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Tackling water theft: an empirical framework for compliance-inducing penalties under uncertainty

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Abstract

Water theft accounts for 30-50% of global water supply, and its incidence is growing. Water theft penalties are typically based on the environmental damages caused and often fall short of the profits driving non-compliance, thus failing to deter illegal water use. Here we develop a replicable empirical framework to estimate compliance-inducing penalties under uncertainty, integrating multi-model ensemble economic modelling, Global Sensitivity Analysis (GSA), and remote sensing and field data. Applied to the profitable Doñana region (Spain), where 20.75 million m³ of illegal water annually generate an estimated gross margin of EUR 15.91 million, the framework shows that the median compliance-inducing penalty (EUR 3.01/m³) substantially exceeds observed sanctions of 0.29–1.35 EUR/m³. The GSA shows that prosecution and conviction probabilities dominate deterrence, followed by crop prices and yields. These results demonstrate that effective deterrence depends jointly on enforcement credibility and agricultural profitability, implying that fixed damage-based penalties are unlikely to remain effective under changing socioeconomic and environmental conditions.

Main

Water theft, defined as the use of water without any right or beyond the established limits of the right, is estimated to account for 30%-50% of the global water supply^{1,2}. Most water theft is linked to irrigation in agricultural regions, including in Southern Europe, where as many as half of existing wells are illegal; or in Africa, where the number of illegal wells has skyrocketed from 2 to 25 million in less than a decade³. Enforcement policies, including penalties, have largely failed to curb illegal abstraction, which is still on the rise⁴. At the core of this ineffectiveness lies a fundamental failure to understand the adaptive responses by economic agents such as irrigators⁵, which can be affected by socioeconomic (e.g., commodity price fluctuations), environmental (e.g., climate change, water scarcity) and institutional processes (probability of detection, prosecution, conviction) whose impacts are difficult to foresee⁶.

Loch et al.² propose a conceptual framework that builds on Becker's⁷ social compliance model to explain why users commit water theft, and how effective deterrence can be achieved. Intuitively, the framework posits that water theft occurs where returns (incremental profit) from illegal abstractions exceed the costs of non-compliance, where the latter equate to the penalty multiplied by the product of detection, prosecution and conviction probabilities; and the former are a function of commodity prices, input costs, water availability, and yields. Loch and colleagues⁴ note that in calculating effective theft penalty values, due consideration must be given to the multiple equilibria that can rapidly emerge from changing socioeconomic, institutional and environmental conditions, where water availability, commodity prices, and other key variables can rapidly shift to increase the chance of nonlinear outcomes that amplify water values and render penalties less effective for preventing illegal behavior (see Fig. 1). Thus, they propose a structural transition away from traditional damage-based models (where theft can be approached as "cost of business" by offenders) toward a profit-based penalty framework designed to systematically disgorge the illicit enrichment alongside an added punitive surplus multiplier. However, Loch et al.^{2,4} signaled that limited water theft data and the computational costs of (and lack of protocols for) testing multiple equilibria under uncertainty constrained the application of their conceptual framework at the time, and thus invited others to empirically test the framework once the conditions to address these gaps were met.

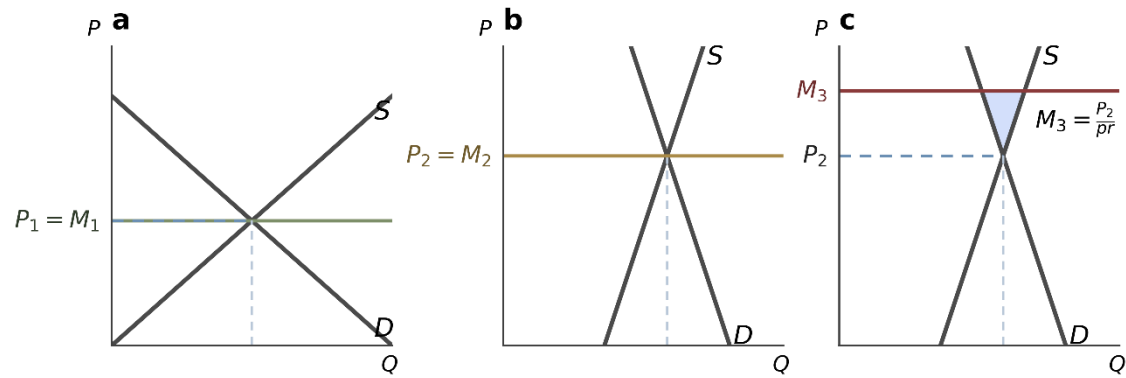
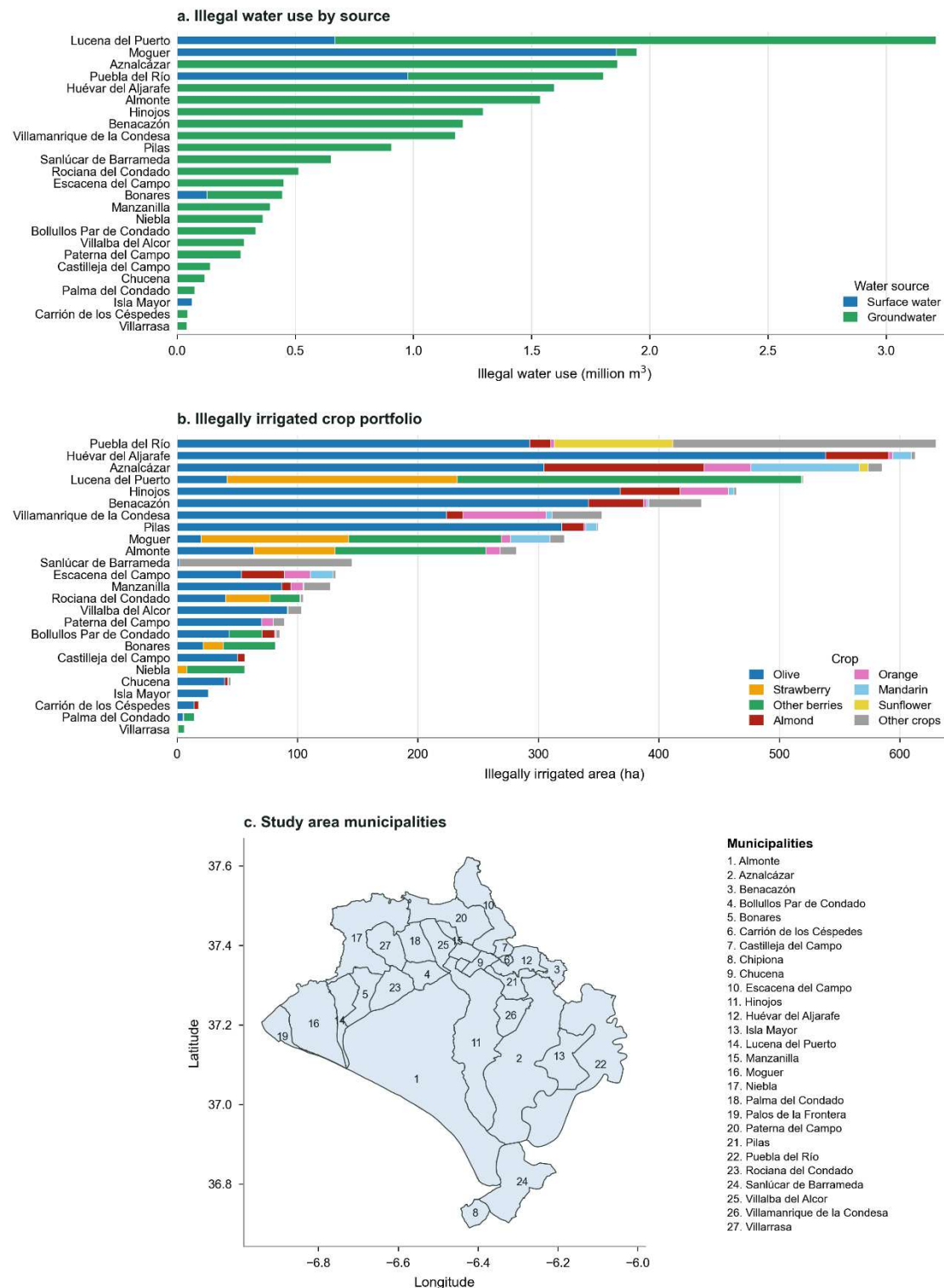


