Forecast-Informed, Market-Responsive Conjunctive Operations for Multi-Reservoir Water–Energy Systems

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Focal Area(s)

This paper addresses the water-for-energy nexus through co-optimized hydropower and cascading reservoir operations, managed alongside flood risk, environmental constraints, and conjunctive surface–groundwater storage (Ploussard et al., 2025). It also addresses the energy-for-water nexus through flexible scheduling of energy-intensive water activities, such as Managed Aquifer Recharge (MAR) and conveyance pumping. These operations have the potential to be coordinated through forecast-informed decisions with exogenous electricity price signals, using cross-sector tools that link ensemble forecasts to operations via risk-aware optimization and real-time water-value analytics. We adopt Forecast-Informed Reservoir Operations (FIRO) principles as a decision-support framework that leverages meteorological and/or hydrologic forecasts, uncertainty quantification, and operational constraints to inform storage, release, spill, recharge, and pumping decisions across time and space (Delaney et al., 2020). In this white paper, FIRO is proposed as a modular, reproducible workflow with common data and interface standards, not a single model or codebase, designed for consistent implementation across basins and agencies. Related FIRO–MAR work (e.g., by California Department of Water Resources (DWR)) provides important precedent (California-DWR, 2018), and this effort explicitly emphasizes energy-system coupling, including conveyance energy optimization. As an example of implementation focus and significance, the Central Valley Project (CVP)/State Water Project (SWP) system is a candidate pilot; the SWP is among the largest electricity consumers in California Independent System Operator (CAISO), and conveyance energy costs and timing are central to water delivery. Sub-watershed granularity will be used where operationally relevant to represent routing, travel-time lags, and constraints, while allowing hydrologic forecasts to be provided by partner systems.

Existing Challenge

While FIRO has proven valuable at single-reservoir scales, practices and tools across agencies are heterogeneous, which limits portability across multi-reservoir cascades. Heterogeneity includes terminology, data schemas, objective formulations, and implementation details, and makes cross-site comparability and scaling costly. Notably, several groups, including the U.S. Army Corps of Engineers (USACE), have advanced formulaic and well-documented approaches. Reproducibility has improved within these efforts, yet broader standardization and interoperability across agencies, models, and basins remain open challenges. USACE have initiated multi-reservoir work (e.g., in the Willamette Valley), but nothing on the size and institutional complexity of the California Central Valley has yet been demonstrated. Conjunctive surface–groundwater operations are often omitted in current practice; MAR and aquifer storage/recovery are rarely co-optimized with reservoir releases, limiting drought mitigation, seasonal carryover, and flood-mitigation synergies. Ensemble-aware routing and explicit uncertainty propagation are underutilized; they inhibit the quantification of how upstream releases shift downstream exceedance probabilities, expected annual damages, and environmental compliance thresholds (e.g., temperature targets). Although risk-aware methods for flood control have progressed, including chance constraints and related formulations, since at least (Delaney et al., 2020), their consistent encoding alongside energy and groundwater objectives is still uncommon. A timescale gap persists: many flood-control models operate daily or 6-hourly, whereas hydropower revenues and pumping costs are highly sensitive to sub-daily (hourly to 6-hourly) price variation. Energy-market coupling is limited: hydropower scheduling and water-sector loads (e.g., recharge or conveyance pumping) are not consistently co-optimized with locational marginal prices and peak-load impacts, even when prices are available as exogenous inputs. Finally, real-time marginal water values are rarely exposed to operators, which limits transparent tradeoff navigation among hydropower revenues, spill-bypass reduction, flood-damage risk, environmental obligations, and groundwater banking benefits under forecast uncertainty.

Near-Term Opportunity (3-5 Years)

We think there is a need to develop and pilot a reproducible, open framework that operationalizes FIRO principles for multi-reservoir cascades with conjunctive surface–groundwater management and explicit energy coupling. The framework will standardize workflow and data schema to enable consistent deployment across basins, featuring clear interfaces, consistent units/coordinate references, and documented uncertainty handling. The system will ingest ensemble meteorological forecasts and/or ensemble hydrologic forecasts (e.g., Hydrologic Ensemble Forecast System (HEFS), (Brown et al., 2014)) and route flows across river networks, accounting for travel-time lags and sub-watershed connectivity. Hydrologic forecasting components will be modular; pilots may rely on partner-provided forecasts to focus effort on operations optimization. Operations will be optimized using method-agnostic approaches appropriate to the pilot (e.g., model predictive control, linear, quadratic/convex, mixed-integer, or stochastic programming as needed), with explicit risk management. Risk-aware formulations may include chance constraints to bound the probability of exceeding downstream flood-stage thresholds and coherent risk measures such as Conditional Value-at-Risk (CVaR) to manage tail risks in flood damages and shortages (Rockafellar and Uryasev, 2000). Alternative risk formulations will be supported to suit stakeholder preferences and data. Real-time water-value analytics will expose marginal values (shadow prices) for surface storage, groundwater banking, and conveyance pumping that internalize energy revenues, spill/bypass opportunity costs, expected flood damages, shortage penalties, and recharge benefits. Electricity prices (e.g., day-ahead/hour-ahead Locational Marginal Price (LMP)s) will be treated as exogenous inputs. The framework will not clear markets but will schedule hydropower and flexible water-sector pumping price-responsively, exploit low-price periods, provide eligible ancillary services where applicable, and mitigate peaks. A rigorous backtesting and benchmarking harness will: Compare against established baselines without FIRO-style coordination (e.g., existing rule curves or established tools such as California Flood-Managed Aquifer Recharge and Environmental Water Supply (CALFEWS) or Plan Formulation and Evaluation Model (PFEM), depending on pilot), and evaluate FIRO variants and emphasize different objectives (Brodeur et al., 2025): (i) maximize reservoir storage subject to flood/environmental constraints, (ii) maximize total storage (surface plus groundwater recharge/recovery), and (iii) maximize hydropower value, alongside explicit multi-objective optimization that produces Pareto tradeoff sets rather than relying on fixed scalar weights. To support portability and collaboration, we will define a standardized Application Programming Interface (API) and data contract for FIRO components, harmonize time-series formats, metadata fields, units, coordinate references, and uncertainty representations. This contract will define inputs (ensemble forecasts, observations, exogenous prices) and outputs (recommended releases, recharge/pumping schedules, storage targets, and uncertainty/risk summaries). Orchestration of forecast ingestion and optimization will be containerized and scripted for reproducibility. Visualization and reporting will be built around 'operator-in-the-loop' dashboards that transparently present multi-objective tradeoffs, marginal water values, risk profiles, and recommended actions, enabling human selection among Pareto-efficient options when weights are contentious (Zaniolo, Mauter, and Fletcher, 2025).

