

AGRICULTURAL WATER REUSE IN CALIFORNIA: CLIMATE RESILIENCE LESSONS

LA RÉUTILISATION DE L'EAU DANS L'AGRICULTURE EN CALIFORNIE : LES ENSEIGNEMENTS EN MATIÈRE DE RÉSILIENCE CLIMATIQUE

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ABSTRACT

Agricultural water reuse is becoming an increasingly important strategy for improving water security in semi-arid regions facing recurrent droughts, groundwater depletion, seawater intrusion, and competition among users. California provides one of the most mature examples of agricultural recycled water implementation, with more than three decades of experience across coastal, inland valley, and desert farming systems. This paper synthesizes the evolution, agronomic relevance, economic constraints, and future direction of agricultural water reuse in California, with emphasis on practical lessons for climate-resilient irrigation management. The analysis is based on a comparative review of mature and emerging systems, including Monterey One Water, Pajaro Valley Water Management Agency, NapaSan, Del Puerto Water District, Eastern Municipal Water District, Coachella Valley Water District, Escondido MFRO/AgX MFRO, and Harvest Water. Particular attention is given to the Monterey Wastewater Reclamation Study for Agriculture and the NapaSan vineyard studies, which provided long-term evidence on food-crop safety, salinity, ion toxicity, and grower confidence. The reviewed systems show that successful agricultural reuse depends not only on treatment capacity but also on basin-scale planning, conveyance infrastructure, cost-sharing, grower participation, water-quality monitoring, and agronomic management. Coastal systems demonstrate the role of reuse in reducing groundwater pumping and controlling seawater intrusion, whereas inland and desert systems highlight its value for supply reliability, groundwater protection, and nutrient management.

Emerging projects point toward crop-specific advanced treatment and reuse integrated with groundwater recharge and environmental co-benefits. California's experience demonstrates that agricultural reuse is no longer only a drought-response measure, but a structural component of diversified water portfolios. These lessons are relevant for Mediterranean and other semi-arid regions seeking to integrate recycled water, groundwater sustainability, advanced treatment, and resilient agricultural production under increasing climate uncertainty.

Keywords: Agricultural water reuse; groundwater protection; nutrient management; drought-response measure; climate uncertainty.

RÉSUMÉ

La réutilisation de l'eau agricole devient une stratégie de plus en plus importante pour améliorer la sécurité hydrique dans les régions semi-arides confrontées à des sécheresses récurrentes, à l'épuisement des nappes phréatiques, à l'intrusion d'eau de mer et à la concurrence entre les utilisateurs. La Californie offre l'un des exemples les plus aboutis de mise en œuvre de la réutilisation de l'eau agricole, avec plus de trois décennies d'expérience dans les systèmes agricoles côtiers, des vallées intérieures et des zones désertiques. Cet article synthétise l'évolution, la pertinence agronomique, les contraintes économiques et les perspectives de la réutilisation de l'eau agricole en

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Californie, en mettant l'accent sur les enseignements pratiques pour une gestion de l'irrigation résiliente au changement climatique. L'analyse repose sur une étude comparative de systèmes matures et émergents, notamment Monterey One Water, la Pajaro Valley Water Management Agency, NapaSan, le Del Puerto Water District, l'Eastern Municipal Water District, le Coachella Valley Water District, l'Escondido MFRO/AgX MFRO et Harvest Water.

Une attention particulière est accordée à l'étude de Monterey sur la récupération des eaux usées à des fins agricoles ainsi qu'aux études menées par NapaSan dans les vignobles, qui ont fourni des données à long terme sur la sécurité des cultures vivrières, la salinité, la toxicité ionique et la confiance des agriculteurs. Les systèmes examinés montrent que la réussite de la réutilisation agricole dépend non seulement de la capacité de traitement, mais aussi de la planification à l'échelle du bassin, des infrastructures de transport, du partage des coûts, de la participation des agriculteurs, de la surveillance de la qualité de l'eau et de la gestion agronomique. Les systèmes côtiers démontrent le rôle de la réutilisation dans la réduction du pompage des eaux souterraines et le contrôle de l'intrusion d'eau de mer, tandis que les systèmes de l'intérieur des terres et des zones désertiques soulignent son intérêt pour la fiabilité de l'approvisionnement, la protection des eaux souterraines et la gestion des nutriments.