Figure 1 | Fixed penalties versus dynamic shadow prices (value) of water (adapted from Loch et al.⁴). In dynamic and uncertain settings, water can rapidly shift in terms of both supply and demand to increase the chance of nonlinear outcomes. When there is little scope for users to cope without water, their values will change and penalties may become less effective for preventing illegal behaviour. (a) Normality and probability of detection, prosecution, and conviction (pr) = 1. (b) Dry-period and pr = 1. (c) Dry-period and pr < 1. P , shadow price/value of water; Q , quantity; S , supply; D , demand; M , compliance-inducing penalty

This paper addresses the gaps identified by Loch et al.⁴ by providing an empirical framework for compliance-inducing penalty calculation under uncertainty. The framework combines novel satellite- and field-level land and water use data on legal and illegal irrigation with economic agricultural data to calibrate an ensemble of Positive Mathematical Programming (PMP) models of irrigators' behavior^{8–10}, and generates SHAP (SHapley Additive exPlanations)¹¹ values from a tree-based emulator to implement a Global Sensitivity Analysis (GSA) that assesses how uncertainty in socioeconomic, environmental and institutional inputs changes compliance-inducing penalties across plausible model equilibria. This allows us not only to identify where illegal abstraction is concentrated and which crops and users drive the problem, but also to assess how enforcement probabilities (detection, prosecution and conviction), prices, costs, yields and water availability interact to shape the penalties required for effective deterrence—including under uncertainty and nonlinear outcomes. The paper therefore contributes empirically by documenting the structure and drivers of illegal water use, and from a governance perspective by informing compliance-inducing penalty design under uncertainty.

Our empirical assessment is illustrated with an application to the Doñana Region in southwestern Spain—a hotspot for water theft^{12,13}. The Doñana region is Europe's most significant sanctuary for migratory birds¹⁴, recognized internationally as a UNESCO World Heritage Site¹⁵ and protected under conservation frameworks like the Water Framework Directive¹⁶ and the Ramsar Convention¹⁷. Because of overallocation, theft, and hydrological transformations (i.e., river

channel modifications and the construction of watercourses)¹⁸, the region's marshlands receive today less than 20% of the 400 million m³ water inflows they received in the 1950s, placing their sustainability under severe threat¹⁹. The primary driver of this ecological degradation is the highly lucrative agricultural sector, which produces 70% of Spain's strawberries and generates up to EUR 17,950 ha⁻¹ and EUR 400 million in export revenues¹⁹. On the other hand, observed penalties are based on the damage done (instead of the profit made from theft) and range between 0.29 EUR/m³ and 1.35 EUR/m³, although effective payments are typically lower^{20,21} due to statutory prompt-payment discounts of up to 40% under the Spanish Common Administrative Procedure Act²², protracted judicial appeals where courts routinely reduce fines because regulators struggle to meet the strict evidentiary burden required to prove accurate extraction volumes, or subsidiary insolvency that shields harvest profits and leaves the state to collect only a fraction of the nominal penalty^{23,24}. Nonlinear outcomes and inconsistent enforcement amplify water theft values and limit the ability of penalties to deter illegal abstraction, with the illegally irrigated surface having grown to an estimated 5,647 hectares (Fig. 2). This illicit expansion compounds the pressure from 9,000 hectares of regulated agriculture that already exhaust the available groundwater resources. Following repeated warnings from UNESCO and concerns raised by the agroindustry itself²⁵, the European Commission referred Spain to the European Court of Justice, which in a landmark 2021 ruling condemned Spain for its failure to protect the groundwater bodies sustaining the Doñana marshlands²³—a critical breach that remains unresolved today.



108

109 **Figure 2 | Water Theft in the Doñana Region.** (a) water theft by source, (b) Histogram of illegally irrigated
 110 crop portfolio, and (c) Map of the municipalities in the study area (the agents in our modeling and analysis).
 111 The baseline illegal water footprint across the Doñana municipalities amounts to 20.75 million m³ over
 112 5,647 ha, associated with an estimated gross margin of EUR 15.91 million. Water theft is dominated by
 113 olive (7.65 million m³), other berries (4.53 million m³) and strawberry (2.89 million m³), which together
 114 account for 72.6% of the illegal water use in the baseline. Strawberry production alone generates up to
 115 EUR 17,951 ha⁻¹ and EUR 7.98 million overall profit (50% of the total gross margin from illegal water
 116 use). Illegal abstraction is predominantly groundwater (17.06 million m³, 82.2%), with 3.69 million m³

from surface sources. At the municipality level, Lucena del Puerto leads with 3.21 million m³ of illegal water, followed by Moguer (1.95 million m³) and Aznalcázar (1.86 million m³). Water theft values are obtained from a combination of digital image processing techniques, visual analysis using available aerial imagery, and field data (See Methods Section). Surface water source refers to farms located in areas where most of the legal irrigation uses this source.

