Collaborative modeling-based evaluation of groundwater sustainability in coastal aquifers using simulation optimization

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Abstract

Sustainable groundwater management in coastal aquifers requires methods that are both scientifically robust and responsive to socio-ecological complexity. This paper introduces a collaborative modeling-based simulation optimization framework that integrates stakeholder participation with state-of-the-art hydrologic simulation and evolutionary optimization. The methodology operationalizes groundwater sustainability by combining (i) stakeholder co-design of objectives, constraints, and scenarios; (ii) a climate-sensitive recharge estimation module; (iii) a three-dimensional, variable-density groundwater flow model; and (iv) a parallelized Covariance Matrix Adaptation Evolution Strategy (CMA-ES) for multi-objective optimization. Participatory processes were engaged in every phase of the modeling lifecycle, ensuring that scientific assessments are not only technically valid but also socially legitimate and policy relevant. Optimization routines are configured to efficiently explore high-dimensional decision spaces, making the framework tractable even in real-world planning environments. Collaborative modeling-based simulation optimization provides a reproducible pathway for co-producing groundwater sustainability strategies that balance environmental protection, economic development, and cultural values across diverse hydrogeological settings. While demonstrated in the context of Hawaiʻi's Pearl Harbor aquifer, the approach is designed for global applicability in regions facing climate stress, land-use pressures, and aquifer governance challenges.

1. Introduction

In recent years, water resources and environmental managers are increasingly shifting toward participatory and collaborative modeling with diverse stakeholders (Gray et al., 2018; Hedelin et al., 2021; Jordan et al., 2018; Langsdale et al., 2013; Sterling et al., 2019; Voinov et al., 2018, 2016; Shuler and Mariner, 2020; Ocampo-Melgar et al., 2022; Salas and Pennington, 2024). In comparison to participatory modeling, collaborative modeling refers to a high degree of participation and cooperation between the modeling team and stakeholder (Basco-Carrera et al., 2017a). Hereinafter, for simplicity, we use the term participation modeling to refer to both participatory and collaborative modeling with stakeholders unless otherwise specified. A stakeholder is a person, group, or entity that has an interest and concern, can significantly impact, and is influenced by the topic of concern (Elshall et al., 2020a; Martinez-Santos et al., 2008). Stakeholders in water resources management include water regulators, water managers, experts, specific water users and interest groups, and the public. Participatory modeling can be adopted through any phase or the entire modeling process to support groundwater management decisions. Phases of the modeling process include the model study plan, model building and evaluation, model-based analysis and decision support. These phases further extend to the implementation and monitoring of the water management decisions with model support, and post implementation review of the water management decisions with corresponding model updates.

Through trans-academic research and co-production of knowledge with stakeholders, participatory groundwater modeling improves the merits of the scientific assessment (Mussehl et al., 2023; Ricart and Kirk, 2022). Participation adds credibility, legitimacy, and saliency to the scientific assessment (Cash et al., 2003) as well as to the modeling process through improving the technical merits and quality of the model. As emphasized by Zare et al. (2021), improving the modeling process requires the modeling team and stakeholders to evaluate the effects of each modeling assumption and decision. For example, Martin et al. (2021) show that integration of end-users' knowledge through group model building is an essential component to enhance the effectiveness of nature-based solutions such as the reduction of pumping rates, managed aquifer recharge, soil conservation practices, vegetation cover increase, and increasing citizen awareness.

Participatory modeling adds credibility to the modeling process through consensus building. Groundwater management deals with a complex social and economic system, where significantly different views are upheld even within the main stakeholder collectives (Henriksen et al., 2007; Langsdale et al., 2013; Martinez-Santos et al., 2008). Stakeholders often hold valuable knowledge about socio-environmental dynamics and a participatory-based model acts as a boundary object to collectively reason about environmental and water resources problems (Gray et al., 2018). A boundary object is any object that is part of multiple technical disciplines and social worlds that facilitate communication among them. Accordingly, participatory modeling helps to raise awareness and facilitate discussion with and among stakeholders, which can lead to consensus building (Iwanaga et al., 2020; Zare et al., 2021).

Additionally, participatory groundwater modeling adds *legitimacy* to the modeling process resulting in stakeholder a more comprehensive, equitable, and inclusive modeling process. Collaborative modeling combines technical skills such as understanding of the water-ecology-human system, and process skills such as understanding the institutional setting, stakeholder engagement, and trust building to make water resources management an equitable, inclusive, and effective process (Langsdale et al., 2013). For example, Manda and Klein (2014) assessed the process of stakeholder involvement and found that public participation and procedural justice played major roles in resolving groundwater resource management problems in eastern North Carolina, and resulted in an effective plan that ensures the long-term sustainable use of groundwater. Participatory groundwater modeling adds *saliency* to the modeling process through responding to actual community needs at the right time and location. Through participatory modeling, an adequate qualitative overview and shared vision of the problems can be attained, realistic modeling scenarios can be devised, and stakeholder preferences with respect to management alternatives can be identified and evaluated (Hadley et al., 2021; Iwanaga et al., 2020; Martinez-Santos et al., 2008; Molina et al., 2011). Specifically, future pumping conditions (e.g., preferred locations and aquifer formations for new wells, and distribution of future pumping between existing and new wells) can better be defined based on stakeholder preferences than by the modeling team (Hadley et al., 2021). Also, to explore sustainable water management options with possible futures of farm profitability and ecological outcomes, Iwanaga et al. (2020) show that participatory modeling was critical for understanding issues and concerns surrounding ecological aspects, improving modeling assumptions, and identifying potential management opportunities and intention to adopt them. Overall, the abovementioned examples show that adding credibility, legitimacy, and saliency to the modeling process through participatory modeling can lead to more effective and readily adoptable groundwater management decisions (Elshall et al., 2020a).

Additional advantages of participatory modeling that are particularly significant for groundwater sustainability include policy compliance and awareness raising. Participatory modeling is not only required for knowledge synthesis and tackling uncertainty, but active stakeholder involvement is also a groundwater sustainability policy requirement in many locations worldwide, as indicated in the State

Water Code of Hawai'i (1987), the National Water Act of South Africa (1998), the European Union Water Framework Directive (WFD, 2000), the National Water Initiative in Australia (2004), and the California Sustainable Groundwater Management Act (SGMA, 2014), among others (Elshall et al., 2020a, 2022). Additionally, participatory modeling helps to raise awareness among stakeholders (Iwanaga et al., 2020; Martin et al., 2021; Mayer et al., 2017; Zare et al., 2021). One case, Mayer et al. (2017) evaluated three participatory modeling workshops to develop integrated water resources management strategies in a water-stressed basin in Sonora México, and the evaluation indicates that participants believed their modeling abilities increased and beliefs in the utility of models. Awareness raising is particularly important because sustainable groundwater management requires aware and involved citizens (Tuinstra and van Wensem, 2014), and because human behaviors can be a root cause of unsustainability as well as part of the solution (Castilla-Rho, 2017a; Castilla-Rho et al., 2017, 2019).

This study fills a gap in the literature on collaborative modeling based simulation optimization for groundwater decision support. Simulation optimization is a commonly used approach in groundwater management (Gorelick et al., 2015; Hesamfar et al., 2023; Mishra et al., 2023). Simulation optimization integrates a simulation model with an optimization algorithm to identify feasible solutions given the management objectives. Simulation optimization has been widely used in many groundwater management applications, including groundwater contamination remediation and source identification (Elshall et al., 2020b; Li et al., 2021), monitoring network design (Song et al., 2019), hydroeconomic modeling (Mulligan et al., 2014a), optimizing hydrological and farming processes (Fowler et al., 2015), coastal aquifer management, and groundwater sustainability evaluation (Delottier et al., 2017; Farhadi et al., 2016; Yazdian et al., 2021). Different variants of participation-based modeling in water resources management literature are referred to as participatory modeling, participatory simulation, participant(s) modeling, collaborative modeling, cooperative modeling, companion modeling, interactive modeling, mediated modeling, fast integrated systems modeling, group model building, computer-aided dispute resolution, computer-aided negotiation, and shared vision planning (Basco-Carrera et al., 2017b; Langsdale et al., 2013). Our systematic review of peer-reviewed literature indicates that few studies have addressed participatory modeling-based simulation optimization for groundwater management. For instance, Raei et al. (2017) integrated a bioremediation simulation model with multi-objective optimization for optimal design of in situ groundwater bioremediation system, considering preferences of stakeholders. Similarly, Fowler et al. (2015) coupled the MODFLOW-FMP2 groundwater model with an optimization framework to identify trade-offs in crop selection under water-limited conditions. These two studies highlighted that participatory modeling combined with optimization is essential not only for dialogue but also for quantifying competing objectives and identifying management strategies acceptable to multiple stakeholders.

This study addresses a critical gap in groundwater management by introducing a novel framework that formally integrates collaborative modeling with simulation optimization. The primary methodological advancement is a process where stakeholder participation directly informs the formulation and analysis of complex management strategies using simulation optimization, ensuring that solutions are not only technically optimal but also socially relevant and legitimate. We demonstrate this stakeholder-driven method by developing and applying a simulation-optimization tool to evaluate the sustainable yield of the Pearl Harbor aquifer in Hawaiʻi, which serves more than one-third of the state's population. This application showcases the framework's innovative capabilities for advancing management of coastal aquifers with ecological constraints. By operationalizing stakeholder knowledge within a rigorous quantitative framework, this work offers a transferable method for advancing groundwater sustainability in complex coastal regions worldwide.

2. Case study

2.1 Groundwater sustainability policy in Hawai'i

Modern groundwater management in Hawaiʻi is continuously developing to better align with groundwater policy in the state. The state-mandated water code stipulates that the water regulators should estimate groundwater sustainable yield for all major aquifer systems in Hawaiʻi (HRS Chapter 174C, 1987). As such, sustainable yield evaluation is a major component of the Hawaiʻi Water Resources Protection Plan. The State Water Code (HRS Chapter 174C, 1987) defines sustainable yield as “the maximum rate at which water may be withdrawn from a source without impairing the utility or quality of the water source as determined by the commission.” The commission refers to the Commission on Water Resources Management (CWRM), which is the state water regulator. The definition of “without impairing the utility or quality of the water source” involves a large number of aquifer performance and governance factors.

