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RESEARCH ARTICLE

Groundwater models through stakeholders' eyes: Evaluating benefits, challenges, and lessons for SGMA implementation

Given transparent communication and adequate time, groundwater models can enhance stakeholders' system understanding and decision-making.

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Abstract

The Sustainable Groundwater Management Act (SGMA) requires stakeholder participation in developing groundwater sustainability plans (GSPs) to ensure the reliability of groundwater resources. Groundwater models became widely used in GSP development (e.g., to evaluate management actions). This study explores stakeholder perceptions of the benefits and challenges of using these models in GSP development and of models' abilities to deal with uncertainties arising from existing data gaps. Qualitative interviews and minutes from groundwater advisory committee meetings from three groundwater basins reveal that groundwater models can improve stakeholders' understanding of the groundwater system and help stakeholders identify management actions. However, model complexity and uncertainty in terms of hydrogeological processes and data gaps hinder stakeholders' full understanding of the model development and results. Modelers should leverage stakeholder knowledge to build trust and collaboratively improve model accuracy through active participation in the modeling process. To prevent misunderstanding, future and ongoing processes should prioritize transparent communication about the model design, assumptions, and limitations. In general, SGMA's regulatory process facilitates decision-making amid uncertainty and ensures lasting collaboration between modelers and stakeholders.

In 2014, California enacted the Sustainable Groundwater Management Act (SGMA), aiming to ensure the enduring reliability of groundwater resources across the state (Harter 2020). To implement SGMA, local groundwater sustainability agencies (GSAs) were established and tasked with developing groundwater sustainability plans (GSPs) by 2022 in medium- and high-priority basins together with local stakeholders (California Department of Water Resources 2023c). The involvement of local stakeholders was considered to be crucial in ensuring successful SGMA implementation (Dobbins et al. 2015; Perrone et al. 2023).

Given the complexities and uncertainties in natural resource management (Hedelin et al. 2017), and especially groundwater management (Castilla-Rho 2017; Lall et al. 2020), computer-based modeling approaches representing aquifer dynamics (Bredehoeft 2002) became widely used to foster sustainable groundwater management (Jakeman et al. 2016). Stakeholder involvement in the modeling process, known as collaborative or participatory modeling (Basco-Carrera et al. 2017), spans from joint problem and parameter definition to scenario development, application and

The authors' research shows that transparent communication from modelers is essential to realize the full potential of groundwater models in participatory groundwater management. *Photo*: Kelsey McNeill.

evaluation, and can lead to the implementation of management actions (Hedelin et al. 2021; Sterling et al. 2019; van der Vat et al. 2019; Voinov and Bousquet 2010).

The advantages of participatory modeling have been researched in prior studies, highlighting the enhancement of model accuracy and reducing modeling uncertainties by including stakeholder knowledge and enabling social learning throughout the joint modeling process, increasing both the stakeholder's and modeler's understanding of the issues at stake (Gaddis et al. 2010; Greenhalgh et al. 2022; Mannix et al. 2022; Moallemi et al. 2021; Zellner et al. 2012). While the majority of studies have evaluated the benefits of participatory modeling primarily for the scientific and modeling community (Mannix et al. 2022; Zellner 2008), Borowski and Hare (2007) highlighted the divergent attitudes and understandings of modeling tools between researchers and stakeholders in European river basin management.

Though SGMA does not explicitly require the engagement of stakeholders in the modeling process, it strongly encourages GSAs to use modeling tools for tracking water budgets and evaluating management actions (California Department of Water Resources 2016). This approach provides an opportunity to explore an ongoing participatory modeling process from the stakeholders' perspective. In this study, we focus on stakeholders' perceptions of engaging with groundwater models in GSP development and their implications for decision-making within a participatory process.

Study area and interviews

We conducted qualitative interviews and analyzed meeting minutes from groundwater advisory committees across three medium-priority groundwater basins in Siskiyou County, Northern California, to investigate stakeholders' perceptions of groundwater models used in GSP development: Scott River Valley, Shasta Valley, and Butte Valley (fig. 1). In all three basins, agriculture is the major groundwater user (table 1). GSPs for these basins were submitted as required by January 2022 (California Department of Water Resources 2023b). The Scott Valley Integrated Hydrological Model (SVIHM), developed by co-authors Foglia and Harter in 2011 before SGMA passed, was utilized to study groundwater–surface water interactions. Its application was integral to an action plan addressing temperature total maximum daily load requirements in the Scott River (Foglia et al. 2018). Development of the groundwater models in Shasta and Butte valleys began in 2018 as part of SGMA.