Les projets émergents s'orientent vers des traitements avancés chaque culture et des solutions de réutilisation intégrée à la recharge des nappes phréatiques, avec des avantages collatéraux pour l'environnement. L'expérience californienne démontre que la réutilisation agricole n'est plus seulement une mesure de réponse à la sécheresse, mais une composante structurelle de portefeuilles hydriques diversifiés. Ces enseignements sont pertinents pour les régions méditerranéennes et autres régions semi-arides cherchant à intégrer l'eau recyclée, la durabilité des nappes phréatiques, les traitements avancés et une production agricole résiliente dans un contexte d'incertitude climatique croissante.

Mots-clés : Réutilisation de l'eau agricole; Protection des eaux souterraines; Gestion des nutriments; Mesure de réponse à la sécheresse; Incertitude climatique.

1. INTRODUCTION

Agricultural production in semi-arid regions is increasingly constrained by recurrent droughts, groundwater depletion, seawater intrusion, rising water demand, and stricter environmental regulations. These pressures are particularly relevant in irrigated agricultural areas where high-value crops depend on reliable supplies but conventional water sources are becoming less reliable. In this context, recycled water is no longer considered only an emergency or supplemental resource, but an increasingly important component of diversified and climate-resilient agricultural water portfolios (California Natural Resources Agency, 2022; The Water Research Foundation, 2019).

California provides one of the most advanced examples of agricultural water reuse at the regional scale. Recycled water has been incorporated into irrigation systems serving coastal vegetable production, berry crops, vineyards, citrus, avocado, desert agriculture, and mixed farming systems. State planning documents identify recycled water expansion as a priority for adapting to hotter and drier conditions, improving local reliability, and reducing pressure on overused freshwater resources (California Natural Resources Agency, 2022; California State Water Resources Control Board, 2024).

The Californian experience is especially relevant because it combines infrastructure development with long-term agronomic sustainability. Monterey provided a pioneering validation of recycled water for food crops consumed raw, while NapaSan provided long-term evidence for vineyard irrigation under managed salinity and nutrient conditions (Sheikh et al., 1990; Weber et al., 2014; Beutel et al., 2024). Other systems, including Pajaro Valley, EMWD, and Coachella rely more strongly on operational monitoring, blending, and regional water-quality management. Large regional projects such as Del Puerto illustrate supply substitution, whereas Escondido MFRO and Harvest Water represent emerging models focused on crop-specific quality, groundwater recharge, and basin-scale resilience (Richardson, 2017; The Water Research Foundation, 2023).

This paper synthesizes the evolution, agronomic relevance, economic feasibility, and future opportunities of agricultural recycled water reuse in California. Its objective is to identify practical lessons for Mediterranean and other semi-arid regions where agriculture faces similar challenges related to water scarcity, salinity, groundwater overdraft, and climate uncertainty.

2. EVOLUTION AND CASE-STUDIES

California's agricultural water reuse trajectory has evolved through several stages. Initially, recycled water was developed mainly as a local response to drought, wastewater disposal constraints, groundwater depletion and seawater intrusion along the coast. Over time, it became increasingly linked to regional water supply planning, aquifer protection and climate adaptation. Figure 1 illustrates the evolution of agricultural recycled water reuse in California and the major policy and climate drivers shaping its expansion.



Figure 1. Evolution of agricultural recycled water reuse in California

The earliest and most influential agricultural reuse experience was developed in Monterey County. The Monterey Wastewater Reclamation Study for Agriculture, initiated in 1976, provided one of the first long-term evaluations of recycled water for irrigating food crops consumed raw. The later Castroville Seawater Intrusion Project built on this evidence and became an international reference for the use of tertiary-treated recycled water in high-value vegetable production under strict monitoring conditions (Sheikh et al., 1990; Monterey One Water, 2024).

A second phase was characterized by the expansion of recycled water as a tool for groundwater protection and basin-scale management. In coastal basins such as the Salinas and Pajaro valleys, recycled water became part of broader strategies to reduce groundwater pumping and slow seawater intrusion. In Pajaro Valley, the Coastal Distribution System supplies blended water to coastal farmland, combining recycled water with other sources to reduce dependence on groundwater and protect freshwater aquifers (The Water Research Foundation, 2019; Mendiola, 2025).

