

HIDRIX FOR CONTINUOUS IMPROVEMENT AND TRACEABILITY IN IRRIGATION MANAGEMENT

HIDRIX POUR L'AMELIORATION CONTINUE ET LA TRAÇABILITE DE LA GESTION DE L'IRRIGATION

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ABSTRACT

Water-scarce basins increasingly require irrigation that is not only efficient, but also auditable: farms must be able to show how irrigation decisions were made, what was applied, and how performance is improving over time. This paper presents HIDRIX, an on-demand irrigation and fertigation management system developed and demonstrated under the LIFE4DOÑANA initiative, and discusses how its operational design supports continuous improvement and full traceability at farm scale.

HIDRIX combines short-term forecasting of crop water needs with multi-point field monitoring and autonomous execution through the irrigation head unit. A model-based seasonal strategy ("roadmap") is established jointly with farm staff and then refined in near real time using distributed sensors that capture spatial variability. The control loop records the full chain of inputs (weather and evapotranspiration forecasts, crop/soil parameters, sensor streams), decisions (recommended schedules and thresholds) and actions (executed irrigation and fertigation events), enabling objective evaluation and iterative optimisation across campaigns.

Results from commercial-scale demonstrations in strawberry farms and an additional avocado farm show that the approach can reduce irrigation volumes while maintaining production. Across the pilot farms, irrigation volumes were reduced by 15.8% on average, fertiliser inputs were reduced by 11.7% for nitrogen and 13.8% for phosphorus (P2O5), and water productivity increased by 21.2%, with yields maintained (+0.7% on average). Beyond the LIFE demonstration, HIDRIX is now deployed in nine commercial farms, several operating fully on-demand, reporting strong gains in water optimisation, stable or improved production, and a measurable reduction in workload and decision pressure for key farm personnel.

HIDRIX illustrates how innovative irrigation services can evolve from "decision support" to traceable execution, embedding continuous improvement and accountability into daily operations.

Keywords: On-demand irrigation; decision support; automation; Traceability; Water productivity; Fertigation.

RÉSUMÉ

Les bassins déficitaires en eau exigent de plus en plus une irrigation à la fois efficace et vérifiable : les exploitations doivent pouvoir démontrer comment leurs décisions ont été prises, quelles quantités ont été appliquées et comment les performances progressent. Cet article présente HIDRIX, un système de gestion de l'irrigation et de la fertigation à la demande développé et testé dans le cadre de l'initiative LIFE4DOÑANA, et montre comment sa conception opérationnelle assure l'amélioration continue et une traçabilité complète à l'échelle de l'exploitation.

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HIDRIX combine la prévision à court terme des besoins en eau des cultures, un suivi multipoint sur le terrain et une exécution autonome par l'intermédiaire de l'unité de tête du réseau d'irrigation. Une stratégie saisonnière fondée sur un modèle, ou « feuille de route », est définie avec le personnel de l'exploitation, puis ajustée presque en temps réel au moyen de capteurs répartis qui reflètent la variabilité spatiale. La boucle de commande enregistre toute la chaîne : les données d'entrée (prévisions météorologiques et d'évapotranspiration, paramètres de la culture et du sol, données des capteurs), les décisions (calendriers et seuils recommandés) et les actions (irrigations et fertigations exécutées), ce qui permet une évaluation objective et une optimisation itérative d'une campagne à l'autre.

Les démonstrations à l'échelle commerciale menées dans des exploitations de fraises et dans une exploitation d'avocats montrent que cette approche réduit les volumes d'irrigation tout en maintenant la production. Dans les exploitations pilotes, ces volumes ont diminué en moyenne de 15,8 %, les apports d'engrais de 11,7 % pour l'azote et de 13,8 % pour le phosphore (P2O5), tandis que la productivité de l'eau a augmenté de 21,2 %, avec des rendements maintenus (+0,7 % en moyenne). Au-delà de la démonstration LIFE, HIDRIX est désormais déployé dans neuf exploitations commerciales, dont plusieurs fonctionnent entièrement à la demande ; celles-ci signalent une forte optimisation de l'eau, une production stable ou accrue et une réduction mesurable de la charge de travail et de la pression décisionnelle du personnel clé.

HIDRIX montre comment des services d'irrigation innovants peuvent évoluer de « l'aide à la décision » vers une exécution traçable, en intégrant l'amélioration continue et la responsabilisation aux opérations quotidiennes.

Mots clés: Irrigation à la demande; Aide à la décision; Automatisation; Traceability; Productivité de l'eau; Fertigation.

