Supplementary material for From irrigation efficiency to sustainable basin water management

This supplement provides study characteristics and sources (S1), contextual variables (S2), model derivations and sensitivity calculations (S3), comparisons of reported effects (S4), considerations for future field evaluation (S5), and literature-search and screening methods (S6). The accompanying Supporting_Data folder contains the records and calculation files named in S6.4.

S1 Study characteristics and data sources

Table S1 describes 41 publications discussed in detail. The detailed cases were selected to explain technology adoption, area and crop responses, water reuse and allocation across farm, irrigation-district and basin scales, and to compare findings from different research designs. Table S1 identifies the design and purpose of each publication; reviews and residential-demand studies serve as background, while companion reports supply measurement detail. Table S5 examines the outcomes and comparison conditions in six studies spanning adoption, infrastructure support, historical water accounts and economy-wide modeling. Section S6 describes the selection of reports for the full evidence inventory. Citation numbers follow the main-text bibliography.

Source versions used for detailed numerical comparisons are identified below. The same version labels and source locations are retained in the calculation files.

Kansas author manuscript: https://mcameronharp.com/wp-content/uploads/2024/05/cameronharp_hendricks_irrigation-tech-transition.pdf

South India World Bank working paper: https://documents1.worldbank.org/curated/en/475611624561753275/pdf/Efficient-Irrigation-and-Water-Conservation-Evidence-from-South-India.pdf

Australia published article: https://digital.library.adelaide.edu.au/server/api/core/bitstreams/9717249f-6e2e-483f-b472-9134b608a53b/content

Spain author manuscript: https://helvia.uco.es/xmlui/bitstream/handle/10396/21945/1_energized%20water-3.pdf?isAllowed=y&sequence=1

Idaho publisher article: https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2023.1188139/full

Table S1. Characteristics and findings of the studies discussed in the main text.

The table records study designs, measured or modeled water quantities, principal findings and the conditions relevant to comparison. Studies from the same region are distinguished from reports based on shared datasets or the same intervention.

Study and setting	Design and comparison	Water quantity and principal finding	Context for comparison
Ward and Pulido-Velazquez (2008) [4]; Irrigated agricultural system	Hydro-economic comparison of efficiency-subsidy and model-baseline scenarios	Applications; consumptive use. Subsidies can reduce water applications while increasing consumptive use within the modeled system.	The model combines farm decisions, water allocation and connected flows within the study system.
Berbel et al. (2015) [5]; Spain	Literature review with a Spanish modernization case	Deliveries; land; production indicators. Modernization outcomes vary across production and programme conditions.	The reviewed programs combine infrastructure changes with changes in management and institutions.
Lankford (2023) [8]; Irrigated systems	Analytical irrigation and depletion accounting under alternative allocations	Depletion; evapotranspiration; recoverable flows; reallocation. Reducing non-productive evaporation can permit depletion savings.	The analysis relates irrigation flows to depletion and the allocation of water released by an intervention.
Pfeiffer and Lin (2014) [11]; Western Kansas, USA	Econometric analysis of conventional-center-pivot to dropped-nozzle adoption	Groundwater extraction; crop choices. Reported extraction increases after adoption were associated partly with crop changes.	The study concerns a particular irrigation transition in western Kansas. Aquifer implications also depend on recharge and storage.
Li and Zhao (2018) [12]; Kansas, USA	Econometric analysis of low-energy precision application and water-right conditions	Groundwater extraction; intensive and extensive adjustment. Responses varied with the size and binding character of water rights.	Responses differ with the size of the water right and whether it constrains pumping.
Cameron-Harp and Hendricks (2025) [13]; Kansas, USA	Staggered-adoption difference-in-differences with transition-specific controls	Groundwater withdrawal; area; application depth. No significant evidence of backfire for flood/furrow-to-pivot and traditional-pivot-to-LEPA transitions. Author-manuscript samples cover 1991–2015 and 1991–2019, respectively.	The first transition uses later adopters as controls; the second includes never-adopters. The author manuscript reports sample periods in Table 2 and volume effects in Table C.1 (PDF p. 59).
Fishman et al. (2023) [14]; South India	Randomized offer of application assistance and additional drip subsidy; baseline 2016 and endline August 2019	Reported pump-operation days/hours; crop outcomes; groundwater transfers. No detectable reduction in reported pumping duration followed randomized encouragement, alongside production and transfer responses.	Electricity rationing and groundwater transfers shaped the response. Pumping duration was used as a proxy for extraction because volumetric metering was impractical (Working Paper 9713, Section 4.3).
Berbel and Mateos (2014) [17]; Spain	Agro-economic simulation with alternative technology, land and initial-irrigation conditions	Applications; crop water consumption. Outcome signs depend on baseline water deficits, application conditions and land constraints.	Initial crop-water deficits and the limits imposed on area and water use differ among scenarios.

Study and setting	Design and comparison	Water quantity and principal finding	Context for comparison
Nemati et al. (2023) [20]; Residential water-demand context	Temporal decomposition of demand and conservation persistence	Residential water demand. Post-drought demand recovery can concern conservation persistence rather than improved technical efficiency.	Contributes evidence about demand recovery and conservation persistence in a residential setting.
Kendy and Bredehoeft (2006) [22]; Connected stream–aquifer systems	Transient analysis of groundwater pumping and surface-irrigation returns	Streamflow; pumping; irrigation returns; delayed groundwater response. Changes in pumping and returns can alter streamflow with a delay.	The timing of streamflow changes depends on aquifer connectivity and delayed irrigation returns.
Berbel et al. (2018) [23]; Spain	Field-scale analytical comparison of technology, water-price response and initial irrigation conditions	Applications; water consumption. Lower application can coexist with limited consumption change under fixed-area conditions.	The analysis holds area fixed and varies technology, water price and initial irrigation conditions.
Ao et al. (2021) [26]; Kansas High Plains, USA	Analysis of farm growth and groundwater depletion	Farm size; groundwater depletion. Farm scale is associated with groundwater depletion.	The analysis concerns changes in farm size and consolidation in the Kansas High Plains.
Singh et al. (2024) [27]; Four states, India	Recall before–after survey of 404 micro-irrigation adopters	Irrigated area; crop mix; pumping hours. Respondents reported area expansion alongside generally shorter pumping duration.	Respondents recalled conditions before adoption. Area and pumping duration describe separate responses; pumping volumes were not directly measured.
Fishman et al. (2015) [28]; India	Groundwater-use scenarios under improved irrigation efficiency and alternative expansion assumptions	Groundwater use; technical conservation potential; irrigated production. Additional irrigated production can reduce the modeled technical conservation potential.	National saving scenarios depend on the assumed expansion response and groundwater account.
Berbel et al. (2019) [29]; Spain, 2002–2015	Sectoral and case synthesis of irrigation modernization	Deliveries; land; production indicators. Modernization outcomes vary across bundled programme conditions.	The modernization package combines infrastructure, financing, reliability and institutional changes.
Dumont et al. (2013) [30]; Spain	Conceptual and case interpretation of irrigation modernization	Modernization mechanisms; water-resource management. District programmes combine infrastructure changes with allocation and institutional changes.	Explains district mechanisms and the interaction of infrastructure with allocation rules.
Wheeler et al. (2020) [31]; Australia	Adjusted observational recipient–non-recipient comparisons: regression adjustment, AIPW, IPWRA and matching; OLS benchmark	Reported extraction; 2,481 survey records and 1,604 final adjusted observations. Adjusted recipient extraction differences were 21–28% across estimators.	The published article reports sample sizes in Table 1 and adjusted estimators in Appendix C. The 21–28% range describes differences across estimators.
Loch and Adamson (2015) [32]; Murray–Darling Basin, Australia	Drought and allocation analysis used to examine production-risk mechanisms	Water allocations; production risk. An irrigation system can enable different production responses across allocation and drought conditions.	Production responses depend on drought sequence, allocation reliability and the comparison period.