Results

We calculate the compliance-inducing penalty under multiple plausible socioeconomic, environmental and enforcement equilibria leveraging SHAP and using an ensemble of PMP models (including the Standard, Average, and Paris models)^{8–10}. The compliance-inducing penalty is calculated as the foregone profit resulting from eliminating illegal water use across all economic agents (municipalities)—scaled by the probability of detection, prosecution and conviction—under uncertainty (see Methods).

Across simulation runs, the compliance-inducing penalty has a median of 3.01 EUR/m³ and an average of 27.23 EUR/m³. The interquartile range (range between 25th and 75th percentiles, IQR henceforth) is 0.68–10.86 EUR/m³, while the 10th–90th percentile range is 0.06–37.09 EUR/m³, confirming a strongly right-skewed deterrence distribution. Method-specific estimates of compliance-inducing penalty are lowest under the Standard calibration, with a mean of 23.44 EUR/m³, and higher under the Average and Paris calibrations, with means of 24.29 and 33.95 EUR/m³, respectively, signaling the relevant impact of model choice on the results (or structural uncertainty). In Figure 3, we report the overall median across models (2.22, 2.41, 4.56 for Standard, Average, and Paris respectively).

Compared with the observed penalties in Doñana, ranging between 0.29–1.35 EUR/m³^{20,21}, the modeled compliance-inducing penalties under uncertainty remain substantially higher. Weighting each equilibria (or simulation under uncertainty) by the illegal-water volume it removes, about 83.0% of illegal-water volume lies to the right of 0.29 EUR/m³, and 66.6% to the right of 1.35 EUR/m³, meaning as much as 66.6% of the illegal-water abstractions would not be deterred by the upper observed penalty.

Figure 3 highlights these results both at the municipality level and across the pooled distribution of simulations. Municipal-specific penalty distributions consistently exceed the currently observed sanction range, although the extent of uncertainty differs among municipalities. The pooled kernel-density estimate confirms the highly asymmetric nature of the compliance-inducing penalty distribution, with most probability mass concentrated at relatively low penalties but a long

upper tail extending beyond 30 EUR/m³. Consequently, while the median provides a useful measure of the typical deterrence threshold, the mean and upper percentiles reveal the presence of scenarios in which substantially stronger economic disincentives would be required to eliminate illegal abstraction.

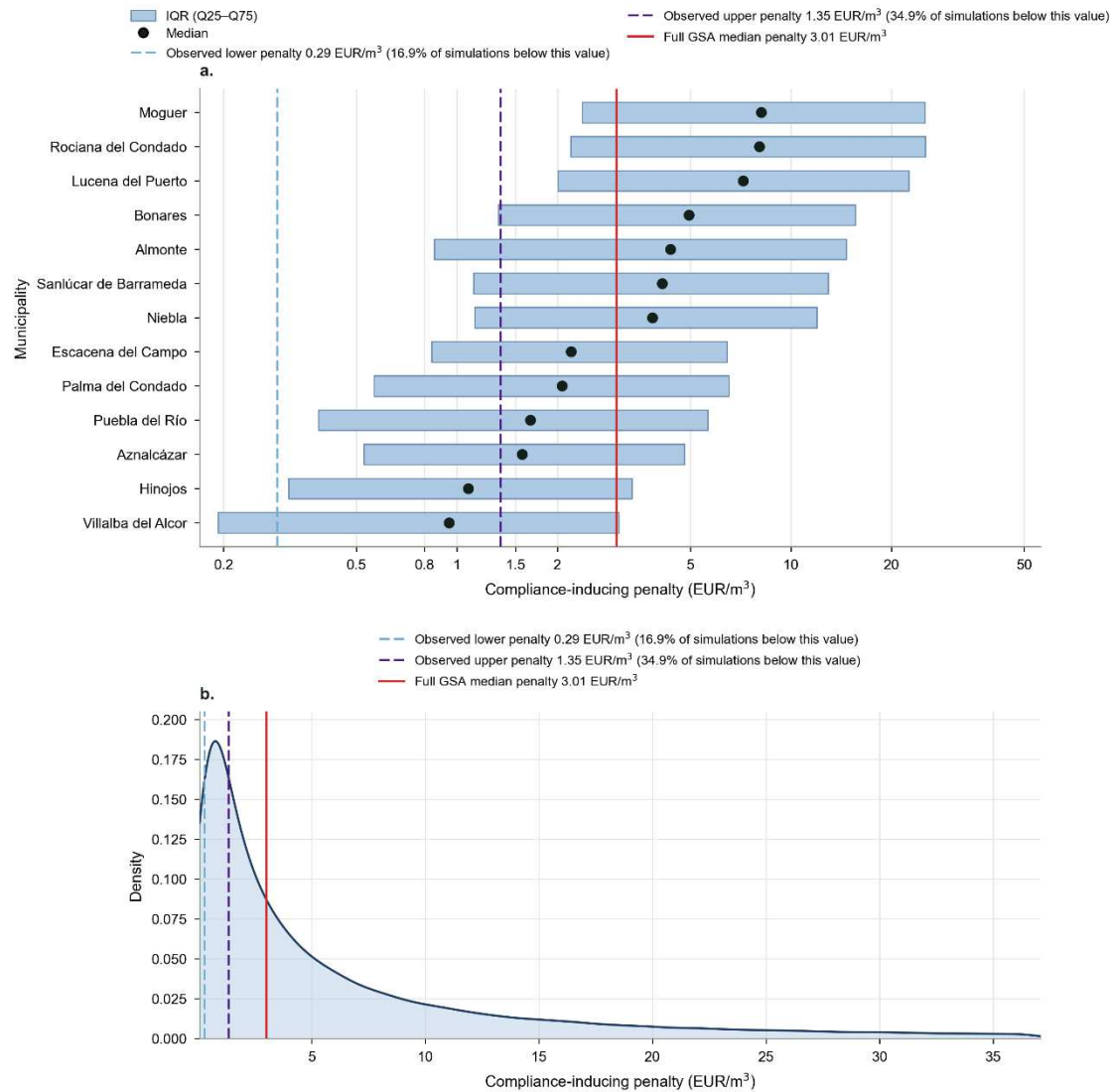


Figure 3 | Compliance-inducing penalties significantly exceed observed penalties across municipalities. (a), Municipal distributions of modelled compliance-inducing penalties, shown as IQR (Q25–Q75) with median values. The dashed light-blue line marks the lower observed penalty (0.29 EUR/m³)²⁰, the dashed dark-purple line marks the higher observed penalty (1.35 EUR/m³)²¹, and the red line marks the full GSA median penalty (3.01 EUR/m³). (b), Kernel-density estimate of the compliance-inducing penalty distribution within the P10–P90 range (0.06 – 37.09 EUR/m³). The distribution is strongly right-skewed: although the median penalty is 3.01 EUR/m³, the mean rises to 27.23 EUR/m³, with Q80 and Q90 reaching 15.04 and 37.09 EUR/m³, respectively. The observed penalty range lies in the lower tail of the distribution and would address only 16.9–34.9% of simulated cases.