Sustainable yield has been widely calculated in Hawaiʻi using an analytical model known as the robust analytical groundwater flow and salinity transport model (Liu, 2007; Liu and Dai, 2012). RAM2 is based on the seminal work of Mink (1981) that developed the robust analytical model (RAM) for estimating sustainable yield in Hawaiʻi. Rigorously derived from groundwater flow and transport equations, RAM2 is a simple mathematical tool to estimate aquifer yield in basal coastal aquifers by simulating the variation of the hydraulic head and the expansion of the transition zone under pumping stress. RAM2 is an easy-to-use model with only few parameters that can be applied satisfactorily with limited field monitoring data

(Liu and Dai, 2012). However, the RAM2 model has two limitations. First, it estimates only safe yield since it does not account for induced recharge. Induced recharge is part of the groundwater captured due to groundwater development. Induced recharge includes leakage from surface water bodies, recharge in areas that previously discharged groundwater to the surface and increase in lateral inflow (in administratively defined but physically unbounded groundwater formations). Also, RAM2 lumps leakage into one term. Accordingly, RAM2 does not provide insights about separate leakage components such as submarine groundwater discharge, spring discharge, base-flow, evapotranspiration, drains, and decrease in lateral inflow. Quantifying different leakage components is important for managing groundwater dependent ecosystems, which is a stakeholder priority in Hawaiʻi (Adler et al., 2018). Second, RAM2 is a lumped model that does not provide insights about the spatial distribution of withdrawals with respect to the spatial distribution of hydraulic conductivity, dispersity, porosity, recharge, and other model parameters. For example, (Oki and Meyer, 2001) compare results obtained by a distributed numerical model and by RAM with field measurements and find that RAM underestimates water-level declines in areas where a low-permeability confining unit exists, and in the vicinity of withdrawal wells. This can result in aquifer yield overestimation. The current permitted withdrawal scheme in the study area based on the RAM2 solution overestimates sustainable yield by at least 30% as shown in the supplementary material (Elshall and Gebremedhin, 2025). Accordingly, using a distributed finite-element density-dependent flow model is needed to overcome these challenges along with an optimization algorithm to operationalize the sustainable yield policy in Hawaiʻi.

2.2 Simulation optimization problem

2.2.1 Method justification

In response to the need to improve the decision support tools related to sustainable yield management, we developed a simulation optimization tool to evaluate sustainable yield in Hawaiʻi. Simulation optimization is a commonly used technique in groundwater management (Gorelick and Zheng, 2015) that solves an objective function stating the management objectives aided by the simulation models and an optimization algorithm to find optimal management solutions. The management objectives, which were identified through stakeholder engagement, include minimizing saltwater intrusion and drawdown, and controlling spring discharge and submarine groundwater discharge. The Pearl Harbor aquifer system, which is an important aquifer system serving a population of about half a million people in Hawaiʻi is used as a prototype. The simulation optimization method was formulated based on a stakeholder driven modeling process using United States Geological Survey (USGS) developed models that are trusted by the stakeholder in the state. The finite element groundwater SUTRA model of Pearl Harbor (Oki, 2005) was used to simulate density dependent groundwater flow. The Hawaiʻi Water Budget Model (HWBM, Engott et al., 2017) is used to generate recharge maps for different climate and land-use scenarios. Given the objective function, the simulation optimization procedure consists of the optimization algorithm CMA-ES (Hansen et al., 2003) that links the management objectives with the HWBM and the groundwater density dependent flow model. To permit feasible computational cost, the simulation optimization runs are carried out using parallel CMA-ES (Elshall et al., 2015). This simulation optimization tool can be used to evaluate sustainable yield under different natural processes and societal preferences. Natural processes include the impact of climate change on top recharge, in-land lateral boundary recharge, and sea level rise. Societal preferences include withdrawal management schemes that account for different ecological constraints on spring discharge and land-use scenarios. The simulation optimization procedure to address different groundwater management questions is presented in Fig. 1.

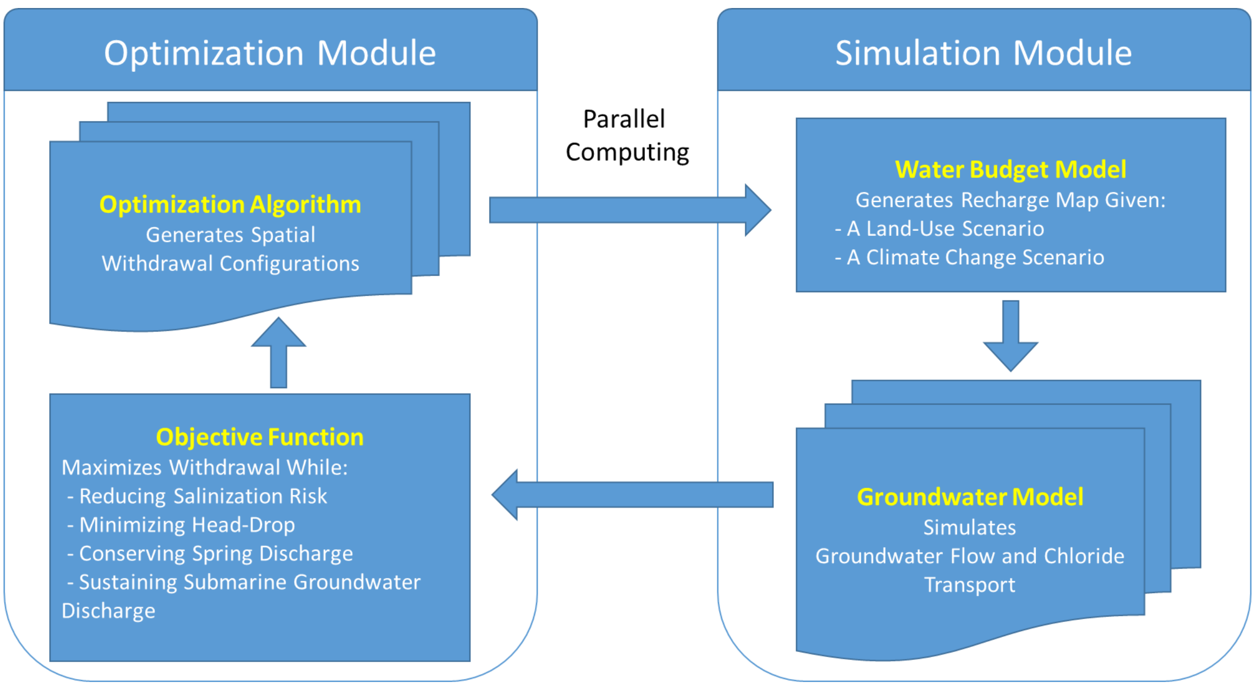

Fig. 1: Simulation optimization procedure to address different groundwater management questions

2.2. Problem formulation

Assuming a linear combination of multiple objectives, the problem of finding an optimal solution can be stated as the following minimization function:

$$\min_{z\in\Omega_z} f(z) = \min_{z\in\Omega_z} \sum_{k=1}^{K} -f_k \qquad (1)$$

where f is the objective function that is generally formulated in a minimization convention; $\mathbf{z}(\mathbf{u},\mathbf{w})$ is a vector of decision variables that consists of a vector $\mathbf{u}$ of state variables and a vector $\mathbf{w}$ of decision variables; $\Omega_z = \Omega_u \cup \Omega_w$ is the feasible region of the decision variables $\mathbf{z}$ as represented by a set of constraint equations such that Ω_u represents the feasible region of the state variables $\mathbf{u}$, and Ω_w represents the feasible region of the decision variables $\mathbf{w}$. Given two objective functions $K = 2$, our state variables $\mathbf{u} \in \{u_1, u_2\}$ are the pumping wells chloride concentration and drawdown, and spring discharge, respectively. When $K > 1$ the optimization problem is termed multi-objective. The decision variables, $\mathbf{z}$, are withdrawals at the pumping wells. Our constraints are the minimum or maximum thresholds, which the state variables $\mathbf{u}$ should not violate.

Our objective is to find the maximum allowable withdrawal without violating these constraints. For any m number of pumping wells, we used a withdrawal dependent objective function

$$f_1 = \sum_{i=1}^{m} r_i \times q_i \times p_i \qquad \begin{cases} p_i = -1 & \forall W_{i,obs} > W_{i,threshold} \\ p_i = 1 & \forall W_{i,obs} \leq W_{i,threshold} \end{cases} \tag{2}$$

such that the solution will be penalized if the chloride concentration or drawdown $W_{i,obs}$ in any pumping well i exceeds the chloride concentration or drawdown threshold $W_{i,threshold}$ for that pumping well; q_i is the withdrawal of pumping well *i*; p_i is a penalty term. The weighting term r_i represents the relative importance of pumping well *i* and we assume equal weighting for all decision variables. We observe the chloride concentration and drawdown $W_{i,obs}$ at the end of the simulation period. The spring objective function is a hard penalty constraint

$$f_2 = 4000 \times p \qquad \begin{cases} p = -1 & \forall S_{Obs} < S_{threshold} \\ p = 0 & \forall S_{Obs} \geq S_{threshold} \end{cases} \tag{3}$$

where S_{obs} is the total spring discharge observed at the end of simulation period; $S_{threshold}$ is the spring discharge threshold for all springs combined; p is a penalty term for total spring discharge. The parameterization of this simulation optimization problem, such as selection of decision variables, design period, and threshold values were informed by technical experts.

3. Collaborative modeling for simulation optimization problem formulation

3.1 Overview

Collaborative modeling tools were developed through several activities, including a participatory approach with multiple government agencies to design land use scenarios (Bremer et al., 2021), and social learning activities with community members to better understand relational values and prioritize important ecosystem services that are related to spring discharge (Burnett et al., 2020). Here we report the collaborative modeling method that we used to formulate the simulation optimization problem. To simultaneously integrate model building with a participatory process, Langsdale et al. (2013) developed guiding principles and best practices for collaborative modeling for decision support in water resources. To help standardize the field of participatory modeling, Gray et al. (2018) developed a reporting approach for the conceptual, procedural, and technological design of the participatory modeling. To address the complexities of groundwater sustainability, this study introduces a collaborative modeling framework that integrates and extends the guiding principles of Langsdale et al. (2013), while using the standardized reporting method of Gray et al. (2018) as illustrated in Fig. 2. The reporting approach of Gray et al. (2018) has four components--purpose (why), process (how), partnership (who), and products (what)--the first three of which are presented in this section. The fourth component is presented in the results and discussion section (Section 4.2).

