Highlights

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- Stakeholders envision fundamentally different futures for water and agriculture in the San Joaquin Valley.
- Modelling shows that scenarios with state oversight and community engagement improve resilience.
- Changes in water governance are needed to address rural communities' and small growers' vulnerability to perturbations.

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Abstract

Broad transformations in natural resource governance are needed to address environmental change and inequities. Current human-water systems models fall short in their ability to explore such transformations by overlooking changes to infrastructure and institutions and how they impact power dynamics and vulnerability among water users. Here, we introduce a complex systems approach to examine the viability of different transformation narratives for California's San Joaquin Valley, and their implications for the power and vulnerability of different groups. Using interviews and focus groups with growers, advocacy groups, and rural residents, we develop and model governance scenarios based on these narratives. While most scenarios maintain or exacerbate existing disparities, we find a path towards equitable water governance involving a shift towards greater state oversight and community engagement in governance, and smaller-scale agriculture with more direct benefits to rural communities.

Keywords: sustainability transformations, water governance, complex adaptive systems, transformation narratives, participatory modeling

1. Introduction

Sustainable, resilient, and equitable management of our most critical natural resources will require fundamental changes in the economic, social, and political interactions that mediate our relationships with these resources – in short, sustainability transformations (Haberl et al., 2011; Pelling, 2010; O'Brien, 2012). Water and agricultural systems exemplify this need, with crises such as droughts, overdrawn aquifers and rivers, and disparities in drinking water access, sparking efforts to change entrenched water governance and infrastructure systems to be more equitable and sustainable (Savelli et al., 2023; Rusca et al., 2023b). However, existing models of human-water systems typically fall short in their ability to explore sustainability transformations in two main ways. First, the scenarios modeled are typically limited to parametric changes in climate, hydrology, management practices and infrastructure, and technologies, neglecting the structural economic and socio-political changes that characterize transformations (Rusca et al., 2023a; Fletcher et al., 2022). Second, they fail to consider how such changes impact not only hydrologic variables or water supply objectives, but also the power and vulnerability of different groups to hydrologic and socio-political shocks.

This study addresses these challenges by combining an analysis of different narratives of water governance transformation with complex systems modeling. Central to this approach is an understanding of governance as a complex system, in which interactions among actors produce emergent outcomes - such as equity or sustainability - that cannot be reduced to the sum of individual actions (Berardo and Lubell, 2019; Lubell and Morrison, 2021; Thiel et al., 2019). The interactive processes through which diverse actors negotiate reforms are often studied through a deliberative democracy approach emphasizing participatory forums and systems of deliberation (Habermas, 2015; Pigmans et al., 2019; Brandeler et al., 2014). While this study does not focus on deliberative processes directly, it complements such perspectives by placing these processes in context of the broader structural conditions, such as existing water flows, infrastructure, and institutional arrangements, that shape both the possibilities and limits of deliberation (Dryzek and Pickering, 2017). To capture these structural dynamics, we draw on complex systems modeling, which offers a formalized way of understanding how multiple processes interact in shaping transformations. Transformations are conceptualized here as discontinuous shifts from one equilibrium, or set of self-reinforcing processes, to another (Folke et al., 2010; Hölscher et al., 2018). Modeling transitions in this way allows for linking overall dynamics and emergent phenomena to underlying elements and processes. This approach has been used to explore the conditions under which systems undergo regime shifts or tipping points in contexts such as food (Bodirsky et al., 2022; Gordon, 2022), energy (Trutnevyte et al., 2014), transportation systems (Köhler et al., 2009), and urban development (Rusca et al., 2023a, 2024). Complex systems modeling thus offers an approach for exploring substantial changes away from the current equilibrium represented by typical water systems models.

1.1. Narratives of Transformation

Combining complex systems modeling with diverse visions for the future allows for fully realizing their potential for studying transformations. Sustainability transformations are inherently contested, from debates over how systems are understood to disagreements about which goals should be pursued (Leach et al., 2010; Smith et al., 2005; Stirling, 2011, 2015). This study approaches this plurality of visions for the future through narratives, which are storylines connecting facts and experiences in order to make sense of reality (Riessman, 2008; Patterson and Monroe, 1998; Koch et al., 2021). They embed understandings of a system and its dynamics, particularly of social relations and who has the power and responsibility to address a problem, and imply particular ways in which these should change. While not all narratives necessarily entail practically realizable pathways, narratives do play an important role in determining and justifying which pathways are realized (Leach et al., 2010; Ingram et al., 2019). A substantial body of literature recognizes the importance of public deliberation and scrutiny of governance practices and generating new ideas and discourses (Habermas, 2015; Dryzek and Pickering, 2017). Narratives play an important role in shaping these processes, with dominant narratives often "closing down" debate and alternative narratives "opening up" options and possibilities (Stirling, 2011). Modeling the changes implied by different narratives brings assumptions and understandings embedded in narratives to the forefront, allowing us to explore which pathways are realizable, including marginalized ones, and understanding who is served by different narratives by making explicit their consequences for different groups (Williams et al., 2022; Leblond and Trottier, 2017).

1.2. Combining Modeling and Qualitative Data

Modeling systems with numerous actors and institutions, such as the one in this study, requires many assumptions about interactions that are difficult to quantify. Additionally, the process of translating and incorporating qualitative data into quantitative model inputs is inherently fraught and requires grappling with the tension between quantitative methods that have traditionally been posed as objective with qualitative methods that largely reject notions of objectivity (Rusca and Di Baldassarre, 2019). The prevailing approach to participatory modeling emphasizes the importance of understanding models as ultimately subjective and value-laden constructs that reflect the modeler's positionality. Participatory modeling, therefore, does not seek to represent a single consensus "objective" understanding of a system. Rather, best practices to participatory modeling emphasize employing diverse methods, models, scenarios, and participants to embrace plural perspectives and uncertainty (Rusca et al., 2024; Rusca and Di Baldassarre, 2019; Leach et al., 2010) and focusing on qualitative model outputs (Elsawah et al., 2020). To this end, a number of modeling methods have been developed to systematically bridge qualitative data and quantitative models. System dynamics and agent-based models are often used for representing complex social-ecological feedbacks (Naugle et al., 2024) and have been used in participatory modeling processes (Bots and van Daalen, 2008). System dynamics models in particular lend themselves to visual mapping of causal loop diagrams that can then be translated into systems of ordinary differential equations. However, they require numerous assumptions about parameters and functional forms and can be computationally expensive with larger systems. Fuzzy cognitive modeling (FCM) is another common approach that similarly involves stakeholders identifying key factors in the system and drawing links (with perceived strengths/directions) between them (Malek, 2017). The result is a cognitive map that can be analyzed mathematically, simulating how a change propagates through the network. FCMs thus straddle qualitatively expressed relationships and numerical simulation, and have been used in environmental management to incorporate local beliefs into model structure (Salberg et al., 2022). However, FCMs are limited in the types of interactions they can represent, which can be problematic for the types of non-linear interactions characterizing complex systems. Like system dynamics models, they can also be computationally expensive for larger systems, making it difficult to test the implications of model structure assumptions.