The basins are influenced by the introduced emergency regulations in 2021 from the State Water Resources Control Board (SWRCB), which

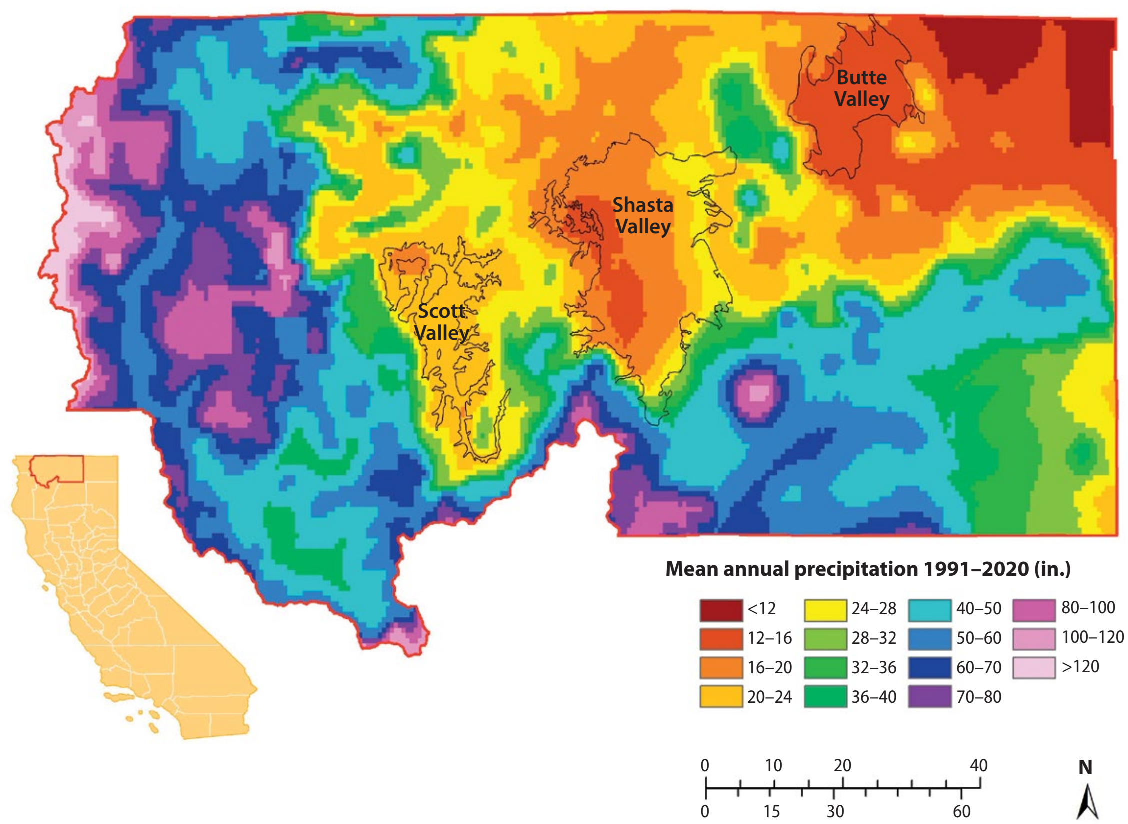

FIG. 1. Location of the basins in Siskiyou County, Northern California, and the long-term mean annual precipitation (1991–2020) in inches (Johnson and Belitz 2014; Northwest Alliance for Computational Science and Engineering 2024; State of California 2019).

TABLE 1. Characteristics of groundwater basins

Basin name	Basin number	Basin area (sq mi)	Groundwater extraction (acre-feet)	Major groundwater users	Primary crops
Butte Valley	1-003	125	63,000	Agriculture	Alfalfa, hay, strawberry
Shasta Valley	1-004	341	32,500	Agriculture	Pasture, alfalfa, grain, hay
Scott River Valley	1-005	100	36,000	Agriculture	Pasture, alfalfa, grain

Sources: California Department of Water Resources 2023a, 2024; Siskiyou County Flood Control and Water Conservation District Groundwater Sustainability Agency 2021, 2022a, 2022b.

implemented groundwater withdrawal curtailments in Scott and Shasta valleys to protect instream flows for Coho and Chinook salmon in the Scott and Shasta rivers (State Water Resources Control Board 2023). This state enforcement is independent of and at least temporarily supersedes local GSP implementation of measures to address depletion of surface waters from groundwater pumping. However, the SVIHM serves as a key information source to address the question of whether the proposed minimum streamflow, advocated by Native American tribes and environmental nongovernmental organizations, could be sustained in the basins under various scenarios, e.g., when agricultural groundwater pumping is curtailed. Thus, ongoing processes to maintain minimum instream flows in the Scott and Shasta rivers are influencing stakeholder discussions about the benefits and challenges of using a groundwater model in regulatory processes.