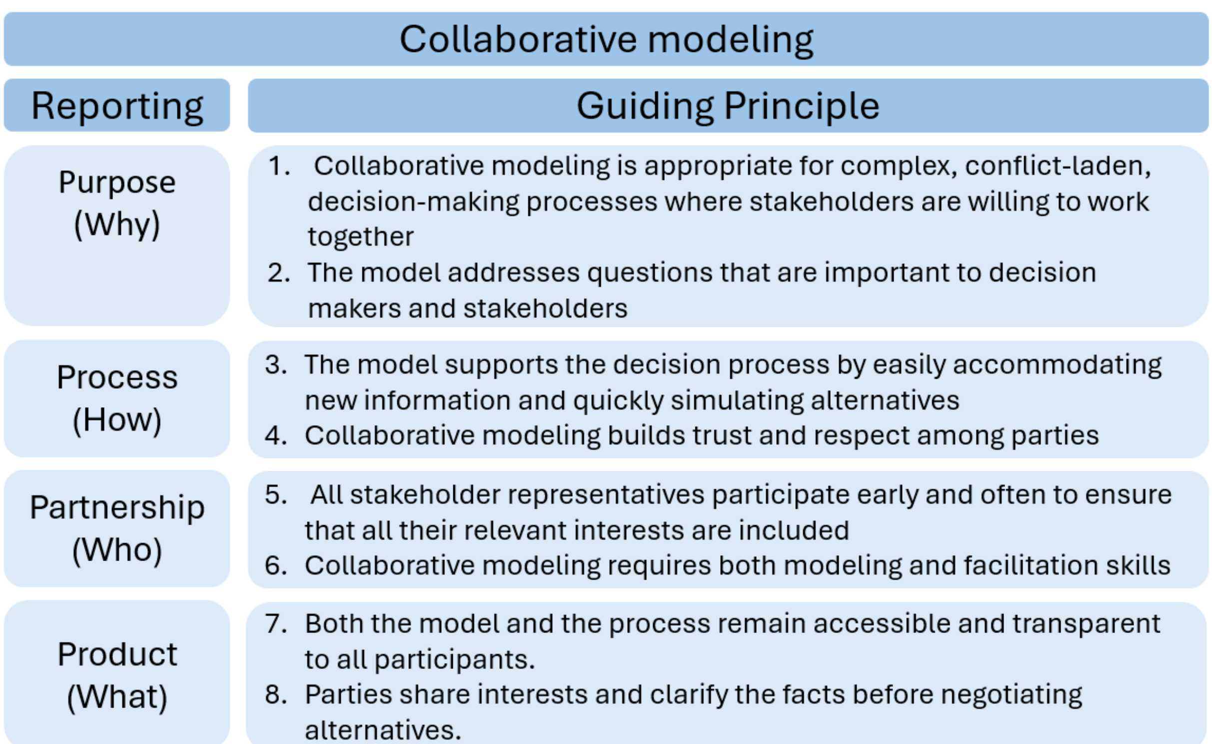

Fig. 2: Collaborative modeling methodological framework to develop simulation optimization tool for decision support in groundwater sustainability following the guiding principles from Langsdale et al. (2013) and standardized reporting approach from Gray et al. (2018).

3.2 Purpose

Following the reporting approach in Fig. 2, we described the participation purpose and the model purpose alongside Principle 1**.** We included stakeholders in the modeling process for several purposes. First, participation is an integral policy component in Hawai'i in that the Commission on Water Resource Management is obliged to cooperate with agents for "the purpose of utilizing and conserving the waters of the State, and assist these organizations and agencies in coordinating the use of their facilities and participate in the exchange of ideas, knowledge, and data with these organizations and agencies" (§174C-5, HRS Chapter 174C, 1987). Second, this participation process is imperative to attain an adequate qualitative overview of the problem, and a shared vision of the problem with stakeholders (Martinez-Santos et al., 2008; Molina et al., 2011). Third, collaborative modeling as a form of participation can lead to more effective solutions being identified and adopted (Watson, 2005). This is mainly because participation involves tapping into institutional knowledge, exchange of experiences, deeper understanding, consensus building, and raising commitment toward resource management (Carr et al., 2012; Castilla-Rho, 2017b; Mays, 2013). Stakeholder input in this case is broadly useful, ranging from understanding historical factors and local knowledge, to devising realistic modeling assumptions, scenarios, and management alternatives. In addition, collaborative modeling makes the developed simulation optimization framework applicable to the stakeholders' decision-making context, and ensures that the knowledge and needs of the stakeholders are incorporated in the simulation optimization framework (Gray et al., 2018). Additionally, collaborative modeling allows stakeholders to vet, correct and improve modeling assumptions. Finally, collaborative modeling is an effective uncertainty analysis method. As shown below, this collaborative modeling approach is helpful for dealing with uncertainty related to the complexity of the socioeconomic system that is difficult to address otherwise.

The adopted simulation optimization framework has several purposes and multiple problems to address. According to Principle 2 illustrated in Fig. 2, collaborative modeling prioritizes designing the model based on its intended purpose, rather than developing a technically driven model first and finding users afterward (Langsdale et al., 2013). As each model has specific purposes, understanding the model's purposes is important to decide on the model scope and level of analysis. With respect to improving hydrologic and environmental decision-making in the context of groundwater sustainability in Hawai'i, the main purpose of this simulation optimization framework is the proof of concept of the value of numerical modeling within a simulation optimization framework to evaluate groundwater sustainability.

The use of an analytical model such as RAM2 versus a numerical model such as SUTRA is a highly debated topic as reviewed by Elshall et al. (2020). Analytical models can be inadequate for evaluating groundwater sustainability (Henriksen et al., 2008; Kalf and Woolley, 2005; Mulligan et al., 2014b) because they lack the ability to simulate various leakage components, their treatment of the interaction between inflow and outflow components is often not rigorous, and they are typically not designed to consider spatiotemporal relationships. While analytical models are subject to criticism, the choice of analytical model versus numerical model is case-specific and depends on data availability, sustainability factors of interest, and aquifer type (Elshall et al., 2020a). Yet apart from the advantages and disadvantages of analytical models, there is a need for a tool to evaluate groundwater sustainability in Hawaiʻi that can flexibly account for hydrological systems, groundwater-dependent ecosystems and human activities under different natural and anthropogenic stresses. Serious challenges of groundwater sustainability are arising in coastal aquifers due to climate change and socioeconomic development (Michael et al., 2017).

The situation in Hawaiʻi and similar islands is more critical due to their special hydrological features and sea level rise combined with anthropogenic impacts causing water stress (Werner et al., 2017). Evaluating groundwater sustainability with respect to these challenges requires integrating hydrologic models with different constraints such as socioeconomic demographics, human activities, societal preferences, groundwater dependent ecosystems, climate change impacts and mitigation, and regulations, among other aquifer performance and governance factors (Alley, 2018; Custodio, 2002; Gleeson et al., 2012; Griffioen et al., 2014; Kalf and Woolley, 2005; Pierce et al., 2013; Rudestam and Langridge, 2014; Sikdar, 2019). Illustrating the essential factors to consider when evaluating groundwater sustainability, as shown in Fig. 3, can be useful in collaborative modeling to understand the scope of the evaluation. Several of these factors Fig. 3 are considered in this study. With respect to recharge rates and storage conditions we consider climate change, land use and landcover change impacts, drawdown, natural and induced recharge, and storage. With respect to water quality, we consider saltwater intrusion. With respect to capture, discharge rates, and environmental flows we consider beneficial usages for springs and submarine groundwater discharge. With respect to facilities and technologies we consider pumping, nature-based infrastructure, and desalination for groundwater substitution. With respect to legal and institutional constraints we consider water rights, restrictions on production well locations and depths, restrictions on specific activities, and sustainable yield policy. With respect to societal values and preferences we consider mainly instrumental, intrinsic, relational and aesthetic values. With respect to economic feasibility, we consider and discuss groundwater substitution and pumping costs, although these factors are not quantitatively incorporated into the model. Combining these different aquifer performance and governance factors requires a modular tool. We demonstrate how this modeling framework can better address major concerns such as incorporating aquifer governance parameters related to groundwater usage and accessibility, spring discharge, sea level rise, and future recharge scenarios into groundwater sustainability evaluation in Hawaiʻi.

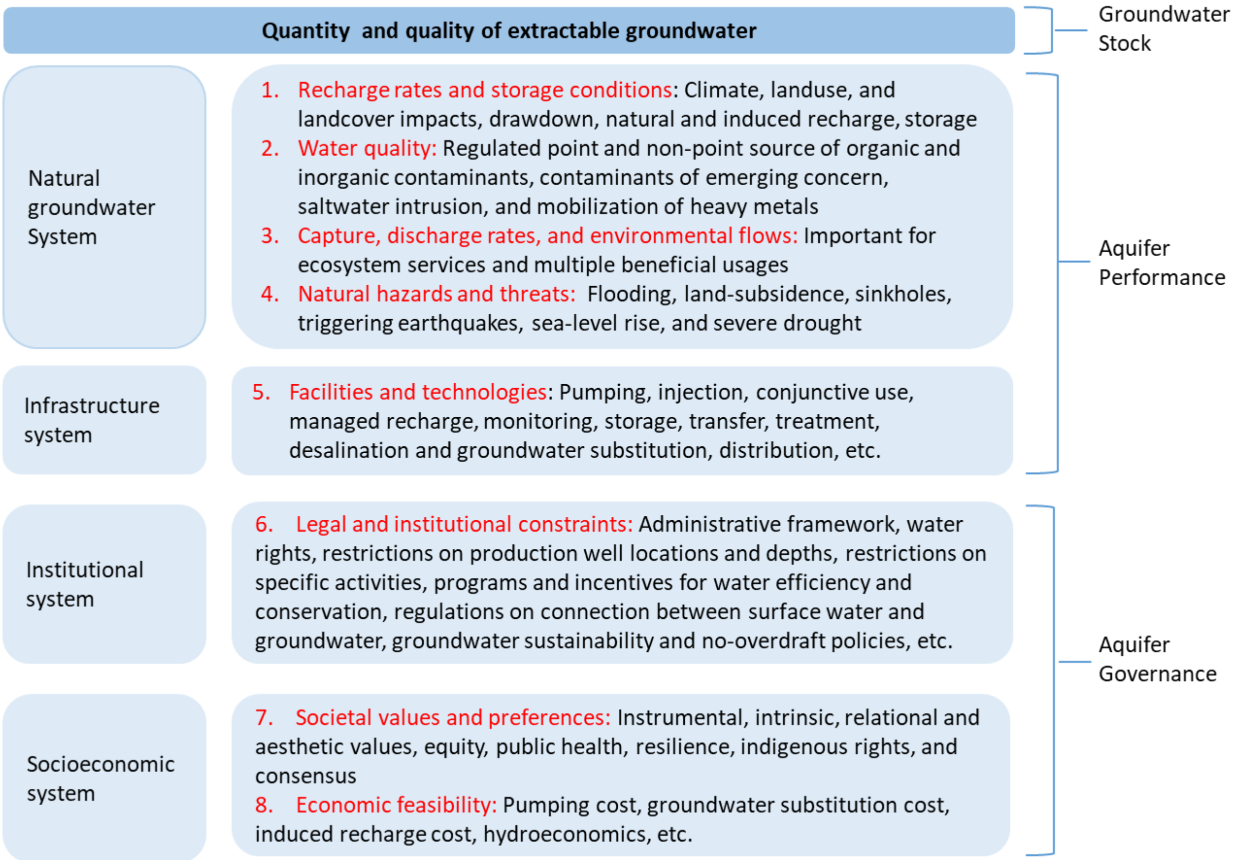

Fig. 3. Factors to consider for groundwater sustainability evaluation modified from (Elshall et al., 2020a)