Our approach draws on similar methods for using qualitative information to determine model structure, but addresses their shortcomings by using generalized modeling, which reduces the information required to capture qualitative behavior in complex systems (Gross and Feudel, 2006). Generalized modeling is a form of dynamical systems analysis, which focuses on the qualitative analysis of system equilibria, or stable states in which the system experiences no net change unless perturbed by a sufficiently large external force. Typical dynamical systems models typically consist of a small number of variable in order to remain mathematically tractable, limiting their use in more complex empirical contexts. Generalized modeling allows for directly computing system equilibrium behavior based on a conceptualization of the system variables and interactions without specifying functional forms (Gross and Feudel, 2006). It thus allows for an approach to exploratory modeling (Moallemi et al., 2020) that is primarily focused on the *structure* of interactions between different variables - in this case the actors, water resources, and institutions and infrastructure mediating water access - rather than the details of the mathematical formulations. Generalized modeling incorporates a large degree of uncertainty in the specifics of interactions in playing out their implications. This approach is also well-suited to participatory modeling because this type of structural information is intuitive and easier to elicit through visual system mapping exercises (Elsawah et al., 2020).

This study develops and applies this approach to modeling narratives in the context of water and agriculture in California's San Joaquin Valley, a region characterized by high variability in precipitation (Swain et al., 2018; Rhoades et al., 2018) and decades of over-extraction of groundwater (Hanak et al., 2019). It has also been shaped by complex and heavily contested institutions and infrastructure, including a fragmented system of state agencies and local water districts determining how to allocate surface water among various interests (Pannu, 2012), and an elaborate system of reservoirs and canals to transport surface water to the Valley (Laćan and Resh, 2016), as well as a history of racial exclusion and unequal development in farmworker communities in the region, leading to high levels of poverty and inequity in water access (Martin and Taylor, 1998; London et al., 2018; Pannu, 2012). Additionally, California's first statewide groundwater legislation, the Sustainable Groundwater Management Act (SGMA), has the potential to reshape the economy of the region if groundwater basins are indeed to achieve sustainability (Hanak et al., 2019, 2023; Ayres et al., 2022). However, recent research on SGMA implementation suggests that it may be poised to perpetuate the exclusion of marginalized rural communities and smaller growers from water management decisions (Dobbin, 2020; Dobbin and Lubell, 2019). The San Joaquin Valley thus exemplifies a context in which considering diverse narratives of transformation is necessary, and in which a complex systems approach is useful in understanding the dynamics of power and vulnerability within a socio-technical system of infrastructure and institutions.

The study consists of three main parts: 1) identifying divergent narratives about the future of water and agriculture in the San Joaquin Valley, 2) using a complex systems model to explore the implications of these different futures for the system's ability to resist perturbations, and 3) exploring the implications for different actors' power and vulnerability in the system and disentangling how these impacts are driven by social and hydrologic drivers.

Methods

Case Study Background

Agriculture in the San Joaquin Valley relies on an elaborate system of water infrastructure designed to store and transport surface water from the Sacramento-San Joaquin Delta and snowpack in the Sierra Nevada Mountains to the arid Valley (Preston, 1981; Reisner, 1987). The allocation of surface water through this system has been heavily contested among agricultural, environmental, and urban interests from the outset regarding which uses of water are most beneficial and who should bear the costs and benefits of this infrastructure. In recent years, for example, the conflict between releasing enough water from the Delta to maintain endangered fish populations and salinity levels and exporting surface water to growers in the San Joaquin Valley has become particularly contentious (Lakoff, 2016; Moyle et al., 2018). The allocation of surface water is negotiated through a combination of individually held water rights and contracts with the state and federal reservoir projects. Growers within irrigation districts typically supplement surface water with until recently largely unregulated groundwater extraction, leading to long-term overdraft and subsidence of the aquifer. This leads to vulnerability for growers outside of irrigation districts, known as "white area" growers, and small rural communities that only have access to groundwater (Pauloo et al., 2020). Thus, while those who could afford to drill deeper wells have had unrestricted groundwater access, rural communities and growers that cannot afford deeper wells, particularly those in areas without surface water access, are particularly vulnerable to the effects of groundwater overdraft and contamination. By directly modeling these asymmetries in access to water, infrastructure, and governance, we can explore their implications for the power and vulnerability of different groups under different visions for the future of water and governance. A full conceptual diagram of the socio-hydrologic processes incorporated in the model can be found in the Supplementary Information (Figures S1 and S2).

Interviews and Model Parameterization

We conducted 25 interviews and 2 focus groups, with a total of 44 participants, from 2020-2022 over Zoom and in person throughout the San Joaquin

Valley. Interviews focused on participants' beliefs about the causes and solutions to water issues, with a focus on the role of governance structures and policies in the issues and solutions. The second part of the interview centers around a mapping exercise that draws heavily on Net-Map, an exercise that has been used to monitor policy interventions, coordinate multi-stakeholder governance, and facilitate community-based projects (Schiffer, 2007).

Interviews are analyzed in two distinct tracks. The first track focused on identifying narratives about water issues and governance, using iterative inductive coding that began concurrently with data collection. This process started with an initially empty codebook that was populated through open coding based on emerging concepts, eventually grouping codes based on their co-occurrence within interviews (Cope, 2010; Dittmer, 2010). These co-occurring codes reflect coherent storylines around the causes and solutions to water issues and forms the basis of the four narratives listed in Table 1. See Supplementary Information for the full codebook and visualizations of the code clusters. These qualitative narratives, combined with publicly available data and analyses of surface and groundwater supplies, are used to parameterize four scenarios for water governance and agriculture in the San Joaquin Valley within the generalized modeling framework described below.

The structure of the model was determined using network conceptualizations from the mapping exercise, and parameterized based on a deductive coding process. These data were aggregated and translated into parameter ranges to model various system realizations (see Supporting Information for codebooks). All qualitative coding took place in Nvivo. These system conceptualizations from interviews and focus groups are aggregated and, combined with qualitative analysis using NVivo, used to parameterize realizations of a governance model. The NVivo codebook for this process and the aggregated system diagrams can be found in the Supplementary Methods.

Modeling Approach

The model consists of two types of state variables (i.e. "stocks"): 1) hydrologic, indicating the quantity of surface water and groundwater, and groundwater quality; 2) the organizational capacity of various types of actors, including water users, which directly impact or are impacted by the hydrologic states; non-government organizations, or private institutions, which are not directly impacted by water levels but still have an interest in the issues, and governmental entities, which have the ability to directly mediate resource users' interactions with the resource. Organizational capacity, hereafter referred to as capacity, broadly refers to a group of actors' ability to act collectively on the system through resources such as volunteer or staff labor, legal, technical, or administrative expertise, funds, or grassroots engagement. It is thus an indication of a group's power based on its internal level of organization, engagement, and resources. This capacity is in turn influenced by actors' interactions with each other.

Between these state variables, the model represents four types of interactions (Figure 1): 1) water flows or interactions, representing water extraction or impacts on water quality by users, 2) inter-actor relationships, such as support or collaboration, that influence the capacity of other actors, 3) interventions in water flows through policies or infrastructure by governmental entities, and 4) interventions in those policies or infrastructure by actors, such as through lobbying and advocacy.