Inland and desert systems expanded in response to supply reliability challenges. Del Puerto and the North Valley Regional Recycled Water Program illustrate large-scale inland supply substitution, whereas

EMWD and Coachella show how recycled water can support agriculture in regions where urban demand, groundwater protection, and imported-water limitations interact. NapaSan provides one of the clearest examples of agronomic validation for perennial crops, with recycled water supporting vineyards, golf courses, and landscape irrigation in Napa Valley. In 2024, NapaSan reported 3.10 million m³ of recycled water use, including 0.96 million m³ for vineyards (NapaSan, 2025).

Emerging systems such as Escondido MFRO/AgX MFRO and Harvest Water illustrate the new generation of agricultural water reuse. Escondido uses membrane filtration and reverse osmosis to produce low-salinity water suitable for sensitive crops such as avocado and citrus. Harvest Water, in the Sacramento region, is designed to deliver up to 61.7 million m³/year of recycled water to more than 6,475 ha while supporting groundwater recovery and environmental co-benefits (Regional San, 2025; Richardson, 2017). Figure 2 shows the location of the main case-study systems considered in this paper.



Figure 2. Geographic distribution of major agricultural recycled water reuse systems in California

3. AGRONOMIC PERFORMANCE AND WATER-QUALITY MANAGEMENT

Agronomic performance is one of the critical factors determining the long-term success of agricultural recycled water reuse. The evidence base varies among projects. Monterey and Napa are supported by specific studies that evaluated crop safety, soil salinity, and ion accumulation. Pajaro Valley, EMWD and Coachella rely more strongly on operational monitoring, blending and adaptive water-quality management, while Escondido and Harvest Water are moving toward crop-specific quality and integration with recharge.

The Monterey experience demonstrated that agronomic acceptance required more than compliance with health regulations: it required evidence that recycled water would not reduce crop quality, affect marketability or generate unacceptable soil and salinity impacts. Napa provides complementary evidence for perennial crops. The recycled water used in vineyard studies had moderate salinity, with average EC of approximately 0.95 dS/m, SAR close to 3.9, chloride around 4.3 meq/L and boron around 0.4 mg/L. Field soil samples after long-term use showed saturated-paste electrical conductivity below 0.8 dS/m, below the grapevine yield threshold, and the studies concluded that recycled water did not cause salinity or ion-toxicity problems under local conditions (Weber et al., 2014; Beutel et al., 2024). Salinity, sodicity and specific-ion toxicity remain the most important agronomic concerns. Recycled water may contain higher concentrations of sodium, chloride, bicarbonate and nutrients than conventional surface water or high-quality groundwater. These constituents may affect soil structure, infiltration, crop uptake and root-zone salinity. Therefore, successful reuse systems include regular monitoring of EC, SAR, chloride, boron, nitrogen, pH and, increasingly, broader cation balance. Where

necessary, these risks are managed through blending, source control, leaching management, gypsum application, crop selection, rootstock selection and advanced treatment (Kisekka et al., 2024a; Kisekka et al., 2024b).

Recent research has questioned the sufficiency of SAR alone as an indicator of soil structural risk. SAR remains useful because it is reported in historical datasets and regulatory monitoring, but it does not fully capture the effects of potassium and magnesium on soil permeability and aggregate stability. CROSS has been proposed as an improved index because it incorporates the dispersive effect of potassium and differentiates the flocculating effect of magnesium from calcium (Rengasamy and Marchuk, 2011; Smith et al., 2015; Oster et al., 2016; Qadir et al., 2021). This is particularly relevant for modern reuse programs that require dynamic interpretation of water quality rather than fixed thresholds alone.

Since the earliest studies, advances in irrigation scheduling, pressure-compensated drip systems, soil and plant sensors, remote sensing, variable-rate irrigation, tolerant cultivars and rootstocks, and decision-support tools have increased the capacity to predict and mitigate soil and crop risks. The main agronomic risks and management strategies are summarized in Table 1.