3.3 Process

Process reporting includes reporting the level of participation, interaction between the participants and the model, and the relationship between the collaborative modeling and the decision-making process (Gray et al., 2018). We used collaborative modeling to formulate the simulation optimization problem. Collaborative modeling refers to a high degree of participation and cooperation between the modeling team and stakeholder. Given the ladder of participation and types of cooperation chart proposed by (Basco-Carrera et al., 2017a), our approach is a discussion and co-design type of participation that is more than just consultation, but less than co-decision making, and a collaboration type of cooperation that is more than just unilateral action or coordination, but less than joint-action as shown in Fig. 4. Given this level of participation, the simulation optimization framework is constructed based on the stakeholder knowledge, which increases the degree of model transparency and the stakeholder understanding of model assumptions.

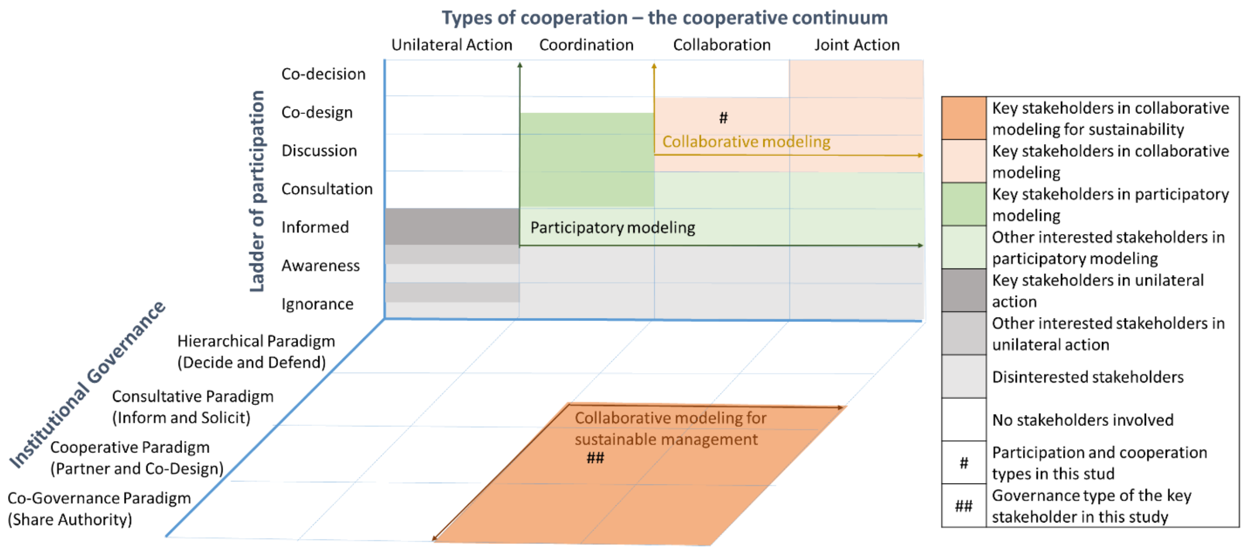

Fig. 4. Framework for stakeholder engagement integrating institutional governance of key stakeholders with the type of participation and cooperation, extended and modified from the ladder of participation and types of cooperation chart proposed by (Basco-Carrera et al., 2017a).

The interaction between the participant and the model is based on a technocratic version of the modeling framework that serves as a boundary object to facilitate the co-design of the modeling framework with stakeholders. The Principle 3 in Fig. 2 focuses on integration and resolution of many issues rather than the depth and precision, and thus keeping the model relatively simple and at a high level is recommended at this stage, and then detailed and precise analysis can be conducted after prioritizing options (Langsdale et al., 2013). The modeling team developed a simulation optimization procedure from a purely hydrologic perspective regardless of the social context. Thus, assumptions about decision variables, initial conditions, observation points, among other settings were set based on the research team's general modeling experience, rather than hands-on experience about aquifer management. For example, our decision variables $\mathbf{z}$ are either selected pumping wells or pumping clusters. Optimizing withdrawal of the 92 pumping wells in the study area is a high dimensional problem. This is computationally unfeasible since the iteration size n and the number of iterations to reach convergence increase with the number of decision variables m . Also, having a high dimensional problem is not technically recommended since a large number of decision variables can cause solutions non-uniqueness, resulting in multimodality. A common approach to reduce the problem of dimensionality is to group pumping wells into clusters such that the number of decision variables m is the number of pumping clusters instead of the number of pumping wells (Pholkern et al., 2019). We grouped the 92 pumping wells into 20 clusters based on spatial proximity using the k-mean clustering method as shown in supplementary material (Elshall and Gebremedhin, 2025). Although this is a reasonable assumption, it does not tap into the local knowledge of aquifer managers. Similarly, we made reasonable assumptions about other settings as shown in Table 1, and obtained simulation optimization solutions that serve as a starting point for the co-design process.

We presented the developed simulation optimization method and solution to promote collaborative learning in line with Principle 4 in Fig. 2**.** The meeting agenda was designed to first introduce the project and modeling assumptions, and then ask participants to contribute to the model development through providing data, improving model assumptions, validating outputs, prioritizing important scenarios, and providing insights from real-life experiences about the aquifer. Langsdale et al. (2013) note the importance of positive relationship building, beyond simply bringing people together. In particular, when emotional participants tend to be more open to discussion and accepting new ideas. Additionally, involving trusted and respected community members in the modeling team can greatly aid positive relationship building. In this case study, these factors helped to develop a shared or co-learning approach, which is a form of collaborative learning, where information flows from research team to stakeholder and vice versa (Basco-Carrera et al., 2017a). As such, the research team presented the simulation optimization method, problem formulation, solution and capabilities to the stakeholder for feedback. The resulting discussions, which tapped into the stakeholder's collective knowledge about the aquifer, supported the co-design of the simulation optimization problem. The stakeholder's collective knowledge includes (1) well-rounded knowledge about aquifer stakeholder regulations including relationships with other stakeholders, (2) hands-on experience about aquifer management including experience about the most relevant hydrogeological features of the aquifer and social dynamics of the aquifer management, and (3) an in-depth understanding of aquifer users' perceptions, concerns and preferences. Such collaborative learning assists in the acquisition of collective skills and increase in individual knowledge within the social context (Basco-Carrera et al., 2017a). In addition, this collaborative learning and co-design directly relates the modeling framework to the decision context.

3.4 Partnership

Partnership reporting involves reporting the participant selection process, and the steps participants are involved with. Identifying stakeholders and defining avenues for participation is largely contextual (Carr et al., 2012; Kusters et al., 2017). The stakeholder selection process in this case study is straightforward as there is no need to extend the collaborative modeling beyond key stakeholders. As connections are made first, defined by the Hawaiʻi (HRS Chapter 174C, 1987), the main stakeholder with respect to sustainable yield evaluation in the state is the Commission on Water Resource Management (CWRM), which is the state water regulator. According to Principle 5 Fig. 2by Langsdale et al. (2013), all stakeholder representatives should engage early and frequently to ensure that their relevant interests are adequately represented. A common policy practice is that the general public (Elshall et al., 2020a). CWRM acts as a representative for community members and entities who have interest and concern about groundwater as it includes members most directly involved with the model building team, communicate with key stakeholders, who act as a trusted link to interested parties. Thus, the CRWM inputs are intended to ensure that the interests of the wider community are represented, and alternatives are evaluated, while attempting to balance the many diverse interests, in order to identify the most beneficial decision. A second important stakeholder is the local water manager in the study area, Board of Water Supply (BWS), a semi-autonomous agency that manages Oʻahu's municipal water resources and distribution system.

The nature of the partnership, as defined by institutional governance, is a key dimension when considering sustainable groundwater management or sustainability in general. This dimension, as shown in Fig. 4, captures the fundamental governance character of a stakeholder, ranging from the hierarchical paradigm of a technocratic institution with a strong engineering and regulatory mandate to the deeply stewardship-oriented and consensus-driven approach that, for example, can be found within Indigenous communities. In this study, CWRM exemplifies cooperative governance (Fig. 4), as CWRM is mandated by the State Water Code to "participate in the exchange of ideas, knowledge, and data" with other agencies and organizations. This pre-existing collaborative paradigm is a critical enabling factor for creating a receptive environment for the co-design of sustainable groundwater management. The distinction is crucial, as high-level engagement like co-decision making may still fail to produce sustainable outcomes if the institutional partner does not have a genuinely cooperative governance style.

Participants are involved through multiple steps, starting with informal meetings and communication to inform stakeholders about the project, assess the avenues and level of participation that they are interested in, and obtain updated pumping data to start designing the technocratic version of the simulation optimization framework before the collaborative modeling process. The collaborative modeling process involves a full-day workshop to co-design the simulation optimization framework. According to Principle 6 (Fig. 2) of Langsdale et al. (2013), collaborative modeling requires the integration of both technical modeling expertise and facilitation skills. The role of the lead modeler was to lead technical discussions, distill expectations, synthesize the inputs of the stakeholders, and build a co-designed model with the stakeholders. The role of the facilitator was to contact stakeholders to plan for the workshop and facilitate discussion during the workshop. This workshop was followed by a meeting to present the updated simulation optimization results based on the co-design process. These two events were attended by the modeling team and CWRM staff. At the project completion a third meeting occurred, which was attended by CWRM, BWS, and the modeling team. The objective of the meeting was to obtain stakeholder feedback on the modeling output and discuss future steps.