The authors participated in two rounds of groundwater advisory committee meetings in August and October 2023 within each basin. The advisory committee meetings were established by the local GSA in compliance with SGMA to engage local stakeholders. These advisory committees include representatives for all beneficial users of groundwater: private pumpers, tribal entities, environmentalists, residential communities, and the general public. The regular meetings provided opportunities for stakeholders to engage, ask questions, and receive model updates. At the Scott Valley Groundwater Advisory Committee meeting in October, the modelers delivered a wrap-up presentation, as requested by the stakeholders, which detailed the history, assumptions, and outcomes of the SVIHM. The advisory committee meeting minutes are publicly available (Siskiyou County California 2023).

In addition to participating in the advisory committee meetings, the first author conducted 10 semi-structured interviews across the basins (table 2) together with French researchers, exploring stakeholder involvement and knowledge acquisition within participatory processes. Interviewees, mainly members of the three groundwater basin advisory committees, had diverse backgrounds and included private pumpers, municipal and environmental representatives, and members of the general public. In addition, interviews were also conducted with a GSA employee who manages the basins and a California Department of Water Resources (DWR) employee. To protect interviewee anonymity, their professional qualifications and role are undisclosed. Notably, none have a background in numerical modeling. However, because the SVIHM was developed prior to SGMA, all Scott Valley interviewees were exposed to it prior to 2018 through infrequent ad hoc meetings similar to the groundwater advisory committee meetings under SGMA.

The interview questions were structured into three main parts: (1) the organization and functioning of the Advisory Committee, including the interviewee's role and participation in GSP development, (2) the interviewee's perceptions of the decision-making process during GSP development, and (3) the interviewee's individual learnings throughout the process related to groundwater, modeling, decision-making, and participation skills. While the interview content was extensive, with a primary focus on knowledge acquisition through participatory processes, this study emphasizes discussions on the role of groundwater models in GSP development (2018–2021). Thus, this part of the interview included the following questions about the benefits and challenges of using and engaging with a groundwater model:

- How easy was it for the interviewee to understand the numerical model and its underlying principles?
- How did the groundwater model support the interviewee in developing the GSP, or if it did not, what hindered its use?

Given the model's pivotal role in the advisory committee meetings, all interviewees elaborated in detail on its challenges and benefits, even when not

TABLE 2. Interviewees and model exposure duration

Interviewee	Basin	Duration
A	Scott/Shasta	Since 2018
B	Scott	Since 2006 (preparatory work for SVIHM)
C	Scott	2018–2021
D	Shasta	Since 2018
E	Scott	Since 2006 (preparatory work for SVIHM)
F	Scott/ Shasta/Butte	Since 2018
G	Shasta	Since 2018
H	Butte	Since 2018
I	Butte	—
J	Scott	Since 2018

SVIHM = Scott Valley Integrated Hydrological Model.

specifically prompted about the groundwater model. The transcribed interviews and the advisory committee meeting minutes were analyzed with QualCoder version 3.3 (Curtain 2023), an open-source software for qualitative research. The material was coded using an inductive qualitative analysis method, wherein the codes were derived from the material (Brailas et al. 2023). Data saturation typically occurs after 12 interviews (with basic elements already evident by the sixth, which was also the case in this analysis), meaning that the 13th interview is unlikely to introduce new themes or codes (Guest et al. 2006; Marshall et al. 2013). Given the diverse perspectives of participants both in the interviews and advisory committee meetings, and the authors' participation in two rounds of advisory committee meetings, along with the depth and quality of the 10 interviews (each lasting between 60 and 100 minutes), the methodology meets qualitative research standards and supports drawing conclusions from the findings (Boddy 2016; Hopf 2004).

