storage of water could escalate tensions into international conflicts (R10).

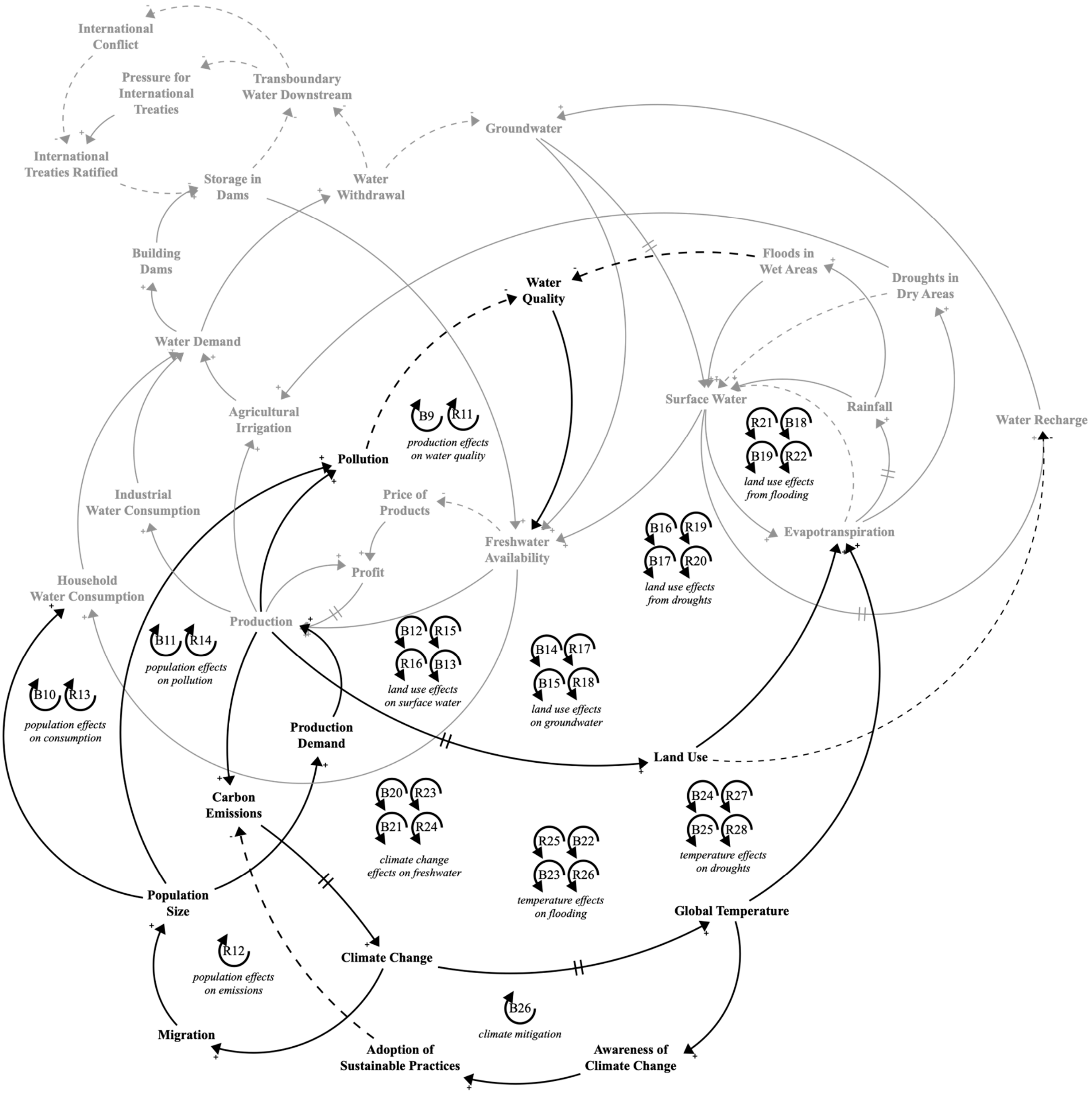

Figure 3. Synthesized causal loop diagram depicting the collective mental model of the hydrologic–human–climate feedback structure (solid links: positive polarity; dashed links: negative polarity; double stroke on link: significant delay; R: reinforcing loop; B: balancing loop; grey areas: structure previously depicted and described).

