Resilient California water portfolios require infrastructure investment partnerships that are viable for all partners

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Key Points

- Water portfolio planning frameworks need to account for heterogeneity across participating partners, not just "average" performance
- Exploratory modeling shows how most infrastructure partnerships are highly unequal in their water deliveries and financial risks
- Viable partnership design is shown to be especially difficult for dry hydrologic scenarios, or when building conveyance without storage

Abstract

Water scarcity is a growing problem around the world, and regions such as California are working to develop diversified, interconnected, and flexible water supply portfolios. To meet their resilient water portfolio goals, water utilities and irrigation districts will need to cooperate across scales to finance, build, and operate shared water supply infrastructure. However, planning studies to date have generally focused on partnership-level outcomes (i.e., highly aggregated mean cost-benefit analyses), while ignoring the heterogeneity of benefits, costs, and risks across the individual investing partners. This study contributes an exploratory modeling analysis that tests thousands of alternative water supply investment partnerships in the Central Valley of California, using a high-resolution simulation model to evaluate the effects of new infrastructure on individual water providers. The viability of conveyance and groundwater banking investments are as strongly shaped by partnership design choices (i.e., which water providers are participating, and how do they distribute the project's debt obligation?) as by extreme hydrologic conditions (i.e., floods and droughts). Importantly, most of the analyzed partnership structures yield highly unequal distributions of water supply and financial risks across the partners, limiting the viability of cooperative partnerships. Partnership viability is especially rare in the absence of groundwater banking facilities, or under dry hydrologic conditions, even under explicitly optimistic assumptions regarding climate change. These results emphasize the importance of high-resolution simulation models and careful partnership structure design when developing resilient water supply portfolios for institutionally complex regions confronting scarcity.

1 Introduction

In May 2021, California Governor Newsom announced a $5.1 billion package for "immediate drought response and long-term water resilience investments" (Office of Governor Gavin Newsom, 2021). This follows the administration's Water Resilience Portfolio Initiative (WRPI), an ambitious blueprint for bolstering the state's water security (Newsom et al., 2020). The WRPI recommends a suite of actions to overcome challenges such as population growth, groundwater overdraft, and aging infrastructure, as well as climate change, which is already making droughts more frequent and severe (AghaKouchak, Cheng, Mazdiyasni, & Farahmand, 2014; AghaKouchak et al., 2021; Berg & Hall, 2017; Diffenbaugh, Swain, & Touma, 2015). Focal point recommendations in the WRPI include (1) expanding, improving, and diversifying the state's water storage and conveyance infrastructure, (2) developing flexible institutions for water sharing (e.g., groundwater banking), and (3) preparing for more climate change-related extreme droughts and floods. The WRPI envisions a future in which separate agencies, utilities, and stakeholder groups collaboratively develop and manage a shared network of water infrastructure that bridges local, regional, and statewide scales. However, at present, it is not clear that planners have the tools they need to build this "cohesive, resilient '*water system of systems'* across California" (Newsom et al., 2020). In this work, we show that traditional water supply planning tools are unsuitable for the task at hand. Exploratory modeling contributes new insights for designing and evaluating collaborative water investment partnerships under uncertainty. These insights have broad relevance beyond California, including the entire Western

U.S. and other water-scarce regions around the world seeking to develop more resilient water supply systems.

Water supply planning analyses generally rely on simulation models to evaluate the impacts of alternative policies and investments. However, modern supply networks in regions such as California are extremely complex, both in terms of the engineered system of reservoirs, canals, and groundwater recharge facilities, as well as the institutional systems of environmental regulations, water rights, and groundwater banking arrangements (Escriva-Bou, Mccann, et al., 2020). Exacerbating these complexities, atmospheric rivers deliver a large fraction of the state's annual precipitation during a few short events (Dettinger, Ralph, Das, Neiman, & Cayan, 2011; Gershunov, Shulgina, Ralph, Lavers, & Rutz, 2017), introducing strong interdependencies between floods and droughts. This makes it critical to resolve daily-scale dynamics (Hanak, Jezdimirovic, et al., 2018; Kocis & Dahlke, 2017; Malek et al., 2022; Zeff et al., 2021), while simultaneously multi-decadal simulations are needed to properly evaluate the impacts of long-term infrastructure investments, the slow dynamics of groundwater storage change (Manna, Walton, Cherry, & Parker, 2019), and the deep uncertainties in climatic, economic, and regulatory changes. Lastly, it is critical that planning models resolve a wide range of spatial scales and system actors in order to evaluate how water moves through statewide infrastructure networks in response to local actions by individual water utilities, irrigation districts, and water storage districts (Zeff et al., 2021) (hereafter referred to collectively as "water districts"). To date, much of this complexity is beyond the reach of the state's primary water resources planning models (e.g., CalSim (California Department of Water Resources, 2017; Draper et al., 2004), CalLite (Islam et al., 2011), CALVIN (Draper, Jenkins, Kirby, Lund, & Howitt, 2003)).

California has over $33 billion of water-related expenditures per year, 85% of which are funded by local agencies (Hanak, Chappelle, et al., 2018). Despite recent high-profile commitments to water infrastructure from state and federal governments (Office of Governor Gavin Newsom, 2021; The White House, 2021), individual water districts are responsible for the vast majority of the funding. Water districts typically finance large capital projects through debt that must be repaid over decades using water sales revenues. A key question is whether the additional water gained from a project will generate sufficient revenues to cover debt payments without requiring budget cuts, unpopular customer rate hikes, or even bankruptcy (Chapman & Breeding, 2014; Jeffrey Hughes et al., 2014; Leurig, 2010). However, benefits can be difficult to assess in light of system complexities and uncertainties as described above. Moreover, as the state's water supply portfolio becomes more diverse, flexible, and inter-connected, it becomes increasingly difficult for water districts to evaluate individual capital projects due to interactions across the infrastructural and institutional networks (Haimes, 2018).

Cooperative finance and operation of infrastructure can benefit water districts through economies of scale, reduced redundancy, and increased flexibility (Escriva-Bou, Sencan, Hanak, & Wilkinson, 2020; Jeff Hughes & Fox, 2019; Riggs & Hughes, 2019). Larger and more diverse coalitions may also be better positioned to raise capital and harness state and federal subsidies (Cypher & Grinnell, 2007; Hansen, Mullin, & Riggs, 2020; Newsom et al., 2020). However, cooperation introduces significant new complexities related to the heterogeneity of outcomes across the participants. Capital projects that look favorable at the partnership level may yield poor results for individual partners due to differences in water rights, groundwater recharge capacities, and locations within the infrastructure network. Some partners may also bear an outsized share of the risk in unfavorable future scenarios (i.e., losses under climate change) (Gold, Reed, Trindade, & Characklis, 2019; Gorelick, Zeff, Hughes, Eskaf, & Characklis, 2019; Herman, Zeff, Reed, & Characklis, 2014). An additional challenge is assigning the share of project debt to be borne by each partner; standard approaches for apportioning cost shares to multiple beneficiaries are unsuitable when there is significant uncertainty or a large number of potential partners (De Souza, Medellín-Azuara, Lund, & Howitt, 2011; Giglio & Wrightington, 1972). Recent water portfolio planning studies (San Joaquin River Restoration Program, 2011; Sunding, 2015; U.S. Bureau of Reclamation, 2017, 2020) have focused on expected costs/benefits at highly aggregated levels, typically under minimal uncertainty, while vulnerability assessments under broader uncertainty have focused on individual water districts (Groves et al., 2015; Lempert & Groves, 2010; Tariq, Lempert, Riverson, Schwartz, & Berg, 2017) or aggregate regional outcomes (Connell-Buck, Medellín-Azuara, Lund, & Madani, 2011; Schwarz et al., 2019, 2018; Selmon et al., 2019). There is little research to date on disaggregating costs, benefits, and risks to design robust partnerships that are broadly satisfactory to all partners (Herman, Reed, Zeff, & Characklis, 2015; Jafino, Kwakkel, & Taebi, 2021).

In this work, we contribute an exploratory modeling framework (see detailed review by Moallemi, Kwakkel, de Haan, & Bryan, 2020) for testing thousands of candidate infrastructure partnership structures across multiple future hydrologic scenarios, using a flexible and high-resolution water resources simulation model, the California Food-Energy-Water System (CALFEWS (Zeff et al., 2021)). Each partnership structure is assessed in terms of aggregate performance as well as its impacts on individual partners, in order to search for investments that are viable for all partners across multiple plausible futures. We take an explicitly optimistic view of uncertainty in this study by modeling outcomes under present-day demands, institutions, and regulatory contexts. Similarly, we assume a limited degree of hydrologic uncertainty by focusing on stationary hydro-climatic variability, rather than explicitly focusing on the more severe floods and droughts expected with climate change (Gonzalez et al., 2018). A major aim of this exploratory analysis is to show that, even under these strongly optimistic assumptions, traditional planning frameworks are unlikely to produce viable investment partnerships.