Models facilitate system understanding

Our analysis showed that groundwater models served as valuable tools for stakeholders in achieving a conceptual understanding of the groundwater system (interviewees A/B/C/F/G/H/J). Interviewees affirmed that the model played a key role in enhancing their comprehension of the basin, validating their preexisting perceptions regarding aquifer behavior or quantifying unknown processes (A). The models facilitated the conceptual understanding of the processes and interconnections, even for stakeholders who already had extensive knowledge about groundwater (C). The model also played a pivotal role in evaluating management actions to improve groundwater sustainability (A/C), as emphasized by interviewee A:

> *What maybe seems like a laughable concept ten years ago, now it seems like it's something that you can get a little bit of real time information on, and [. . .] we're approaching a decision point where we should irrigate our crop more or do we stop because the river's at this type of condition when we've gotta find that balance between surface water and groundwater interaction and agricultural beneficial uses and environmental uses? (A)*

This was particularly evident in the Scott Valley basin, where the groundwater model has been under development since 2011 and some of the stakeholders have been involved in the preparatory work since 2006. Stakeholders valued the model's utility in estimating and evaluating the impacts of specific management actions within the valley (E/J). This aspect remains underdeveloped in Butte and Shasta valleys, as there has been limited time since 2018 to create an in-depth model suitable for testing and evaluating management actions (D/G/H).

Nevertheless, the majority of interviewees mentioned that they still lack in-depth knowledge and a comprehensive understanding of the basin's dynamics (A/C/F/G/H). This was noted by interviewees from all basins, including Scott Valley, where stakeholders had been exposed to the model for years (A/C/F). This knowledge gap was primarily attributed to the model's intricate nature and the complexity inherent in the groundwater system. This complexity arises from the specific hydrogeological characteristics, dynamic flow behavior, and interconnections between aquifers and surface and groundwater, particularly in Butte and Shasta valleys. In these valleys, model development commenced only in 2018, and the volcanic aquifers — formed by volcanic activity and characterized by high heterogeneity (Wood 1960) — exhibit a greater degree of complexity compared to the alluvial basin of Scott Valley (D/G/H). Furthermore, interviewees from all basins underscored the presence of uncertainties in the groundwater–surface water interaction and the uncertain impacts on groundwater-dependent ecosystems (G/H/J).

Interviewees mentioned that unknowns persist concerning (1) the influence of specific wells on the aquifer system (B/G), and (2) the consequences of groundwater pumping and climate change (precipitation patterns, rainfall, and snow) on streamflow (Butte Valley Advisory Committee Meeting Aug/E/Scott Valley Advisory Committee Meeting Aug/J). The deficiency in comprehending the entanglements within the aquifer systems is also closely tied to the scarcity of information and the existence of unknowns within the model, as acknowledged by interviewee D: "So the model is only as good as the data you put in it. And it's very limited."

These unknowns include unaccounted groundwater abstractions (D/Shasta Valley Advisory Committee Meeting Aug), the absence of comprehensive monitoring and well data (D/G/H/J), the lack of streamflow data (A/G), and not using existing fish data in the model to assess management actions and their impact on aquatic species (E/J). The inadequacy of data and information compounds the challenge faced by stakeholders when it comes to making informed decisions or determining management strategies based on the model, especially in the Butte and Shasta valleys (D/F/H), where the model development time is short compared to that in Scott Valley.

Modeling concepts pose difficulties

The model's inherent inaccuracies can erode stakeholder confidence in its decision-making suitability and make processes like calibration seem opaque and unreliable. What is considered satisfactory accuracy for a modeler may not necessarily meet the criteria for stakeholders (B/E/Scott Valley Advisory Committee

Meeting Aug). This discrepancy is highlighted by interviewee B's statement:

> *When we have all the groundwater models a meter off, all it's plus or minus a meter in its accuracy. And [the modeler] kept saying, "Oh, that's wonderful. That's a great accuracy." For the farmers that's whether they survive or not. (B)*

Stakeholders also observed disparities between their long-term experiences living in the area and the model's outputs (F). Particularly in the volcanic aquifers of Butte and Shasta valleys, stakeholders felt that the model did not capture the area's hydrogeological intricacies. Consequently, the model may depict certain processes inaccurately or fail to encompass dynamics that stakeholders have observed in the past (F), leading to questions about its validity. Discrepancies were also identified for model inputs such as the water usage assumptions for specific crops utilized in the model (A/C).