The SHAP analysis indicates that uncertainty in probability of prosecution and conviction is the strongest driver in the SHAP compliance-inducing penalty values. Normalized mean absolute SHAP values assign conviction and prosecution probability comparable and dominant weight

(34.9% and 33.6%, respectively), followed by price (13.8%), yield (11.1%), cost (4.4%), legal water availability (1.5%) and detection probability (0.8%). These percentages summarize the mean absolute contribution of each input to the random-forest predictions over the sampled parameter space. Probability of detection contributes comparatively little because it is sampled over a narrow, high range (0.80–1.00) reflecting an assumed systematic-monitoring regime (80-100%, see Methods Section), whereas prosecution and conviction span 0.01-0.99 (i.e., 1–99%). These results indicate that while agro-economic variables define the private opportunity cost of illegal water, prosecution and conviction probabilities determine how strongly that opportunity cost is translated into the monetary penalty required to remove incentives for illegal abstraction.

Figure 4 illustrates these relationships. The beeswarm plot shows that prosecution and conviction probabilities generate the largest contributions to predicted penalties across the sampled parameter space, whereas economic variables produce comparatively secondary effects. The accompanying dependence plots reveal an inverse relationship between enforcement probabilities and the required compliance-inducing penalty, with penalties declining rapidly as prosecution or conviction probabilities increase before gradually approaching an asymptote. This pattern reflects that stronger enforcement reduces the monetary sanction required to offset the expected profitability of illegal abstraction.

The penalty scales inversely with the joint enforcement probability, so the distribution reported here is conditional on the sampled support for detection, prosecution and conviction. We deliberately sample prosecution and conviction over their full admissible range (0.01–0.99), discretised on a 0.01 grid rather than imposing a prior on enforcement performance, because credible and recent empirical distributions for Doñana are not available, and those previously existing suggest low to very low probability of prosecution and conviction. Two alternative enforcement supports, both derived from the probabilities reported for Doñana by Loch et al.⁴, are examined and available in the Supplementary Materials section.

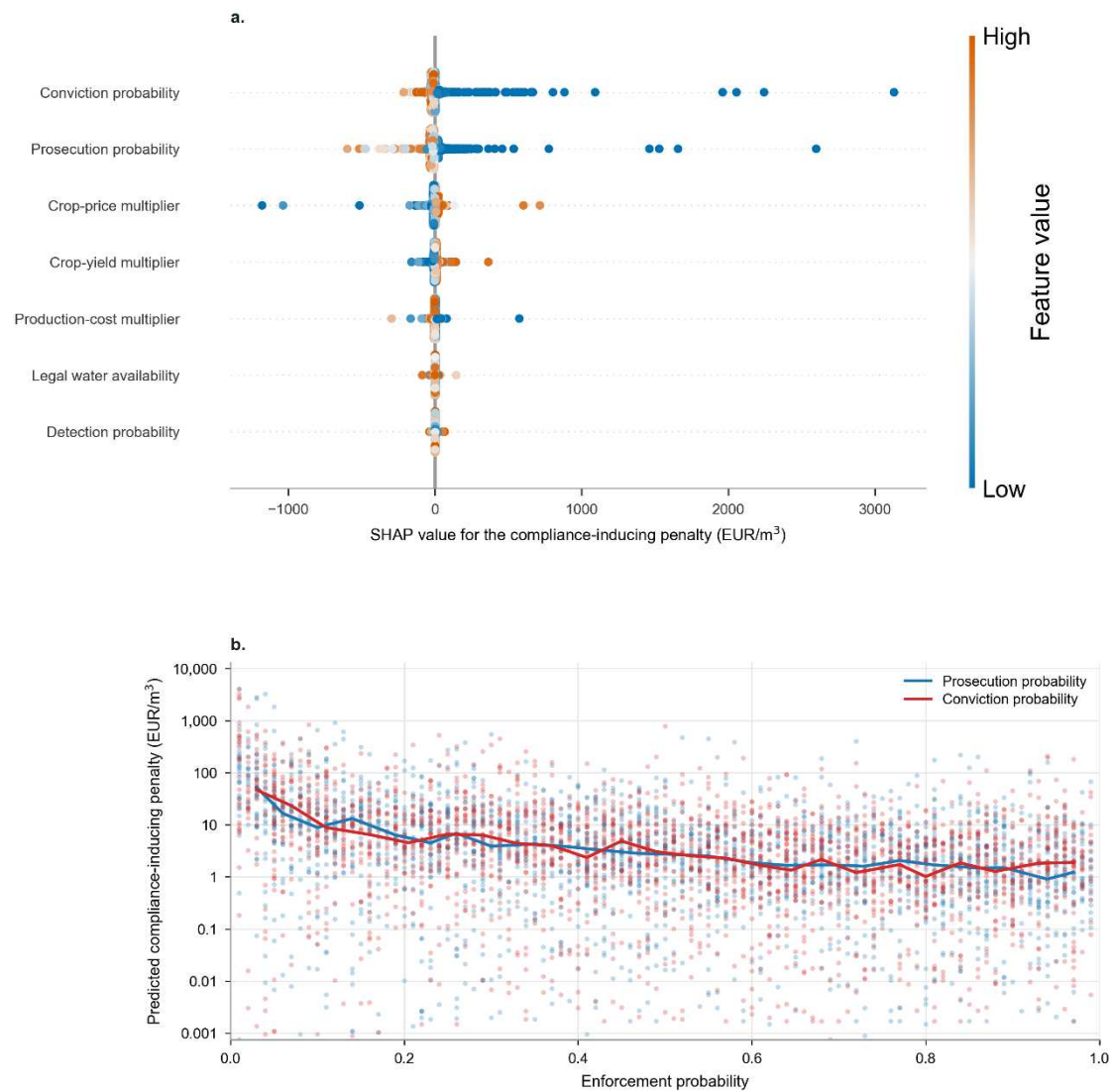


Figure 4 | SHAP value distributions for the compliance-inducing penalty. (a). The beeswarm plot reports TreeSHAP values across the sampled parameter space; each point is one model draw, with horizontal position showing the signed contribution to the SHAP-predicted penalty and color indicating the corresponding parameter value. Parameters are ordered by mean absolute SHAP value. (b). The scatterplot reports the predicted compliance-inducing penalty against the enforcement probabilities, each dot representing one simulation, with the blue line showing the median trend for prosecution probability and the red line the median trend for conviction probability. SHAP values are computed through a random-forest emulator built from the simulation draws; the random-forest emulator attains a training R^2 of 0.99 and an out-of-bag R^2 of 0.98.