INTRODUCTION

Irrigated agriculture is facing a dual transition. First, water availability is declining in many basins due to prolonged droughts, competing demands and tighter allocation rules, as it is the case for Guadalquivir River basin in Spain. Second, expectations from authorities, buyers and society are moving from voluntary “good practice” to demonstrable performance: farms are increasingly asked to quantify water use efficiency, nutrient losses and compliance with limits. In this context, irrigation management must deliver two outcomes simultaneously: (i) higher resource efficiency without compromising yield and quality, and (ii) traceability of decisions and actions so that improvements can be verified, repeated and transferred.

In many high-value crops, particularly those grown on sandy or heterogeneous soils, irrigation is still managed through a combination of experience, periodic field checks and conservative safety margins. While this approach can be robust, it tends to over-apply water and nutrients, increases drainage and leaching risk, and places heavy responsibility on a small number of key people (irrigation managers, head growers, technical advisors). Digital tools and sensors can help, but “monitoring” alone does not guarantee better decisions; nor does “recommendation” guarantee adoption when time is limited and risk aversion is high.

HIDRIX was developed to address these limitations through an on-demand operational model that couples forecasting, monitoring and autonomous execution. The system was demonstrated under commercial conditions in the Doñana area (Huelva, Spain), where water bodies are under significant pressure and farms need practical pathways to maintain competitiveness while reducing environmental impacts. This paper focuses on two questions aligned with ICID Topic Q67.1: (1) How can on-demand irrigation services enable continuous improvement at farm scale? and (2) How can the same services deliver end-to-end traceability, turning daily irrigation operations into an auditable dataset for management, advisory and reporting purposes.

HIDRIX SYSTEM OVERVIEW

HIDRIX is designed as a closed-loop irrigation and fertigation management framework (the overall workflow of HIDRIX is shown in **Figure 1**). It integrates: (a) a modelling layer that forecasts crop water demand and supports seasonal planning; (b) a monitoring layer that captures irrigation execution, soil–plant response and key water quality/nutrition indicators; and (c) an automation layer at the irrigation head unit that executes schedules and prioritises sectors according to the agreed strategy and real-time constraints.

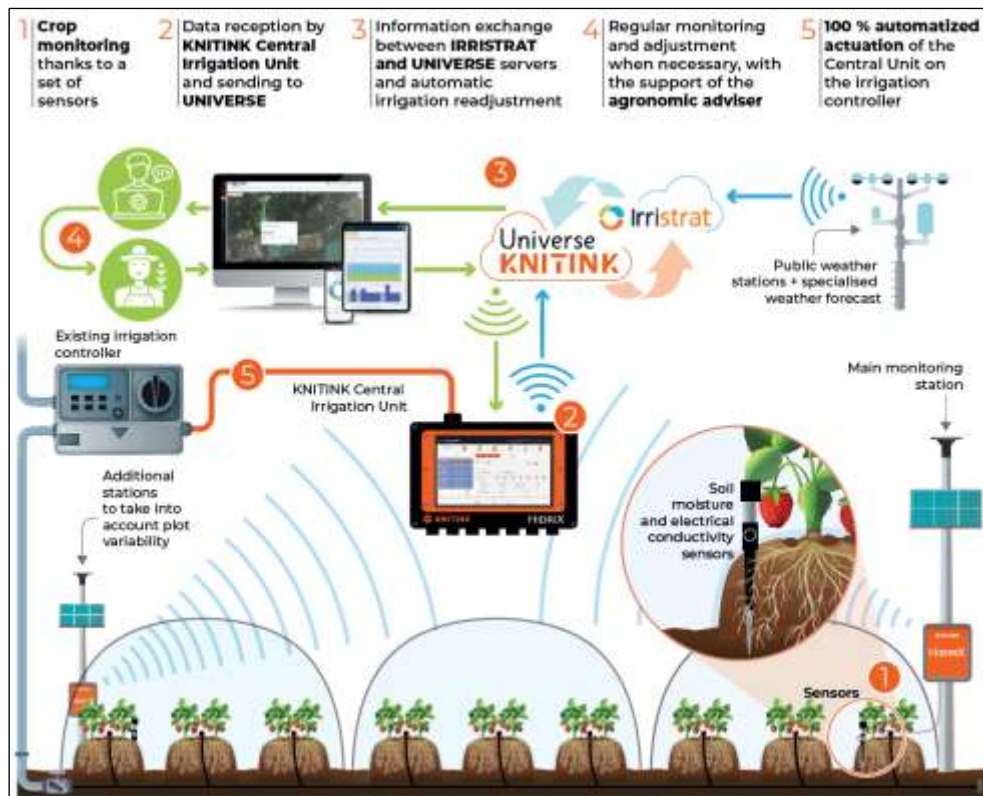


Figure 1: HIDRIX on-demand irrigation workflow

The modelling layer translates weather forecasts, reference evapotranspiration and crop coefficients into a weekly and daily target for irrigation volumes. This “roadmap” is not a rigid prescription; it is a baseline strategy that includes an explicit safety margin to accommodate uncertainty, sensitive phenological stages and site-specific constraints such as salinity management or minimum pulse duration.