A vital aspect of modeling involves making assumptions and estimations for processes that may be challenging to measure in the field, or obtaining necessary information, such as the hydrogeology of the valleys or groundwater abstraction data from domestic and agricultural wells. Some stakeholders acknowledge the model's assumptions (J), but their confidence is diminished when assumptions are perceived as sources of inaccuracy in the model outputs or when stakeholders are unaware of the assumptions (G/J/Scott Valley Advisory Committee Meeting Aug). Another factor that raised doubts among certain stakeholders (B/E) was the calibration procedure within the modeling framework, as outlined by interviewee E:

> *Is it matched because you've tweaked the model or matched it because it's a good model? [. . .] Because if you keep tweaking your model to match the data, then it's not a model. (E)*

The practice of adjusting and calibrating the model to closely align with observations, such as streamflow data, is, according to stakeholder E, not an adequate criterion for evaluating the model's quality. This stakeholder has expressed concerns regarding the transparency of this calibration process and the means of verifying the model and its associated outcomes.

Dealing with uncertainties

> *I think you can say that you don't have to know everything about something in order to make good decisions. Like we don't need to absolutely know where every drop of water is in the basin but we need to know enough to make good decisions. (F)*

Stakeholders have identified strategies to deal with the uncertainties they have encountered when using the model for GSP development and for future decision-making, including sharing (private) data and knowledge to close data gaps — which is likely also influenced by the curtailment processes — and creating precautionary management approaches. One key strategy revolves around addressing data gaps. Stakeholders highlighted the need to collect additional data in areas where information deficits were identified to better understand the aquifer's functioning, especially to enhance the understanding of the hydrogeological functioning of groundwater resources and the groundwater–surface water interaction. Addressing gaps in climate data, monitoring, and well data to gain a more comprehensive understanding of the dynamics and interrelationships between groundwater use and its impacts on streamflow and surface waters is a concern voiced by almost all interviewees (A/B/D/F/G/H/J/Scott Valley Advisory Committee Meeting Aug/Shasta Valley Advisory Committee Meeting Aug). Therefore, addressing these data gaps is a key element of the developed GSPs and is recognized by stakeholders as a crucial part of GSP implementation.

Certain stakeholders are advocating for the installation of meters on domestic and agricultural wells to validate the groundwater use assumptions in the model (D/G). However, some stakeholders have pointed out the intricacy, financial costs, and time-intensive nature of this endeavor (D/Shasta Valley Advisory Committee Meeting Aug), as well as the political considerations and reservations from some stakeholders regarding the sharing of well data (Butte Valley Advisory Committee Meeting Oct/D/G/Shasta Valley Advisory Committee Meeting Aug).

Another strategy for dealing with uncertainties is the sharing of knowledge and data by stakeholders as inputs to the model to increase its accuracy (A/C). Some stakeholders felt that the modeling process reduced uncertainties about the functioning of the groundwater system or supported perceptions the stakeholder had about the aquifer's functioning (A). Utilizing information from stakeholders as inputs during model development helped improve model accuracy (C/F). Using the information provided by the stakeholders also improved their confidence in the model and outputs (e.g., water consumption values). Furthermore, there was a noticeable shift in the mindset of certain stakeholders towards a greater willingness to share private well data based on how this would improve the model. This shift has been observed in the recent past and is expected by some interviewees to intensify in the future (A/B/C/D/F/G/J). This stakeholder attitude toward data sharing has likely evolved in the context of the emergency curtailments imposed by the SWRCB in Scott and Shasta valleys, as emphasized by interviewee A:

> *Changing mentalities and timelines and now it's a rush. Now we wish we had these five-year long data sets [. . .]. Because data is what is the truth.*

That's what's gonna help us [. . .]. And if the truth is that agriculture is using too much water here, we better understand that. And we better change our management. (A)

Stakeholders have come to recognize the intrinsic value of data and the importance of gaining a more comprehensive understanding of aquifer functionality to improve the accuracy of the model (A/B/F). In particular, stakeholders from the Scott and Shasta basins recognized that by improving the model through data sharing, they can better defend their positions on more than one issue, not just on the issue of curtailment processes, whether they represent agricultural or environmental interests (D/G/J). However, respondents also indicated that this view is not shared by the majority of stakeholders and the general public (D/G).

In addition to the efforts focused on data collection and sharing, stakeholders have had to employ strategies to effectively address the unknowns and uncertainties in GSP development. The strict timeline of SGMA required stakeholders to make decisions by 2022. One strategy adopted involves acknowledging the existence of unknowns and uncertainties while maintaining transparency about them within the GSP (F). In addition, stakeholders adopt conservative management approaches by defining conservative minimum threshold criteria, particularly in cases where the available data was deemed insufficient (H).