Study and setting	Design and comparison	Water quantity and principal finding	Context for comparison
Molle and Tanouti (2017) [33]; Morocco	Policy and institutional analysis of modernization goals	Production incentives; intensification; conservation objectives. Conservation goals can conflict with higher-value irrigated production expansion.	Explains institutional incentives and the negotiation of conservation and production objectives.
Hamidov et al. (2022) [34]; Uzbekistan	Stakeholder-based assessment of irrigation-efficiency opportunities	Perceived production and behavioral pathways. Stakeholders anticipate opportunities for additional production after irrigation improvements.	The assessment records stakeholder expectations about future production and water use.
Morrisett et al. (2023) [35]; Henrys Fork watershed, Idaho, USA	Long-term hydrology, imagery and irrigator interviews; 1978–2000 versus 2001–2022	Surface diversions; net river reach gain. Historical annual reductions were 311 and 299 Mm^3/year, respectively.	Net reach gain combines river–aquifer exchanges. Period comparisons and their interpretation are reported in Sections 3.3 and 4.2 of the published article.
Sanchis-Ibor et al. (2024) [36]; Spanish irrigation–wetland systems	Case analysis of allocation and management alongside drip adoption	Water allocation; irrigation–wetland dependencies. Ecological dependencies and allocation arrangements can change with adoption.	Wetland dependence on irrigation flows changes alongside allocation and management.
Song et al. (2018) [38]; China	Regional agricultural production and efficiency analysis using constructed rebound measures	Aggregate agricultural water inputs; constructed agricultural rebound. Scale and crop structure influence inferred offsets.	Decomposition retains shared water terms and distinguishes efficiency, scale and crop-structure components.
Xu et al. (2021) [39]; China	Agricultural water-use efficiency and rebound analysis using regional production comparisons	Agricultural water use and efficiency in 30 Chinese provinces, 2000–2017. The reported rebound estimate is 88.81%; area expansion increased water demand, while changes in crop composition reduced it.	The comparison uses provincial water-use and efficiency measures that share water-input data.
Pei et al. (2024) [40]; Xinjiang, China	Regional agricultural rebound and driver analysis	Agricultural water use and irrigation efficiency in Xinjiang, 2001–2020. The reported rebound estimate is 112.10%, alongside expansion of cultivated and irrigated land.	The regional analysis examines efficiency and expansion over a period of changes in cultivated and irrigated land.
Freire-González (2019) [42]; Spain	Dynamic water-economy computable general equilibrium model for Spain under an annual 50% improvement in water efficiency.	Economy-wide water demand under the efficiency scenario; used here to introduce economy-wide adjustment.	Background for the economy-wide mechanism. The detailed closure comparison in Section 3.3 uses Zhou et al. [43].
Zhou et al. (2021) [43]; China	Multi-sector computable general equilibrium scenarios with short- and long-run closures	Water utilization in efficiency units representing delivered water services. Responses vary across sectors and model closures.	Short run: fixed wages and sectoral capital, with employment adjustment. Long run: mobile capital with equalized returns, fixed employment and wage adjustment (source Sections 3.1 and 3.3).

Study and setting	Design and comparison	Water quantity and principal finding	Context for comparison
Drysdale and Hendricks (2018) [37]; Kansas, USA	Difference-in-differences evaluation of a locally governed allocation restriction	Groundwater use; irrigation intensity and other response margins. The policy was associated with an estimated 26% reduction in water use, mainly through intensity adjustment.	The intervention restricts groundwater allocation and allows farmers to adjust irrigation intensity.
Fei et al. (2021) [53]; China	Evaluation of a water-right system pilot reform	The pilot reform was associated with an increase in the agricultural rebound index. Reported average short- and long-run rebound estimates were approximately 49% and 66%.	The outcome is an agricultural rebound index used to compare the pilot reform with other observations.
Sheng et al. (2025) [54]; China	Evaluation of water-rights trading policy	The study reports a reduction in its agricultural rebound measure under water-rights trading, with heterogeneous effects across settings.	The analysis compares policy-related changes in agricultural rebound across different settings.
Xu and Song (2022) [44]; Hetao Irrigation District, Yellow River Basin, China	Regional analysis of irrigation-rebound drivers	Irrigation water use in Hetao, 1949–2017. Expansion of sown area and the irrigated share were the main contributions to increased water use; the authors report an average rebound estimate of 344.38%.	The decomposition examines long-term changes in water use, sown area and the irrigated share of land.
Chai et al. (2024) [45]; Agricultural production environments	Analysis of climate conditions and crop-mix relationships	Agricultural water use, efficiency, climate and crop mix. The reported irrigation-efficiency elasticity is −0.319; humid conditions and cash-crop shares modify the estimated relationship in different directions.	Climate and crop composition modify the estimated association between efficiency and water use.
Raeisi et al. (2019) [46]; Integrated agricultural water system	Integrated simulation of alternative agricultural water-saving measures	Withdrawal; evapotranspiration; recharge; return flows. The model traces hydrological effects and side effects of alternative measures.	Model calibration, maintained behavior and scenario assumptions govern the hydrological outputs.
Lankford et al. (2025) [48]; Irrigation–allocation nexus scenarios	iGains4Gains model comparison of irrigation and allocation alternatives	Water; food production; carbon emissions; nature outcomes. Scenarios permit comparison of multiple resource and production outcomes.	The scenarios compare water, food, carbon and ecological outcomes under alternative irrigation and allocation choices.
Espinosa-Tasón et al. (2020) [41]; Spain, 2004 and 2017	Historical national water–energy reconstruction; source Table 3	Abstraction; estimated consumption; derived residual returns; application efficiency; area. Abstraction declined by 15.78%, estimated consumption by 7.12% and derived returns by 29.99%.	The author manuscript reports abstraction and estimated consumption in Section 3.2 and Table 3; returns are calculated as their difference. The quantities therefore share inputs.
Hoffmann and Villamayor-Tomas (2025) [55]; Spanish water-user associations	Exploratory experiment concerning mental accounting of modernization gains	Ownership expectations; mental accounting. Users and funding bodies can assign different meanings to the disposition of savings.	The experiment examines how water-user associations perceive and assign the benefits of modernization.