Our results focus on the southern Central Valley, a water-stressed and agriculturally-productive region that relies heavily on overdrafted aquifers to meet its irrigation and drinking water demands, particularly during drought, and may face severe cutbacks under the Sustainable Groundwater Management Act (Faunt & Sneed, 2015; Hanak et al., 2019; Levy et al., 2021; Newsom et al., 2020). Water districts are mobilizing to develop new infrastructure (e.g., canals, groundwater recharge facilities) and flexible institutions (e.g., water trading, groundwater banking) in order to balance supplies and demands (Escriva-Bou, Sencan, et al., 2020; Hanak, Jezdimirovic, et al., 2018; Jezdimirovic, Hanak, & Escriva-Bou, 2020; Scanlon, Reedy, Faunt, Pool, & Uhlman, 2016). Thus, the region is emblematic of the challenges and opportunities facing water supply organizations throughout the Western U.S. and other water-stressed regions of the world, and can advance our ability to develop resilient and sustainable water portfolios capable of managing intensifying scarcity and climate-related uncertainty (AghaKouchak et al., 2021; Famiglietti, 2014; Jiménez Cisneros et al., 2015; Lall et al., 2018).

2 Methods

2.1 Overview

The Friant-Kern Canal is a major water conveyance system in the southeastern Central Valley. As part of the Central Valley Project, it diverts San Joaquin River water from Lake Millerton to the "Friant contractors" to the south (Figure 1). The canal also conveys water from other local rivers to a wider array of water districts and groundwater banks willing to take surplus deliveries during high-flow periods. However, widespread subsidence caused by groundwater overdraft has damaged the canal and reduced its capacity by 60% along critical reaches (Faunt & Sneed, 2015; Friant Water Authority, 2019). Water districts relying on the canal, especially the Friant contractors, are advocating for its rehabilitation. Simultaneously, many water districts are working to build more groundwater recharge and banking facilities (Dahlke et al., 2018; Hanak, Jezdimirovic, Escriva-Bou, & Ayres, 2020; Jezdimirovic et al., 2020; Scanlon et al., 2016). Building conveyance and groundwater recharge simultaneously could yield synergistic benefits when the additional deliveries due to canal expansion, which primarily occur during high-flow periods, exceed immediate irrigation demands and require storage until drier periods (Alam, Gebremichael, Li, Dozier, & Lettenmaier, 2020; Hanak, Jezdimirovic, et al., 2018; Kocis & Dahlke, 2017; Wendt, van Loon, Scanlon, & Hannah, 2021). Local farms, water districts, and politicians have lobbied for external support, but subsidies are unlikely to fund the projects in full (Whisnand, 2021). Thus, water districts that stand to benefit will need to collaborate to raise the remaining capital, creating the challenge of defining, designing, and evaluating these investment partnerships.

In this study, an exploratory ensemble modeling approach is used to evaluate thousands of plausible partnership structures. Each candidate partnership structure contains a subset of 41 water districts (Tiers 1-3 in Figure 1) that could potentially benefit from rehabilitating the canal and/or adding a new groundwater bank along the canal. Our exploratory sampling design assigns to each partner an ownership share that controls its access to capacity in the new infrastructure and its share of debt payments. Each candidate partnership structure is applied to three different capital projects (canal rehabilitation, groundwater bank development, and both). Each of the capital projects are evaluated using three different 50-year hydrologic scenarios (wet, average, and dry) that are selected from a larger stochastic streamflow ensemble that captures the system's internal hydro-climatic variability. All partnership structure, capital project, and hydrologic scenario combinations are simulated using the CALFEWS model (Zeff et al., 2021).

Water portfolio investments are assessed using two key performance metrics. First is the captured water gain in billions of liters per year, GL/year (or thousands of acre-feet per year, kAF/year). This metric measures the expected "new water" delivered by the investment, defined as the difference in average annual water deliveries to partner districts with and without the new infrastructure under a particular hydrologic scenario. Each capital project represents a large up-front investment that requires annual debt payments, with each partner's share of debt equal to its ownership share. The second measure of performance is the cost of gains in dollars per million liters, \$/ML, (or dollars per acre-foot, \$/AF), defined as the annual debt payment divided by the captured water gain. Effective partnerships will reliably provide their partners with significant water gains at relatively low cost.

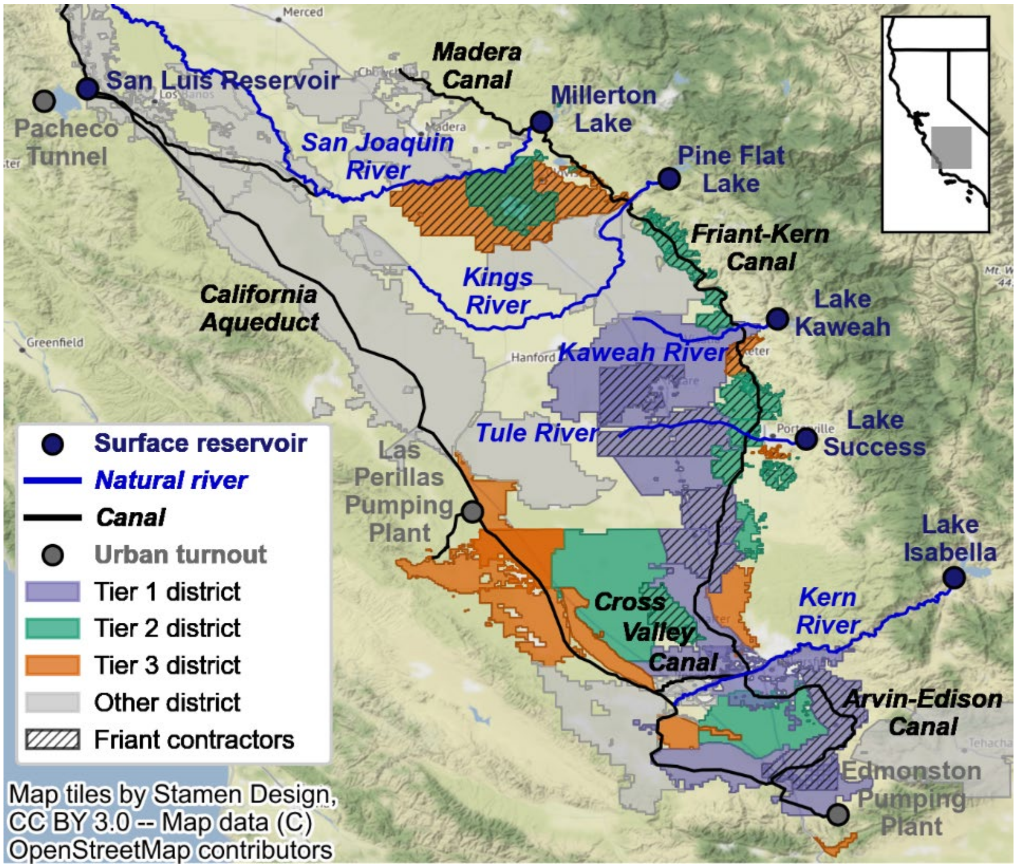

Figure 1. Geography of water supply in the southern Central Valley. Five major reservoirs store runoff from the Sierra Nevada mountains in the east and release it into the region's major rivers, where much of the flow is withdrawn by water districts. Millerton Lake diverts San Joaquin River water into the Madera Canal and Friant-Kern Canal (FKC) as part of the Central Valley Project (CVP). Water districts receiving CVP contract water from the FKC are shown as "Friant Contractors". The CVP and State Water Project also pump water from the Sacramento-San Joaquin River Delta to San Luis Reservoir, where it is routed via a series of pumps and canals to water districts in the valley and urban districts along the coast. Water districts are grouped into three tiers based on the results of the experiment, with Tier 1 districts having the highest potential to benefit from new infrastructure and Tier 3 districts having the lowest potential. Note that three coastal urban districts from the experiment are not shown (one Tier 2 and two Tier 3).

2.2 CALFEWS simulation model

The California Food-Energy-Water System (CALFEWS) is an open-source, Python/Cython-based model for simulating the movement of water supplies within California, with a focus on the Central Valley (Zeff et al., 2021). CALFEWS operates across multiple scales, from statewide representation of major inter-basin transfer projects to distributed local representation of district-level conjunctive surface and groundwater management. The model has been found to reproduce historical reservoir storages, canal flows, surface water deliveries, and groundwater banking accounts with a high degree of fidelity.

CALFEWS has three major advantages when compared to more commonly-used water supply models in California (e.g., CalSim (California Department of Water Resources, 2017; Draper et al., 2004), CalLite (Islam et al., 2011), CALVIN (Draper et al., 2003)). Firstly, it models dynamics at a finer spatio-temporal resolution (water district representation, daily time step), while still allowing for simulations to be run at a statewide scale over many decades. This gives CALFEWS an unprecedented ability to track the impacts of district-level decision-making on statewide water supply projects, and the impacts of short-lived high-flow periods (e.g., atmospheric rivers) on long-lived infrastructure investments. Secondly, CALFEWS uses a rules-based representation of system dynamics, in contrast to the mathematical programming techniques used by the aforementioned models. This rules-based approach can more flexibly represent system complexities such as adaptive operations, environmental regulations, groundwater banking arrangements, and distributed district-level decision-making. Lastly, ensembles of CALFEWS simulations can be dispatched in parallel on high-performance computing infrastructure, enabling high-throughput exploratory modeling approaches (see Section 2.5).