Prioritizing communication and transparency

Considering the challenges described, the interviews revealed several improvements suggested by stakeholders for future application of numerical models in engagement processes, including raising stakeholders' awareness about modeling principles and enhancing communication by modelers. For stakeholders it is crucial to acquire a comprehensive understanding of the modeling principles from the beginning of a participatory process. This basic understanding is important in order to develop realistic expectations of the model's usefulness, to define its limitations, and to recognize areas where the model should not be used (E). Interviewee E acknowledged this by stating:

This is a tool. This is like every tool, like a shovel, you can dig a hole with it. You don't want to try to fix a window with it or something. And the same thing with a model, what is it good at? [. . .] It's a good tool. You just have to know that it's a tool. It's not reality, it's a tool. And you have to understand well enough to understand its limitation. (E)

The interviewees highlighted the lack of stakeholder understanding of modeling concepts (D) and emphasized the importance of stakeholders' understanding that a model serves as a pedagogical tool that is fraught with unknowns and thus may appear to deviate from an accurate representation of reality (B/E/H). Consequently, it becomes increasingly important to explain the underlying model assumptions to stakeholders, thus promoting transparency (J). Ensuring transparency of the modeling process and associated assumptions is closely related to the stakeholders' desire for regular workshops or presentations of the model's basic concepts; they felt this would facilitate a deeper understanding of the underlying assumptions behind the model (Scott Valley Advisory Committee Meeting Aug and Oct/Shasta Valley Advisory Committee Meeting Aug). This is especially important for newcomers to the advisory committees and members of the public who might have not been involved in the modeling process from the beginning (F).

In terms of model communication, in-person presentations and discussions with the modelers were perceived as favorable aspects (A/C/H/J), as well as the accessibility of the modelers (A/C). The interviewees mentioned the value of listening to the presentations of modelers (J) and being able to ask questions, even outside of official meetings (A). At the same time, the interviewees mentioned the challenge of dealing with a huge amount of technical information, which mostly referred to the modeling approaches, use of the model, or data to set the sustainability criteria (C/E/I). An additional concern affecting the explanation and communication of the model and technical information pertains to linguistic challenges. These challenges encompass both spoken language, in cases where modelers have English as a second language (B/J), and the technical language primarily utilized by professionals with technical backgrounds (B/I/J). Interviewee B highlighted this issue:

And then the technical language is just horrendous for someone. They know how to operate their well, they know how to farm. And you get into all of this, you know, language, it's very complicated. (B)

Linguistic uncertainties gave rise to misunderstandings among stakeholders (J). Stakeholders proposed enhancements to improve communication regarding technical intricacies, model inputs, and model outcomes. Employing accessible language that can be comprehended by all stakeholders and simplifying and summarizing the model results are essential (E/J). Stakeholders have suggested the utilization of mediators or facilitators to serve as intermediaries, bridging the communication divide between the modelers and the stakeholders (I/J).

Given the 2022 submission deadline for the GSP, the GSA and the technical team had a limited window of opportunity, commencing in 2018, for data collection and the initiation of groundwater model development, specifically in Butte and Shasta valleys. Therefore, time constraints were another significant impediment that hindered stakeholders' understanding of the model and the technical information (B/E/F/I/J), as outlined by interviewee E:

> *People who are coming to the meeting without having spent ten years, you can't do it. And a lot of people can't do it anyway because it takes time to understand it. (E)*

The statement underscores the amount of time interviewee E invested in grasping the model and the technical data, starting with SVIHM development. The quote indicates that adequate time for explanations and discussions regarding the model and technical data is critical for stakeholders to gain a comprehensive understanding of the model's underlying processes. Most interviewees emphasized that allowing ample time for stakeholders to understand the material builds trust in both science and modelers (A/C/D/E/F/G/J/Scott Valley Advisory Committee Meeting Aug). It became also evident that stakeholders place a considerable amount of trust in the modelers after collaborating with them for some time (A/C/E/F/G/H/J).