4. Results and discussion

4.1 Simulation optimization tool

We developed a simulation optimization code that has eight options to answer questions related to water allocation, spring discharge, climate change impact on recharge and sea-level rise, land-use scenarios, and economic analysis of withdrawal cost. The simulation code is the finite element SUTRA model - Version 2.0 (Voss and Provost, 2002). This is a USGS model to simulate density dependent groundwater flow, and the code is written in Fortran. We used a special version of SUTRA Version 2.0 (2D3D.1) (Oki, 2005) that is specifically tailored for Hawaiʻi to account for specific yield. The simulation code is CPU intensive and constrained by clock frequency of the processor. The optimization module consists of the CMA-ES algorithm (Hansen et al., 2003) in a parallel computing environment (Elshall et al., 2015) with high throughput serial execution of model iterations, and after each iteration the results are processed and new solutions for the next iteration are proposed accordingly (Elshall et al., 2015). The software has integrated checkpointing to enable the simulation to resume at the last completed iteration in the event it is interrupted or does not converge, which ensures that there are no wasted cycles.

4.2 Product

Formulating the simulation optimization problem involves making assumptions about different settings. Formulating the simulation optimization problem is done iteratively through a collaborative modeling process (Fig. 2). Then we formulated the simulation optimization problem given the stakeholders' feedback to evaluate various management questions accordingly. Based on various stakeholders' feedback (Table 1), we updated the pumping wells map. Fig. 5 shows the updated pumping well map based on stakeholder participation in which pumping wells are categorized by aquifer formation that are either basalt or caprock. Stakeholders suggested relaxing the salinity threshold at the caprock to 1,000 mg/l chloride since this area could naturally have high salinity and the groundwater is mainly used for irrigation purposes. Pumping wells are also categorized by aquifer administrative unit according to the Department of Land and Natural Resources: Ewa-Kunia, Waipahu-Waiawa, Waimalu and Moanalua. To be consistent with the current management practice, we report on the sustainable yield for each administrative unit. In addition, the wells are categorized according to three main interest groups that include (1) Board of Water Supply (BWS) wells and shafts, (2) federal wells, and (3) other wells such as state government wells, irrigation wells, home associations wells, wells with missing information, and other private wells. The current withdrawal of BWS wells and shafts, federal wells and other wells are 90.25, 19.07 and 7.63 million gallons per day (mgd), respectively. The current permitted withdrawal of BWS wells and shafts, federal wells and other wells are 124.97, 22.67 and 33.46 mgd, respectively. The stakeholder mentioned that BWS wells should be prioritized as decision variables, while federal wells are generally managed separately. Finally, the wells are categorized by current withdrawal: >0.01 and ≤0.1 mgd (48 wells), >0.1 and ≤1 mgd (44 wells), and >1 mgd (27 wells). Stakeholders suggested to start by optimizing withdrawal for pumping wells with current withdrawal above 1 mgd.

These simulation optimization runs are for a 50-year design period. Pumping wells with current withdrawal less than 1 mgd are not included as decision variables. The salinity thresholds for the caprock and the basalt aquifers are 250 mg/l and 1000 mg/l chloride, respectively. The head-drop threshold is 1 m from the pre-development conditions. The decision variables are wells with average withdrawal from 2001 to 2015 larger than 1 mgd. The two cases, in which Navy wells are excluded from and included in the set of decision variables, have 24 and 27 decision variables, respectively (Fig. 5).

Table 1: Questions to and feedback from stakeholders are represented by black and blue font, respectively. The underlined text represent the settings of the simulation optimization solutions that were presented to the stakeholders in the first workshop.

Topic	Questions and feedback
Initial condition	Q: Current withdrawal for prediction period from 2001 to 2015: (i) monthly average, (ii) annual average, (iii) period average or (iv) other? Period averaging is a reasonable assumption, and missing data should not be included as zeros in the averaging. Using that current data without any averaging is also a reasonable choice
Decision variables	Q: Pumping wells: (i) selected pumping wells, (ii) pumping clusters or (iii) all pumping well Clustering can be avoided by selecting relevant pumping wells such as the Board of Water Supply (BWS) wells and the Navy wells. Private wells, especially those with low withdrawal rates, do not need to be included in the decision variables

Topic	Questions and feedback
	Q: Time-dependent withdrawal: (i) constant withdrawal or (ii) time variant withdrawal Constant withdrawal is a reasonable assumption as time-variant withdrawal is not needed and it is difficult to present and communicate
	Q: Withdrawal rates: (i) minimum and maximum withdrawal per pumping well if any or (ii) a uniform distribution from zero to a large number For initial test runs defining minimum and maximum withdrawal per pumping well is not needed, yet that can be later incorporated based on feedback from BWS
Clustering/zonation	Q: Withdrawal clusters: (i) K-mean clustering, (ii) aquifer units, or (iii) other Clustering can be avoided, yet pumping wells can be categorized by (i) DLNR aquifer units, (ii) Interest groups (e.g., BWS wells, Navy wells, irrigation wells, private wells, etc.) and (iii) aquifer property (e.g., basalt aquifer, Caprock, valley-fill barrier, etc.). Salinity threshold at the Caprock wells should be 1000 mg/l chloride versus 250 mg/l for the basalt aquifer
	Q: Withdrawal ratios for pumping wells in each cluster: (i) current, (ii) permitted, (iii) evenly distributed or (iv) other Using the current ratio is a reasonable assumption, but this is not needed if we will avoid clustering
	Q: Withdrawal rates for the fixed pumping wells: (i) permitted, (ii) current or (iii) zero Using the current rates is a reasonable assumption
	Q: Current withdrawal: (i) monthly average, (ii) annual average, (iii) average from 2001 to 2015 or (iv) other Using an average withdrawal from 2001 to 2015 is a reasonable assumption
Observation	Observation locations (i) decision variable pumping wells, (ii) decision variable pumping wells plus additional observation locations, (iii) other?

Topic	Questions and feedback
	The current selection is reasonable and additional observation locations can be included depending on feedback from BWS
	Observed salinity: (i) per node, (ii) water mixing per pumping well or (ii) water mixing per cluster? The current selection of water mixing per pumping well is reasonable
	Observation time: (i) Observation at the end of simulation, (ii) observation at time shift (maximum), (iii) observation at time shift (average)? Observation at the end of the simulation is a reasonable assumption as it is not stringent and reflects the desired situation at the end of the design period in 2070
Additional feedback	Other points? There is public pressure on CWRM and BWS to report on the impact of withdrawal on submarine groundwater discharge

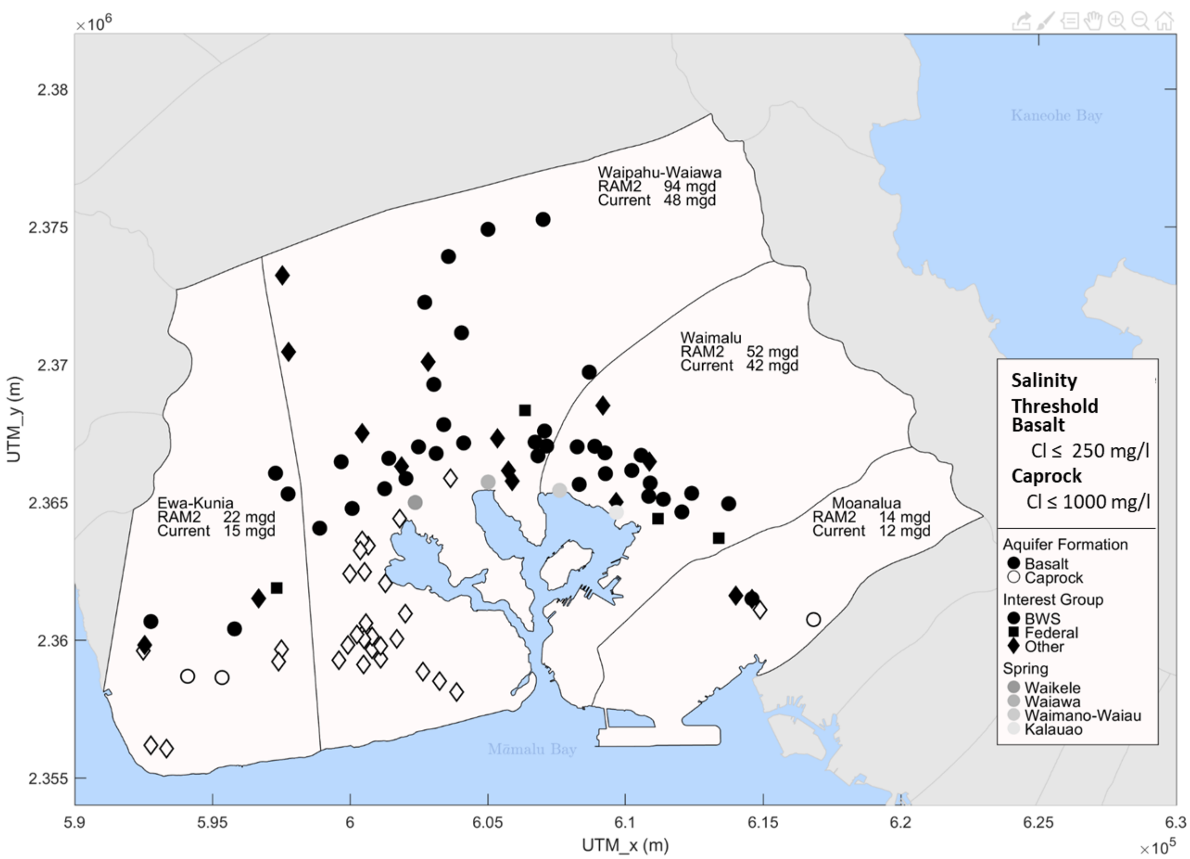

Fig. 5. Updated pumping well map based on stakeholder engagement, in which pumping wells are categorized by aquifer property (basalt and caprock), aquifer unit (Ewa-Kunia, Waipahu-Waiawa, Waimalu and Moanalua) and interest group (BWS, Navy and Private).