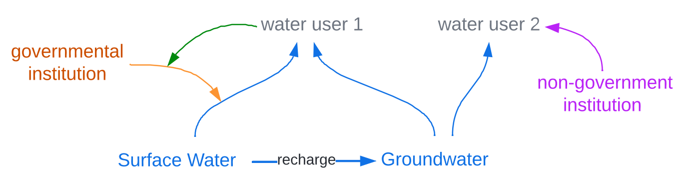
Each of these variables and processes is described in more detail below. The derivation of the model parameters following the generalized modeling approach can be found in the Supplementary Methods.

Water Resources Variables. The model consists of three state variables related to water resources in the Tulare Lake Basin: 1) The aggregate quantity of surface water held in reservoirs that contribute to flow into the Delta and in the major local reservoirs of Pine Flat and Isabella. Even though only a portion of Delta inflows are exported to the San Joaquin Valley, this proportion is mediated by project contracts, environmental regulations, and infrastructure constraints, which are determined by the political processes represented in the model. Therefore, the total amount of water stored in reservoirs is treated as potentially available to the Valley. 2) The quantity of groundwater in the Tulare Lake Basin aquifer, and 3) The quality of groundwater in the Tulare Lake Basin aquifer. The quality of the groundwater is modeled because of its importance as the main source of drinking water for rural communities in the basin.

Surface water is modeled by

$$\dot{R}_1 = S_1(R_1) - \sum_n E_{1,n} - T - L_1(R_1) \tag{1}$$

where S_1 represents net inflow, $E_{1,n}$ the rate of loss from extraction by water user n, T the total rate of recharge from surface water to groundwater, and L_1 the natural loss or outflow. T is thus represented as a loss for surface water and a gain for groundwater. Since extraction is mediated by policies



Interaction	Model Processes	Interaction Between...
1) water flows	extraction (*E*), contamination (*D*), and groundwater recharge (*T*)	water and water users
2) inter-actor relationships	support or undermining other actors ($C^{+/-}$,$P^{+/-}$)	actors or governmental institutions and actors
3) interventions in water flows (through infrastructure/institutions)	technical interventions (**E**), infrastructure or policies on water use (*G*), infrastructure or policies on managed aquifer recharge (*T*)	governmental institutions or non-government institutions and interaction 1 (nested)
4) interventions in infrastructure/institutions	Advocacy/lobbying for or against policies on water use (**G**) or managed aquifer recharge (**T**)	actors and interaction 3 (nested)

Figure 1: Example system representation demonstrating the types of state variables and processes included in the model. The full system is depicted Supplementary Figures S1 and S2. 2.

and infrastructure, $E_{1,n}$ is in turn a function of technical ($\mathbf{E}_{1,k,n}$) and policy interventions ($G_{1,m,n}$) by private and public institutions, which can increase or decrease water users' ability to access surface water:

$$E_{1,n} = E_{1,n}\left(R_1, \left(G_{1,m,n}\right)_{m=1}^{M}, \left(\mathbf{E}_{1,k,n}X_k\right)_{k=1}^{K}\right) \tag{2}$$

where $G_{k,m,n} = G_{k,m,n}\left(X_m, \left(\mathbf{G}_{k,a,m,n}X_a\right)_{a=1}^{A}\right)$, representing how these interventions are themselves functions of the product of actors' organizational capacities (X_a) and the proportion of their effort that they allocate to influencing that intervention (e.g. through lobbying, refusal to comply with regulations, or advocacy) ($\mathbf{G}_{k,a,m,n}$). The notation $(s_k)_{k=1}^{K}$ refers to the sequence $s_1, \ldots, s_K$; for example, $G_{k,m,n}\left(X_m, \left(\mathbf{G}_{k,a,m,n}X_a\right)_{a=1}^{A}\right)$ denotes $G_{k,m,n}\left(X_m, \mathbf{G}_{k,a,m,n}X_1, \ldots, \mathbf{G}_{k,A,m,n}X_A\right)$. Similarly, the rate of recharge is mediated by policies and infrastructure:

$$T = T\left(R_1, \left(H_m\right)_{m=1}^{M}, \left(\mathbf{T}_kX_k\right)_{k=1}^{K}\right) \tag{3}$$

where $H_m = H_m\left(X_m, \left(\mathbf{H}_{a,m}X_a\right)_{a=1}^{A}\right)$, representing how the the policies are influenced by actors through the $\mathbf{H}_{a,m}X_a$ terms.

Therefore, through these multiple levels of nested functions, water availability, the strength of institutions that mediate water users' access to water, and the efforts of resource users' to influence the capacity of these institutions are intertwined.

Groundwater availability is modeled similarly by Equation 4, with the only difference being that the recharge from surface water to groundwater, T, is represented as a gain rather than a loss.

$$\dot{R}_2 = S_2(R_2) + T - \sum_n E_{2,n} - L_2(R_2) \tag{4}$$

Finally, groundwater quality is represented by

$$\dot{R}_3 = \frac{1}{R_2}\left[\sum_n D_n - R_3\left[S_2(R_2) + T\right]\right] \tag{5}$$

where R_3 represents abstractly the aggregate contaminant concentration of the groundwater, rather than any specific contaminant, and $D_n =$

$D_n\left(\left(F_{m,n}\right)_{m=1}^{M}, \left(\mathbf{D}_{k,n}X_k\right)_{k=1}^{K}\right)$. Consistent with representing a concentration, R_3 depends on groundwater quantity such that increases in the groundwater level from natural and managed aquifer recharge, S_2 and T, respectively, decrease the contamination level, and a greater quantity of groundwater mitigates contamination to an extent by diluting contaminants over a greater volume. D_n represents the rate of discharge of contaminants by water user n and similarly to extraction and recharge, is a function of interventions by private and public institutions, which are then subject to interventions by actors.

Actor and Decision Center Organizational Capacity Variables. The organizational capacity of water users, non-government organizations, and decision centers is modeled by Equation 6, where U_t represents their gain and loss in capacity based on their own capacity, representing for example, growth due to recruitment or word of mouth, and loss due to attrition and switching attention to other issues, respectively. $\sum B_{r,n}$ represents user n's gain in capacity motivated by their access to water, aggregated across groundwater, surface water, groundwater quality, representing either actors becoming more agitated due to lack of access, or more invested in ensuring continued water access as their water use, and thus the value associated with it, increases. $\sum_a C_{a,t}$ represents the aggregate gain from collaboration with or support from other actors or loss from being undermined or demobilized by other actors, and $\sum_m P_{m,t}$ represents the aggregate gain or loss in capacity from governmental policies.

$$\begin{aligned}\dot{X}_t = & U_t^+(X_t) + \sum_r B_{r,n}(E_{r,n}) + \sum_a C_{a,t}^+ + \sum_m P_{m,t}^+ \\ & - \sum_a C_{a,t}^- - \sum_m P_{m,t}^- - U_t^-(X_t)\end{aligned} \tag{6}$$

The model is parameterized such that entities whose capacity is not directly influenced by water access, namely non-government organizations and decision centers, do not have a gain based on the resource ($\sum B_{r,n}$ in Equation 6).