Table 4. Description of feedback loops identified in the climate system.

Description	Label	Causal Pathway
Production effects on water quality	B9	Freshwater Availability → (+) Production → (+) Pollution → (−) Water Quality → (+) Freshwater Availability
	R11	Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Pollution → (−) Water Quality → (+) Freshwater Availability
Population effects on emissions	R12	Carbon Emissions → (+) Climate Change → (+) Migration → (+) Population Size → (+) Production Demand → (+) Production → (+) Carbon Emissions

Table 4. *Cont.*

Description	Label	Causal Pathway
Population effects on consumption	B10	Climate Change → (+) Migration → (+) Population Size → (+) Household Water Consumption → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	R13	Climate Change → (+) Migration → (+) Population Size → (+) Household Water Consumption → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
Population effects on pollution	B11	Climate Change → (+) Migration → (+) Population Size → (+) Pollution → (−) Water Quality → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	R14	Climate Change → (+) Migration → (+) Population Size → (+) Pollution → (−) Water Quality → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
Land use effects on surface water	B12	Land Use → (+) Evapotranspiration → (−) Surface Water → (+) Freshwater Availability → (+) Production → (+) Land Use
	R15	Land Use → (+) Evapotranspiration → (−) Surface Water → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Land Use
	R16	Land Use → (+) Evapotranspiration → (+) Rainfall → (+) Surface Water → (+) Freshwater Availability → (+) Production → (+) Land Use
	B13	Land Use → (+) Evapotranspiration → (+) Rainfall → (+) Surface Water → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Land Use
Land use effects on groundwater	B14	Land Use → (+) Evapotranspiration → (−) Surface Water → (+) Water Recharge → (+) Groundwater → (+) Freshwater Availability → (+) Production → (+) Land Use
	R17	Land Use → (+) Evapotranspiration → (−) Surface Water → (+) Water Recharge → (+) Groundwater → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Land Use
	B15	Land Use → (−) Water Recharge → (+) Groundwater → (+) Freshwater Availability → (+) Production → (+) Land Use
	R18	Land Use → (−) Water Recharge → (+) Groundwater → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Land Use
Land use effects from droughts	B16	Land Use → (+) Evapotranspiration → (+) Droughts in Dry Areas → (−) Surface Water → (+) Freshwater Availability → (+) Production → (+) Land Use
	R19	Land Use → (+) Evapotranspiration → (+) Droughts in Dry Areas → (−) Surface Water → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Land Use
	B17	Land Use → (+) Evapotranspiration → (+) Droughts in Dry Areas → (+) Agricultural Irrigation → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability → (+) Production → (+) Land Use
	R20	Land Use → (+) Evapotranspiration → (+) Droughts in Dry Areas → (+) Agricultural Irrigation → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability Price of Products → (+) Profit → (+) Production → (+) Land Use
Land use effects from flooding	R21	Land Use → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (+) Surface Water → (+) Freshwater Availability → (+) Production → (+) Land Use
	B18	Land Use → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (+) Surface Water → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Land Use