4.3 Mid-century projection

The mid-century projection of groundwater conditions based on current pumping rates, recharge levels, climate and land use are illustrated in Fig. 6. The projected groundwater withdrawal will decline by 12% from the current pumping scheme due to saltwater intrusion. Climate change showed a significant impact on projected groundwater availability via changes in recharge, sea level rise, and land use management, as shown in the supplementary material (Elshall and Gebremedhin, 2025). Under a future dry climate scenario, both top and boundary recharge decline, resulting in a 26% reduction in freshwater pumping compared to current conditions. This decline in fresh groundwater is due to the compounding effects of lower rainfall and reduced recharge capacity, which intensify saltwater intrusion into the aquifer system. Under the combined climate change and sea-level rise (0.5 m) scenario, projected freshwater withdrawal drops to 63 mgd from the current pumping rate of 117 mgd, reflecting a 46% decline. Compared to accounting only for climate-driven reductions in recharge, the inclusion of sea-level rise leads to a much sharper decline in freshwater availability. The inclusion of suboptimal land-use management combined with climate change and sea-level rise results in a 48% reduction in projected fresh groundwater compared to current withdrawal levels. This indicates that, compared to the scenario with climate change and sea-level rise, the addition of suboptimal land-use practices resulted in a slight further decline of 2% in fresh groundwater availability.

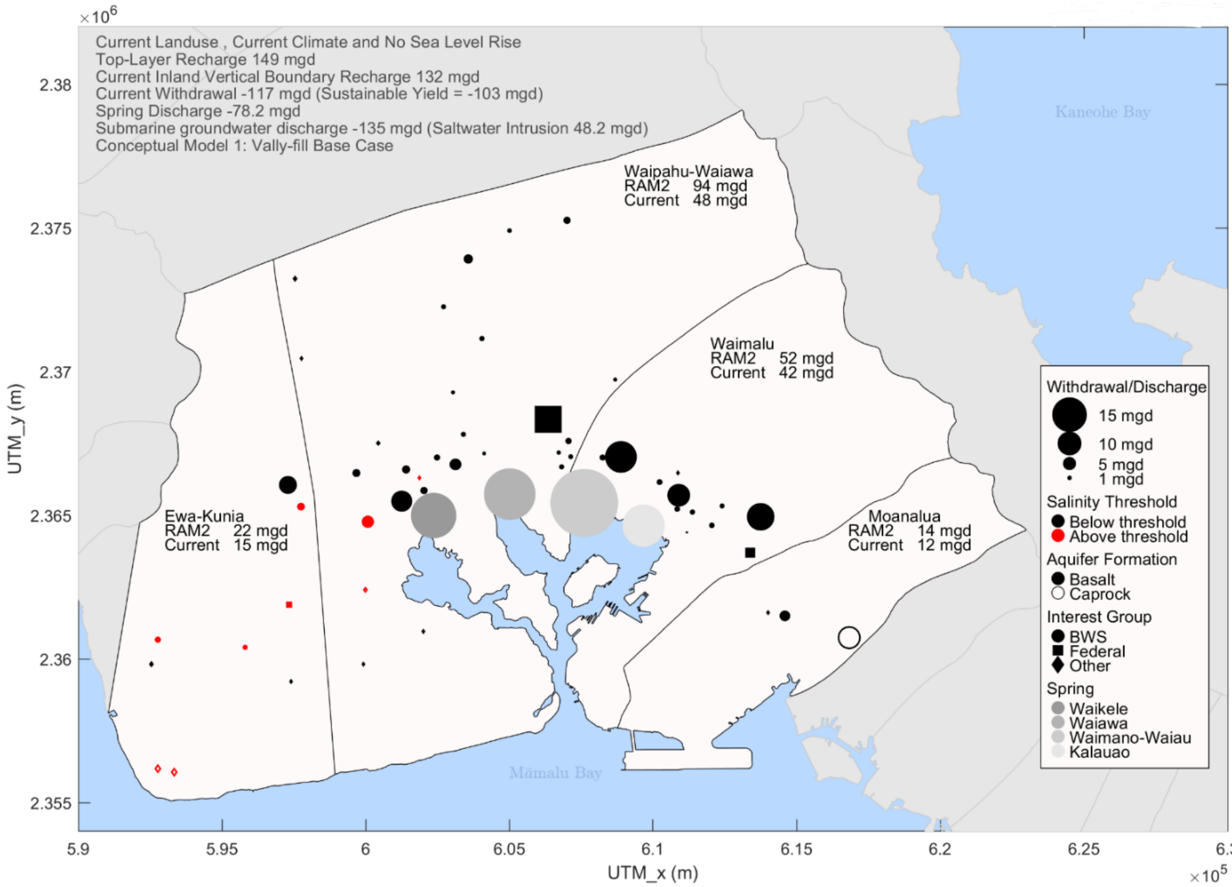

Fig. 6. Future projected fresh groundwater with the current land use, climate, and withdrawal trend.

4.4 Pumping optimization for mitigation

4.4.1. Groundwater accessibility scenarios

The projected fresh groundwater availability under an optimized pumping strategy that constrains spring discharge to current levels is presented in Fig. 7. The maximum withdrawal rate of 127 mgd represents an 8% increase compared to the projection based on current conditions (Fig. 6). This indicates that the optimal pumping schedule can effectively reduce saltwater intrusion, which was the driver behind the 12% decline in the non-optimized fresh groundwater projection.

The optimization code can accommodate various withdrawal schemes to account for different water allocation scenarios that the stakeholder may be interested in evaluating. The V5111 code refers to fixed withdrawal for 27 decision variables, while V5101 refers to withdrawal for 24 decision variables. The user has four digits (e.g., V5111) to assign decision variables. Using the first digit, the user can select a value from 2 to 5 to set pumping wells with current withdrawal greater than or equal to a predefined threshold of 0, 0.01, 0.1, and 1 mgd, respectively, as decision variables. This will result in 92, 72, 55 and 27 decision variables, respectively. Setting the first digit to 2, 3 or 4 is not currently recommended as discussed below, and the current default value for the first digit is 5. Using the second to fourth digits, the user can choose to include or exclude the BWS wells, federal wells and other wells. For example, the code V5111 will select pumping wells with current withdrawal greater than or equal to 1 mgd, including BWS wells, federal wells and other wells, resulting in 27 decision variables. In this case, all pumping wells with current withdrawal less than 1 mgd will be fixed at their current withdrawal. The code V5101, on the other hand, will select pumping wells with current withdrawal above 1 mgd, including BWS wells and other wells, but excluding federal wells, resulting in 24 decision variables. In this case, all federal wells, and all pumping wells with current withdrawal less than 1 mgd are fixed at their current withdrawal.

We evaluated two withdrawal schemes, V5111 and V5101, to understand the impact of including and excluding federal wells as shown in the supplementary material (Elshall and Gebremedhin, 2025). For the withdrawal scheme V5111, the maximum allowable withdrawal is 127 mgd. As noted above, the optimal solution for withdrawal schemes V5111 has 27 decision variables (22 BWS wells, 3 federal wells and 2 other wells), while other wells are fixed at their current withdrawal. Wells with withdrawal less than 0.1 mgd are not shown. The RAM2 estimated withdrawal (RAM2), current withdrawal (current), and simulation optimization maximum withdrawal (optimum) are shown for each administrative unit. Note that the sustainable yield (SY) value is defined as the maximum allowable extracted water that does not exceed the salinity threshold. Submarine groundwater discharge (SGD) and saltwater intrusion refer to outflow and inflow at the coastal boundary, respectively. For all of the aquifer administrative units, the estimated maximum allowable withdrawal is greater than or equal to current withdrawal. However, for withdrawal scheme V5101 that does not include federal wells as decision variables, the maximum allowable withdrawal is reduced to 124 mgd. The inclusion of the Navy wells provided added flexibility of 2.4% in optimized groundwater withdrawal. The impact of increasing the number of decision variables on sustainable yield needs further investigation. Increasing the number of pumping wells to be included in the optimization will increase the degrees of freedom, and thus may result in higher maximum allowable withdrawal, although it will simultaneously increase computational costs.

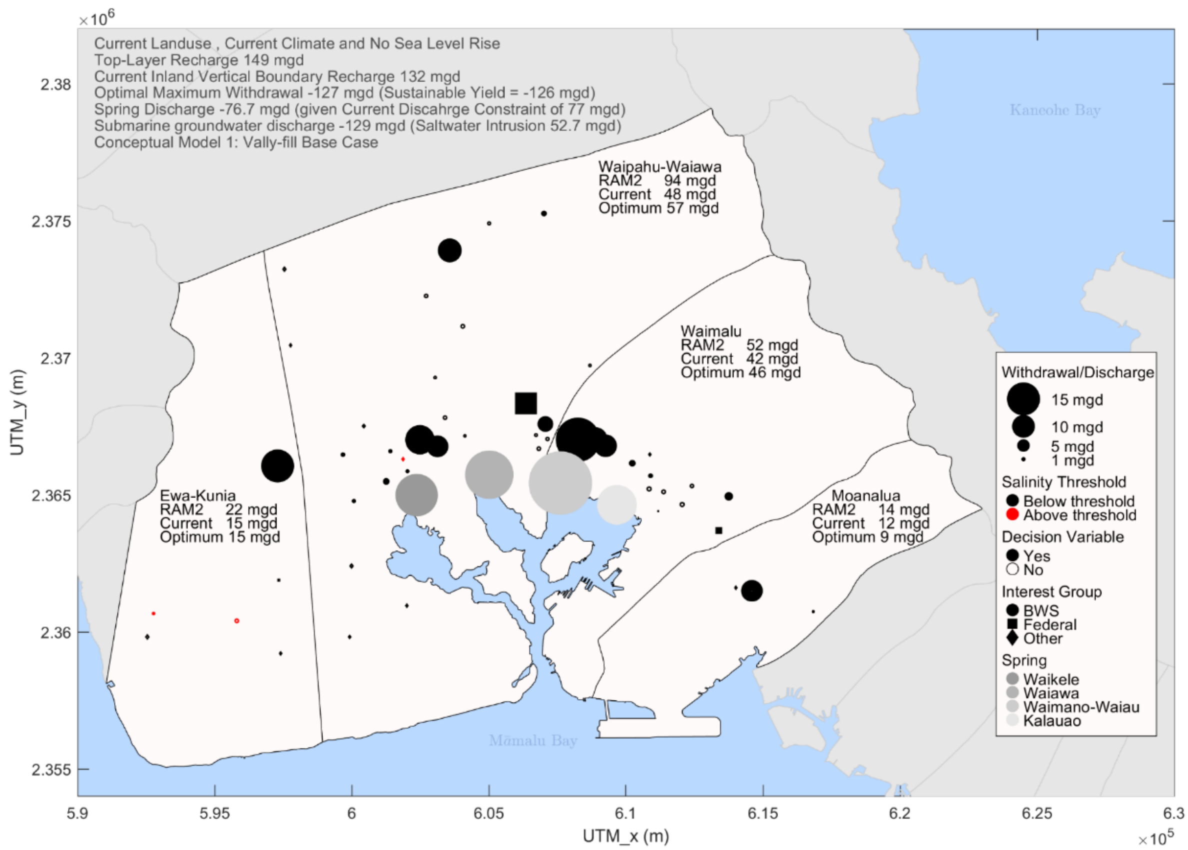

Fig. 7. Projected groundwater availability under an optimized pumping strategy that constrains spring discharge to current levels