Parameterization and Sampling

As described above, the generalized modeling process leads to scale or share parameters which denote the magnitude of fluxes, such as turnover rates or the relative importance of different processes, and exponent parameters, which indicate the sensitivity of a process to another process or variable. These parameters are estimated from hydrologic data and qualitative data from interviews and focus groups. The goal of the parameterization process is to capture the structure of the interactions of the different scenarios - which interactions between actors, or between actors and water resources, exist and the relative strengths of these interactions. Thus, all of the parameters are sampled from uniform distributions (n=1000) to account for uncertainty about the exact magnitude or form of these processes. The different scenario parameterizations focus on *qualitative* differences - turning on or off different interactions, or changing the how important interactions are relative to each other, to represent structural uncertainty.

For parameters related to socio-political processes, scale parameters are derived from statements about how important one process is compared to another (e.g. "X is more important than Y for building farmer capacity"), or from the frequency of a process being mentioned in interviews (e.g. how often gains in actor capacity are attributed to support from another group as opposed to motivated by changes in water access). To account for the inherent uncertainty associated with translating these parameters from qualitative data, they are sampled from uniform distributions with upper and lower bounds of +/- 10 to 20% of the mean. The exponent parameters are parameterized based on statements about the sensitivity of one process to another. For example, one of the types of exponent parameters in the model indicates how much influence actors have on a policy, which are parameterized based on actors' assessments of their participation or influence on that policy. For actors that have little influence on a policy despite their efforts, the exponent parameter indicating how their influence scales with their efforts would be between 0 and 0.5 to indicate a sub-linear relationship between their efforts and the effectiveness of the policy. On the other hand, for actors that are influential, this exponent would be closer to 1 to indicate that their influence on the institution or policy corresponds to their effort. Where there is not enough information for a parameter, a default range of values that encompasses the plausible range of parameters is sampled (usually between 0 and 1 for exponent parameters). For the water resources variables, parameters were computed based on historic hydrologic data on water allocations and groundwater pumping and hydrologic and infrastructure limitations, such as for determining feasible levels of managed aquifer recharge, pumping rates, and capacity for water exports. See Supplementary Material for the codebook used to determine parameters from qualitative data, hydrologic data and calculations, and full parameterization for each scenario.

Computing Stability

Conceptually, local asymptotic stability, hereafter referred to as stability, is an indication of a system's ability to retain its structure and function in the face of local perturbations in the variables controlled by the system (Guckenheimer and Holmes, 1983). In this context, the stability of a scenario indicates its long-term feasibility. Unlike in typical dynamical systems stability analysis, the functions in the equations above are not assigned specific functional forms. Rather, the Jacobian is directly parameterized from these equations, following the approach of Gross et al. (2009). The first step in defining these parameters is normalizing the functions by the unknown steady state. For example, the normalized resource dynamics would be represented by

$$\dot{r}_1 = \frac{S_1^*}{R_1^*}s_1 - \sum_n \frac{E_{1,n}^*}{R_1^*}e_{1,n} - \frac{T^*}{R_1^*}t - \frac{L_1^*}{R_1^*}l_1.$$

where S_1^*, R_1^*, etc. are the values of the corresponding functions or state variables at equilibrium, and s_1, r_1, etc. represent the normalized functions or state variables. The normalization leads to the introduction of unknown factors $\frac{S_1^*}{R_1^*}$, $\frac{E_{1,n}^*}{R_1^*}$, $\frac{T^*}{R_1^*}$, and $\frac{L_1^*}{R_1^*}$. However, these factors are constants and are treated as parameters, namely share parameters. Share parameters denote the magnitude of fluxes, such as turnover rates or the relative importance of different processes. We define $\phi_1 := S_1^*/R_1^* = \sum_n E_{1,n}^*/R_1^*$, which represents the overall turnover rate of the resource, ψ_1, which represents the proportion of surface water outflow that is extracted, $\overline{\psi}_1$, which represents the fraction that is transferred to groundwater, and $\widetilde{\psi}_{1,n}$, which represents the proportion of water extraction that each water user is responsible for. The normalized resource dynamics can then be written as

$$\dot{r} = \phi_1 \left(s_1(r) - \psi_1 \sum_n \widetilde{\psi}_{1,n} e_n(r, g_{1,n}, \ldots, g_{M,n}) - \overline{\psi}_1 t(r_1) - (1 - \psi_1 - \overline{\psi}_1) l_1(r_1) \right).$$

An example of an entry of the Jacobian based on this equation can then be computed as

$$\frac{\partial \dot{r}_1}{\partial r_1} = \phi_1 \left[\frac{\partial s_1}{\partial r_1} - \psi_1 \sum_n \widetilde{\psi}_{1,n} \frac{\partial e_{1,n}}{\partial r_1} - \overline{\psi}_1 \frac{\partial t}{\partial r_1} \right].$$

The derivatives $\dfrac{\partial s_1}{\partial r_1}$ and $\dfrac{\partial e_{1,n}}{\partial r_1}$ are unknowns that are also treated as parameters, namely exponent parameters. These parameters are an indication of the sensitivity of processes to variables, in this case the growth rate and the extraction rate to the resource state, respectively. In general, exponent parameters indicate the non-linearity of a process at equilibrium. Once the Jacobian is parameterized, the stability can be determined by checking whether the real part of all eigenvalues is less than 0. Because stability is binary, the proportion of stable systems across the ensemble of 1000 samples for each scenario is computed. Confidence intervals are computed using binomial confidence intervals.

These parameters collectively provide all of the information needed to compute the stability of the system. Varying the generalized modeling parameters allows for exploring the stability of a wide variety of topological configurations and feedbacks.

Sensitivity and Influence Calculations

In addition to system-level stability, the different structures of institutions and infrastructures explored in the different scenarios also shape actors' influences and vulnerability to change. This is operationalized through the sensitivity and influence metrics. Conceptually, influence represents how impactful an entity is on the rest of the system, while their sensitivity represents how impactful a perturbation in the system is to them. We look at both the aggregated influences and sensitivities - that is the influence over and sensitivity to both other entities and hydrologic variables - and disaggregate them to understand how much the influence and sensitivities stem from hydrologic as opposed to social interactions.

The approach for computing the sensitivity and influence of different system components is introduced in an ecological context by Aufderheide et al. (2013). The sensitivity of entity i, Se_i, is computed as

$$\mathrm{Se_i} = -\sum_k \frac{|v_i^k|}{\lambda_k}$$

where $|v_i^k|$is the absolute value of the entry v_i of the kth right eigenvector and λ_k is the corresponding eigenvalue. Similarly, the influence of entity i is computed as

$$\mathrm{In}_i = -\sum_k \frac{|w_i^k|}{\lambda_k}$$

where $|w_i^k|$is the absolute value of the entry w_i of the kth left eigenvector. This calculation is only meaningful in stable systems, so unstable systems are filtered out before the sensitivity and influence metrics are computed.