Study and setting	Design and comparison	Water quantity and principal finding	Context for comparison
Schütze (2025) [56]; Two irrigation-modernization cases, Spain	Governance coordination case studies	Actor coordination; administrative relationships. Ownership and coordination affect the feasibility of allocation arrangements.	Explains actor coordination and the feasibility of locally negotiated allocation arrangements.
Burney, J. et al. (2010) [50]	Matched-village comparison in northern Benin, two treatment and two comparison villages; one year of follow-up after installation.	Livelihood, food-security, production and economic outcomes of a solar-pumping-plus-drip package.	Matched controls used hand-watered vegetable plots. The comparison evaluates the combined solar-pumping and drip-development package.
Hafeez, M.M. et al. (2008) [51]	Observational hydrological water-reuse measurements and economic production-function analysis at five spatial levels during the 2001 dry season.	Water reuse through pumping and check dams at 1500–18000 ha spatial levels.	The study follows reuse and water accounting across five spatial scales.
Yang, G. et al. (2026) [60]	Fractional programming optimization with scenario-based reoptimization and Monte Carlo uncertainty analysis.	Optimized effective irrigation-water utilization and shortage performance under specified supply scenarios.	Monte Carlo analysis varies the supply upper bound and aggregate efficiency in S60, S80 and S100 scenarios; other inputs remain fixed. The framework supports scenario-based allocation updates.
Gong, X. et al. (2020) [61]	Inexact interval programming for economic irrigation/crop allocation in Jinghuiqu, China.	Modeled irrigation requirements and allocation, with crop evapotranspiration, effective precipitation, conjunctive surface-groundwater supply.	The planning model links crop demand, effective precipitation and conjunctive supply within an interval-based allocation problem.

The UPRIIS companion report [52] provides additional measurement detail for the rice-system study [51]. OpenET [62], WaPOR [63] and the Water Measurement Manual [64] support the measurement considerations in S5. Source links are provided below.

Official UPRIIS proceedings:
https://www.mssanz.org.au/MODSIM07/papers/24_s17/SacleEffects_s17_Hafeez_.pdf

Assessing the accuracy of OpenET satellite-based evapotranspiration data to support water resource and land management applications: https://www.nature.com/articles/s44221-023-00181-7

Influence of Spatial Resolution on Remote Sensing-Based Irrigation Performance Assessment Using WaPOR Data: https://www.mdpi.com/2072-4292/12/18/2949

Water Measurement Manual:
https://www.usbr.gov/tsc/techreferences/mands/wmm/WMM_3rd_2001.pdf

Yang et al. [60], publisher full text: https://mdpi-res.com/d_attachment/water/water-18-00612/article_deploy/water-18-00612.pdf

S2 Contextual variables in comparisons of irrigation outcomes

Table S2 relates production conditions, water availability and institutions to the mechanisms examined in the model. A factor's role depends on its timing. For example, pre-existing crop choices may influence adoption, whereas crop changes after adoption may mediate the effect on water use. The comparison should distinguish these roles when estimating the total intervention effect.

Table S2. Contextual variables relevant to irrigation comparisons.

Factor	Relationship to the model	Variables relevant to comparison
Rainfall and evaporative demand	Production conditions; precipitation, recharge and irrigation requirement.	Contemporaneous rainfall and evaporative demand; rainfall-derived and irrigation-derived ET.
Energy price and pumping lift	Energy demand per volume and water cost.	Electricity rationing, energy prices, baseline pumping lift and changes in groundwater head.
Crop prices and markets	Output value and crop shares.	Output prices, market access and price responses within the modeled economy.
Subsidies and finance	Net annualized capital cost and adoption feasibility.	Subsidy offers, actual adoption, infrastructure investment and changes in allocation.
Farm consolidation, labor and land	Expansion costs, land limit and labor demand.	Pre-adoption farm structure, land access, labor availability and changes in farm size.
Groundwater levels and source availability	Pumping lift, supply constraints and aquifer stock.	Water-source substitution, recharge, lateral exchange and storage changes.
Withdrawal caps, rights and area limits	Effective source/total entitlements and land constraints.	Entitlement, actual use, enforcement, transfers and whether allocations bind.
Informal access and local rules	Difference between legal and feasible choices.	Enforcement, unmetered access and actual allocation practices determine whether a legal limit constrains use.
Return-flow dependence and ecology	Recoverable outflow, recharge, river response and target season.	Downstream users, recharge delays, seasonal flows and water quality.

S3 Model derivations and sensitivity analysis

S3.1 Assumptions and responses of irrigated area

The model relates irrigation choices to production, costs and resource constraints. Its water-choice derivation assumes an interior optimum, a fixed output price, differentiable concave f, and a locally constant marginal water cost with respect to w. Here c denotes marginal water cost (the main-text c_w); ϵ is the elasticity of crop-water demand with respect to its unit cost, taken as positive so that a 1% rise in unit cost reduces demand by this percentage locally. The term c may change with technology through energy requirements and water-dependent labor. If cost is nonlinear in application, the elasticity must instead be computed from the full first-order condition.

For a single crop, $W = Anw = Anx/\eta$. Per unit of crop-water service, water costs $u_c = c/\eta$, so $d\ln x = -\epsilon\, d\ln(c/\eta)$. Differentiating the withdrawal identity gives the withdrawal response in Section S3.2. At a binding water cap, the corresponding shadow price enters marginal cost, and the unconstrained elasticity expression cannot be used with that shadow price held fixed. For several positive crop-area shares $s_c = a_c/A$, the exact local identity is

$$d\ln W = d\ln A + \sum_c \omega_c \,(d\ln s_c + d\ln n_c + d\ln w_c), \qquad \omega_c = \frac{s_c n_c w_c}{\sum_k s_k\, n_k w_k}. \qquad \text{(S1)}$$

The weights are water shares. Crop entry and exit require finite changes rather than log derivatives at a zero share.

For the area result, let m_τ^* be the optimized annual net margin per hectare, including intensity, labor and annualized capital costs, with common exogenous prices and slack water constraints. For an interior optimum, $G'(A_\tau) = m_\tau^*$. Strictly increasing G' implies $A_1 > A_0$ if and only if $m_1^* > m_0^*$, provided both optima remain interior and face the same G. With one crop cycle and labor $\ell_\tau(w) = \ell_{0,\tau} + \ell_{1,\tau} w$, the envelope derivative is

$$\frac{dm_\tau^*}{d\tau} = pf'(\eta_\tau w_\tau) w_\tau \frac{d\eta_\tau}{d\tau} - w_\tau \frac{dc_\tau}{d\tau} - p_L \frac{d\ell_{0,\tau}}{d\tau} - \frac{dk_\tau}{d\tau}. \qquad \text{(S2)}$$

Area expansion depends on the change in net returns per hectare. Improved crop-water supply, lower labor requirements and subsidies can increase these returns, while additional energy and capital costs can reduce them.