Rather than producing a single compliance-inducing penalty, the proposed framework characterizes the range of penalties arising from multiple plausible socioeconomic, environmental and enforcement equilibria while simultaneously identifying the uncertain inputs responsible for this variation. The results show that the magnitude of the compliance-inducing penalty and its

variability cannot be understood independently. Although agroeconomic variables determine the opportunity cost associated with illegal water use, the sampled enforcement conditions govern how this opportunity cost is translated into the monetary penalty required to eliminate the incentive for illegal abstraction. Across all model calibrations, this relationship remains consistent despite differences in the estimated penalty magnitudes, indicating that the principal sources of variation are preserved under alternative model structures. Consequently, the uncertainty analysis provides not only an estimate of the compliance-inducing penalty across plausible equilibria, but also a quantitative characterization of the factors driving its dispersion. This combined perspective moves beyond reporting a single deterrence threshold by describing how the required penalty changes across the sampled parameter space and by identifying the uncertain inputs that contribute most to those changes.

Discussion

The current Spanish legal framework governing water theft, articulated in the Spanish Water Law²⁶ and its implementing regulation²⁷, is fundamentally constrained by its damage-based paradigm — a constraint that is not specific to Spain, but built into the European environmental liability regime that national water acts transpose, where liability is defined by reference to the damage caused and the cost of its remediation rather than to the gain obtained from the offence⁴². Basin Authorities are required to calculate penalties based on the demonstrable physical damage to the hydraulic public domain. This approach not only imposes the burden of proof on regulators to quantify precise environmental harm but also bounds penalties to the administrative principle of proportionality. Consequently, judicial rulings frequently strike down penalties that are not only disconnected from immediate physical degradation, but also from the high market profit made by illegally irrigated crops. Under these conditions, rather than a credible deterrent, offenders can internalize these penalties as an operational cost of doing business.

To establish effective compliance, a structural transition away from this damage-based model toward a profit-based regulatory framework was called for by Loch et al.⁴. A recent blueprint for this transition can be found in Australia's Natural Resources Access Regulator (NRAR). Recognizing the failure of traditional administrative penalties to curb illicit water use, the NRAR framework provides for Monetary Benefits Orders designed to systematically disgorge the illicit enrichment derived from non-compliance, alongside civil penalties capped at the greater of approximately *A\$10 million or five times the value of the water taken for corporations*²⁸.

Adapting this profit-based architecture would allow regulators to align the cost of non-compliance with the actual profit from illegal agriculture, fundamentally altering the compliance calculus of the offenders. In Spain and elsewhere, this necessitates amending the baseline penalty calculation

metrics to explicitly account for agricultural profit margins, while concurrently expanding the statutory application of profit confiscation. In Spain, this could be achieved leveraging Articles 247 and 325 of the Spanish Penal Code to elevate water theft from an administrative infraction to an economic and environmental penal crime²⁹. By empowering courts to systematically strip offenders of their illicit gains (in Spanish: *decomiso*) the state can render illegal abstraction economically unviable.

Critically, while disgorging profit from illicit activities is a necessary condition, our results show that Loch et al. may be overemphasizing the capacity of penalties to tackle water theft where institutions fail to enforce compliance. Our results mathematically demonstrate that the effectiveness of penalties, even under advanced technological detection (e.g., satellite monitoring), is neutralized if subsequent prosecution and conviction probabilities remain low, as institutional bottlenecks dilute the expected cost of non-compliance. In other words, where penalties are not enforced, their credibility is eroded, and increasing the sanction alone may not work towards increasing compliance. To sustainably increase enforcement and reduce non-compliance, policymakers should deploy mechanisms to strengthen institutional performance, supported by complementary ex-ante market interventions such as strict supply-chain traceability—leveraging retailer certification schemes—to ensure that illegally irrigated crops cannot reach premium markets. Furthermore, agricultural support mechanisms, such as European Common Agricultural Policy (CAP) subsidies, must be tied to verifiable water-compliance conditionality. By investing in better institutions, restricting market access and stripping public subsidies from non-compliant agribusinesses, regulators can enhance enforcement and reduce non-compliance without the need for increasing administrative penalties further.

Although the model is grounded in Becker's economic theory of deterrence and agent rationality⁷, the results should not be interpreted as implying that compliance with water regulations is determined solely by financial incentives. Decades of research in behavioral economics, criminology and institutional analysis have demonstrated that compliance also depends on social norms, moral values, procedural justice, institutional legitimacy and bounded rationality^{30–33}. Individuals may comply with regulations even when sanctions are weak because they perceive institutions as legitimate, because they value cooperation, or because compliance has become a socially expected behavior. Conversely, where institutions are perceived as ineffective or unfair, increasing penalties alone may fail to generate proportional improvements in compliance³⁴.

Our findings should therefore be interpreted as identifying a necessary, rather than a sufficient, condition for effective deterrence. Behavioral interventions can modify preferences, strengthen cooperation and improve voluntary compliance; albeit they cannot eliminate persistent incentives for illegal behavior when the expected economic return from non-compliance substantially exceeds its expected cost. In Doñana, the estimated profitability of illegal irrigation, together with

low prosecution and conviction probabilities, creates an economic environment in which illegal water use remains individually rational under current enforcement conditions⁷. Under these circumstances, interventions based exclusively on awareness campaigns, information disclosure, nudges or voluntary agreements are unlikely to offset the strong economic incentives generated by highly profitable irrigated agriculture.

We suggest that economic and behavioral instruments should be viewed as complementary rather than competing approaches to water governance. The economic framework developed here identifies the deterrence threshold required to eliminate the private economic incentive for illegal water use under multiple plausible socioeconomic, environmental and institutional equilibria. Once this threshold is reached through credible and adaptive enforcement, behavioral instruments—including social norm interventions, transparency initiatives, and collaborative governance arrangements—can reinforce voluntary compliance while reducing long-term enforcement costs^{31,33}. In other words, behavioral policies are likely to be most effective after the underlying economic incentive for illegal abstraction has been substantially reduced.

This distinction is particularly important under increasing climatic and market uncertainty. Our sensitivity analysis demonstrates that the compliance-inducing penalty is not a fixed legal quantity but a dynamic economic threshold that changes with fluctuations in commodity prices, production costs, yields, water availability and enforcement credibility. Consequently, regulatory systems based on static administrative penalties are unlikely to remain effective as environmental and market conditions evolve. Adaptive enforcement strategies that periodically reassess penalties in response to changing socioeconomic and hydrological conditions are therefore likely to outperform fixed penalty schedules, particularly in regions where climate change is expected to increase both water scarcity and the economic value of irrigation.