The partial sensitivities, $\mathrm{Se}_{i,j}$, or the sensitivity of variable i to variable j, and partial influences, $\mathrm{In}_{i,j}$, or the influence of i on j, are additive, such that the partial sensitivities add up to the total sensitivity, and the partial influences add up to the total influence ($\sum_j \mathrm{Se}_{i,j} = \mathrm{Se}_i$ and $\sum_j \mathrm{In}_{i,j} = \mathrm{In}_i$).

They are also symmetric, such that the sensitivity of variable i to variable j is the same as the influence of j on i ($\mathrm{Se}_{i,j} = \mathrm{In}_{j,i}$).
The partial sensitivity can be calculated from the impact calculation:

$$\mathrm{Se}_{i,j} = |I_{i,j}| = \sum_k |v_i^k| \frac{|w^k \cdot K|}{-\lambda_k}$$

where K is the perturbation unit vector with $K_j = 1$ (representing a perturbation on just variable j). This simplifies to

$$\mathrm{Se}_{i,j} = \sum_k |v_i^k| \frac{|w_j^k|}{-\lambda_k}$$

To make the sensitivity and influence calculations more intuitive, we present a simple example to demonstrate the concept. Consider a system of two ODEs:

$$\dot{x} = -x + y, \tag{7}$$

$$\dot{y} = -2y \tag{8}$$

The Jacobian of this system can be calculated as:

$$J = \begin{bmatrix} -1 & 1 \\ 0 & -2 \end{bmatrix}$$

This yields two eigenvalues, $\lambda_1 = -1, \lambda_2 = -2$. The corresponding right eigenvectors are:

$$\mathbf{v}^{(1)} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

and

$$\mathbf{v}^{(2)} = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

It is clear in this system that x is more sensitive because it is affected by both itself and y, and this can be seen in the right eigenvectors, which govern how the system returns to the steady state after the perturbation. Each pair of left and right and eigenvectors can be considered a dynamical mode, or possible response of the system to a perturbation. The first element of each eigenvector corresponds to x's response to a perturbation, which we can see has a magnitude of 1 in both eigenvectors ($\mathbf{v}_1^{(1)}$ and $\mathbf{v}_1^{(2)}$). The second element corresponds to y's response, which is 0 in the first dynamical mode and 1 in the second ($\mathbf{v}_2^{(1)}$ and $\mathbf{v}_2^{(2)}$). Therefore on average, x will have a greater response to perturbations, making it more sensitive than y. Indeed, using the metrics presented above, the sensitivity of x comes out to $\frac{3}{2}$, whereas y has a sensitivity of 1.

Similarly, we can look at the left eigenvectors:

$$\mathbf{w}^{(1)} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

and

$$\mathbf{w}^{(2)} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

The left eigenvectors characterize the strength of a specific dynamical response when a given element of the system is perturbed. When x is perturbed, for example, there is a response of 1 in the first dynamical mode, but no response in the second. On the other hand, perturbing y impacts the system in both modes ($\mathbf{w}_2^{(1)}$ and $\mathbf{w}_2^{(2)}$). Therefore, on average, perturbing y has a greater impact on the system, making it more influential than x. Calculating the influence metric shows that x has an influence of 1 while y has an influence of $\frac{3}{2}$. Note that the sensitivity of x is equivalent to the influence of y and vice versa. In a system with many two-way interactions (if the change in x and y depended on each other), the sensitivity and influence might be strongly linked and a high sensitivity and influence would reflect that an entity is highly connected. On the other hand, the existence of one-way interactions (such as in the example system where y influences x but not vice versa) makes it possible for these two metrics to be decoupled for a given entity.

The same basic principles apply in the modeled system, with the elements of the system representing different entities and hydrologic variables, as described in the Modeling Approach section. Applied to actors within a governance system, these metrics map directly to how powerful an actor is by virtue of their ability to impact other parts of the system, and how vulnerable they are based on how strongly impacted they are by perturbations to the rest of the system. While in the simple example, it is obvious that y is more influential than x simply from the structure of the differential equations, in a complex real-world context, the metrics help understand how multiple processes - unequal access to public and private infrastructure and differing levels of representation in various governance processes - interact in shaping this influence and sensitivity. In addition, in a system with more than two variables, the ability to calculate partial sensitivities and influences allows for understanding which factors are most influential in shaping the overall power and vulnerability of an actor. In this case, we categorize these factors as social (stemming from interactions with other actors and organizations) and hydrologic (stemming from interactions with water sources) variables. This allows for determining, for example, whether increasing representation in governance processes or raising groundwater levels is more effective in mitigating rural communities' vulnerability.

The influence and sensitivity of each entity is computed for each trial and each scenario. The sensitivities and influences are log-normally distributed and so averages across trials and parametric 95% confidence intervals are computed on the log-transformed values.

Results

Divergent Narratives for the Future of Water and Agriculture in the San Joaquin Valley

The following section and Table 1 describes each narrative and corresponding scenario for water governance and agriculture. The baseline scenario is parameterized based on current interactions and policies at the time of interviews.

Narrative	Changes to Model from Baseline

Regulatory Drought	• Increased access to surface water for all growers, including those previously lacking surface water access • Reduced sensitivity of grower water use to groundwater levels and to regulatory institutions • Growers support state water governance entities rather than oppose them • Increased groundwater recharge from surface water
Physical Availability and Quality of Water	• Increased share of surface water loss and groundwater gain from managed aquifer recharge • Introduce Groundwater Sustainability Agencies (GSAs) as an entity; add support for GSAs from state agencies, environmental justice groups, grower advocacy groups, and large growers • Reduced grower opposition to state agencies • Reduced sensitivity of rural community water access to groundwater levels • Increased share of support for local agencies from statewide agencies and vice versa

Lack of Oversight and Regulation	• Greater sensitivity of growers' impact on groundwater to state groundwater regulations • Increase proportion of opposition to state groundwater regulations from large growers • reduced sensitivity of rural community and growers' access to groundwater to groundwater levels • Increase support for small growers, grower advocacy groups, rural communities, and environmental justice groups from state • Increase support for state groundwater regulation by small growers, rural communities, and environmental justice groups
Exploitative Nature of Agriculture	• Equalized surface water and groundwater extraction and groundwater quality impact by small and large growers • Reduced turnover in small growers • Reduced sensitivity of local agencies to large growers' efforts • Increase share of rural community support from small growers and share of small grower support from rural communities

Table 1: Narrative descriptions and parameterizations

1. **Regulatory Drought:** A common narrative among larger growers and representatives of agricultural organizations, the regulatory drought narrative focuses on lack of water access as primarily a regulatory issue rather than a hydrologic or climatic one. It centers primarily on surface water supply – though water quality regulations are framed as an unfair burden as well – and the conflict between growers and the state, which is seen as aligned with environmentalists, that determines environmental flow requirements in the Delta and blocks the construction of new dams. Solutions in this narrative focus on increasing access to surface water by reducing environmental restrictions in the Delta

and building additional surface water reservoirs, and emphasizing local control and autonomy in water governance.