Let $b_\tau(x)$ denote non-beneficial evaporation plus non-recoverable outflow per hectare and cycle, and let x denote beneficial transpiration in this simplified account. For an irrigation-only balance at unchanged beneficial transpiration, physical consistency requires $0 \le x + b_\tau(x) \le w = x/\eta_\tau$; the remainder is recoverable return flow. The technology parameter η is consequently not interchangeable with one minus the recoverable fraction, because non-beneficial evaporation and other depletion can coexist with beneficial transpiration. With multiple crop classes, the engineering saving expressions sum over the original area, intensity and service of each class.

The model identifies four relationships. With slack constraints and unchanged expansion costs, higher net returns per hectare increase the optimal area, while a lower unit cost increases crop-water demand when $\epsilon > 0$. At unchanged crop-water service, reducing recoverable returns alone lowers withdrawals without lowering depletion. When engineering changes reduce depletion, subsequent expansion or intensification determines how much of that saving remains. For groundwater, lower pumping improves storage relative to the baseline when it exceeds the reduction in recharge, with lateral exchange and groundwater discharge held constant.

S3.2 Withdrawal response and engineering savings

For a single crop with slack constraints, let x be crop-water service, η its technological conversion from applied water and c_w the locally constant marginal water cost. If $\epsilon = -\,\partial\ln x/\,\partial\ln(c_w/\eta) > 0$, the exact local response is

$$\frac{d\ln W}{d\ln \eta} = \frac{d\ln A}{d\ln \eta} + \frac{d\ln n}{d\ln \eta} + \epsilon\left(1 - \frac{d\ln c_w}{d\ln \eta}\right) - 1. \qquad \text{(S3)}$$

The response combines changes in area, cropping intensity and water demand per crop cycle. Under binding water limits, the response follows the constrained solution, including changes in the shadow price of water.

In the irrigation-only account, interpret x as beneficial transpiration and $b_\tau(x)$ as non-beneficial evaporation plus non-recoverable outflow per hectare and cycle. At fixed original area, intensity and crop-water service,

$$ES_W = A_0 n_0 x_0 (1/\eta_0 - 1/\eta_1), \qquad ES_D = A_0 n_0 [b_0(x_0) - b_1(x_0)]. \qquad \text{(S4)}$$

Physical feasibility requires $0 \le x + b_\tau(x) \le x/\eta_\tau$. The residual is recoverable outflow. The conversion from applied water to beneficial transpiration and the recoverable fraction describe different parts of this irrigation-only account.

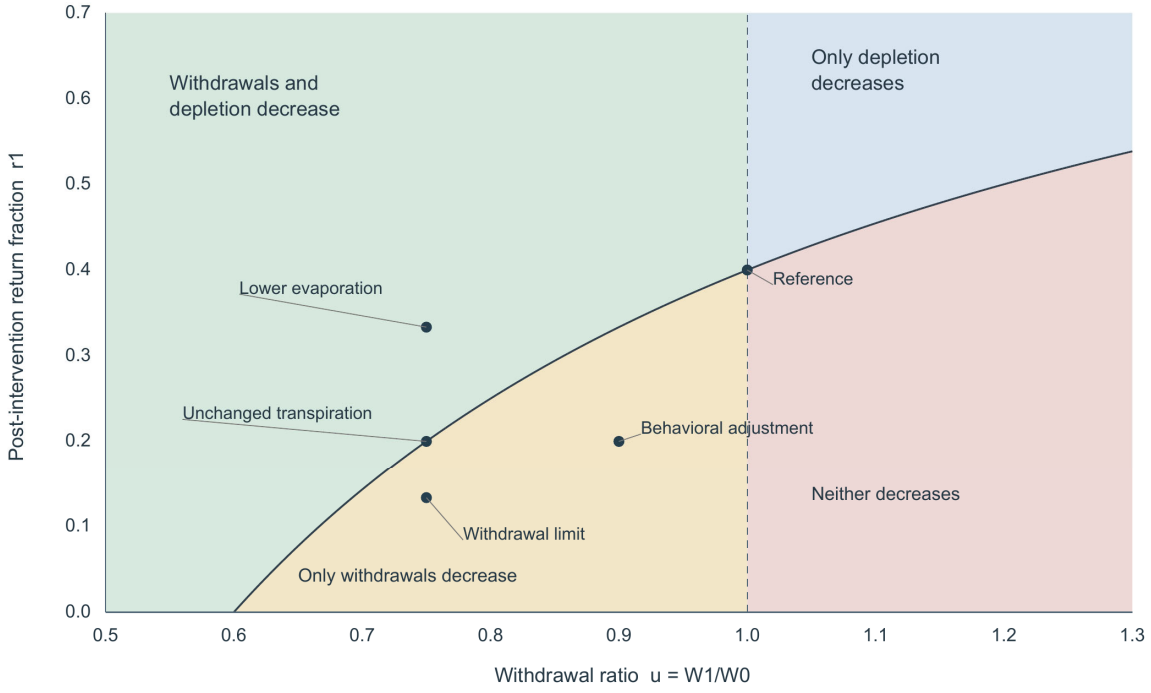


Figure S3.1. Conditions for withdrawal and depletion savings. The baseline return fraction is 0.40; precipitation, other inflows and storage change are held constant. The solid curve marks unchanged depletion, and the dashed line marks unchanged withdrawals. Points correspond to the hypothetical scenarios in main-text Figure 3.

S3.3 Water balances for a field and connected aquifer

For a field and its connected aquifer, write separate balances:

$$W_s + W_g + P + I_f = ET + F_{r,s} + R_g + F_n + \Delta S_f,$$

$$R_g + L_{in} = W_g + Q_g + L_{out} + \Delta S_g.$$

Adding them cancels both internal pumping W_g and internal recharge R_g:

$$W_s + P + I_f + L_{in} = ET + F_{r,s} + F_n + Q_g + L_{out} + \Delta S_f + \Delta S_g. \qquad \text{(S5)}$$

Each external outflow is then classified once according to the defined resource boundary. Recharge is an internal transfer when the connected aquifer is included in the account. Positive $\delta(\Delta S_g)$ means a higher storage change than under the counterfactual; it may still accompany $\Delta S_g^1 < 0$, meaning continued absolute stock decline.

S3.4 Sensitivity of rebound estimates to uncertain savings

As in main-text Section 2.4, E denotes the expected engineering saving and B the realized saving. Irrigated area retains the symbol A.

For perturbations d_E, d_B, exact subtraction gives

$$R(E + d_E, B + d_B) - R(E, B) = \frac{B d_E - E d_B}{E(E + d_E)}. \qquad \text{(S6)}$$

If $|d_E| \le u_E < E$ and $|d_B| \le u_B$, then

$$|\Delta R| \le \frac{|B| u_E + E u_B}{E(E - u_E)}. \qquad \text{(S7)}$$

The bound increases as the lower engineering-saving limit approaches zero. Its magnitude also depends on uncertainty in the realized saving. The acceptable precision therefore depends on the size of the water-use change and the comparison being made. If the engineering-saving interval includes zero, the rebound ratio may be undefined or unbounded over that interval.