2.3 Infrastructure project alternatives

The first infrastructure project considered in this study is the rehabilitation of the Friant-Kern Canal. Widespread groundwater overdraft in the region has damaged the canal via subsidence (Faunt & Sneed, 2015). In certain sections near the Tule River, canal capacity has been reduced by almost 60% (Friant Water Authority, 2019; U.S. Bureau of Reclamation, 2020). Water districts and government representatives have recently been negotiating a partnership to rehabilitate the canal. Although the new design specifications are uncertain, we assume that the entire length of the canal will be returned to its original design capacity and that the cost borne by the districts involved in the partnership will be $50 million. This is based on a recent funding agreement for the project, in which the Friant contractors have agreed to pay $50 million out of an estimated $500 million total (Whisnand, 2021). The remainder will come from federal and state funding sources as well as legal settlement agreements associated with environmental damages and land subsidence. The partnership design efforts in this study are focused on the $50 million share currently allocated to the Friant contractors. This is an unusually favorable case study for infrastructure investment partnerships due to the unusually high level of outside funding available; for other capital projects with lower subsidy levels, viability will generally be more difficult to achieve.

The second capital project is a jointly managed groundwater bank along the Friant-Kern Canal in the vicinity of the Tule River. This project is hypothetical and is not based on any particular existing or planned groundwater bank, but water districts throughout the region have been investing in new recharge facilities and banking relationships (Escriva-Bou, Sencan, et al., 2020; Hanak et al., 2020). The partnership's share of the total capital cost (i.e., after any subsidies) is assumed to be $50 million, in line with cost estimates of other large groundwater banks currently under development (Jezdimirovic et al., 2020). There are three main parameters controlling the function of groundwater recharge and recovery facilities in the CALFEWS model (Zeff et al., 2021): the baseline recharge capacity, the baseline recovery capacity, and the storage volume of infiltration basins. The two "baseline" values refer to initial capacities at the beginning of the recharge or recovery season; both capacities will decrease over the season with extended use. The uncertainty bounds for these parameters are set based on the ranges of pre-existing groundwater banks in the region: infiltration capacity between 0 and 1.5 GL/day (1.2 kAF/day), infiltration pond storage volume between 0 and 1.5 GL (1.2 kAF), and recovery capacity between 0 and 0.9 GL/day (0.7 kAF/day). For comparison, the upper limits of these ranges are 50%, 50%, and 88% of the estimated parameters for the largest groundwater bank in the region, the Kern Water Bank (Kern Water Bank Authority, 2021).

Access to both pieces of infrastructure is restricted to the set of water districts investing in the partnership. Additionally, each partner is assigned priority access to a fraction of the new capacity that is proportional to its ownership share in the project (e.g., a district with a 20% ownership share will have priority access over 20% of the new capacity). If a district is not using its priority capacity at any given time, access is opened up to the broader set of partners. Note that the canal rehabilitation project does not impact non-partners' access to the existing capacity. It only restricts access to the expanded capacity at the top of the canal.

Both capital projects are assumed to be financed with revenue bonds that require equal-sized annual payments over a 50-year period with 3% interest. This is a conservative assumption (in the sense of not over-estimating costs) because recent revenue bonds issued by California water districts have generally carried between 2.5-3.5% interest with maturities of 25 years or fewer (California State Treasurer's Office, 2020), and a 50-year maturity bond would carry an additional premium in practice. Under these assumptions, partnerships would make annual debt payments of approximately $1.943 million for either canal rehabilitation or groundwater bank development, and $3.887 million for both projects. Each partner's share of the overall debt payment is proportional to its ownership share.

2.4 Hydrologic scenarios

The hydrologic scenarios used in this work are generated using the California and West Coast Power System (CAPOW), an open-sourced, Python-based model for simulating the operation of the U.S. west coast bulk electric power system. CAPOW has a major focus on the impact of hydrometeorological variables (streamflow, temperature, wind speed, insolation) on system reliability and pricing (Su, Kern, Denaro, et al., 2020). As such, a major component of the model is its stochastic engine, which uses a hybrid vector autoregressive-bootstrapping approach to generate daily synthetic records of hydrometeorological variables at many locations across the west coast. These synthetic records are shown to maintain historical correlation patterns across space (i.e., northern vs. southern California) and time (i.e., intra- and interannual autocorrelation), while overcoming the limitations of the limited length of historical hydro-climatic observations. Although CAPOW is trained on historical data, it enables the generation of statistical replicate time series of synthetic hydro-climatic scenarios, better capturing a wide variety of plausible futures as well as extremes beyond the limited number of observed rare events in the modern historical record. This makes it a valuable tool for planning over the medium term (e.g., initiating capital investments in the next decade), where interannual variability is a major contributor to overall hydrologic uncertainty (Doss-Gollin, Farnham, Steinschneider, & Lall, 2019; Lehner et al., 2020; Su, Kern, Reed, & Characklis, 2020).

For the present work, the CAPOW stochastic engine is used to generate daily synthetic full natural flow records at fifteen major water supply reservoirs in California. These full natural flow records can be used to statistically reconstruct more detailed time series of streamflows, gains, and snowpacks (Zeff et al., 2021). We generate 101 alternative 50-year time series, which span a wide range of hydrologic outcomes across extreme quantiles of interest. Figure 2 and Supporting Information (SI) Figure S1 compare each 50-year synthetic record with the 111-year historical record in terms of 1-, 2-, 4-, and 8-year flow duration curves of full natural flow across the major South San Joaquin River Basin (SSJRB) reservoirs (Millerton, Pine Flat, Kaweah, Success, and Isabella), and the major Sacramento River Basin (SRB) reservoirs (Shasta, Oroville, New Bullards Bar, and Folsom), respectively. These curves demonstrate that the stochastic engine can accurately represent regional flows in terms averages, extremes, and persistence of multi-year wet and dry periods, while also providing a wider range of extremes for risk assessment.

These 101 scenarios are then sorted in terms of total 50-year full natural flow across the SSJRB reservoirs. The time series with the highest, median, and lowest flows are selected to represent "wet", "average", and "dry" hydrologic scenarios, respectively. The "average" scenario is found to track the historical flow duration curve well in the SSJRB (Figure 2), while the "wet" and "dry" scenarios are significantly wetter and drier, especially with respect to normal and wet periods (e.g., mid- to high-range exceedance). With respect to the most extreme droughts (e.g., low exceedance), the "average" scenario is found to be quite extreme, while the "dry" scenario is similar to the historical record. The "wet" and "dry" scenarios are less extreme in the context of the SRB (SI Figure S1), and the "average" scenario appears to be wetter than average. This is due to the imperfect correlation in hydrologic conditions across the state; the wettest years in northern California are not necessarily the wettest years in the southern Central Valley, and vice versa. The SSJRB reservoirs are used for scenario selection because they have the most direct influence on the Friant-Kern Canal.

2.5 Exploratory modeling framework

This study employs a random sampling framework to develop 3,000 plausible candidate partnership structures. The sampling design requires a three-step process to generate each partnership structure. First, the size of the partnership *np* is randomly drawn from a Poisson distribution with a mean of 8 partners, excluding zero. This distribution, which creates partnership structures ranging from approximately one to twenty partners, was selected to strike a balance between relatively dense sampling at smaller partnership sizes (which are more likely to be viable) and broader exploration of larger partnership structures. Second, *np* partners are randomly selected without replacement from the set of 41 candidate water districts. Third, the ownership shares of the *np* partners are sampled from a uniform distribution and normalized to sum to one.