Table 4. *Cont.*

Description	Label	Causal Pathway
	B19	Land Use → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (−) Water Quality → (+) Freshwater Availability → (+) Production → (+) Land Use
	R22	Land Use → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (−) Water Quality → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Land Use
Climate change effects on freshwater	B20	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (−) Surface Water → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	R23	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (−) Surface Water → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
	B21	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (−) Surface Water → (+) Water Recharge → (+) Groundwater → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	R24	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (−) Surface Water → (+) Water Recharge → (+) Groundwater → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
Temperature effects on flooding	R25	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (+) Surface Water → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	B22	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (+) Surface Water → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
	B23	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (−) Water Quality → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	R26	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Rainfall → (+) Floods in Wet Areas → (−) Water Quality → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
Temperature effects on droughts	B24	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Droughts in Dry Areas → (−) Surface Water → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	R27	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Droughts in Dry Areas → (−) Surface Water → (+) Freshwater Availability → (−) Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
	B25	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Droughts in Dry Areas → (+) Agricultural Irrigation → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability → (+) Production → (+) Carbon Emissions → (+) Climate Change
	R28	Climate Change → (+) Global Temperature → (+) Evapotranspiration → (+) Droughts in Dry Areas → (+) Agricultural Irrigation → (+) Water Demand → (+) Water Withdrawal → (−) Groundwater → (+) Freshwater Availability Price of Products → (+) Profit → (+) Production → (+) Carbon Emissions → (+) Climate Change
Climate mitigation	B26	Climate Change → (+) Global Temperature → (+) Awareness of Climate Change → (+) Adoption of Sustainable Practices → (−) Carbon Emissions → (+) Climate Change

3.3. *Hydrologic–Human–Climate Feedback Loops*

Participants further expanded the model boundary to account for the environmental and climate feedback as a consequence of human activities. Specifically, they focused on the environmental consequences of production, including pollution and carbon emissions, as well as land use expansion. For one, an increase in production, a variable stakeholders can influence, is expected to contribute to more environmental pollution that would degrade water quality, thus reducing freshwater availability and impacting further production (B9 & R11). Concurrently, energy-intensive production emits more carbon into the atmosphere and contributes to climate change over time. Climate-induced migration, consequently, could increase a certain country's population size, which increases the demand for production and thus results in more carbon emissions (R12). Participants envisioned that a larger population size could further strain the country's water resources through increased household consumption and groundwater withdrawal, which could either lead to more production as prices increase, thus contributing further to climate change (R13) or the waning of production over time due to the lack of water resources (B10). Moreover, the effects of pollution and carbon emissions could synergize: a larger population size from climate migration could intensify pollution from increased household waste, affecting water quality, freshwater availability, and climate change-inducing production (B11 & R14)

The other main anticipated corollary of production is land use. Land use expansion from increased production could result in faster rates of evapotranspiration (ET). ET results in the evaporation of surface water, reducing total freshwater available for production (B12 & R15) as well as the rate of water recharge from the surface to the ground (B14 & R17). While increased ET can lead to more moisture in the atmosphere and thus increased potential for rainfall that replenishes surface water (R16 & B13), participants expected higher incidences of flooding in wet areas due to excess rainfall (R21 & B18). They further anticipated a reduction in water quality from flooding, thus diminishing the actual amount of excess freshwater that would be available for consumption (B19 & R22). Increased ET from land use expansion is also expected to cause droughts in arid areas, which depletes the amount of freshwater available from surface runoff (B16 & R19). Droughts, in turn, are perceived to increase the demand for groundwater withdrawal for agricultural irrigation, thus reducing the groundwater level as well as the long term flowback from the ground to the surface (B17 & R20). Moreover, land use expansion is expected to directly reduce groundwater recharge, as less water is expected to seep back into the ground to aquifers (B15 & R18).

Similar to land use, rising global temperature from long-term climate change is predicted to increase rates of ET. This, in turn, exacerbates the effects of ET on water resources and production as discussed above. Briefly, intensified ET could hasten surface water evaporation (B20 & R23) and groundwater depletion from less recharge (B21 & R24); it could also exacerbate flooding (R25 & B22) and reduce water quality (B23 & R26); and it could worsen droughts (B24 & R27) and consequently heighten rates of groundwater withdrawal (B25 & R28). As the effects of climate change and rising temperature become more pronounced, participants are hopeful that increased awareness will encourage the adoption of sustainable practices that combat carbon emissions and thus mitigate climate change over time (B26).

3.4. Areas of Convergence, Divergence, and Uncertainties

All three groups captured the hydrological cycle related to groundwater recharge, surface water, precipitation, and evapotranspiration. They all also considered the climate effects on the hydrologic system, however, to varying levels of detail. Group 1 simply identified a negative link between climate change and water recharge as well as positive links to floods and droughts. Groups 2 and 3, however, understood the climate effects in terms of increased global temperature from carbon emissions and land-use change, which exacerbates evapotranspiration. Groups 1 and 3 further showed a shared concern for water quality and freshwater availability. While the first conceived the impact on water quality as an adverse consequence of climate-induced flooding, the latter conceptualized it as a function of pollution of water bodies from the population.