For a rectangle $E \in [e_L, e_U]$ and $B \in [b_L, b_U]$, with $e_L > 0$, set

$$v = \{b_L/e_L, b_L/e_U, b_U/e_L, b_U/e_U\}; \quad R_{min} = 1 - \max(v), \quad R_{max} = 1 - \min(v). \qquad \text{(S8)}$$

The expression also applies when the realized-saving interval crosses zero, provided the engineering-saving interval remains positive. Information linking the two quantities may exclude some combinations and narrow the range. The resulting bounds describe the specified feasible inputs; a statistical confidence interval additionally requires a joint uncertainty model.

Using the three water-quantity outcomes (Q^0, Q^{eng}, Q^1), the gradient of R is $(-R/E, (R-1)/E, 1/E)$. Equivalently,

$$\mathrm{Cov}(E, B) = \mathrm{Var}(Q^0) - \mathrm{Cov}(Q^0, Q^1) - \mathrm{Cov}(Q^{eng}, Q^0) + \mathrm{Cov}(Q^{eng}, Q^1). \qquad \text{(S9)}$$

The covariance may therefore be material even if the original outcome estimates are otherwise independent. For storage, $\mathrm{Var}(\Delta S) = \mathrm{Var}(S_{end}) + \mathrm{Var}(S_{start}) - 2\mathrm{Cov}(S_{end}, S_{start})$. Comparisons of stock change across counterfactuals also require their cross-covariance or explicit joint bounds. Converting groundwater-level changes to volume requires a storage relation and its uncertainty.

The sensitivity calculations describe the effect of specified changes in return flows and other balance terms. Probabilistic estimation of $\Pr(R > 1)$ requires joint estimates of the intervention counterfactual, engineering saving at unchanged crop-water service and uncertainty in the water-balance terms.

S3.5 Numerical example of rebound calculation

Figure 3 compares hypothetical irrigation water balances. Its reference is $(W, ET, F_r) = (100,60,40)$, engineering outcome at unchanged transpiration is $(75,60,15)$, behavior-adjusted outcome is $(90,72,18)$, and withdrawal-cap outcome is $(75,65,10)$. These scenarios set precipitation, other inflows and storage change to zero and satisfy $W = ET + F_r$. Therefore $ES_W = 25$, $AS_W = 10$, $R_W = 0.60$, $ES_D = 0$, and $AS_D = -12$ for the behavior-adjusted comparison. R_D is undefined.

In the reduced-evaporation scenario, withdrawal is 75 units, ET is 50 and return flow is 25. Productive transpiration remains at 45, while non-productive evaporation falls from 15 to 5. Relative to the baseline, withdrawals fall by 25 and depletion by 10 units. These are savings for the stated scenario; no additional behavioral response is assumed.

For the numerical example, let $ES_W \in [20,30]$ and $AS_W \in [8,12]$. Allowing every combination within these intervals gives $[1 - 12/20, 1 - 8/30] = [0.400, 0.733333]$. The ranges illustrate the interval calculation in Equation (S8). The perturbation grids for Spain and Henrys Fork span the values at which the calculated differences change sign; their widths are scenario choices.

S3.6 Sensitivity of the Spanish water-use comparison

Espinosa-Tasón et al. [41] report national historical estimates $W_0 = 17{,}808$, $W_1 = 14{,}998$, $F_0 = 6{,}743$, $F_1 = 4{,}721$, all in hm³/year. These imply $r_0 = 0.378650045$, $r_1 = 0.314775303$, and the difference in estimated annual consumption

$$S_{hist} = (W_0 - F_0) - (W_1 - F_1) = 788 \text{ hm}^3/\text{year}. \qquad \text{(S10)}$$

Here subscripts identify the two historical years. Under equal other inflows and storage change, holding the baseline return fraction fixed, the later return fraction that gives no consumption change is

$$r_1^* = 1 - \frac{(1 - r_0)W_0}{W_1} = 0.262234965. \qquad \text{(S11)}$$

The reported later fraction exceeds this threshold by approximately 0.0525 (5.25 percentage points). If each fraction varies independently by the absolute change h, the resulting range is $788 \pm (17{,}808 + 14{,}998)h$. The lower bound reaches zero at $h = 0.024019996$, approximately 2.40 percentage points.

Let $K = -\delta P - \delta I + \delta(\Delta S)$. The general historical account is $S_D = S_{hist} + K$. For $K \in [K_L, K_U]$, add K_L and K_U to the respective endpoints below. At the nominal fractions, the calculated reduction is positive when $K > -788$ hm³/year. Under the ±0.02 variation in each fraction, the entire range remains positive if $K_L > -131.88$ hm³/year.

Table S3. Sensitivity of the Spanish annual consumption difference to return fractions.

Assumed variation in return fraction	Lower difference (hm³/year)	Upper difference (hm³/year)
Reported values	788.00	788.00
±0.01 (1 percentage point) at each date	459.94	1116.06
±0.02 (2 percentage points) at each date	131.88	1444.12
±0.03 (3 percentage points) at each date	−196.18	1772.18

The calculation allows the return fraction at each date to vary separately. If the same additive error affects both fractions, the sensitivity coefficient is $W_1 - W_0 = -2810$ hm³/year per unit change in the fraction. This contrasts with varying the two fractions in opposite directions. Consumption is recalculated from each perturbed return fraction and the fixed abstraction volume.

S3.7 Sensitivity of the Henrys Fork water-use comparison

Morrisett et al. [35] report a 311 Mm³/year reduction in surface-water diversion and a 299 Mm³/year reduction in net river reach gain between the two periods. The difference is $311 - 299 = 12$ Mm³/year. The reach-gain reduction is approximately 96.1% of the diversion reduction. Net reach gain combines groundwater and other river exchanges, so interpreting this difference as a change in depletion also requires the remaining terms of the connected stream–aquifer balance.

Holding the diversion reduction fixed and perturbing the net reach-gain reduction by a relative change h gives $12 \pm 299h$. The residual changes sign at $h = 12/299 = 0.040133779$, approximately 4.01%. If both reported reductions were independently uncertain by the same relative half-width, the resulting range would instead be $12 \pm 610h$, with a threshold of approximately 1.97%. The thresholds give the perturbations at which the historical residual changes sign.

Table S4. Sensitivity of the Henrys Fork annual diversion–reach-gain difference.

Assumed variation in net reach-gain reduction	Lower difference (Mm³/year)	Upper difference (Mm³/year)
Reported values	12.00	12.00
±2%	6.02	17.98
±4%	0.04	23.96
±5%	−2.95	26.95
±10%	−17.90	41.90

An additive term K for changes in the remaining stream–aquifer balance shifts the calculated difference. At the reported values, an offset of −12 Mm³/year reduces it to zero. For the ±4% range in Table S4, the lower endpoint is 0.04 Mm³/year, so a negative offset larger than this in magnitude removes the positive lower bound. The physical interpretation depends on the climate, pumping, storage and other exchanges represented by that term.