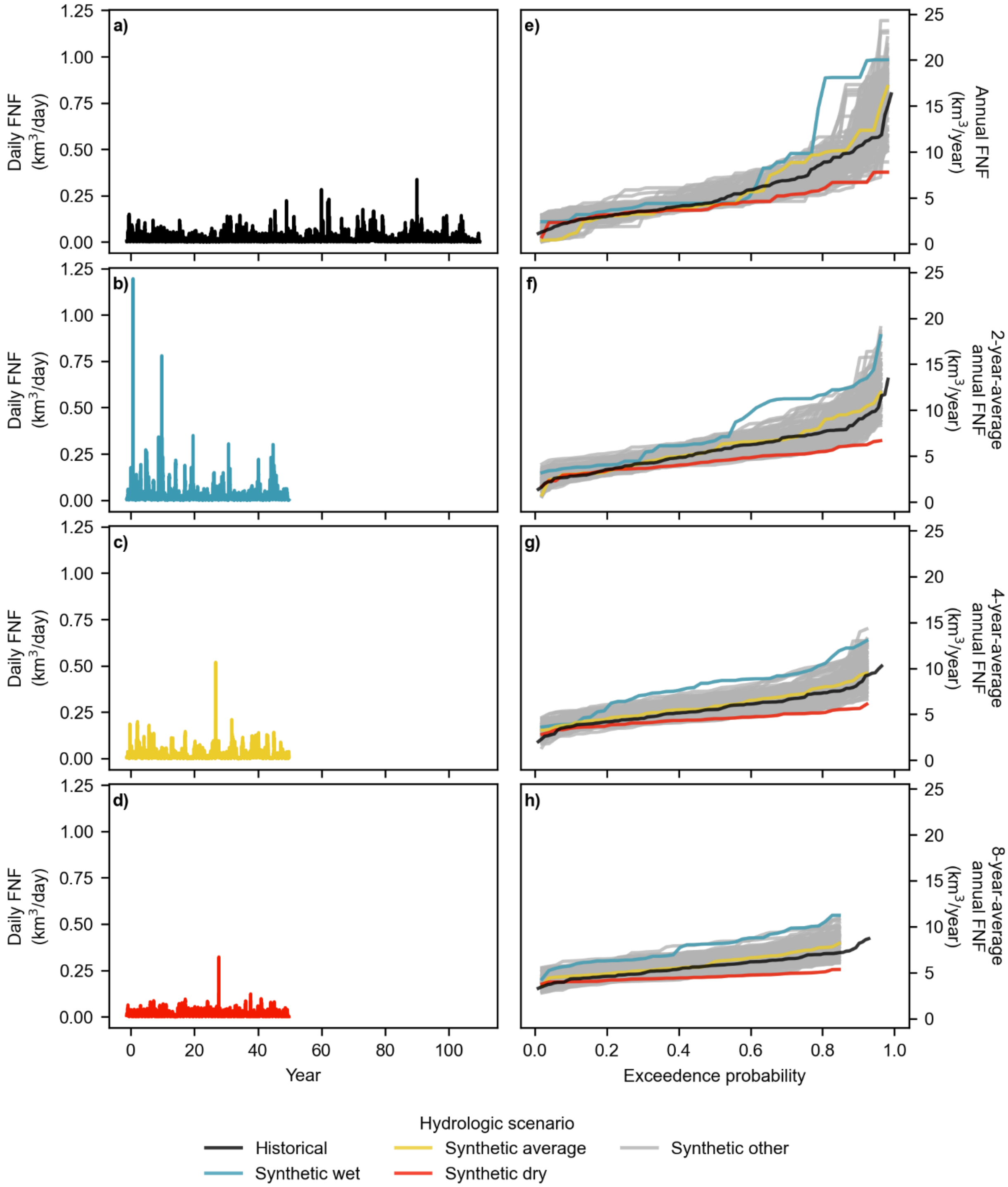

Figure 2. Comparison of synthetic and historical full natural flow (FNF) for the Tulare Lake Basin. Panels **(a-d)** show the total full natural flows for the five major reservoirs of the South San Joaquin River Basin (Millerton, Pine Flat, Kaweah, Success, and Isabella), under the historical record and the wet, average, and dry synthetic scenarios. Panels **(e-h)** show the full natural flow duration curves for each time series over 1-, 2-, 4-, and 8-year periods.

Each of the 3,000 sampled partnership structures is combined with each of three capital projects: canal rehabilitation, groundwater bank development, and both. Three groundwater recharge and recovery parameters are randomly sampled from uniform distributions across their uncertainty bounds (Section 2.3). This results in 9,000 partnership structure/capital project combinations, to which we add the "Friant-16" canal rehabilitation partnership representing business-as-usual planning (see Section 3.4), and the baseline case with no new infrastructure. Lastly, each of these combinations is combined with each of the three stochastic hydrologic scenarios: dry, average, and wet. In total, this represents 27,006 partnership structure/capital project/hydrologic scenario combinations.

Each of these 27,006 combinations is evaluated using the CALFEWS model. Simulations are dispatched in parallel across 800 cores using the Longleaf Cluster at the University of North Carolina at Chapel Hill. Results such as reservoir releases, canal flows, water contract deliveries, and groundwater banking balances for each simulation are stored using the hdf5 file format. Each simulation is evaluated by comparing its performance to the performance of the baseline no-infrastructure case under the same hydrologic scenario.

3 Results

3.1 Evaluating new infrastructure investments along the Friant-Kern Canal

The candidate partnerships explored in this study display a wide range of partnership-level performance (Figures 3a-b). Five percent deliver at least 62 GL/year (50 kAF/year) of captured water gains, with a maximum of 118 GL/year (96 kAF/year). For context, Lake Millerton has a capacity of 642 GL (521 kAF), and 1 GL (1 kAF) is enough irrigate roughly 0.82-2.2 km^2 (250-667 acres) of crops in the region (University of California Agriculture and Natural Resources, 2021). Five percent of candidate partnerships cost less than \$45/ML (\$56/AF), with a minimum of \$30/ML (\$36/AF). These results would be competitive with other water supply projects under consideration throughout the Central Valley (Jezdimirovic et al., 2020). However, most candidate partnerships perform more modestly, with a median gain of 21 GL/year (17 kAF/year) and a median cost of \$120/ML (\$147/AF). This cost of gains, which includes only the investment's debt payments and not the additional costs of procuring and transporting the water itself, would represent a significant increase above typical rates of \$32-154/ML (\$40-190/AF) charged by water districts for irrigation deliveries in the region. Worse still, 9% of candidate partnerships yield negative captured water gains, representing investments that actually reduce partners' water deliveries on average. This occurs when new infrastructure triggers unpredictable dynamics within the water system that allow non-partners to benefit over partners. The cost of gains for these partnerships is effectively infinite, and more broadly 13% of partnerships have very high costs over \$1,000/ML (\$1,233/AF). These capital investments represent a serious financial risk if the future water gains are insufficient to allow partners to sell enough water to pay off their debt, even under our explicitly optimistic assumptions in this study that neglect the broader extremes possible under climate change. Thus, near term capital investments can have very complex and potentially severe downside risks for partners.

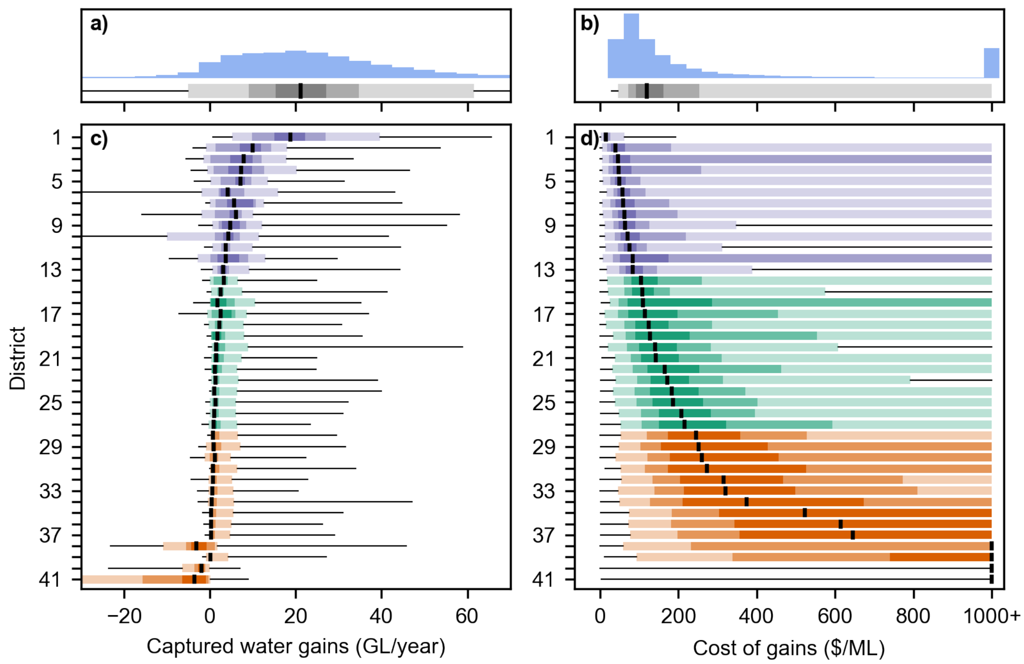

Figure 3. Distribution of performance for thousands of candidate infrastructure investment partnerships. (a) Distribution of partnership-level captured water gains. (b) Distribution of partnership-level cost of gains. (c) Distribution of captured water gains for individual water districts. (d) Distribution of cost of gains for individual water districts. Distributions show the variability of results across all candidate partnership structures, capital projects, and hydrologic scenarios. For Panels (b) and (d), all costs over $1,000/ML ($1,233/AF) are consolidated into "1000+". Water districts are grouped into three tiers based on the results of the experiment, with Tier 1 districts having the highest potential to benefit from new infrastructure and Tier 3 districts having the lowest potential.