4.4.2 Pumping optimization for climate impact mitigation

Under RCP 8.5 midcentury rainfall, groundwater recharge is expected to decline by around 16% compared with baseline rainfall conditions, with the most pronounced reductions in high-elevation forested areas (Bremer et al., 2021). Sustainable yield is also projected to decline, which indicates the combined effect of decreased recharge and increasingly binding salinity constraints on pumping capacity. Under the future climate scenario with optimized groundwater pumping, projected freshwater availability is 2% lower than the current withdrawal rate, as shown in the supplementary material (Elshall and Gebremedhin, 2025). This indicates that the optimization schedule improves freshwater availability by 24% compared to the non-optimized condition. We also evaluated the combined impact of climate change and sea level rise to understand how the optimal solution changes under the current land use. The projected freshwater availability under this combined impact with optimized groundwater pumping is presented in Fig. 8. In this scenario, the projected fresh groundwater experiences only a 15% decline compared to current withdrawal levels, which is a 31% improvement over the same conditions without any optimization (Fig.

6). These results highlight the effectiveness of pumping optimization in reducing the impacts of decreased recharge and increased saltwater intrusion.

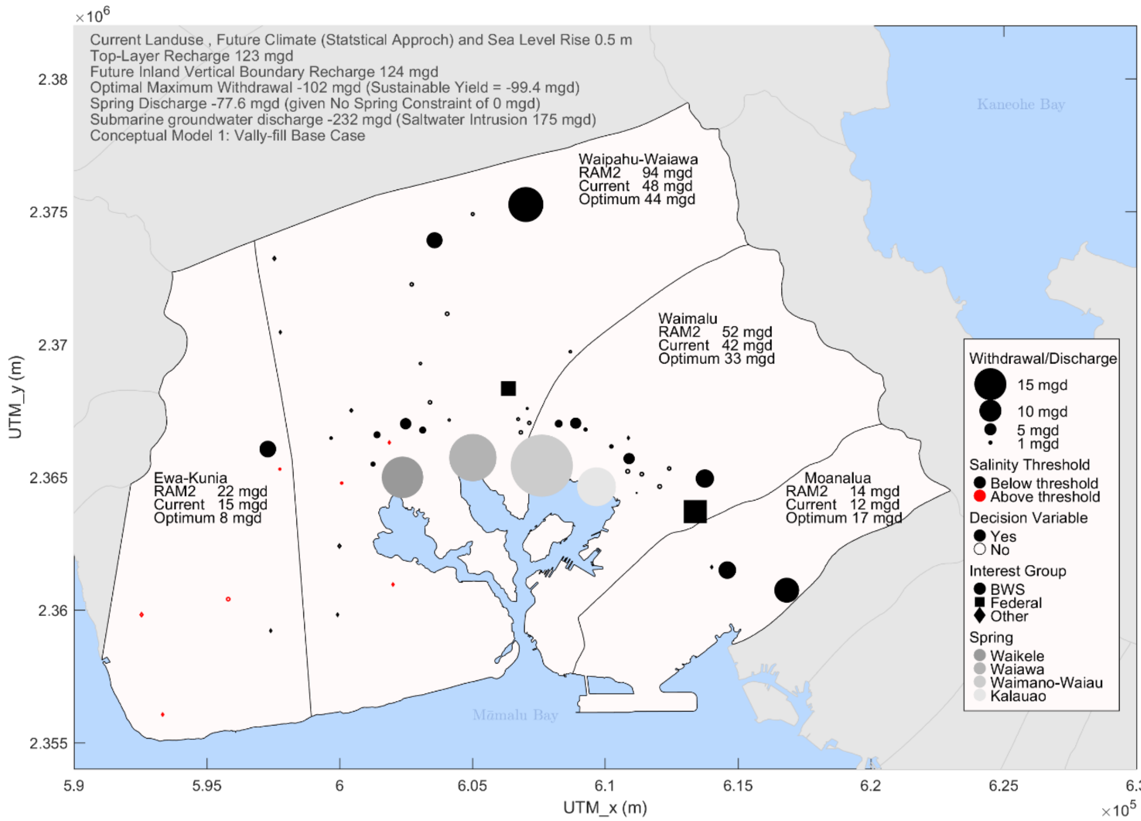

Fig. 8. Optimized future fresh groundwater given expected climate change impacts on recharge and sea-level rise

4.5. Mitigation with nature-based solutions and best management practices

Land-use and watershed management practices play a crucial role in shaping groundwater sustainable yield, particularly under projected climate change stressors. Land cover change can influence recharge and sustainable yield, though is likely a less significant driver of groundwater recharge than climate change in the study area (Bremer et al., 2021). High forest protection can, however, substantially mitigate climate impacts and improve groundwater yield, as presented in Fig. 9. While the difference in groundwater yield between corridor and sprawl development scenarios is modest in terms of pumping volume, sprawl development introduces more negative socio-environmental consequences, including habitat fragmentation, water and air pollution, increased infrastructure costs, inequality, and social homogeneity. Scenario b in Fig. 9 (corridor development with high forest protection) shows a notable increase of 32 mgd in total pumping capacity compared to scenario a (current conditions)Fig. 9, indicating the hydrologic value of nature-based solutions. With optimization alone, 22 mgd more than current withdrawal can be sustainably pumped, but incorporating forest protection allows for an additional 11 mgd, highlighting the synergistic benefits of combining pumping strategies with watershed restoration. These results affirm that nature-based solutions like forest protection are a cost-effective and scientifically supported strategy to enhance climate resilience in groundwater management.

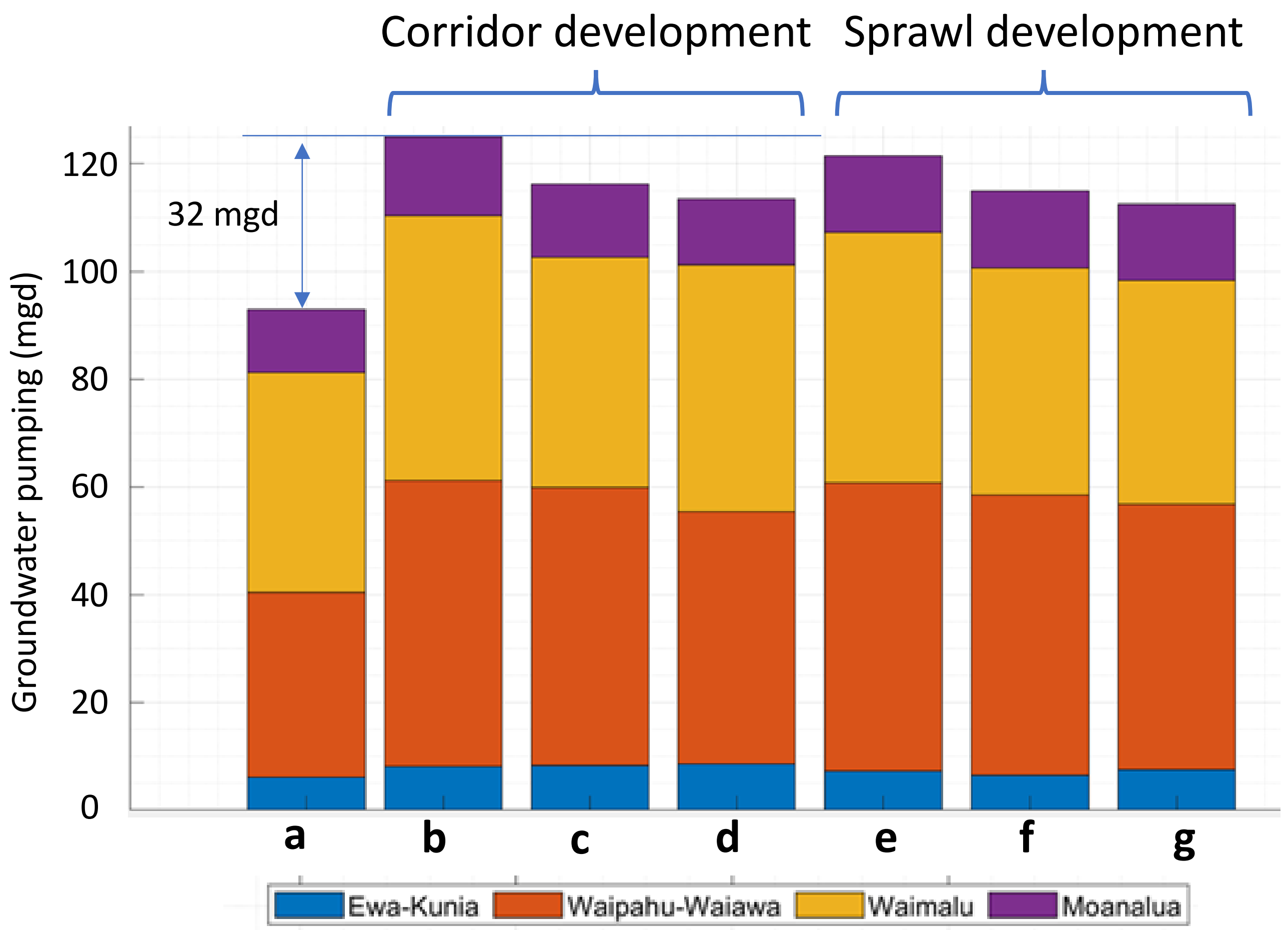

Fig. 9. Projected groundwater pumping under six land-use and watershed management scenarios, combining two development patterns and three forest protection levels: (b–d) Corridor development with high, targeted, and no forest protection; (e–g) Sprawl development with high, targeted, and no forest protection. (a) represents the current condition.