The calculations are reproduced by reproduce_sensitivity.py in Supporting_Data/Reproducibility_Original. Its input values, ranges and results are recorded in technical_sensitivity_results.json.

S4 Comparison of reported effects

S4.1 Outcome definitions and normalization

Each extraction identifies the study, intervention contrast, water outcome and follow-up period. Table S5 lists the inputs reported for six studies selected to compare outcomes and their interpretation. For positive no-intervention Q_q^0, a common target population, quantity, boundary and period define

$$a_q = \frac{Q_q^0 - Q_q^1}{Q_q^0}, \qquad e_q = \frac{Q_q^0 - Q_q^{\text{eng}}}{Q_q^0}. \tag{S12}$$

The engineering comparator holds the stated crop-water service, area, cropping intensity and crop mix constant; the realized outcome allows subsequent adjustment. Equation (2) then gives $R_q = 1 - a_q/e_q$ for a credible $e_q > 0$. Withdrawal, source-specific pumping, consumption and depletion remain separate outcomes. Reported pumping duration requires a measured or otherwise supported discharge conversion before it can enter a volumetric comparison.

Historical changes use a different label:

$$d_q = \frac{Q_{q,\text{before}} - Q_{q,\text{after}}}{Q_{q,\text{before}}}, \qquad Q_{q,\text{before}} > 0. \tag{S13}$$

Effects from log models retain the scale reported in the source. Table S5 identifies the quantities available for each comparison. Interval estimation on a common scale would require uncertainty in both the effect and its baseline; variation across estimators instead describes sensitivity to the estimation method.

For matched withdrawal and depletion accounts, Equation (9) implies

$$a_D = \frac{W^0}{D^0} a_W - \frac{L_F}{D^0} + \frac{K}{D^0}, \qquad W^0, D^0 > 0. \tag{S14}$$

Here $L_F = F_r^0 - F_r^1$ and $K = -\delta P - \delta I + \delta(\Delta S)$, using the main-text intervention-minus-counterfactual convention. The denominators differ by water quantity, so return-flow changes are calculated from volumes before normalization. Derived returns share uncertainty with the inputs used to calculate them.

S4.2 Context and dependence among estimates

Table S5 compares water quantities, interventions, periods and hydrological settings. Allocation limits and enforcement explain opportunities for adjustment, while return flows and recharge delays connect withdrawals to other water-resource outcomes. Crop changes after adoption describe a behavioral response. Estimates from shared samples and alternative estimators are considered together.

Table S5. Quantities and comparisons available in six selected publications.

The table compares reported effects, historical changes and model scenarios using their original quantities and comparisons. Equation (S12) defines a common normalization, while the table records which numerical inputs are available for each study.

Study	Reported quantity and comparison	Reported result and uncertainty	Basis for comparison
Cameron-Harp and Hendricks [13], Kansas; author manuscript Table C.1, PDF p. 59	Annual groundwater withdrawal per water-right group; flood/furrow-to-pivot, 1991–2015, and traditional-pivot-to-LEPA, 1991–2019; different controls.	Reported ATT in acre-feet per water-right group per year: +2.79 (95% CI −14.66 to 20.23) and −6.78 (95% CI −17.29 to 3.72), respectively. Positive values indicate increased withdrawals.	The reported volume effects refer to each adoption group and period. A corresponding rebound ratio combines the effect with the counterfactual mean and engineering withdrawal benchmark for that same comparison.
Fishman et al. [14], South India	Reported pump-operation days/hours; randomized subsidy-and-assistance offer, 2016–2019.	Reported pumping duration showed no statistically significant change after the randomized subsidy offer, alongside changes in production and groundwater transfers.	Pumping time describes operation; discharge connects time to volume. The subsidy offer and installed technology define different interventions. Electricity rationing and water transfers shape the observed response.
Wheeler et al. [31], Australia	Reported extraction; adjusted grant-recipient versus non-recipient comparison.	Adjusted extraction estimates were 21–28% higher for grant recipients than non-recipients. The range summarizes results across estimators.	The estimators use the same survey evidence. Baseline extraction and the model transformation determine the corresponding change in water volume.
Espinosa-Tasón et al. [41], Spain	National 2004/2017 abstraction, estimated consumption and derived returns.	Historical changes: d_W = 15.78%, d_C = 7.12% and d_{Fr} = 29.99%. Each percentage uses the respective initial quantity as its denominator.	Each percentage describes a historical change relative to its initial volume. Consumption is estimated, and returns are calculated as abstraction minus consumption, so the quantities share inputs. Positive d_{Fr} indicates reduced returns.
Morrisett et al. [35], Idaho	Annual surface diversion and net river reach gain; 1978–2000 versus 2001–2022 averages.	Annual diversion and net reach gain declined by 311 and 299 Mm³/year; their difference is 12 Mm³/year.	The difference describes changes in diversion and net river reach gain between periods. Climate, pumping, storage and other stream–aquifer exchanges complete its hydrological interpretation.
Freire-González [42], Spain CGE	Economy-wide water demand under a dynamic efficiency scenario for Spain.	Annual water-efficiency improvement of 50%; qualitative use here to explain economy-wide adjustment.	Background comparison; the explicit short- and long-run closure assumptions discussed in Section 3.3 are from Zhou et al. [43].

In the hypothetical example in Figure 3, a_W = 0.10, e_W = 0.25 and R_W = 0.60. For depletion, a_D = −0.20 and e_D = 0, leaving R_D undefined. Spain's three historical changes are normalized to their respective

initial quantities. The shared source account partitions the abstraction reduction as 2810 = 788 + 2022 hm^3/year in estimated-consumption and derived-return reductions.

The normalized quantities are reproduced by reproduce_effect_mapping.py in Supporting_Data/Reproducibility_Original. Inputs and results are recorded in effect_mapping_inputs_and_results.json and the accompanying CSV files. Historical changes and intervention effects retain separate labels.

S5 Considerations for future field evaluation

S5.1 Combining water-balance observations with intervention comparisons

A future application can evaluate the proposed mechanisms within a defined field, irrigation district or connected aquifer–river system. Relevant observations include withdrawals, channel flows, rainfall, soil water, groundwater levels, crop areas and pump operation. Groundwater levels require a storage relation to estimate volume changes. Independent field observations can assess remotely sensed ET. Where the aquifer is inside the boundary, pumping and recharge connect the component balances as internal transfers.

Model parameters can be estimated from one set of observations and evaluated against other sites, seasons or events. Differences between predicted and observed discharge, ET and storage describe model performance, including seasonal bias and the timing of returns. Water-balance residuals and measurement uncertainty help identify missing or poorly measured flows. Observations used to fit a residual or calibrate a parameter are distinguished from those used for independent evaluation.

The physical observations can then be combined with an intervention comparison and an engineering estimate at unchanged crop-water service. Changes in climate, allocation, prices and cropping explain both external influences and behavioral responses. Reporting the intervention effect, engineering saving and water-balance changes separately makes their relationship explicit.