This study provides the first empirical implementation of a compliance-inducing penalty framework for illegal water use under uncertainty. By integrating remote sensing of illegal irrigation, Mathematical Programming, GSA and SHAP within a Beckerian deterrence framework⁴, we identify the penalties required to eliminate the economic incentive for illegal water use across multiple plausible socioeconomic, environmental and institutional equilibria. Applied to the Doñana region, the framework shows that the private returns from illegal water use substantially exceed current penalty levels, explaining why existing penalties have failed to deter non-compliance despite recent improvements in detection technologies. We show that the penalties required to induce compliance emerge from the interaction between agricultural profitability and enforcement credibility, with prosecution and conviction probabilities representing the dominant institutional bottlenecks and crop prices and yields defining the underlying financial incentive for illegal water use. Consequently, the compliance-inducing penalty is not a fixed legal quantity, but a dynamic economic threshold that evolves with changing

market conditions, water scarcity and institutional performance. These findings have important implications beyond Doñana. Regulatory systems based on static, damage-based administrative penalties are unlikely to remain effective where illegal water use generates substantial economic rents and enforcement is uncertain. Instead, effective governance requires adaptive penalty frameworks that account for both evolving agroeconomic conditions and enforcement credibility, while complementing deterrence with institutional and market-based measures that reduce the profitability of non-compliance. As water scarcity intensifies under climate change, aligning the expected cost of illegal water use with its expected private benefit will be essential for protecting freshwater resources and ensuring the long-term sustainability of irrigated agriculture.

Methods

Farmers' behavior is represented through an ensemble of three PMP models calibrated at municipal level. Let m index municipalities and $c \in C_m$ index crops available in municipality m . The decision variable x_{mc} denotes the share of agricultural land allocated to crop c . Crop price, yield, subsidy, insurance payment and variable production cost are denoted by p_{mc} , y_{mc} , s_{mc} , i_{mc} and k_{mc} , respectively. The linear benchmark used for calibration maximises observed gross margin:

$$\max_{x_{mc}} \Pi_m^{LP} = \sum_{c \in C_m} (p_{mc}y_{mc} + s_{mc} + i_{mc} - k_{mc})x_{mc} \quad (1)$$

subject to total land availability constraint:

$$\sum_{c \in C_m} x_{mc} \leq Total\ Land \quad (2)$$

and crop-calibration bounds:

$$x_{mc} \leq x_{mc}^{obs}(1 + \varepsilon) \quad \forall c \in C_m. \quad (3)$$

Here x_{mc}^{obs} is the observed land share of crop c and ε is a small numerical tolerance. Equations (1)-(3) are used only in the calibration stage to reproduce the observed crop portfolio and recover the dual values associated with the crop-specific upper bounds.

The calibrated simulation model replaces the observed linear cost term with a crop-specific non-linear PMP cost function. For each crop, total calibrated cost is represented as:

$$C_{mc}(x_{mc}) = \alpha_{mc}x_{mc} + \frac{1}{2}\beta_{mc}x_{mc}^2 \quad (4)$$

where α_{mc} is the linear cost component and β_{mc} controls the curvature of marginal cost. The PMP simulation therefore maximises:

$$\max_{x_{mc}} \Pi_m^{PMP} = \sum_{c \in C_m} x_{mc} \left[(p_{mc}y_{mc} + s_{mc} + i_{mc}) - \left(\alpha_{mc} + \frac{1}{2}\beta_{mc}x_{mc} \right) \right]. \quad (5)$$

This specification preserves the observed allocation in the baseline while allowing the model to simulate substitution across crops when water availability or economic conditions change.

Calibration of the PMP cost function

The calibration procedure follows the standard PMP logic of recovering crop-specific shadow values from the observed data. Solving the linear programming section listed in equations (1)-(3) yields the dual variable μ_{mc} associated with the calibration constraint for crop c . This value measures the implicit marginal value of relaxing the observed crop-allocation bound and is used to parameterise the non-linear PMP cost function.

To account for structural uncertainty in the specification of calibrated marginal costs, three alternative PMP calibration approaches are implemented:

$$\begin{array}{lll} \text{Standard:} & \alpha_{mc} = k_{mc}, & \beta_{mc} = \frac{\mu_{mc}}{x_{mc}^{obs}}, \\ \text{Average-cost:} & \alpha_{mc} = k_{mc} - \mu_{mc}, & \beta_{mc} = \frac{2\mu_{mc}}{x_{mc}^{obs}}, \\ \text{Paris:} & \alpha_{mc} = 0, & \beta_{mc} = \frac{k_{mc} + \mu_{mc}}{x_{mc}^{obs}}. \end{array} \quad (6)$$

The Standard⁹ specification retains observed variable cost (k_{mc}) as the linear component and assigns the calibration residual to the non-linear term. The Average⁸ specification redistributes the calibration residual between the linear and non-linear components. The Paris¹⁰ specification sets the linear component to zero and places the full observed cost and calibration residual in the non-linear component. The three approaches are retained because they represent alternative assumptions about the curvature of crop-specific marginal cost and therefore provide a structural uncertainty envelope for the deterrence estimates.

Penalty calculation

To represent non-compliance, observed water use is separated into legal and potentially illegal components (see the Data section).

Let w_{mc} denote crop water requirement in cubic metres per hectare, W_m^L legal water availability and W_m^I illegal water use. The observed water constraint is:

$$\sum_{c \in C_m} w_{mc} x_{mc} \leq W_m^L + W_m^I \quad (7)$$

The observed water constraint yields the observed profit (gross margin) Π_m^0 . To calculate the penalty we must first simulate the profit Π_m^S obtained from removing the illegal water pool W_m^I from the water constraint:

$$\sum_{c \in C_m} w_{mc} x_{mc} \leq W_m^L \quad (8)$$

Next, the foregone profit (change in gross margin) for each model agent (municipality) is obtained as follows:

$$\Delta \Pi_m = \frac{\Pi_m^0 - \Pi_m^S}{W_m^I} \quad (9)$$

Foregone profit is expressed in EUR/m³ and represents the private economic value for each cubic meter of illegal water removed. It is not a measure of environmental damage and should not be interpreted as the fine legally recoverable under the current Spanish framework. Rather, it is a metric of the expected changes in gross margin, necessary for the next step.

Following Becker's deterrence logic, illegal abstraction ceases to be individually rational when the expected penalty exceeds the private gain from non-compliance. Let p_d , p_p and p_c denote the probabilities of detection, prosecution and conviction, respectively. The minimum compliance-inducing penalty per cubic meter is calculated as:

$$E = p_d p_p p_c \quad P_{m^3}^* = \frac{\Delta \Pi_m}{E} \quad (10)$$

Where E represents the enforcement probability calculated from the probabilities of detection, prosecution and conviction, and $P_{m^3}^*$ is the penalty required to offset the private return from illegal abstraction, conditional on enforcement credibility. The expression makes the deterrence threshold jointly dependent on agricultural profit, legal water availability and the enforcement probabilities.