2. **Physical Availability and Quality of Water:** This narrative focuses on the physical availability of water as a result of California' natural aridity and climate change, and thus focuses on developing technical solutions to water scarcity and quality issues. In terms of governance, this narrative focuses on developing the institutional infrastructure for supporting technical innovation and improved on-farm management practices, including greater collaboration among agencies and establishment of local groundwater management entities.
3. **Lack of Oversight and Regulation:** This narrative focuses on groundwater overdraft and contamination as resulting from lack of oversight and regulation at the state level. The state is presented as a potential counter to the power of grower-dominated local agencies in protecting the interests of smaller growers and rural communities. This narrative thus emphasizes stronger regulations and the state taking a more active role in ensuring engagement of marginalized groups in decision-making.
4. **Exploitative Nature of Agriculture:** This narrative focuses on the nature of the agricultural industry itself in terms of its relationship with the rural communities in which farmworkers live. By emphasizing delivering greater benefits to the communities that provide agricultural labor and longer term resilience to environmental shocks, this narrative implies more dramatic changes to agricultural practices than those of the second scenario, such as dryland farming and reduced reliance on imported water, improved labor practices, and more favorable policies for smaller growers. The scenario based on this narrative incorporates state-level groundwater management and stronger regulations similar to the previous scenario, as well as broader changes to the distribution of water and political influence among growers.

Stabilizing Effect of Strong State Oversight and Rural Community Engagement

The stability of the different potential equilibria gives insight into their long-term feasibility as transition outcomes. Scenarios in which a greater proportion of system realizations are stable suggest that such a system configuration can withstand local perturbations whereas unstable systems cannot, making them unlikely to be maintained or even realized. As revealed by Figure 2, the first two scenarios are not different from the baseline in terms of stability, whereas the second two are significantly more stable. This suggests that the increased state oversight and transformed agriculture scenarios, once reached, are system configurations that are more likely to maintain themselves. These two scenarios share strong state oversight and enforcement of water regulations, in contrast to those being delegated to local-level agencies in the other scenarios, additional state assistance to rural communities and small growers, and greater involvement of rural communities and small growers in governance while reducing the influence of larger growers. Thus, the greater stability of these scenarios likely stems from greater centralization of governance at the state level as well as the presence of countervailing forces to balance the influence of large growers. While stability itself is not necessarily inherently desirable, these aspects of the scenarios do have normative implications, which are explored in greater detail in the next section.

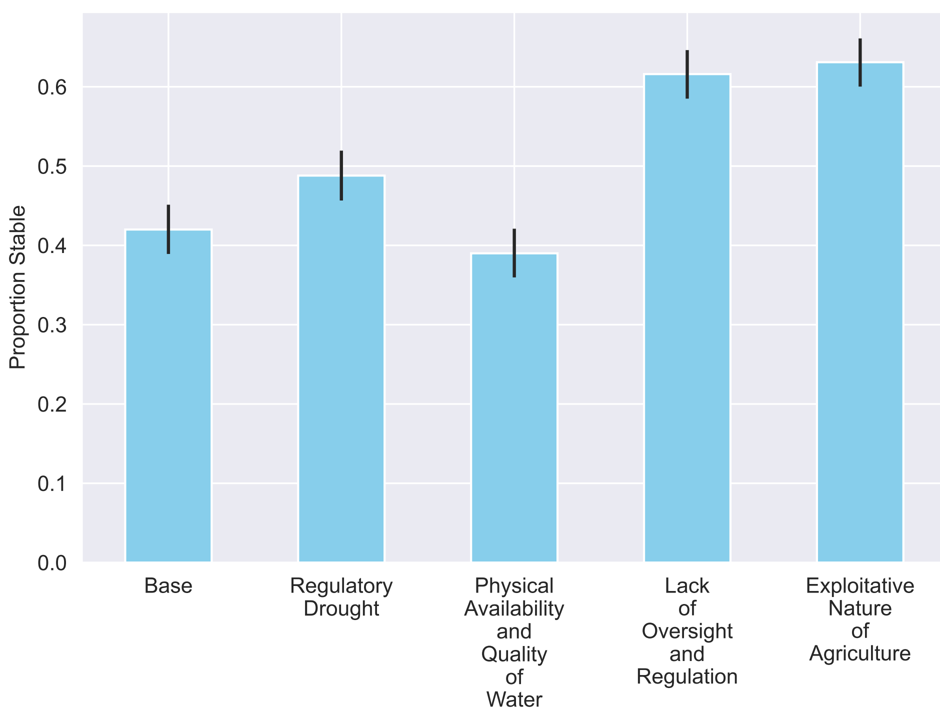


Figure 2: Proportion of stable systems (out of an ensemble of 1000) for each scenario. Error bars indicate 95% confidence intervals.

Actors' Power and Vulnerability Under Different Scenarios

In addition to the understanding the implications of the narratives for system-level responses to perturbations, we want to understand disaggregated impacts for different actors. We do so through the influence and sensitivity metrics. As demonstrated in the Methods section, the advantage of this approach is that the metrics are derived directly from the structure of the system dynamics and have clear implications for the power and vulnerability of different actors. However, some interpretation is needed to understand the equity implications of these metrics. Equity issues arise when there is a disproportionate relationship between influence and vulnerability, such as when an actor who is more vulnerable to changes in water access also has little say in water governance. However, this relies on the assumption of some commensurability between the sensitivities of different groups, which clearly does not hold in some cases. For instance, the sensitivity associated with large growers' profits from water use does not equate to the sensitivity of rural communities, who depend on their wells for drinking water. Similarly, small growers' sensitivity is an indicator of their capacity to maintain their livelihood whereas for investor growers, for example, agriculture may be a part of a larger investment portfolio and they can shift assets in response to changes in water availability. Given these differences in the meanings of the sensitivity metric for different water users, it may be justifiable for groups for which sensitivity is tied to their livelihood or drinking water access to have a greater influence relative to their sensitivity.

Figures 3 show the effects of each narrative on the total sensitivity and influence among water users, while Figure 4 disaggregates the changes in sensitivity and influence from the baseline stemming from hydrologic factors, such as the redistribution of water among different entities or increasing water imports, versus social factors, such as the creation of new regulatory bodies.

The results reveal that the baseline scenario already embeds disparities in power and vulnerability. Small growers, for example, are as sensitive as their larger counterparts, but much less influential, likely reflecting their reliance on the same water sources but with shallower wells and lower pumping capacities, and less representation in irrigation and water districts. Thus, despite consuming less water, small growers are as sensitive as larger growers to changes in hydrologic conditions and to the impacts of regulations, but have far less influence in water governance. Rural communities face a similar disparity and are among the most sensitive, likely because of their reliance on groundwater as their only source of drinking water.