S5.2 Measurement scale and uncertainty

The management objective determines the spatial and temporal scale of measurement. For ET, the product, algorithm version, resolution, cloud gaps and local validation affect interpretation. Comparing field boundaries with the effective observation footprint helps identify where estimates represent individual fields or larger groups. Shared meteorological inputs and spatial dependence influence uncertainty. The OpenET evaluation provides a published example of comparison with field observations [62].

Flow observations can combine continuous measurements at major drains with sampling at smaller channels. Rating curves, device calibration, operating range and interruptions affect the conversion from discharge to volume [64]. Rainfall and diversion histories help distinguish runoff and upstream reuse from irrigation returns. Delayed subsurface flows require groundwater and river observations over their response period.

A practical design combines spatial coverage from remote sensing with direct measurements at major supply and drainage points and representative field sites. Additional observations are most useful where uncertainty in a flow or storage term changes the interpretation of conservation. Monitoring budgets include equipment purchase and installation, calibration, maintenance, field visits and data processing. Group monitoring spreads these costs across farms; field sampling should cover the area and management

conditions represented by the account. Main-text Table 3 proposes observation schedules and identifies lead institutions and supporting participants.

S6 Literature search and evidence selection

The evidence map records irrigation interventions, behavioral responses and connected water balances at report level. The inventory identifies sources, versions, selection decisions and extracted outcomes. Counts refer to reports; publications sharing an experiment or dataset are linked where that relationship was established.

S6.1 Search strategies and eligibility

Web of Science All Databases and Scopus were searched on 9 October 2026 using three strategies: explicit rebound terminology (A), irrigation technology combined with adoption or behavioral responses and water-use outcomes (B1), and return flows, recharge, reuse or water accounting in relation to irrigation efficiency (B2). OpenAlex searches on the same date and checking of the manuscript's references supplemented these databases. The full queries are reproduced below and in Supporting_Data/Search_Strategies.csv.

Eligible reports examined agricultural irrigation interventions or directly relevant water balances across connected fields, aquifers or basins and presented original water-resource, land-use, cropping, behavioral or hydrological outcomes. Empirical studies, formal models and original water accounts were eligible. Reports concerned only with crop yield, equipment performance or adoption intention were excluded from the evidence map. Reviews and contextual sources informed the narrative discussion. Eligibility did not restrict publication year, language, region or outcome direction.

OpenAlex, title and abstract search, 9 October 2026: irrigation AND (rebound OR Jevons OR paradox). Records retrieved: 1,041.

OpenAlex, title and abstract search, 9 October 2026: "drip irrigation" AND (efficiency OR "water saving") AND (scale OR boundary OR "water balance"). Records retrieved: 698.

OpenAlex, title and abstract search, 9 October 2026: water AND rebound AND (markets OR trading OR rights). Records retrieved: 470. All result pages were retrieved; no year, language or document-type filters were applied to these OpenAlex searches.

The exported Web of Science All Databases records comprised A = 417, B1 = 4,195 and B2 = 3,398. Scopus exports comprised A = 232, B1 = 2,871 and B2 = 2,246. Counts below refer to the exported records before deduplication.

Web of Science All Databases — A (TS; 417 records)

```
TS=(irrigat* OR "agricultural water")
AND
TS=(rebound* OR Jevons OR "efficiency paradox"
OR "irrigation paradox" OR "efficiency trap")
```

Web of Science All Databases — B1 (TS; 4,195 records)

```
TS=(
(irrigat* NEAR/3 efficien*)
OR (irrigat* NEAR/3 technolog*)
```

OR (irrigat* NEAR/3 moderni*)
OR "irrigation infrastructure"
OR "drip irrigation"
OR "micro-irrigation"
OR "sprinkler irrigation"
OR "precision irrigation"
)
AND
TS=(
adopt* OR subsid* OR incentiv* OR moderni*
OR expans* OR intensif*
OR "crop choice" OR "crop mix" OR "cropping pattern*"
OR "water right*" OR "water market*" OR "water trad*"
OR reallocat*
)
AND
TS=(
"water use" OR "water saving*" OR "water conservation"
OR "water withdrawal*" OR "groundwater extraction"
OR "water abstraction" OR "consumptive use"
OR "water depletion" OR "irrigated area" OR pumping
)

Web of Science All Databases — B2 (TS; 3,398 records)

TS=(irrigat*)
AND
TS=(
"return flow*" OR "recoverable flow*" OR "water reuse"
OR "groundwater recharge" OR "water accounting"
OR "basin water balance" OR "catchment water balance"
OR "net reach gain*"
)
AND
TS=(
efficien* OR moderni* OR technolog*
OR "water conservation" OR "water saving*" OR "water-saving"
)

Scopus — A (TITLE-ABS-KEY; 232 records)

TITLE-ABS-KEY(irrigat* OR "agricultural water")
AND
TITLE-ABS-KEY(rebound* OR Jevons OR "efficiency paradox"
OR "irrigation paradox" OR "efficiency trap")

Scopus — B1 (TITLE-ABS-KEY; 2,871 records)

TITLE-ABS-KEY(
(irrigat* W/3 efficien*)
OR (irrigat* W/3 technolog*)
OR (irrigat* W/3 moderni*)
OR "irrigation infrastructure"
OR "drip irrigation"
OR "micro-irrigation"

```
OR "sprinkler irrigation"
OR "precision irrigation"
)
AND
TITLE-ABS-KEY(
adopt* OR subsid* OR incentiv* OR moderni*
OR expans* OR intensif*
OR "crop choice" OR "crop mix" OR "cropping pattern*"
OR "water right*" OR "water market*" OR "water trad*"
OR reallocat*
)
AND
TITLE-ABS-KEY(
"water use" OR "water saving*" OR "water conservation"
OR "water withdrawal*" OR "groundwater extraction"
OR "water abstraction" OR "consumptive use"
OR "water depletion" OR "irrigated area" OR pumping
)
```

Scopus — B2 (TITLE-ABS-KEY; 2,246 records)

```
TITLE-ABS-KEY(irrigat*)
AND
TITLE-ABS-KEY(
"return flow*" OR "recoverable flow*" OR "water reuse"
OR "groundwater recharge" OR "water accounting"
OR "basin water balance" OR "catchment water balance"
OR "net reach gain*"
)
AND
TITLE-ABS-KEY(
efficien* OR moderni* OR technolog*
OR "water conservation" OR "water saving*" OR "water-saving"
)
```

S6.2 Deduplication, screening and full-text retrieval

The searches and reference checks identified 15,573 records: 8,010 from Web of Science All Databases, 5,349 from Scopus, 2,209 from OpenAlex and five from reference checking. Deduplication used source identifiers, DOI and normalized title, year and author information, with conflicting identities examined separately. Removing 4,280 duplicate records and 649 patent or grant records left 10,644 records. Text rules excluded 4,366; assessment of the remaining 6,278 titles and abstracts excluded 4,198. Full texts were sought for 2,080 reports, and 477 were assessed for eligibility. Of these, 123 were excluded and 354 entered the evidence map (Figure S6.1).