Lessons learned

This study highlights the crucial role of numerical groundwater models in GSP development. However, these models should not be seen as a one-size-fits-all solution for groundwater management challenges. It is essential to acknowledge the associated challenges and explore potential enhancements to make their use more beneficial for both modelers and stakeholders (fig. 2). Indeed, the models provide stakeholders with a conceptual framework to understand the complexities and dynamics of the groundwater system, test management actions and scenarios, and assess their impact, which is in line with previous findings (Borowski and Hare 2007; Foglia et al. 2018; Zellner et al. 2012). However, groundwater models only improve stakeholders' system understanding and evaluations of management actions if they have sufficient time to understand the model setup and its limitations.

These findings highlight the challenge stakeholders face in comprehending the model's underlying assumptions and limitations, as earlier findings also revealed (Greenhalgh et al. 2022; Zellner et al. 2012). This highlights the need for modelers to effectively communicate the model's structure and the underlying assumptions

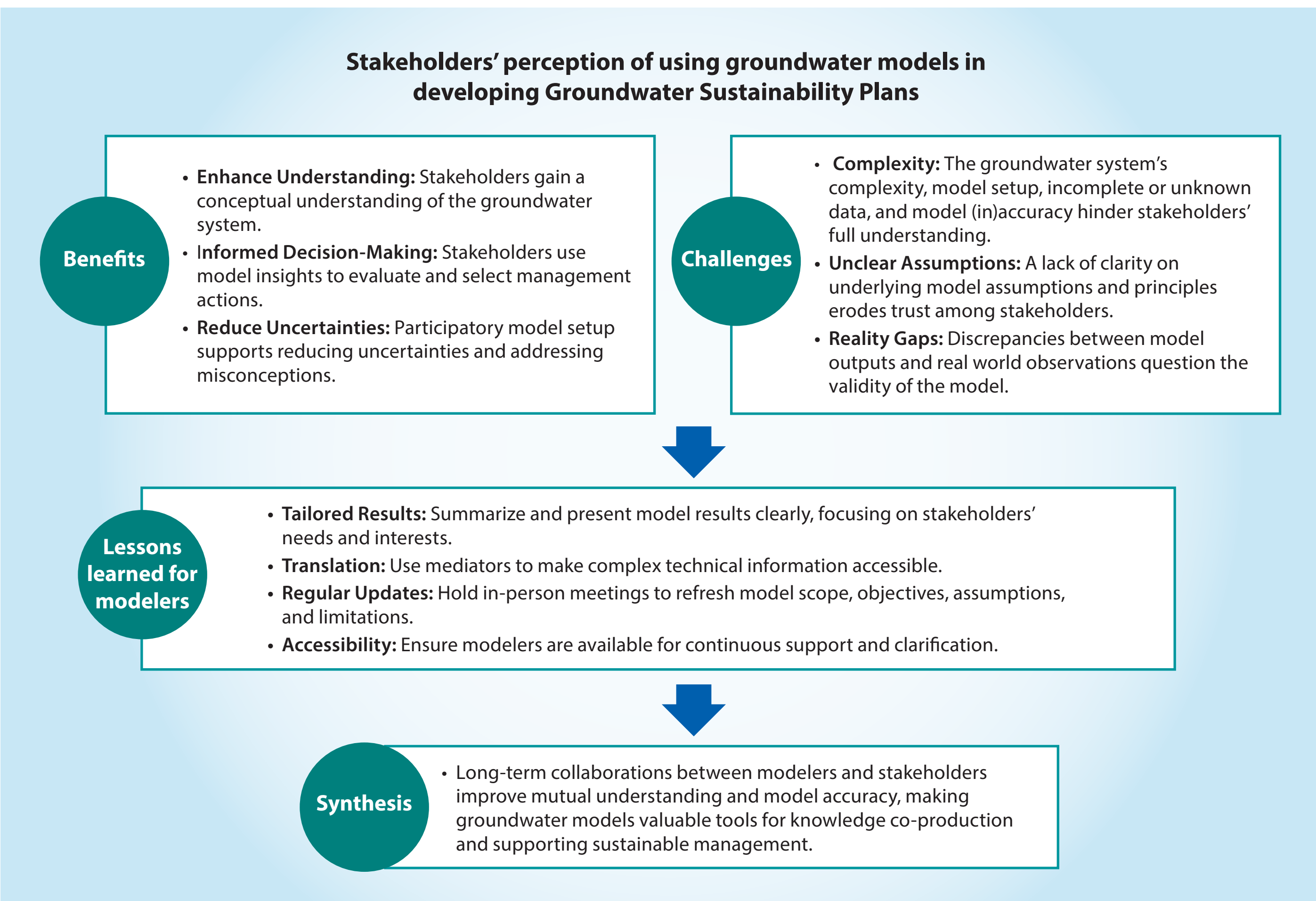

FIG. 2. Summary of key findings on the benefits and challenges of stakeholders' perceptions of using groundwater models in developing groundwater sustainability plans, along with lessons learned for modelers to improve existing processes or guide future GSP development in other basins.