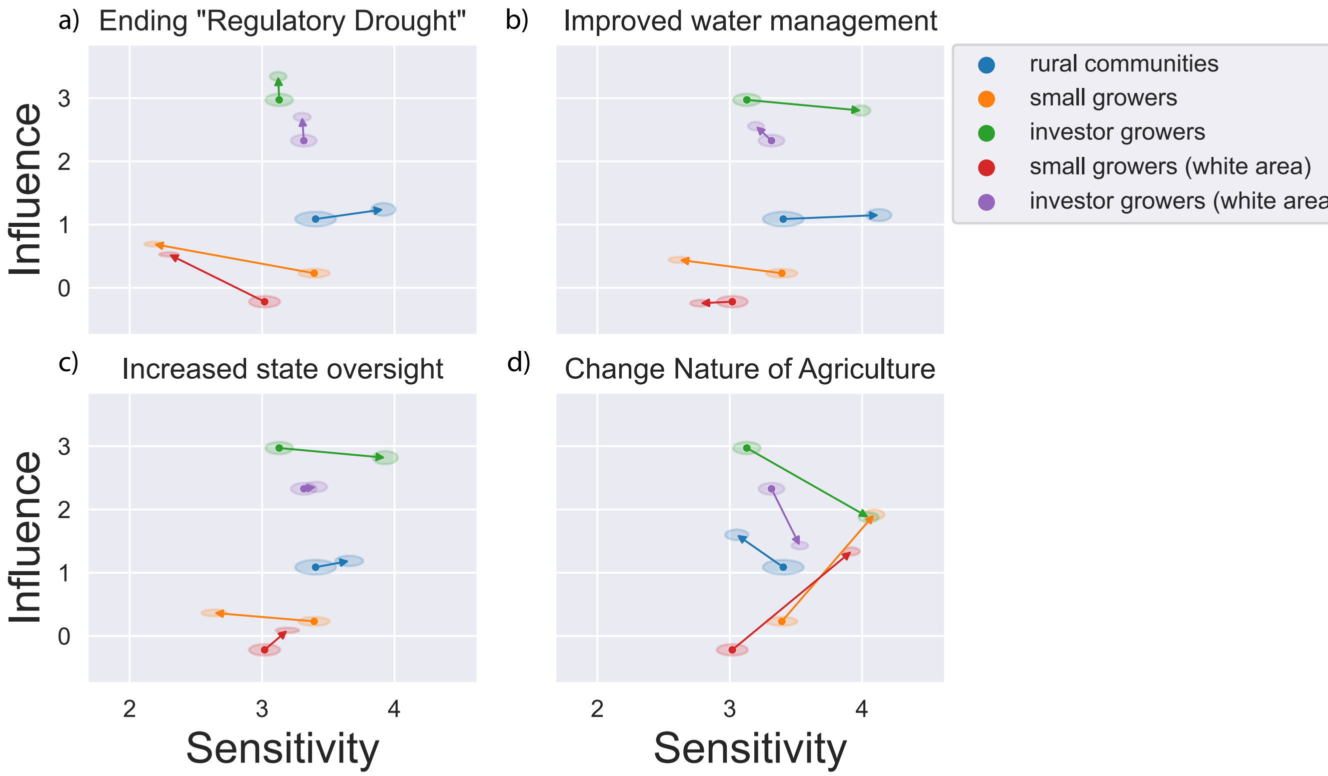


Figure 3: Comparison of each scenario (represented by the arrowhead) with the baseline (the circle). The points represent the average (log-transformed) sensitivity and influence over 1000 samples. The ellipses represent 95% confidence intervals on the sensitivities and influences. “White area” growers are those who rely exclusively on groundwater.

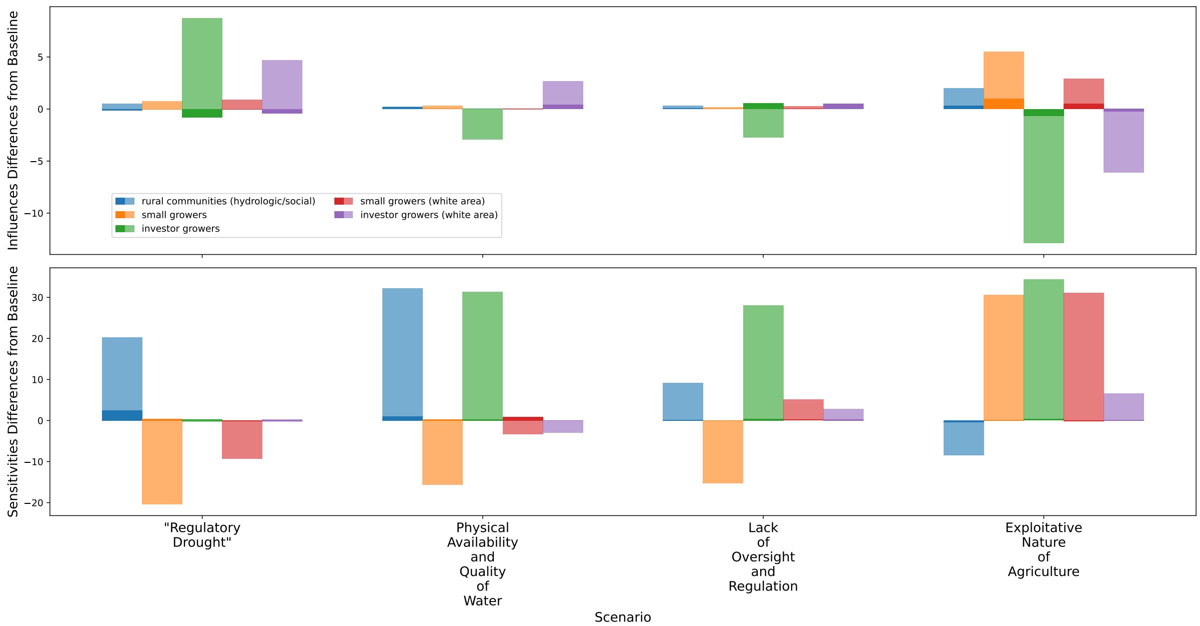


Figure 4: Change in influences (a) and sensitivities (b) from base scenario, broken down by contributions from water (darker color bar), and from social interactions (lighter color).

In the first scenario, Figure 3a indicates that additional surface water actually exacerbates existing inequities in some ways, reducing small growers' sensitivity but raising that of rural communities while increasing growers' influence. Disaggregating the impacts (Figure 4a) reveals that growers' direct influence over water declines, likely because they are now relying more heavily on public infrastructure for surface water conveyance rather than private wells. However, this is more than compensated for by their increased influence over entities governing surface water distribution. Small growers, especially those who gain surface water access in this scenario, are the biggest winners, experiencing a significant decrease to their sensitivity because they rely less on groundwater, where they are at a disadvantage to larger growers in terms of pumping capacity, and an increase in their influence as well. Rural communities, on the other hand, who do not gain access to surface water in this narrative, and actually see their sensitivity increase without a corresponding gain in influence. This suggests that whatever benefits they gain through increased groundwater access because of reduced extraction by growers is of limited benefit in addressing their overall sensitivity and influence. The results of this scenario reveal that despite the narrative that ending the "regulatory drought" and increasing the surface water supplied to the Valley is a win for everyone, it mainly benefits growers, even without taking into account that the water is not in fact "free" and incurs costs to water uses in the Sacramento-San Joaquin Delta, which is not included in the model.