Decomposing these results by hydrologic scenario, the costs of gains are generally highest in the dry scenario (Figure 4) because the size of debt payments is independent of how much water ends up being available. However, costs in the wet scenario are similar to the average scenario, suggesting an important asymmetry: the downside risk in a drier future is larger than the upside risk in a wetter future. Decomposing variability by capital project, we find similar cost distributions for canal rehabilitation projects vs. joint canal-groundwater banking projects. However, the latter risks underperformance in dry scenarios if insufficient water is available to warrant the capital cost of both projects. Groundwater bank-only partnerships generally perform well in the wet scenario but much poorer in average and dry scenarios.

Although the project type and hydrologic scenario do impact performance in important ways, substantial variability remains after accounting for these factors (Figure 4). This variability is attributed to the partnership structure itself (i.e., which water districts are included as partners, and what ownership share does each partner take?). For example, the subset of candidate partnerships that expand the canal under the wet hydrologic scenario (Figure 4a) are identical other than their partnership structures, yet experience widely varying partnership-level costs ranging from $32/ML to over $1,000/ML ($39-1,233/AF). For candidate partnerships with groundwater banking (either alone or in combination with canal expansion), three additional capacity factors also contribute to the variability of outcomes (e.g., soil infiltration rate). However, these appear to play a minor role compared to partnership structure. Thus, the impacts of water portfolio investments can depend critically on the subset of water districts in the partnership and their relative ownership shares. This represents a major challenge for standard infrastructure planning approaches that focus primarily on physical design parameters such as capacity (perhaps in combination with climate-related vulnerability analyses), while neglecting contractual design factors such as infrastructure access and ownership.

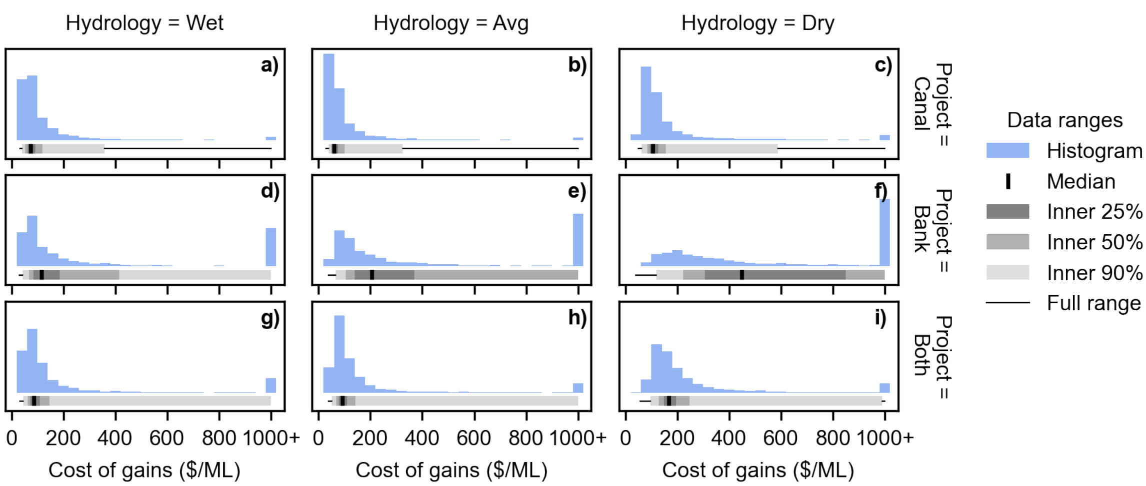

Figure 4. Distribution of performance (partnership-level cost of gains) for candidate partnerships across different capital projects and hydrologic scenarios. Panels (a-c) involve a canal expansion, (d-f) involve a groundwater bank, and (g-i) involve both projects. Panels (a/d/g) use the wet hydrologic scenario, (b/e/h) use the average scenario, and (c/f/i) use the dry scenario. All costs over $1,000/ML ($1,233/AF) are consolidated into "1000+".

3.2 Potential benefits are highly heterogeneous across water districts

Next, we disaggregate partnership-level performance into the captured water gains (Figure 3c) and costs of gains (Figure 3d) experienced by each of the 41 water districts in the exploratory experiment. Each district's results include only the subset of candidate partnership structures for which it is a participant. Most districts display a wide range of captured water gains (e.g., from <0 to >20 GL/year), but with outcomes concentrated in a narrower band (e.g., >90% of partnerships between 0-10 GL/year). The range of costs experienced by each district is even wider, with all districts except for one spanning from near-zero to over $1,000/ML. Despite the high variability within each district, there are clear distributional differences as well. Water districts can be grouped into three roughly-equal sized tiers based on their median cost of water gains: Tier 1 under $100/ML ($123/AF), Tier 2 under $240/ML ($296/AF), and Tier 3 over $240/ML. Tier 1 districts have the highest potential to benefit from partnering in these investments, while Tier 3 districts have the lowest. These distributional differences provide crucial information for the partnership negotiation process, but would be unavailable using traditional aggregate cost-benefit analyses.

Decomposing the district-level performance into separate components for each capital project and hydrologic scenario, we find costs to be highly variable across all combinations, highlighting the importance of partnership structure on district-level outcomes (Figure 5). Tier 1 districts generally have much lower costs than Tier 2-3 for canal-only projects, while the distributions are more uniform across tiers for bank-only projects. Joint canal-groundwater banking projects exhibit intermediate behavior; Tier 1 districts generally have lower costs than Tier 2, which have lower costs than Tier 3, but these differences are more gradual than in the canal-only partnerships. With regards to hydrology, the costs of gains are significantly higher on average in the dry scenario than the average and wet scenarios, but this effect varies across districts, suggesting that some districts will experience more climate-related risk than others. We reiterate that our experimental design is expressly optimistic with regards to climate uncertainty, considering extreme realizations of stationary stochastic variability but not anthropogenically forced climate non-stationarity. Thus, under climate change, the downside climate-related risks are likely even greater than represented here.

The geographic distribution of the tiers provides useful context (Figure 1). Tier 1 stretches from the Kaweah River to the Kern River along the western side of the Friant-Kern Canal, before wrapping around the other major canals to the south. These districts' proximity to the confluences of major canals and rivers allows them to receive water from multiple sources, increasing their chances of capitalizing on the investment. Additionally, many of the Tier 1 districts overlie highly suitable soils for groundwater recharge (O'Geen et al., 2015) (SI Figure S2), which has allowed them to build dedicated recharge facilities within their boundaries (Alam et al., 2020; Scanlon et al., 2016; Wendt et al., 2021). These facilities increase the benefits from canal expansion by storing more surplus flows during winter/spring months when agricultural demands are limited. Districts without significant groundwater recharge capacity are more limited in how much water they can receive during these periods. This also helps to explain why the benefits from groundwater bank development are more uniformly distributed across the districts (Figure 5d-f) because these facilities level the playing field by allowing districts with unsuitable soils to store groundwater off-site. Lastly, Figure 1 shows that the water districts with the highest potential to gain from new infrastructure are not necessarily the most "obvious" ones. In this case, we find a number of Friant contractors (the group of districts currently negotiating to invest in the project (Whisnand, 2021)) in Tiers 2-3, while a number of non-contractors are in Tier 1. This demonstrates the value of the exploratory modeling approach to partnership design, which allows a much broader array of suitable alternatives to be discovered.