4.6 Societal preferences: Trade-off between spring discharge and pumping

Spring discharge and submarine groundwater discharge are important aquifer performance factors when evaluating sustainable yield (El-Kadi et al., 2014; Hugman et al. 2015 2017; Post et al., 2018; Stigter et al., 2009). Constraining spring discharge in Pearl Harbor is needed to account for environmental water for groundwater dependent ecosystems, for watercress and other crop cultivation, and for other industrial activities (Oki, 2005). Human activities in this area can be associated with strong relational values that emphasize cultural identity and responsibility. Accordingly, one of the main aims for including spring constraints is to analyze the sustainable yield policy application in Hawaiʻi with relational values in mind.

Rather than merely managing for economic development, the analysis focuses on Pearl Harbor spring discharge, which is important for cultural and ecosystem uses.

Defining a spring discharge threshold to simultaneously meet groundwater dependent ecosystems and human activities demands is not a straightforward task. Unlike a salinity threshold for drinking water, there is no obvious threshold for spring discharge volume and salinity. Accordingly, the objective of this module is to understand how maintaining different levels of spring discharge to meet the aforementioned demands would reduce groundwater withdrawal. To this end, we can set the spring discharge threshold as a fraction of the pre-development spring discharge. To estimate the pre-development spring discharge, we used the Pearl Harbor model 1880-2000. The Pearl Harbor springs are inland near the margin of the caprock, discharging from areas where volcanic rocks are exposed as diffuse seeps where the caprock is thin (Oki, 2005). The discharge from the Pearl Harbor springs is directly dependent on the head in the aquifer such that the discharge is high when head in the aquifer is high, and discharge is low when head in the aquifer is low (Oki, 1998; 2005).

The spring discharge can be constrained to a user defined threshold. This threshold can be set to no spring constraint, current spring discharge, user-defined fraction from pre-development spring discharge, or pre-development spring discharge. We conducted six simulation optimization runs with different spring thresholds of 40%, 56%, 60%, 80%, and 100% of pre-development discharge, and compared the results to the case of no spring constraint. Note that the threshold of 56% is the current spring discharge. When the spring constraint is set to 100% of pre-development spring discharge (i.e. 137 mgd), the optimization cannot reach that limit. The maximum spring discharge achievable is 84% of pre-development discharge (i.e. 115 mgd). The optimization cannot achieve 100% pre-development discharge for at least two reasons. First, our decision variables are only 27 pumping wells and the remaining 65 pumping wells are fixed. The total withdrawal of these fixed pumping wells is 15.32 mgd. Thus, the optimization cannot turn off these wells as they are not decision variables. Second, even if we turned off these pumping well, achieving 100% pre-development discharge may not be even possible due to a deficit of 29 mgd between the pre-development recharge (307 mgd) and the current recharge (278 mgd). Note that the estimated recharge in 1880 is 307 mgd, including 175 mgd of top-recharge and 132 mgd of in-land vertical boundary recharge; the estimated current recharge is 278 mgd, including 146 mgd of top-recharge and 132 mgd of in-land vertical boundary recharge.

The simulation optimization results given the spring constraint are shown in Fig. 10. Optimal maximum withdrawal decreases with increasing the spring discharge. Constraining the spring discharge to current discharge reduces the optimal maximum withdrawal from 155 mgd to 121 mgd. Fig. 10 also demonstrates the correlation between submarine groundwater discharge and spring discharge; increasing spring discharge by reducing withdrawal will result in higher submarine groundwater discharge as well. In summary, this simulation optimization tool can provide decision makers in Hawaiʻi with the trade-offs between sustainable groundwater withdrawal for economic development and maintaining different levels of spring discharge for providing ecosystem services and reinforcing relational values.

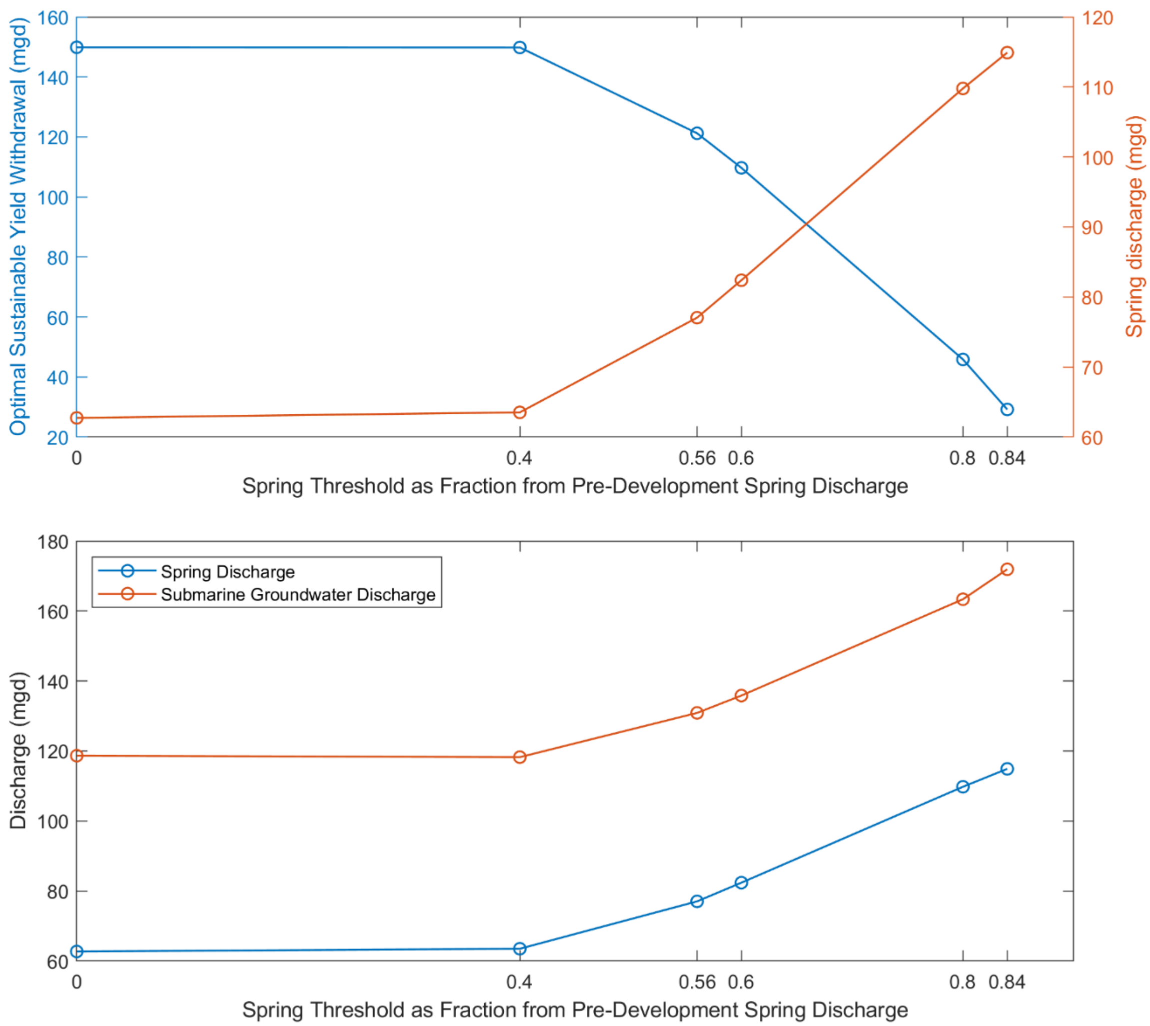

Fig. 10. Maximum allowable withdrawal, spring discharge and submarine groundwater discharge for 6 simulation optimization runs with different spring thresholds of 0, 40%, 56%, 60%, 80%, and 84%, respectively, from pre-development recharge. Threshold 0 refers to no spring discharge constraint. Threshold of 56% is the current spring discharge. Threshold of 84% is upper limit that the optimization can achieve.

More than 100 simulation-optimization runs were conducted across various scenarios to assess sustainable groundwater yield. The main scenarios include: The simulation–optimization framework was applied under four. First, it compared current groundwater withdrawals with optimized withdrawal strategies under the same climate and land use conditions. Second, it evaluated the influence of climate change by incorporating its impacts on recharge processes and sea level rise relative to a base case. Third, it examined the potential benefits of improved land management practices that enhance recharge. Finally, it accounted for environmental flow requirements by including spring discharge and submarine groundwater discharge, which are critical for sustaining groundwater-dependent ecosystems and human activities. The framework for evaluating sustainable yield that accounts for hydrologic, environmental, and socioeconomic consequences provides several insights for academic researchers, water regulators, and water managers in Hawaiʻi and other coastal regions. Detailed optimization results for all scenarios are provided in the supplementary material (Elshall and Gebremedhin, 2025).

Conclusions

This study introduces a novel stakeholder-informed simulation optimization framework for evaluating groundwater sustainability in complex coastal aquifer systems. By integrating advanced numerical hydrologic modeling, state-of-the-art optimization algorithms, and collaborative modeling processes, the framework offers a powerful, flexible tool for sustainable groundwater management. The methodological approach lies in operationalizing the concept of groundwater sustainability through a dynamically coupled platform that incorporates hydrogeologic processes, environmental thresholds, and policy-driven objectives. The integration of a three-dimensional, density-dependent groundwater model with climate-informed recharge estimates and optimization enables evaluation of trade-offs among competing goals such as maximizing water supply, maintaining ecological flow, and mitigating salinization risk.

A key strength of the approach is the active engagement of stakeholders throughout the modeling lifecycle, which enhances both model relevance and institutional acceptance. Stakeholder input informs the selection of decision variables, performance metrics, and scenario priorities, thereby aligning scientific outputs with regulatory mandates, community values, and operational constraints. In contrast to traditional analytical or lumped models, this framework accommodates spatial heterogeneity that is essential for sustainability assessments. Results demonstrate that relying solely on static or oversimplified methods may significantly overestimate sustainable groundwater yield, potentially undermining ecosystem services and long-term water security.

Moreover, the framework enables explicit evaluation of future scenarios, including those driven by climate change, land management, and socio-economic factors. It highlights the importance of incorporating uncertainty, intergenerational trade-offs, and nature-based solutions into groundwater governance. This approach not only advances methodological rigor but also supports informed decision-making and policy development. Therefore, it can be adapted to diverse hydrogeologic and institutional contexts, making it a valuable tool for advancing groundwater sustainability goals globally.

Acknowledgement:

You can acknowledge our NSF C2H2 projects, because we can use the method presented in the paper for our C2H2 project. I leave the decision to you.

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