Table 1. Main agronomic risks and management strategies in agricultural recycled water reuse

Parameter / issue	Main risk	Management strategy
Electrical conductivity	Root-zone salinity and yield reduction	EC monitoring, blending, leaching management, and crop selection
SAR and CROSS/cation balance	Soil structural degradation, clay dispersion, and reduced infiltration	Use SAR for continuity with historical datasets, but incorporate CROSS with EC where K and Mg are relevant
Chloride and boron	Specific-ion toxicity in sensitive crops and rootstocks	Source control, blending, reverse osmosis where needed, tolerant cultivars, and rootstocks
Nitrogen, phosphorus, and potassium	Potential nutrient imbalance or nitrate leaching	Nutrient budgeting, fertigation adjustment, soil and tissue testing
pH, alkalinity, and clogging risk	Emitter clogging and reduced distribution uniformity	Filtration, flushing, acidification, where needed, and drip-system maintenance
Pathogens and food safety	Risk for crops consumed raw and occupational exposure	Tertiary treatment, disinfection, Title 22 compliance, and multi-barrier approaches
Emerging contaminants and recharge risks	Uncertain long-term soil, crop, or groundwater impacts	Risk-based monitoring, advanced treatment where justified, and soil-aquifer assessment

4. ECONOMIC AND INSTITUTIONAL FEASIBILITY

Agricultural recycled water reuse in California has expanded not only because treated wastewater was available, but because regulatory, economic, and institutional tools created incentives for utilities, irrigation districts, groundwater agencies, and growers to use it as part of regional water management. Title 22 provided a clear framework for safe non-potable reuse, while SGMA created a stronger incentive for alternative supplies in overdrafted basins. These instruments reduced uncertainty and helped connect reuse with groundwater sustainability, seawater intrusion control, and basin-scale planning (Olivieri et al., 2020; California Natural Resources Agency, 2022).

Economic feasibility remains a major constraint. Technologies for treatment and advanced reuse are available, but high capital costs, energy requirements, distribution infrastructure, brine management, and institutional barriers can limit implementation (Edirisooriya et al., 2023; Sedlak et al., 2025). In

agricultural water reuse, treatment is necessary, but conveyance and distribution infrastructure often determine feasibility because wastewater treatment plants are usually located near urban areas, while agricultural demand may be far away. Cost-sharing mechanisms, grants, loans, assessment districts, user fees, and long-term agreements are therefore essential.

Table 2 summarizes the main cost components using SI units. Values are indicative because projects report costs using different accounting methods and because site conditions, distance, topography, pumping, pipe diameter, and farm density strongly affect costs. All monetary values are reported in USD, while volumes and areas are converted to SI units for comparability.

Table 2. Indicative cost structure of agricultural recycled water reuse systems in California

Cost component	Typical expression	Indicative values from California projects	Main interpretation
Treatment/upgrading	USD/m ³ or CAPEX	NapaSan expanded recycled-water capacity from 2.47 to 4.56 million m ³ /year	Necessary, but often only part of the total reuse cost
Advanced treatment	USD/m ³ or CAPEX	Escondido MFRO / AgX MFRO uses membrane filtration and reverse osmosis for low-salinity water	Costs increase when crop-specific quality is required
Conveyance	USD/km or USD/m ³ /km	NVRRWP estimated capital cost: USD 82.5 million for regional conveyance infrastructure	Often, the main cost driver when farms are far from treatment plants
Distribution network	USD/ha served	Pajaro Valley uses a >34 km Coastal Distribution System serving >2,225 ha	Infrastructure-heavy when farms are spatially dispersed
On-farm connection	USD/farm or USD/ha	Napa MST estimated up to USD 2,000/year for 20 years for small properties, excluding on-site improvements	Can affect grower participation
Operation and maintenance	USD/m ³	NVRRWP estimated O&M at about USD 0.024/m ³ , in addition to base water price	Depends on pumping, monitoring, and treatment complexity
Delivered water price	USD/m ³	NapaSan 2024 cost: USD 0.62/m ³ ; NVRRWP base water price capped at about USD 0.18/m ³ plus O&M	Must remain acceptable relative to alternative supplies
Cost-sharing mechanisms	Grants, loans, bonds, fees, assessments	NapaSan received >USD 4 million in grants; Pajaro uses grants, loans, bonds, and user fees	Essential to overcome high upfront CAPEX

These examples confirm that agricultural reuse should not be evaluated only through the unit treatment cost of recycled water. The main constraint is often the capital investment required to convey and distribute water to farms. For Mediterranean regions, reuse planning should therefore compare not only treatment costs, but also distance to demand areas, conveyance needs, farm density, storage requirements and the possibility of cost-sharing among beneficiaries.