The other main convergence between all three groups is the feedback linkages surrounding water demand and therefore groundwater withdrawal in the hydrologic–human systems. Group 1 captured the water demand in terms of all three levels, household, agriculture, and industry, whereas Group 2 focused on households and industry and Group 3 focused solely on agricultural production. Beyond the aforementioned areas of the CLD, the remaining feedback processes were elicited from Group 1, which had a more developed causal map in the human system domain. This group further explored aspects of climate-induced migration and its impact on water demand; climate change awareness and mitigation; and transboundary water storage and the corollary international conflicts.

Based on their respective causal maps, participants were tasked to identify uncertain points or areas that would require more research. All three groups identified the need for better data for groundwater recharge and withdrawal. Groups 1 and 3 showed a shared concern for data-sharing between countries. Groups 1 and 2 indicated data uncertainty for climate change impacts on the hydrologic system, especially on precipitation and water quality. Given their exploration into more social elements of the hydrologic–human system, Group 1 further emphasized the need to study the congruence between scientific assessments and social system realities.

4. Discussion

To our knowledge, this is the first online participatory modeling workshop designed to elicit knowledge on the interrelationships between the hydrologic, human, and climate processes underpinning transboundary groundwater depletion. Through this pilot workshop, we identified a total of 54 feedback loops (28 reinforcing and 26 balancing) across the three systems, demonstrating the potential of participatory system modeling to adequately capture the complexity of (ground)water issues. Here, we discuss the results of this illustrative case study in terms of the successes, lessons learned, and more broadly, the opportunities afforded by the method to advance research that better understands the complex hydrologic, human, and climate interrelationships.

4.1. Conceptualizing Complex Problems

As mentioned, the synthesized CLD presented here reveals how participants conceptualize the complex interactions of system components underpinning groundwater depletion. Complex problems can be debilitating to tackle all at once since everything is interconnected. Through a facilitated process of participatory modeling, participants are able to start small and expand their perception of the problem by mapping the cause-and-effect relationships sequentially. In this instance, the process began by eliciting their knowledge on what causes groundwater to increase or decrease. From there, they worked backwards to identify the drivers (e.g., groundwater withdrawal, which is caused by water demand, which is caused by agricultural irrigation, and so forth). This eventually led up to a larger causal map that provides an overview of the complex interactions between the hydrologic, human, and climate systems. This step-by-step systems approach could perhaps explain why our workshop participants found the focus on causal relationships to be useful for understanding groundwater dynamics (see Table 1). Moreover, based on the convergence between groups, we were able to identify the core feedback interactions at the forefront of their mental models: those between hydrological processes; water consumption from agricultural and industrial production as well as household usage; and the contribution to and effects of climate change. This indicates that understandings of groundwater depletion cannot be simply disentangled from these key system components.

One of the groups was able to move beyond these core structures and explore the political elements in the human system: international conflict and tensions that affect enforcement and adherence to international treaties. Such 'soft' variables are often underrepresented in quantitative models given the operational difficulties in the quantification. However, transboundary aquifers are transnational resources, where political considerations impact system outcomes. Here, participants are not limited by parsimony in model boundaries for hypothesis testing or data availability for operationalization given the qualitative nature of the modeling activity. In turn, this method enables participants to explore soft variables and relationships such as international conflict that otherwise could have been excluded in formal models.

However, we observed that our participants rarely went beyond general water system conceptualizations, leading to inadequate representations of transboundary interactions between two or more territories. This could be a result of the limited duration of our pilot workshop, which precluded extended stakeholder engagements typical of large-scale participatory modeling projects. The limited duration lends itself to higher levels of aggregation at the expense of detailed complexity, which would require in-depth deliberation among stakeholders. Therefore, to improve the quality of the co-produced knowledge, participatory modeling could extend over several workshops for more extensive engagements. Moreover, we observed that capturing these complex systems remains challenging, even for trained academics. The outcomes of this workshop represent participants' perceptions of the system. This includes misperceptions that can lack alignment with scientific findings. Perceptions—whether they are accurate or not—are the basis for decision-making and thus have a role in real-world water decisions at all levels. The difficulties that participants in this session faced parallel those facing use-inspired water research and water decision-making.