Screening and extraction used AI agents in OpenAI Codex, with Python scripts for record processing and text rules. The rules examined titles, available abstracts and keywords for agricultural irrigation and either rebound, connected water accounting, or the combination of technology, behavioral response and water-use outcomes. Records with insufficient metadata were retained for further assessment. After re-examination of uncertain classifications, the final rule exclusions comprised 21 medical-irrigation records, 439 without content on agricultural irrigation and 3,906 without content on rebound or connected water accounting, or the specified combination of technology, behavioral response and water-use outcomes. The rules and final decisions are provided in Supporting_Data/Screening_Rules.txt and

Title_Abstract_Decisions.csv. Conflicting classifications and source identities were re-examined against the available texts and bibliographic metadata within the AI-assisted workflow. Full-text assessment used complete journal articles, working papers or complete article chapters in dissertations; the version assessed is recorded for each report.

Full-text exclusions comprised 71 reports without an eligible outcome, 27 without a relevant intervention or accounting question, 17 non-original sources, six outside agricultural irrigation or with inseparable outcomes, and two duplicate reports or versions. Figure S6.1 separately reports texts not retrieved. Fulltext_Exclusions.csv and Reports_Not_Retrieved.csv identify the corresponding reports.

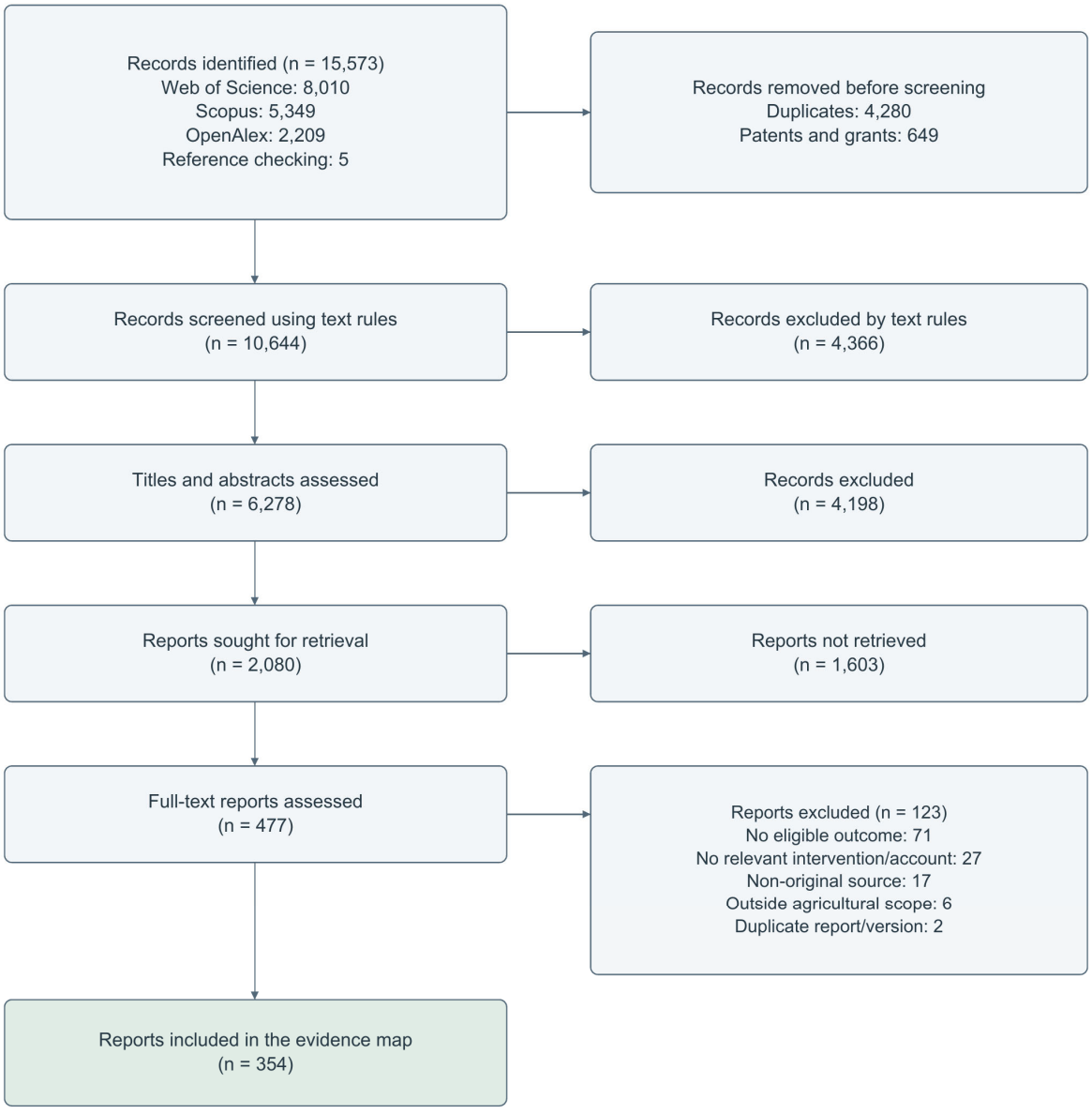


Figure S6.1. Literature identification, screening and full-text selection. Adapted from PRISMA 2020 [15].

S6.3 Data extraction and synthesis

Included_Evidence_Extraction.csv contains the 354-report inventory, including design, setting, intervention, water quantity, comparison, accounting boundary and principal outcome. Source versions

and text locations support the extraction. Shared datasets and companion reports are identified in the study-family fields where established. Main-text Table 2 and Supplementary Table S1 present selected cases that explain the mechanisms discussed.

Extraction distinguishes measured pumping or withdrawal, modeled water requirements, ET, depletion, area and allocation entitlements. Numerical results retain their population, period, boundary and comparison. The synthesis uses intervention studies to examine behavioral responses, models to examine specified mechanisms, and water accounts to relate connected flows and storage.

Qualitative appraisal considers treatment selection, external changes, comparison design, model assumptions and water measurement. Return flows, recharge, storage and accounting period are examined separately from intervention attribution. These observations guide the narrative comparison. Section S4 identifies the engineering and no-intervention quantities needed to express different results as rebound ratios.

S6.4 Supporting data and calculation files

The accompanying Supporting_Data folder contains Search_Strategies.csv (queries, fields, dates and export counts); Title_Abstract_Decisions.csv (10,644 final screening decisions); Included_Evidence_Extraction.csv (354 included reports); Fulltext_Exclusions.csv (123 excluded reports); Reports_Not_Retrieved.csv (1,603 reports); and PRISMA_Counts.json (selection totals). Screening_Rules.txt gives the text-rule definitions and final exclusion counts. Reproducibility_Original contains reproduce_sensitivity.py and reproduce_effect_mapping.py with their JSON and CSV inputs and outputs. File_Descriptions.txt explains the source versions, field meanings and calculation files. These files retain report identifiers for tracing decisions and results.

PRISMA reporting source: Page et al. [15]. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ 2021, 372, n71. https://doi.org/10.1136/bmj.n71. The flow diagram is adapted under CC BY 4.0.