SHAP analysis of parametric uncertainty

Parametric uncertainty is represented by simultaneously varying seven inputs over the ranges used in the simulation experiment: price, cost and yield multipliers ($\pm 50\%$ around baseline); legal water availability (0–1) and prosecution and conviction probabilities (0.01–0.99, sampled on a 0.01 grid); and detection probability (0.80–1.00, consistent with the remote-sensing accuracy range).

Uniform ranges are used because defensible empirical probability distributions are not available. The resulting draws represent uncertainty scenarios rather than estimated frequencies. Parameter draws are generated with a Latin hypercube design over the seven inputs (9,216 parameter combinations), each evaluated for the 13 modelled municipalities and the three PMP calibrations. The Latin hypercube spreads every input across its full support on every draw; it does not retain the A/B/AB block structure required for variance-based Sobol estimation³⁵, which is not used here.

The sampled input vector is:

$$\mathbf{z} = (d_p, d_c, d_y, \lambda, p_d, p_p, p_c), \quad (11)$$

where d_p , d_c and d_y are price, cost and yield multipliers, λ is the legal-water-availability multiplier, and p_d , p_p and p_c are the enforcement probabilities. For every parameter draw, the model solves two calibrated PMP simulations under the same economic shocks and legal-water availability. The first allows illegal water use, while the second removes the illegal-water pool. Their gross-margin difference is divided by the illegal water removed and scaled by the joint enforcement probability to obtain the compliance-inducing penalty. Standard, Average and Paris calibrations are retained as alternative structural specifications; the SHAP analysis below evaluates the seven parametric inputs over the pooled successful simulations.

$$W_m^{L,s} = 0, \quad W_m^{L,s} = \lambda_m W_{m,0}^L, \quad \lambda_m \in [0,1]. \quad (12)$$

To obtain feature attributions at feasible computational cost, we fit a random-forest emulator (120 trees, maximum depth 24) to all simulation draws, with municipality and calibration-method indicators included as control features. The emulator reproduces the simulated penalties with a training R^2 of 0.99 and an out-of-bag R^2 of 0.98 (0.97 on the log scale, Spearman 0.98; the untransformed R^2 is dominated by a small number of extreme draws). TreeSHAP values³⁷ are then calculated for a random sample of 2,500 successful draws. For draw i , the emulator prediction can be expressed as:

$$\hat{f}(z_i, c_i) = \phi_0 + \sum_{j=1}^7 \phi_{ij}^{(z)} + \sum_{\ell=1}^q \phi_{i\ell}^{(c)} \quad (13)$$

Here $\hat{f}$ is the emulator prediction of the compliance-inducing penalty, z_i contains the seven parametric inputs, c_i contains the q control indicators for municipality and calibration method, ϕ_0 is the expected emulator prediction, $\phi_{ij}^{(z)}$ is the SHAP contribution of parametric input j and $\phi_{i\ell}^{(c)}$ is the contribution of control feature ℓ .

$$I_j = \frac{1}{n} \sum_{i=1}^n |\phi_{ij}^{(z)}| \quad (14)$$

$$RI_j = 100 \frac{I_j}{\sum_{k=1}^7 I_k} \quad (15)$$

Here ϕ_{ij} is the contribution of input j to the emulator prediction for draw i relative to the expected prediction ϕ_0 . Mean absolute SHAP values I_j summarize global contribution magnitude, and the normalized values RI_j sum to 100% and are reported as relative feature importance. SHAP values explain predictions from the fitted emulator over the sampled parameter ranges.

The empirical hierarchy and parameter dependencies uncovered by SHAP analysis reflect the underlying microeconomic structure of Beckerian deterrence and constrained profit maximization. Analytically, enforcement probabilities (p_p and p_c) govern the denominator of the deterrence condition as inverse power functions with unitary scale elasticity ($\varepsilon = -1$), explaining why institutional bottlenecks induce hyperbolic escalations in required penalties irrespective of agricultural productivity. Conversely, agro-economic parameters (d_p and d_y) scale the numerator linearly via the marginal value of water along the binding resource constraint, which is amplified in Doñana by the high revenue intensity of berry crops. Furthermore, the negative cross-partial derivative ($\partial^2 P_{m3}^* / \partial d_p \partial p_p < 0$) mathematically validates the interaction effects observed in our SHAP attributions, demonstrating that favorable market prices compound non-compliance incentives most severely when institutional enforcement falters. A formal derivation of the Kuhn–Tucker conditions and the analytical comparative statics validating these empirical sensitivity rankings and interaction dynamics are detailed in **Supplementary Note 2**.

(Illegal) land and water use data

Throughout this paper, references to “illegal” water use denote “potentially illegal” use, as further explained in the Methods, given that the official water-rights inventory used to identify non-compliant areas is neither fully accurate nor updated. A 1:5,000 scale land use cartography that delineates crops within the Doñana Region was produced by integrating Sentinel 2 satellite images, 0.25 m aerial orthophotography and cadastral cartography³⁶. In addition, the 2024 Common Agricultural Policy (CAP) farmers’ land use declarations were used as supporting

information for identifying the types of crops³⁸. The resulting land use map allows us to distinguish existing crops, including strawberry, multi-annual blueberry and raspberry crops, several types of horticultural spring and summer irrigated crops, rice, citrus, stone fruits, and other woody crops including olive, almond, other nut trees, and vineyards.

The methodology for identifying the presence of irrigation across land use types combines digital image processing techniques (use of spectral indices time-series and multispectral classification), visual analysis using available aerial imagery, and field data, depending on the specific characteristics of the crop (e.g., berry crops being grown under plastic macro-tunnels and greenhouses, or rice paddies being grown in specific periods of the growing season). A key challenge is posed by the discrimination of irrigation in low vegetation cover crops, which are also grown as rainfed crops in the area, including olive trees, nuts (almonds, pistachios) and vineyards. In this case, intensive photo interpretation analysis and field data were used to define, map, quantify and normalise relevant criteria, weights and thresholds linked to the likelihood of irrigation in these crops. Relevant criteria include:

- average values per plot of satellite-derived vegetation indexes in the summer period, when water stress is higher,
- existence of consolidated irrigation rights according to the data provided by the Water Authorities,
- declaration of farming plot as irrigated land in the land registry,
- planting density (i.e., hedges, intensive, extensive plantations), and
- the detection of infrastructure that provides strong evidence of potential irrigation, e.g., circular boreholes (concrete ring wells), regulation ponds, and presence of photovoltaic panels linked to pumping stations.