4.2. Bridging and Aligning Perspectives

The synthesized CLD generated from the participatory modeling session explores various aspects of the groundwater system that cross disciplinary lines. While the groups started with hydrological processes, the discussion eventually led them to other disciplinary lenses: for instance, hydro-economic processes in the human system that affect groundwater withdrawal (e.g., production, water demand, profit incentive); anthropogenic effects in the climate system that affect the hydrological processes (e.g., climate change, climate-induced migration, extreme weather events); and even social–political processes in the human and climate systems that affect water management decisions (e.g., water storage, international conflicts, climate mitigation). This was a product of our participants' varied disciplinary backgrounds, which included hydrology, geology, social sciences, system science, and data science. Participatory system dynamics modeling, as a domain-agnostic tool, provided them with a unifying language to communicate and exchange perspectives around the problem. Indeed, CLDs serve as boundary objects that transcend disciplinary, organizational, or cultural fault lines [43,44]. The act of producing tangible visual representations (variable names, directional links, polarities) of cause-and-effect relationships forces individuals to externalize their respective knowledge in relatively concrete real-world terms and search for dependencies among perspectives within the group [43].

The product of the participatory modeling process, however, is not simply a collage of diverse perspectives, but a collection of piecemeal agreements arrived at during the deliberation process. The bridging of perspectives is one of negotiation and contestations, which provoke further clarifications, enrichment, and modification of the visual representations that in turn enable the emergence of shared understanding and further actions to move forward [29]. An extreme example of this process was observed in Group 1′s discussion of the political dimensions, where tensions around the issue of water storage arose due to some participants' national background and historical context. Through careful facilitation, participants were led to express their opinions in terms of concrete and more generalized structures that could be represented in the map. This allowed others to suggest modifications or additions to the representation, such that the tensions that emerged led to productive contributions to the map. We also found support for this approach as our participants indicated that the open and extensive discussion, as well as the focus on causal relationships, were useful. Further, they agreed that their own understanding of the problem as well as that of others has improved as a result of the workshop. In this respect, this method of bridging and aligning perspectives could help promote more effective collaboration and overcome cross-disciplinary barriers within water research, which has become more interdisciplinary over the years. In particular, it could help mitigate the inherent difficulties associated with integrating the quantitative foundations of natural sciences and the qualitative foundations of social sciences, and consequently advance the practice of interdisciplinary water research—see [45–47].

While the ex-post synthesized CLD represents a good integration of cross-disciplinary knowledge, we observed that the richness of the representations in the causal maps varied across individual groups. This is likely due to the uneven distribution of domain expertise within groups. Given the open nature of the workshop, we were unable to assign participants to groups based on disciplinary background prior to the event. For instance, one group reflected that they lacked the expertise of hydrogeology for better representing the physical system. Moreover, since the TGR NoN is led by research universities, it disproportionately attracted researchers. This precluded the inclusion of a more diverse pool of stakeholders such as policy makers, relevant water decision makers, or local communities. In the evaluation survey, some responses called for improving the regional and institutional diversity among the participants. This could explain why the survey question on whether the right people were present in the workshop scored the lowest (3.6 on a 5-point scale).

Therefore, the quality of the deliberation process as well as its outcome (the causal map) could be improved by ensuring a purposive distribution of participants in each group, which reflects the diversity of domain expertise as well as stakeholder groups affected by water issues. In particular, the inclusion of decision-makers and communities with important local knowledge could fill potential knowledge gaps that are under-researched in academia. The knowledge exchange could also help refine the mental models of non-research stakeholders, provide them with a better systems understanding, and even influence their future water decisions. However, in such instances, potential power dynamics may emerge within the groups that could lead to the overrepresentation of certain participant's views at the expense of others. In our workshop, one of the facilitators observed power dynamics within her group: an older professor was dominating the conversation over early career researchers and deviated from the discussion topic several times. Here, good facilitation skills are needed to manage the situation, such as redirecting the conversation to the visual representations at hand, posing probing questions to less engaged participants, and providing a safe space to productively challenge dominant views within the group.