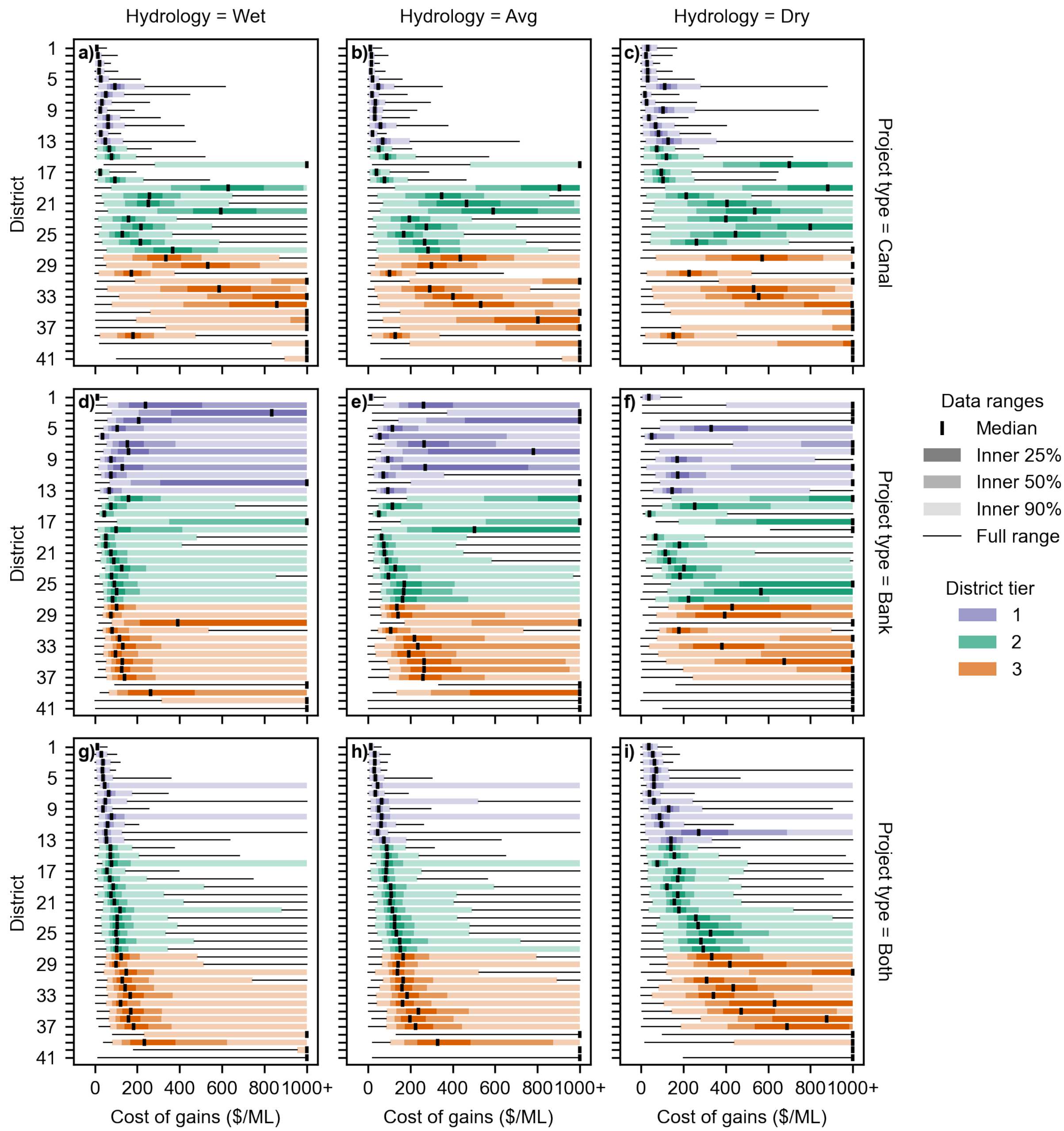

Figure 5. Distribution of performance (cost of gains for individual districts) for candidate partnerships across different capital projects and hydrologic scenarios. Panels (a-c) involve a canal expansion, (d-f) involve a groundwater bank, and (g-i) involve both projects. Panels (a/d/g) use the wet hydrologic scenario, (b/e/h) use the average scenario, and (c/f/i) use the dry scenario. All costs over $1,000/ML ($1,233/AF) are consolidated into "1000+".

3.3 Heterogeneity limits the viability of partnerships

Results thus far have shown how the benefits of water portfolio partnerships can vary widely based on the type of infrastructure, the hydrologic scenario, and the partnership structure itself. We now demonstrate how this range of district-level outcomes can threaten investment viability. The partnerships in this work are assumed to be voluntary, meaning all partners have agreed to the terms of cooperation. This implies that each partner believes they will be better off with the partnership than without it (Giglio & Wrightington, 1972). In practice, coalition-building is complex due to power and information asymmetries, incentive misalignments, and relationships between participants (BenDor & Scheffran, 2019; Hansen et al., 2020; Lubell, Blomquist, & Beutler, 2020; Madani, 2010; Read, Madani, & Inanloo, 2014). However, we adopt the following simple definition: an infrastructure partnership is considered viable under a particular hydrologic scenario if all partners pay less than \$200/ML (\$247/AF) for their share of captured water gains. This is an optimistically conservative definition, in the sense of not erroneously labelling viable partnerships as non-viable, because water districts in the region typically charge their customers \$32-154/ML (\$40-190/AF) for irrigation water (University of California Agriculture and Natural Resources, 2021). Therefore, \$200/ML in new project debt, on top of additional water procurement costs, would represent a significant and likely unacceptable increase.

Despite our optimistically conservative viability definition, only 8% of candidate partnerships we have explored are viable (Figure 6). In the preponderance of cases, the worst-off partner pays significantly more than the partnership-level cost. In 61% of cases, performance is considered viable at the partnership level (i.e., overall cost is <\$200/ML), but non-viable when impacts are disaggregated (i.e., at least one partner pays >\$200/ML). This suggests that in a majority of cases, the limiting factor for project viability is not the overall volume of captured water gains, but rather the uneven distribution of these gains across the partnership in light of each partner's share of project debt. Traditional planning approaches based on aggregate impacts are incapable of uncovering these distributional issues, and thus risk leading to cooperative capital investments that are harmful to a subset of partners.

Decomposing viability by hydrologic scenario also delivers valuable insights (Figure 6 inset). In the wet hydrologic scenario, 15% of candidate partnerships are found to be viable, compared to 9% in the average scenario and 1% in the dry scenario. This suggests that if the future is drier than the past, investment partnerships will be more likely to fail for at least one partner. California has already begun getting hotter and drier under anthropogenic climate change (Gonzalez et al., 2018), which presents a major obstacle to meeting the state's collaborative portfolio investment goals. Decomposing the results by capital project shows that the canal expansion alone is very unlikely to be viable (1%). Groundwater bank development improves the chances of viability, either in isolation (7%) or in combination with canal expansion (17%). It is instructive to compare these results to Figure 4, which shows that canal expansion projects and joint canal-groundwater banking projects have roughly similar odds of achieving viability at the partnership level (i.e., aggregate costs <\$200/ML). Thus, although canal expansion appears promising in aggregate, it tends to distribute captured water gains more unevenly and thus is less likely to satisfy all of the participating districts (see also Figure 5).

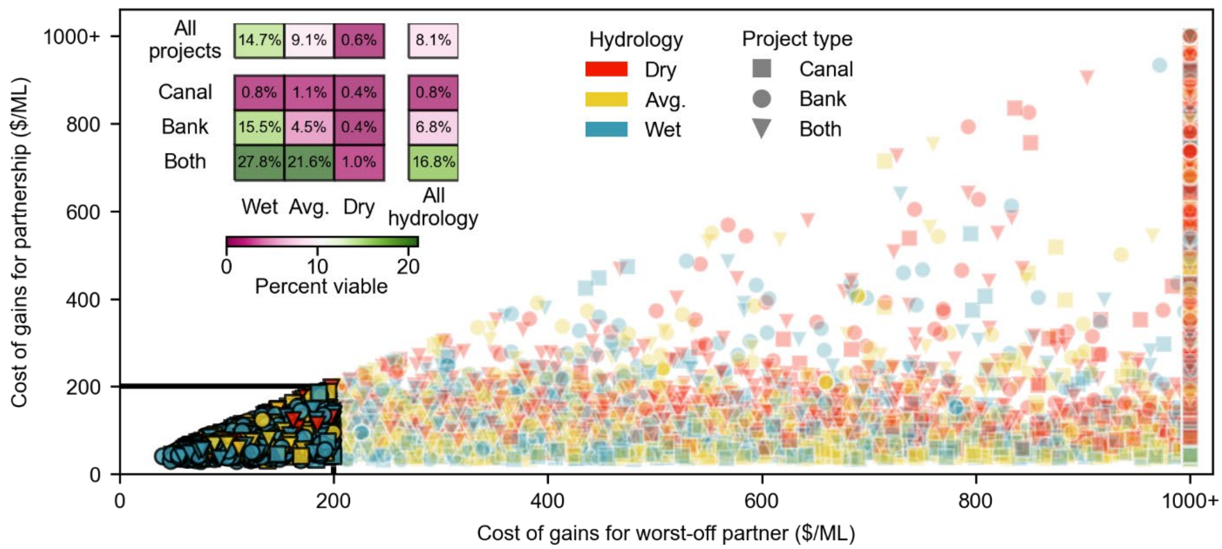

Figure 6. Viability of candidate infrastructure investment partnerships. Each simulated partnership is plotted according to the cost of gains for the partnership as a whole vs. the worst-off partner. The project type and hydrologic scenario used for each simulation are represented by marker type and color, respectively. Viable partnerships (those with costs <$200/ML ($247/AF) for the worst-off partner) are represented with black outlines and higher opacity. All costs over $1,000/ML ($1,233/AF) are consolidated into "1000+". Inset shows the viability of candidate partnership structures under each combination of capital project and hydrologic scenario, represented by color as well as the percentage printed in each square.

3.4 Comparing alternative partnerships

We now explore these issues in more detail through a comparison of three alternative partnership structures. First, we consider a partnership between 16 Friant contractors ("Friant-16") for canal expansion only. In contrast to the randomly sampled partnerships from the exploratory study, Friant-16 is deliberately constructed to represent the baseline performance under business-as-usual planning because the Friant contractors are currently negotiating to establish such a partnership (Whisnand, 2021). The ownership shares for Friant-16 are assumed to be proportional to historical deliveries of CVP-Friant contract water (Congressional Research Service, 2007).