In the second scenario (Figure 3b), local groundwater management increases the sensitivity of large growers due to stronger regulations. The opposite is true for small growers, especially small growers without surface water access, who become more sensitive to the hydrologic variables, but which is counteracted by their decreased sensitivity to other actors and institutions. Rural communities see sensitivity rise due to expanded institutional constraints on groundwater access, with no major changes in influence, consistent with concerns that SGMA presents incremental improvements rather than fundamental power shifts (Dobbin, 2020; Dobbin and Lubell, 2019).

The third scenario (Figure 3c), state oversight and control of groundwater management, has some similar effects as the previous scenario, with the exception of less of an increase in rural communities' sensitivity, and a slight increase in the influence of small growers without surface water access. Since (b) and (c) mainly differ in small growers' and rural communities' engagement in governance, this suggests that representation in decision-making forums is critical for reducing overall vulnerability.

Finally, the last scenario (Figure 3d) equalizes sensitivity and influence among small and large growers due to the redistribution of water resources and power over institutions. The remaining discrepancy in sensitivity between the small and large growers lacking surface water access (white area growers) can be attributed to remaining disparities in sensitivity to changes water levels, such as those resulting from differences in well depths and pump capacities, and differences in turnover rates between small and large growers resulting from higher attrition rates among small growers, as those are the only factors differentiating large and small growers in this scenario. Grower sensitivities increase across the board, reflecting the increased influence of non-grower actors over water governance. However, it also significantly increases the influence of small growers, making this scenario more equitable in terms of actors with greater vulnerability also having greater power. This is also the only scenario that reduces rural communities' sensitivity and increases their influence. This scenario differs from the previous scenario mainly in reallocating water among growers and the beneficial relationship between small growers and rural communities. This reveals that tighter regulations have limited impact in redistributing power as long as large growers have such an outsized impact hydrologically and politically and have a fundamentally exploitative relationship with the rural communities that provide farm labor.

2. Discussion

Overall, these results make explicit the implications of different narratives of water governance - who they benefit, which livelihoods are supported, and who has power over those decisions. For example, despite the idea of "win-win" solutions for growers and rural communities in the regulatory drought and technical solutions narratives, the analysis makes clear that the biggest winners are still large growers. Crucially, this analysis contributes an approach for understanding winners not only in terms of distributions of water, or the proximate dimensions of water access, but also distributions of political access and power, or procedural dimensions, which are often emphasized but rarely formalized in the environmental justice and water governance literature (Zwarteveen et al., 2017; Ranganathan and Balazs, 2015). The value of this is demonstrated in scenarios such as the ending the "regulatory drought" scenario where despite overall increased access to water, rural communities are actually more vulnerable because their water access is more contingent on growers' actions. Additionally, the fact that no two groups are impacted the same in every scenario reveals the importance of considering fundamental asymmetries in the system with regards to water access, such as between growers who have access to surface water and the growers and rural communities that rely entirely on groundwater. They also reveal the intertwined nature of socio-political and hydrologic interactions, with changes to water levels, infrastructure, and policies co-producing power and vulnerability in often non-intuitive ways (Figure 4). This study thus contributes to a hydrosocial conceptualization of water in which control of water flows and political power are tightly intertwined (Rusca and Di Baldassarre, 2019; Damonte, 2019; Hommes et al., 2022; Macpherson et al., 2024).

This analysis also reveals the deep level of change in system structures that are necessary to fundamentally shift who holds power and vulnerability in the system, resonating with political theory perspectives that highlight how entrenched power asymmetries and path-dependent institutions limit the potential of incremental reforms to achieve justice (Stirling, 2015; Barnes et al., 2020). The changes explored in the first three scenarios, for example, while exploring very different water allocation and regulation arrangements produce limited changes in the relative influence of different water users, and even exacerbate disparities in some cases. Broader changes to the nature of agriculture, such as in the fourth scenario in which agriculture is shifted to a smaller scale, is more beneficial to local communities, and is a less dominant force in terms of water use and governance, are required to equalize the influence between small and large growers, and between rural communities and growers. Even still, some disparities remain in their vulnerability due to uneven access to water infrastructure, such as deeper wells, and the social and economic factors that push small growers and farmworkers out of agriculture and decision-making forums. However, this narrative remains fairly marginal, espoused only by a few advocacy groups and rural community residents in very general terms, revealing the discursive power of the current agricultural industry in suggesting that the region relies on agriculture persisting in its current form, limiting the ability to imagine alternatives. However, this analysis reveals that not only are alternative system configurations viable (Figure 2), but necessary to ensure that the future of water and agriculture governance in the Valley does not recreate the same power dynamics as the past.

Finally, despite incorporating stakeholders into the model conceptualization and parameterization, the modeling approach used in this study ultimately involves choices in structure, boundaries and focus that, like all models, reflects in part the modelers' priorities and assumptions. For example, this analysis focuses on differentiated responses to change, with particular concern for equity for the most vulnerable or marginalized groups, rather than assessing what is most economically feasible or optimal, which may not reflect the priorities of all system actors. Additionally, as discussed earlier, model parameterization, even if "fuzzy", involves assumptions and uncertainty about how verbal evidence translates to parameter ranges. However, the width of the confidence intervals resulting from parameter variability compared to the qualitative differences in outcomes between scenarios resulting from structural changes to the model suggest this parametric uncertainty is less consequential than structural uncertainty. Thus, the most important assumptions are about which processes to include and their relative strengths. While we model only four out of many possible scenarios, these scenarios vary enough to identify which processes are most important in shaping outcomes and thus which uncertainties are most important. In this case, the relationship between water levels and water access for different groups (e.g. as shaped by well access or pumping capacity) and turnover rates in actors' engagement and capacity were most influential in shaping vulnerability and power. These parameters were also lacking in quantitative data to serve as a basis for estimates, so we had to rely on qualitative descriptions of these relationships. Ultimately, this study aims to mitigate this structural uncertainty through engagement with the qualitative data not just as model input, incorporating diverse participants and perspectives, and focusing on interpretation of the substantive qualitative insights from the model results rather than on definitive prediction.

3. Conclusion

Overall, the results highlight how socio-political dynamics are critical in determining not only system-level resilience to perturbations, but also the power and vulnerability of different groups under different transformation scenarios. Only the scenario involving a fundamental shift in agriculture, balances power among groups, and even then disparities persist due to uneven access to infrastructure. These findings demonstrate that alternative system configurations are both feasible and necessary for a more equitable water future in the San Joaquin Valley, while also underscoring that incremental reforms alone are insufficient to overcome entrenched inequities.

This work contributes to a growing body of scholarship that seeks to bring power and politics into the analysis of water governance. It complements political theory and environmental justice approaches that emphasize distributive and procedural equity (Zwarteveen et al., 2017; Ranganathan and Balazs, 2015), as well as hydrosocial perspectives that conceptualize water flows and power relations as co-constitutive (Rusca and Di Baldassarre, 2019; Hommes et al., 2022). By formalizing how structural feedbacks shape influence and vulnerability, the modeling framework makes visible the asymmetries that theories of justice and hydrosocial power have long emphasized, while providing a tool for exploring the alternative futures implied by different governance imaginaries (Moallemi et al., 2020; Rusca et al., 2023a). This combination of complexity science, political and environmental justice theory, and participatory exploratory modeling is necessary for envisioning fundamentally different - and more just - futures.

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