4.3. Informing Future Research

Our participants, based on their causal maps, identified the following uncertain but significant variables in the groundwater system: groundwater quality, water recharge, and the effect of climate change on rainfall as well as water quality. In that sense, the outputs of participatory modeling can be used to inform research and the rigorous data collection needs of important system components, benefitting the research community in the long run. Moreover, as mentioned, the CLD generated from the workshop maps out the key variables of the system at the forefront of participants' perceptions of reality. In other words, it serves as an unverified collective mental model of the group. This could inform future research in two ways. First, the CLD can be used to identify knowledge inconsistencies in people's perceptions of the groundwater system. The misperceptions elicited through this modeling process provide a valuable source of insight on knowledge gaps or weaknesses in policy logics. As previously mentioned, perceptions are the basis of decision-making in spite of its accuracy. In that sense, knowing what people do not know provides a valuable foundation for further work in improving groundwater management and policies. Second, the CLD can be used to identify knowledge gaps in the existing literature. To validate the co-produced model, researchers could either verify or falsify each hypothesized causal relationship by triangulating it with the published literature. Where existing knowledge is lacking, the relationships could be verified by expert judgment and, in doing so, set the agenda for future research to fill those gaps.

The validation process of the collective mental model, presented here, could then serve as a springboard for constructing a knowledge repository that provides a comprehensive overview of the feedback loops and the complex interrelationships of groundwater systems. Such a repository would be an invaluable source of information to water decision-makers as well as quantitative modelers. The visual depiction of the system complexity could enable decision-makers to mentally trace how intervening in one part of the system could lead to (un)intended effects in other parts through the various feedback processes. However, such simulation tasks are better handled by computational modelers for efficient scenario analyses and policy testing. In this regard, the knowledge repository, which integrates the co-produced knowledge with expert opinions and the scientific literature, could provide the scaffold for conceptualizing simulation models. Particularly for system dynamics modelers, who seek to quantify the feedback structure of problems under study, such a repository would be instrumental for defining the boundaries of their model.

5. Concluding Remarks

Participatory system modeling rooted in systems thinking and system dynamics have the potential to bring together researchers, communities, and policymakers with the varied expertise necessary to make impactful progress toward transboundary groundwater resilience. We have demonstrated the potential of this method with an illustrative case study from the TGR NoN. Through participatory modeling, researchers with diverse disciplinary backgrounds and a common interest in groundwater resilience were facilitated to co-produce a causal map of the drivers of groundwater depletion. This process elicited feedback linkages between the hydrologic, human, and climate systems. Based on the successes and lessons learned from this endeavor, we conclude that participatory modeling provides an accessible and non-technical forum for people from diverse backgrounds to work together to understand key system components and define priorities. Additionally, it could create a space outside of status quo structures to bridge gaps between scientists and community leaders, as well as to catalyze new ways of synergistic thinking for addressing complex issues. While the end product itself–the lasting visual depiction–has value, systems conceptualizations foster knowledge sharing and set the foundation for collaborative work driven by decision-maker needs.

The system conceptualizations developed through these efforts can also be used to identify and provide critical insight into knowledge gaps and direct future research. Importantly, they could provide initial structures to create full-fledged system dynamics simulation models used for rigorous hypothesis testing. Such computational models, that quantify the feedback linkages among interconnected system components, could advance scientific assessments of water resources and management. Future work that expands on efforts such as the one detailed in this article can help advance the adaptation of participatory system methodologies and harness their transformative potential to advance use-inspired research that accounts for critical dynamics between water, social, and climate systems. While this has direct applicability for communities impacted by transboundary aquifer challenges, we anticipate these advances would benefit use-inspired approaches to water resources research more broadly.

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