In addition, we consider two high-performing partnerships from the exploratory study: one with eight partners ("Alt-8") and one with three ("Alt-3"). Both are joint canal-groundwater banking investments. The selection procedure for choosing Alt-8 and Alt-3 is as follows. First, the set of 27,000 simulations is filtered down to include only those that meet each of the following criteria: (1) the partnership is viable, i.e., the cost of gains for the worst-off partner is less than $200/ML; (2) the partnership-wide captured water gain is greater than 55 GL/year (45 kAF/year); and (3) the total captured water gain for all non-partners in the region is greater than zero. These thresholds are set *a posteriori* by iteratively increasing the constraints until an elite subset of solutions remain. In practice, the thresholds could be defined by decision-makers based on their particular context and preferences. Note that Friant-16 fails on all three criteria under the average hydrologic scenario: its worst-off partner cost is over $1000/ML, its total captured water gain for the partnership is 46 GL/year, and its captured water gain for non-partners is -2 GL/year (i.e., the new infrastructure reduces deliveries to regional non-partner districts). Each of these criteria eliminates a significant subset of simulations (SI Figures S3-S4). After filtering by the three criteria, only 103 simulations remain: 51 from the wet scenario and 52 from the average scenario, while no partnerships remain from the dry scenario. SI Figure S5 shows how these simulations vary along multiple performance metrics. From the 52 candidate partnerships that perform satisfactorily in the average scenario, Alt-3 and Alt-8 are selected manually as examples that perform well across all metrics. Alt-3 is chosen as a representative small successful partnership, while Alt-8 is chosen to from among the larger partnerships, which may be preferable due to political and financial concerns.

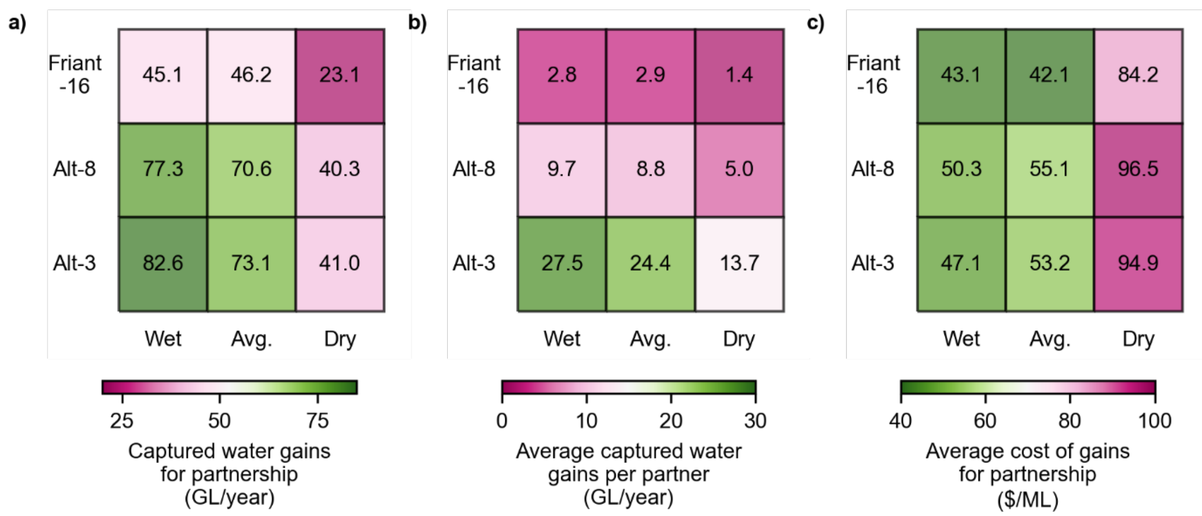

Figure 7. Comparison of three alternative infrastructure investment partnerships at aggregate scale. For each partnership and each hydrologic scenario, Panel (a) shows the total captured water gain for the partnership, Panel (b) shows the average captured water gain per partner, and Panel (c) shows the average cost of gains for the partnership. Results are represented by color as well as the number printed in each square.

At the partnership level, Alt-3 is found to deliver the highest total captured water gains, at 73 GL/year (59 kAF/year) in the average scenario (Figure 7a). Alt-8 delivers 71 GL/year (57 kAF/year) of gains, while Friant-16 delivers significantly less at 46 GL/year (38 kAF/year). Gains in the wet scenario are slightly lower for Friant-16 and slightly higher for the other two partnerships, while dry scenario gains are roughly 50% lower across all partnerships. Because Alt-3 only has three partners, it has significantly higher gains on a per-partner basis (Figure 7b). However, after accounting for the larger debt shares borne by each district in the smaller partnerships and the additional capital expense required for Alt-3 and Alt-8 to develop a groundwater bank, the three partnerships are found to have similar costs of gains (Figure 7c):

$43-50/ML ($53-62/AF) in the wet scenario, $42-53/ML ($52-68/AF) in the average scenario, and $84-97/ML ($104-119/AF) in the dry scenario.

When performance is disaggregated, however, significant differences emerge (Figure 8). District-level captured water gains for each partnership are quite heterogeneous, with some districts receiving less than average and others receiving more. This is not necessarily a problem; as long as each district's captured water gain is proportional to its ownership share and thus its share of project debt, then the costs of gains across the partnership will be uniform. However, this is found to be very uncommon. The costs of gains for Friant-16 are especially heterogeneous, spanning from under $23/ML to over $1,000/ML. This means that some districts receive more than their "fair share" of gains based on their ownership share, and others receive far less than their fair share (in fact, some districts' gains can be negative). The other two partnerships experience smaller but meaningful levels of cost heterogeneity. Interestingly, the costs for Alt-8 are much more heterogeneous under the dry scenario than the wet and average scenarios. This suggests that climate-related risk is unevenly held across the partnership, which is vital information for partners to have when planning major investments under uncertainty. If the future turns out to be drier than the historical record, then planning studies based on historical records are likely to underestimate not only the overall cost of gains from the capital project but also the level of inequality in how these costs are distributed.

District tier is generally indicative of performance across the three partnerships, but imperfectly so. The highest-performing partnership, Alt-3, is composed entirely of Tier 1 districts. In Alt-8, Tier 1 districts have the lowest costs in general, followed by Tiers 2-3. This disparity is exacerbated in the dry scenario, where Tiers 2-3 bear almost all of the negative impacts. Friant-16 displays weaker clustering, with districts from all three tiers present across the low- to mid-ranges of the cost spectrum. However, the highest costs are paid by districts in Tiers 2-3. Overall, these results are consistent with the district-level variability in Figures 3d and 5. It is better, in general, to be Tier 1 than Tier 3, but Tier 3 districts can do very well in well-designed partnerships and Tier 1 districts can do very poorly in poorly-designed partnerships.

Lastly, an important factor in the success of Alt-3 is simply the size of the partnership. All else equal, smaller coalitions are more likely to remain viable because they have fewer partners to satisfy. Smaller partnerships also deliver more water to each partner on average, which is beneficial as districts attempt to maximize their capture of surface water supplies to avoid fallowing under the Sustainable Groundwater Management Act (Hanak et al., 2020). On the other hand, many districts are incapable of accepting very large quantities of water during short-lived high-flow events, and thus may prefer a smaller ownership share within a larger partnership. Additionally, larger and more diverse partnerships will be more capable of harnessing subsidies to lower costs (Cypher & Grinnell, 2007; Hansen et al., 2020; Newsom et al., 2020).