Existence of photovoltaic installations and very high values of the average vegetation indexes were the two criteria with the greatest explanatory power. As an example of the benefits of using this multi-source methodology, Fig. 5 shows a drip-irrigated pistachio orchard with a very low vegetation coverage over the soil, which is difficult to map as irrigated using remote sensing spectral analysis. The detection of the solar panels enabled, however, the inclusion of this plot in the final map of irrigated crops.



Figure 5 | Photos taken of the (a) drip-irrigation systems of pistachio orchards and (b) pistachio field with solar panels in the case study area

Two field campaigns were undertaken to validate the quality of the irrigation detection results, focusing on: (a) La Rocina area, where most of the berry crops are grown; and (b) the Almonte and Marismas groundwater bodies, where woody crops are mostly located. In La Rocina, where more than 5% of the cultivated area was sampled, the methodology to discriminate plastic-covered crops proved to be very accurate, with an overall reliability of 99.7% in the classification of the irrigated crops. In Almonte and Marismas, where more than 1,650 hectares of irrigated woody crops were sampled (representing more than 17% of the estimated irrigated area), the identification of high-coverage woody crops (i.e., citrus and fruit trees) also proved to be very accurate. For low-coverage woody-crops, the accuracy was 91%, with errors concentrated on two large farms with hydrants and manholes, but where the drippers had been removed and there is a certain level of neglect.

As a next step, the volume of irrigation water was estimated leveraging the data from the ‘SiAR’ (Sistema de Información Agroclimática para el Regadío), a Spanish institutional repository estimating irrigation water needs at provincial level.

Finally, the official cartography of farming areas with irrigation rights was used to identify legal and potentially illegal areas. The Guadalquivir Water Authority acknowledges that this cartography is not fully updated and thus, we refer to those irrigated farming areas outside of its

boundaries as “potentially” illegal areas. Although these plots are strong candidates to be illegal, further case by case analysis is required to fully endorse the illegal status of these plots.

In Fig. 2a, we present the estimated distribution of illegal water abstraction across municipalities, considering only water use classified as either legal or illegal. Total classified water use amounts to 310.84 million m³, of which 20.75 million m³ is classified as illegal and 290.09 million m³ as legal or with rights (Table 1). Illegal abstraction therefore represents 6.7% of classified water use. By source, illegal abstraction consists of 17.06 million m³ of groundwater and 3.69 million m³ of surface water, while legal water use consists of 70.73 million m³ of groundwater and 219.36 million m³ of surface water. Plots whose water source the 2024 layer records as unknown (146.56 ha) are counted as groundwater. Lucena del Puerto is the leading municipality, with 3.21 million m³ of estimated illegal water abstraction, equivalent to 15.5% of total illegal water.

For the scope of this study, we consider only Moguer, Rociana del Condado, Lucena del Puerto, Almonte, Bonares, Escacena del Campo, Aznalcázar, Niebla, Puebla del Río, Hinojos, Palma del Condado, Sanlúcar de Barrameda and Villalba del Alcor for the calibration and sensitivity analysis. The other municipalities were excluded for two main reasons. Three municipalities present in the municipal economic dataset were excluded due to their recorded illegal-irrigation being too small to support stable municipality-level PMP calibration; together they account for 6.68 ha of illegally irrigated land. A further eleven municipalities could not be modelled because the municipal economic dataset contains no crop price, yield or cost records for them; these account for 2,198.35 ha, or 38.93% of the illegally irrigated area, and include Huévar del Aljarafe (613.09 ha), Benacazón (435.47 ha), Villamanrique de la Condesa (352.74 ha) and Pilas (349.73 ha). The thirteen modelled municipalities therefore cover 3,442.29 ha, equal to 60.95% of the 5,647.32 ha of illegally irrigated land recorded across the study area.

Table 1 | Summary of water sources in the case study

Status	Groundwater Mm ³	Surface water Mm ³	Total Mm ³
Legal / with rights	70.73	219.36	290.09

<i>Illegal / without rights</i>	17.06	3.69	20.75
<i>Total</i>	87.79	223.05	310.84

Socioeconomic data

The economic data used to calibrate the PMP model are derived from ECREA³⁹, which provides crop-specific information on prices, variable production costs and yields. These variables are used to construct the economic matrix for gross margins per crop in Doñana, and to calibrate the behavioural response of irrigators under alternative legal and illegal water-availability scenarios.

Enforcement and penalty data

Disciplinary proceedings in Doñana are managed by the Guadalquivir River Basin Authority (GRBA) and include the closure of wells and farms (where land is used illegally), and fines ranging from minor (<EUR 10000) to medium (EUR 10000-50000), grave (EUR 50000-500000) and very grave (EUR 500000-1000000) depending on the quantity of water abstracted and the environmental damage caused—i.e., Spanish water theft penalties are based on the damage done instead of the additional profit made^{26,27}. However, the difficulty to identify the final user(s) and quantity of water abstracted typically results in considerably lower fines. Observed water theft penalties range between 0.29 EUR/m³ and 1.35 EUR/m³, albeit effective payments are typically lower (between 0.04 EUR/m³ and 0.78 EUR/m³)^{20,21}. This severe depreciation occurs through several institutional loopholes: offenders frequently utilize statutory prompt-payment discounts of up to 40% under Spanish administrative law²², or deploy protracted judicial appeals where courts routinely reduce fines because regulators struggle to meet the strict evidentiary burden required to prove exact historical extraction volumes. Furthermore, in cases of multimillion-euro fines, corporate offenders may utilize subsidiary insolvency to shield harvest profits, leaving the state to collect only a fraction of the nominal penalty^{24,40}.

This is aggravated by limited enforcement: while the number of water theft cases in the Doñana Region ranged between 1000 and 2000 as of the year 2020 depending on the source (and have grown even more recently driven by advances in satellite data and higher probability of detection), data from the district attorney's office reported a total of 44 guilty verdicts for the same period—a combined prosecution and conviction probability of 2.2-4.4% that burdens the overall enforcement probability (E)^{4,41}.

Data Availability

The remote-sensed land use and irrigation municipal water use that support the findings of this study are available on Zenodo with the identifier <https://doi.org/10.5281/zenodo.22920389>

Code availability

The PMP simulation under Global Sensitivity Analysis and the random-forest emulator with TreeSHAP attribution are available on Zenodo at <https://doi.org/10.5281/zenodo.22920389>. Analyses used Python 3.11.14, Pyomo 6.10 with ipopt 3.14.19, SALib, scikit-learn 1.8.0 and shap 0.51.0.

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Author contributions

G.S.: methodology, formal analysis, data curation, writing—original draft. N.B.: review and editing. M.B.: data curation and collection. C.D.P.-B.: conceptualisation, supervision, writing—review and editing, funding acquisition.

Competing interests

The authors declare no competing interests.

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