5. LESSONS LEARNED AND FUTURE OPPORTUNITIES

The reviewed California experience suggests that agricultural recycled water reuse is most successful when it is planned as part of a broader water-management strategy rather than as an isolated wastewater-disposal option. The strongest projects are problem-oriented: they address seawater intrusion, groundwater overdraft, unreliable imported supplies, salinity management, nutrient recovery or crop-specific quality constraints. This confirms a broader trend identified in the recent literature: non-conventional water resources are becoming structural components of water-security strategies rather than supplementary emergency sources (Medellin-Azuara et al., 2024; Hanak et al., 2021).

A first lesson is that clear regulation and transparent monitoring are indispensable. Agricultural water reuse requires confidence building among regulators, utilities, growers, food companies, and consumers. The Monterey and Napa experiences show that long-term field evidence on crop safety, soil salinity, ion toxicity, and nutrient inputs can transform recycled water from a perceived risk into a managed irrigation resource. However, water-quality constraints remain critical, especially where

salinity, sodium, chloride, boron or emerging contaminants interact with sensitive crops and soils (Drechsel et al., 2023; Kisekka et al., 2024a).

A second lesson is that groundwater policy is changing the role of reuse. SGMA makes groundwater sustainability unavoidable in many agricultural basins, increasing the need for alternative supplies, recharge, water banking, demand management, and land-use adaptation. Recycled water cannot fully avoid agricultural restructuring, but it can reduce the scale of disruption where it is integrated with groundwater sustainability planning and cost-effective conveyance (Hanak et al., 2021; California Natural Resources Agency, 2022).

A third lesson is that future reuse will depend on integration rather than single-solution approaches. Hybrid systems combining recycled water, desalinated or brackish water, surface water, managed aquifer recharge, blending, and digital monitoring can provide greater flexibility under drought and climate uncertainty. Emerging projects such as Escondido MFRO and Harvest Water point toward crop-specific water-quality design and multi-benefit reuse, where irrigation supply, aquifer recovery, ecosystem support, and climate adaptation are considered together (Sedlak et al., 2025; Richardson, 2017). The transferability of California's experience to Mediterranean regions is high, but not automatic. Lower rainfall, higher evaporative demand, fragmented governance, different crop sensitivities, and smaller farm structures may increase salinity and financial risks. Therefore, the California model should be transferred as a set of principles - regulation, agronomic evidence, cost-sharing, grower participation, basin-scale planning, and adaptive water-quality management - rather than as a fixed technical template.

6. CONCLUSIONS

- Agricultural recycled water reuse in California has evolved from a drought-response or wastewater-disposal measure into a structural component of diversified and climate-resilient water portfolios.
- The most robust systems are those linked to clearly defined basin-scale problems, including seawater intrusion, groundwater overdraft, unreliable imported supplies, and the need for aquifer recovery.
- Long-term agronomic validation remains essential for grower acceptance, especially for food crops consumed raw, vineyards, and sensitive perennial crops.
- Treatment level alone does not guarantee sustainability; salinity, sodicity, chloride, boron, nutrients, soil properties, crop sensitivity, and leaching conditions must be managed together.
- SAR remains useful for continuity with historical and regulatory datasets, but CROSS provides a more complete interpretation of soil structural risk where potassium and magnesium are relevant.
- Economic feasibility is often constrained more by conveyance, distribution, and on-farm connection infrastructure than by treatment alone.
- The future of agricultural water reuse lies in integrated systems combining reuse, blending, advanced treatment, managed aquifer recharge, digital monitoring, and groundwater sustainability planning.
- For Mediterranean and other semi-arid regions, California's main contribution is not a single model to copy, but a set of transferable principles: clear regulation, agronomic management, grower participation, economic feasibility, water-quality management, and basin-scale coordination.

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