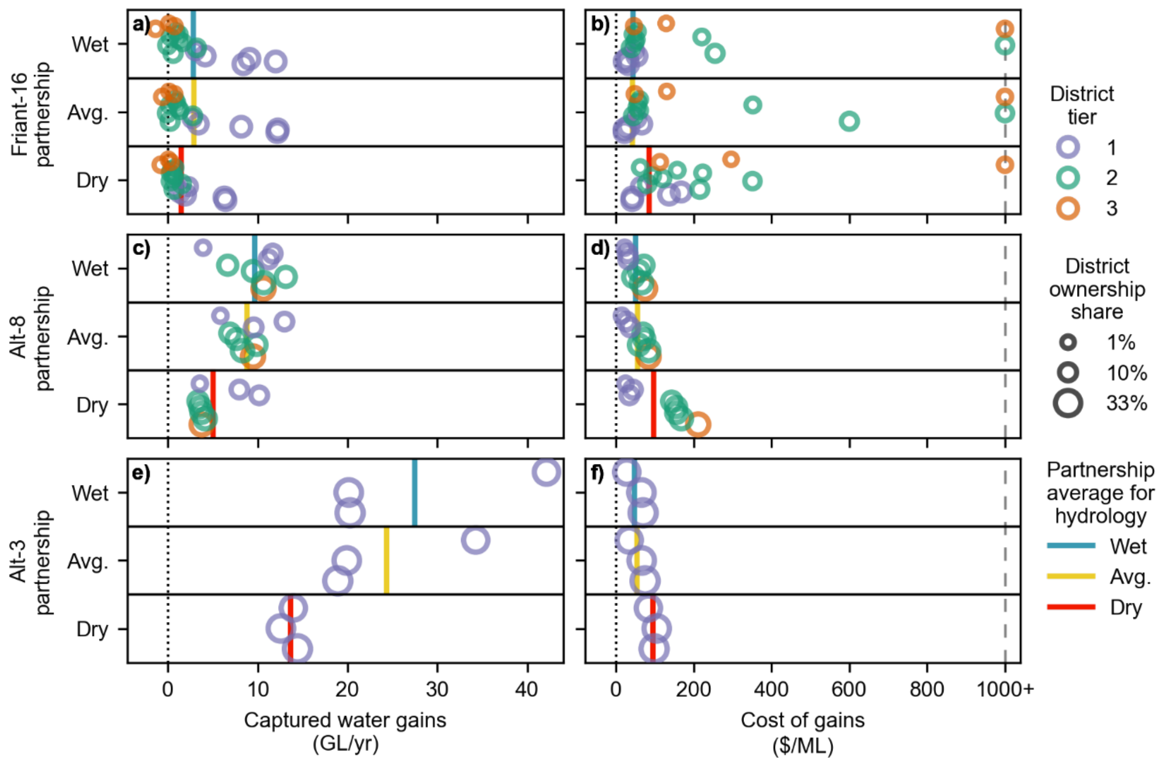

Figure 8. Comparison of three alternative infrastructure investment partnerships. Panels (a/c/e) show the captured water gains for each district in the Friant-16, Alt-8, and Alt-3 partnerships, respectively, while Panels (b/d/f) show the cost of gains for each district in these partnerships. Each panel is split into three layers showing performance on the wet, average, and dry hydrologic scenarios. Each district is represented by a circle, with color and size representing the district's tier and its ownership share in the project, respectively. Within each layer, districts are arranged by ownership share from smallest (top) to largest (bottom). The vertical blue, yellow, and red lines represent partnership-level averages under the wet, average, and dry scenarios. All costs over $1,000/ML ($1,233/AF) are consolidated into "1000+".

4 Discussion

4.1 Policy implications

This work has a number of important policy implications for regions working to adapt to water scarcity through collaborative infrastructure investments. First, these results caution against the use of highly aggregated models and mean cost-benefit performance assessments that fail to resolve specific multi-actor dynamics within complex water supply systems. Traditional capital investment planning frameworks tacitly assume that all partners will benefit equally from joint infrastructure investments, or that benefits will be distributed according to historical usage patterns. Our results show that investment partnership outcomes are often highly heterogeneous across participating water districts, highlighting the importance of disaggregation to ensure that investments provide benefits not only to the "average" partner, but to all partners. In the case of the planned Friant-Kern Canal rehabilitation project, results suggest that the business-as-usual partnership (the Friant contractors) may not be the ideal set of partners, and a wider set of regional water districts should be considered for participation. More broadly, this work highlights that contractual details regarding the operation and ownership of shared infrastructure are crucial design elements on par with physical design parameters such as conveyance capacity. Neglecting these details (a current standard practice in planning studies) can cause large errors in predicted performance.

Our results also emphasize the interconnectedness of the individual components within institutionally complex water supply systems. Multiple capital investments under consideration should be evaluated concurrently based on their interactive and cumulative effects rather than in isolation. Moreover, the bundling of multiple components into a joint portfolio of investments can yield synergistic benefits. For example, pairing canal expansion with storage infrastructure such as groundwater recharge facilities can improve the value of conveyance by increasing local capacity to store surplus flows from the canal. Groundwater banking can also widen the set of water districts willing to invest in conveyance by providing a mechanism for districts with poor local recharge capacity to store their water elsewhere. More broadly, these synergistic effects support California's vision of a flexible infrastructure network that encourages coordination and cooperation across scales.

However, this interconnectedness also amplifies the challenge of accurately evaluating capital projects within complex supply networks. For example, the local capacity for groundwater recharge (both in-district recharge and out-of-district banking) has a large impact on overall project performance, but information about groundwater recharge capacity across the region is widely dispersed and, in some cases, non-existent. Moreover, these capacities are evolving quickly as water districts adapt to new requirements under the Sustainable Groundwater Management Act (Hanak et al., 2020). This makes it difficult to accurately represent groundwater recharge within planning models and therefore to evaluate candidate capital projects. More broadly, this highlights the challenge of modeling an increasingly complex and interconnected system with data that is siloed and diffuse. The state is working to improve data availability following the Open and Transparent Water Data Act of 2016 (California Department of Water Resources, 2021), but more work is needed to inform planning efforts under the WRPI. This is a ubiquitous challenge for water resources systems globally.

Lastly, our results provide a stark picture of the impacts of a drier climate on water infrastructure investments. Even under expressly optimistic assumptions (e.g., a conservative viability threshold, a capital project with unusually high subsidies, and a limited range of hydrologic uncertainty that does not explicitly include climate warming), the vast majority of candidate partnerships are not viable under the dry scenario. Moreover, the downside risks are often borne unequally, with a subset of partners bearing the bulk of ill effects in unfavorable futures. This work thus provides a warning that poorly designed regional water infrastructure investment partnerships may provide marginal supply resiliency benefits if the future turns out to be drier than the past. Simultaneously, long-lived debt obligations from new investments (combined with existing obligations from past investments) can pose serious financial risks for water districts and their customers if benefits turn out to be lower than expected (Chapman &

Breeding, 2014; Jeffrey Hughes et al., 2014). Planning under the WRPI should consider not only water supply resilience, but also financial resilience for the organizations tasked with providing affordable water.

4.2 Future directions

Future work will extend this framework through more advanced solution-generation techniques (e.g., multi-objective evolutionary algorithms (Maier et al., 2014; Nicklow et al., 2010; Reed, Hadka, Herman, Kasprzyk, & Kollat, 2013)) and a broader exploration of robustness under climatic, economic, and regulatory uncertainties (Kasprzyk, Nataraj, Reed, & Lempert, 2013; Lempert, Groves, Popper, & Bankes, 2006; Moallemi, Zare, et al., 2020). Additionally, future work should consider whether supply and financial portfolios in water-scarce regions can be made more resilient using infrastructure real options and adaptive pathways (Fletcher, Lickley, & Strzepek, 2019; Haasnoot, Kwakkel, Walker, & ter Maat, 2013; Herman, Quinn, Steinschneider, Giuliani, & Fletcher, 2020), flexible partnership design (Gorelick et al., 2019), or novel financial tools such as environmental impact bonds or index insurance contracts (Brand et al., 2021; Maestro, Barnett, Coble, Garrido, & Bielza, 2016; Zeff & Characklis, 2013). Lastly, this work has focused primarily on equality at the water district level (i.e., whether costs are equally distributed across partners) as opposed to equity and justice (Jafino et al., 2021; Osman & Faust, 2021) (i.e., whether different water districts and their customers have differing access to water and differing ability to pay for infrastructure, and how these differences intersect with economic and political power, racial injustice, and responsibility for historical groundwater overdraft and subsidence) (Dobbin & Lubell, 2021; Fernandez-Bou et al., 2021; Pauloo et al., 2020). Explicit consideration of these issues in direct co-production with disadvantaged communities (Lemos et al., 2018; Minkler, Vásquez, Tajik, & Petersen, 2008) will be an important extension of this study in light of the WRPI's stated goal of alleviating the growing water affordability challenge.

5. Conclusions

Population growth, groundwater overdraft, and climate change represent an unprecedented challenge to water security in California, the Western US, and other water-stressed regions around the world. The Water Resilience Portfolio Initiative provides a vision for bolstering the state's water supplies through an interconnected, collaborative, and flexible *water system of systems* (Newsom et al., 2020), and represents not only a roadmap for California, but also a potential template for other regions looking to develop their own resilient water supply portfolios. For such a vision to work, individual water providers within the broader system will need to collaborate in financing and building new shared infrastructure. However, traditional planning frameworks based on highly aggregated models and mean cost-benefit estimates are ill-equipped to evaluate multi-party investment partnerships due to the significant complexities and uncertainties within the distributed supply network. In this paper, we demonstrate the need to evaluate partnerships at the level of individual water providers, and the challenge of designing partnerships that can provide acceptable water supply benefits to each partner relative to its share of project debt.

We leverage a high-resolution water supply simulation model within a parallelized exploratory modeling framework in order to explore alternative partnership structures, capital projects, and hydrologic scenarios at an unprecedented scale. Even under explicitly optimistic assumptions regarding climate change and other uncertainties, we find that vast majority of alternative partnership structures tend to deliver water supply benefits and financial risks that are highly uneven, threatening the viability of these cooperative investments. Designing viable partnerships is especially challenging under drier hydrologic conditions, when insufficient surplus water is available to warrant the investment in additional conveyance and storage infrastructure. Additionally, our results demonstrate the synergy between conveyance and storage for capturing surplus water during peak flow events; partnerships may be more likely to succeed if they can combine multiple pieces of infrastructure that interact positively. Importantly, however, partnership design choices (i.e., which water providers are participating, and how do they distribute the project's debt obligation?) may be even more important to the success of a partnership than the future hydrology or the type of infrastructure. As a whole, this research investigates several under-studied challenges in the evaluation and planning of new infrastructure investment partnerships within complex water supply networks. Confronting these challenges will be crucial if California and other regions are to achieve their resilient water portfolio goals.

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Open research

All data and code for this project, including figure generation, will be made available on GitHub and Zenodo prior to publication.

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