(Sterling et al. 2019). Engaging with specific inquiries raised by stakeholders, enhancing communication by adjusting the language or using the potential of moderators as mediators and translators, and focusing on model aspects that particularly pique stakeholders' interest also facilitates the co-production of knowledge between stakeholders and modelers (Basco-Carrera et al. 2017; Mannix et al. 2022). Failing to acknowledge these factors can lead to misunderstandings, frustration, and an erosion of trust among stakeholders. However, trust in both the modelers and the model itself is recognized as a crucial factor for effective participatory modeling, ensuring that the model serves as a foundation for robust decision-making (Basco-Carrera et al. 2017). Thus, modelers should maintain a keen awareness of their responsibility to communicate the model's limitations and its intended purpose, and emphasize that the model serves as a tool to enhance understanding but cannot offer a flawless depiction of reality (Borowski and Hare 2007; Sterling et al. 2019). Although this may be evident to modelers, it is important to continually reinforce these modeling principles with stakeholders. From our analysis, it appears that this reinforcement can be achieved through regular workshops, where modelers can revisit and elucidate the fundamental aspects of the model to ensure that stakeholders remain well-informed and aligned with the model‘s inherent constraints and objectives. Basco-Carrera et al. (2017), Voinov et al. (2016), and Harmel et al. (2014) offer additional guidance on effectively communicating modeling principles for future participatory modeling approaches that may guide future GSP development processes.

Our analysis revealed that navigating decision-making even with uncertainty is made more feasible when regulatory procedures necessitate actions, even in the presence of potential unknowns or incomplete comprehension of the consequences. For example, this can lead to greater willingness among stakeholders to share private water use data to further reduce uncertainties and improve model accuracy. However, stakeholders also expressed concerns about the limitations and uncertainties of groundwater models when used to enforce regulations. They emphasized that the SVIHM should not be relied upon for precise streamflow predictions to inform decisions regarding minimum streamflow in the Scott and Shasta rivers, given the persistent uncertainties in the model despite years of development. Stakeholders noted the significant time investment required to grasp the model's principles and assumptions based on their own experiences. Regulators may struggle to fully understand these complexities during brief presentations at public hearings, where there is limited time to discuss the model's results and underlying assumptions.

This raises an important question about the role models should play in regulatory processes, particularly given the inherent uncertainties and inaccuracies in all models. Kroepsch (2018) documented a process in Colorado, where various groundwater models were used over a decade as the basis for resolving a groundwater dispute. Kroepsch (2018) concluded that models are not objective representations of subsurface processes but rather "world builders" that construct understandings of the subsurface shaped by the perspectives and objectives of those who develop the models. Thus, despite their advantages, models can be perceived as a burden for stakeholders when used to enforce regulations. Hence, future research and decision-making should build on initiatives such as those by the National Research Council (2007), which outlined best practices for incorporating models into environmental regulatory processes.

Jordan et al. (2018) identified the lack of long-term collaborations as a barrier to successful decision-making in participatory modeling, as lasting collaborations are uncommon in academic projects. Thus, implementing regulations such as the Sustainable Groundwater Management Act is an opportunity to capitalize on enduring partnerships, facilitate knowledge co-production, and hence improve decision-making in environmental planning processes. This and earlier studies underscore that lasting collaborations increase trust between stakeholders and modelers (Smajgl and Ward 2013; Voinov and Bousquet 2010), which also increases the willingness of stakeholders to share data with modelers. Data sharing and shaping research questions contribute to model refinement, which can improve the accuracy of the model (Voinov and Bousquet 2010). Consequently, participatory modeling is mutually beneficial for modelers and stakeholders over time, which demonstrates its importance for the adaptive management of complex social-ecological systems against the background of uncertainties (Pahl-Wostl et al. 2007; Schlüter et al. 2019). As climate change intensifies in complexity and uncertainty, potentially elevating the significance of the use of numerical models in decision-making, this study's findings can offer guidance to decision-makers, modelers, and stakeholders involved in managing complex social-ecological systems. CA

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