Solution Approach and Scale: The proposed regional effort focuses on research, development, and demonstration of coupled water–energy optimization in simulation and pilot settings across at least one multi-utility cascade. The scale addresses facility-level operations with explicit conjunctive surface–groundwater coupling through calibrated conceptual banks or, where feasible, integrated groundwater models. The operations approach co-optimizes reservoirs, hydropower units, and water-sector pumps, using forecast-informed pre-releases to reduce expected annual flood damages and create recharge opportunities, while supporting drought planning and environmental compliance. Where advantageous, we will leverage and interface with existing modeling environments (e.g., CALFEWS or PFEM for planning/operations benchmarking) and existing Model Predictive Control (MPC) prototypes (e.g., Python-based toolchains) from partners to accelerate development. Conveyance energy is a first-order focus: FIRO-style coordination will be used to shift pumping into more energy-efficient, lower-price hours, subject to hydraulic and delivery constraints.

Success Measure

Success will be demonstrated through statistically significant resilience and economic gains in a pilot cascade over sufficiently long hindcast periods and multiple operational seasons, with subsequent adoption by multiple entities. Hindcast durations will be tailored to the pilot and data availability, leveraging multi-decadal records where possible (e.g., California Nevada River Forecast Center (CNRFC) hindcasts from 1990–2023 at daily to annual horizons and hourly to 14-day horizons). Improvements should be attributable to standardized FIRO workflows and reproducible interfaces, and portable across sites and teams without extensive retooling. Operator usage of real-time water-value signals and multi-objective tradeoff dashboards in decision briefings will mark practical uptake. Public releases of datasets, code, and results will enable independent replication and validation.

Metrics and Evaluation: Metrics and evaluation will proceed through controlled comparisons against established

baselines, including a no-FIRO baseline reflecting existing practices (and, where appropriate, benchmarking against tools such as CALFEWS or PFEM), and will encompass FIRO variants that emphasize single objectives (maximize reservoir storage; maximize total storage including groundwater recharge/recovery; maximize hydropower value) as well as explicit multi-objective decision support that presents Pareto tradeoffs across flood risk, drought reliability, energy value and cost, environmental metrics, and groundwater outcomes. Energy-for-water and water-for-energy performance will be quantified by increases in hydropower market value (energy and eligible ancillary services) from forecast-informed scheduling using exogenous prices; reductions in spill and bypass and improved turbine utilization during high inflows; and conveyance energy metrics including energy intensity (kWh per acre-foot), reductions in LMP-weighted pumping costs, the fraction of pumping shifted to low-price/low-emission hours, mitigation of coincident peaks at pumping plants, and contributions to ramping flexibility. Flood-risk outcomes will be measured by reductions in the probability of exceeding downstream flood-stage thresholds during atmospheric rivers and by reductions in expected annual flood damages computed via ensemble-aware routing. Water supply, groundwater, and environmental outcomes will be assessed by increases in seasonal managed aquifer recharge and end-of-season carryover storage; improvements in drought-reliability metrics (e.g., supply reliability, shortage frequency and severity); stabilization or recovery of groundwater levels and storage; and maintenance or improvement of environmental flow and temperature compliance. Resilience will be defined and quantified across domains: flood resilience as the ability to keep stage below thresholds and reduce expected damages under forecast uncertainty; drought resilience as the ability to meet demands via conjunctive use and carryover storage during dry spells; energy resilience as the capability to reduce coincident peaks, shift loads to resilient periods, and provide flexibility without compromising water objectives; and operational robustness via satisfaction of chance constraints and management of tail risks (e.g., CVaR). Statistical rigor will be ensured through controlled A/B backtests over long hindcasts, bootstrap tests for significance, and attribution via Observing System Experiment (OSE) and Observing System Simulation Experiment (OSSE) that relate changes in forecast skill (e.g., improvements in Continuous Ranked Probability Score (CRPS)) to operational benefits with positive cost–benefit ratios. Standard forecast and performance metrics (CRPS, Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), Kling-Gupta Efficiency (KGE), reliability/availability indices) will be reported alongside sector-specific drought, flood, and energy indices, and uncertainty and sensitivity analyses using ensemble forecasts and scenario ranges will identify key drivers and guide sensor placement and data assimilation priorities (Brown et al., 2014). Evaluations will be performed at appropriate temporal resolutions (e.g., daily or 6-hourly for flood and hydrology, hourly for energy and pumping).

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