The monitoring layer is intentionally distributed. Rather than relying on a single probe, HIDRIX uses multiple sensing points to represent within-field variability (see **figure 2**). In practice, farms often contain zones that differ in texture, hydraulic behaviour and drainage properties, even within a single irrigation sector. HIDRIX aggregates sensor information into operational indicators (a “virtual sensor”) used to adjust irrigation timing and volumes while maintaining the discipline of the roadmap.

Typical monitored variables include irrigation volumes and flow patterns, soil moisture and/or matric potential, and proxy indicators of plant status. Where relevant, complementary measurements are used for nutrient management and salinity control (e.g., electrical conductivity in soil solution or drainage).



Figure 2: Definition of the location of the monitoring points in the PILOT plot (a), communication node installed in the plot (b) and installation of sensors in the different monitoring points (c).

The automation layer connects the decision logic to the irrigation controller. HIDRIX can operate in different modes, from assisted decision-making (farmer approves or edits schedules) to full on-demand operation where irrigation is triggered and modulated automatically within the agreed constraints. The controller allocates irrigation among sectors when resources are limited (e.g., restricted pumping time or reduced water allotment over the season), and it ensures that executed actions are recorded with timestamps and volumes.

This architecture supports a practical division of responsibilities: strategic settings (crop parameters, phenology milestones, safety margins, minimum/maximum limits) are agreed at a strategic level (farm team, advisor), while the system handles repetitive decisions and execution at event level, with eventually some operation managed by the irrigator. The result is a workflow that can reduce the daily burden on key staff while increasing consistency and transparency.

MATERIALS AND METHODS

Demonstration context and farms

The system was validated under commercial conditions across multiple farms. The primary demonstrations were conducted in strawberry farms representative of intensive soil-based production. In a second phase, an additional avocado farm was included to test transferability to a perennial, high-value crop with different phenology and irrigation patterns. Farms were selected to reflect real operational constraints: existing infrastructure, labour availability, heterogeneous soils, and, during the second monitoring season, severe water scarcity that imposed restrictions on irrigation hours and total volumes.

Experimental approach

The demonstrations were organised around paired comparisons between (i) a pilot area managed with HIDRIX and (ii) a reference area managed with the farm's conventional practice. Pilot and reference areas were chosen to be as comparable as possible in terms of variety, planting date and irrigation layout. In some cases, farms extended the pilot approach to additional sectors ("extended pilot") as confidence increased, enabling assessment of scalability within the same farm.

The primary performance indicators were:

- Irrigation volume (m^3/ha) over the campaign.
- Yield (kg/ha) and relative yield change between pilot and reference. Water productivity (kg/m^3), computed from yield and irrigation volume.
- Fertiliser application, expressed as total units for key nutrients where available, and/or inferred from fertigation solution measurements.

- Qualitative operational indicators including ease of irrigation management and the ability to detect system inefficiencies (flow deviations, sector-level anomalies).

Data collection for irrigation volumes

Irrigation volumes were measured using flow meters connected to the HIDRIX system at the pumping station level, with additional independent flowmeters connected to dataloggers mounted on the drip lines in the field. Data were visualised through the monitoring platform and checked against manual meters. For baseline characterisation, volumes from the season preceding implementation were obtained through a combination of direct measurements and structured interviews when meters were not available, allowing the irrigation strategy and safety margins to be tuned to farm practice.

During the first demonstration season (October 2021-May 2022), irrigation volumes in pilot and reference areas were monitored continuously. Comparisons were complemented with a baseline season comparison where needed, taking into account reference evapotranspiration to ensure that year-to-year climatic differences did not confound interpretation. In the second season (October 2022-May 2023), improved instrumentation and lessons from the first season allowed more robust accounting, with direct comparisons between pilot and reference areas under the same climatic and restriction regime.

Data collection for yield and crop status

Yield was recorded at commercial scale. Farms were provided with simple recording sheets to register harvest from pilot and reference areas. Where packhouse traceability systems were available, those records were used to cross-check field entries. As expected in high-intensity harvesting systems, data completeness varied among farms. When yield partitioning could not be reliably ensured (e.g., mixing at packhouse), those datasets were excluded from aggregate yield calculations. Complementary crop and soil monitoring supported interpretation of results and calibration of the roadmap and thresholds. These measurements included periodic analyses of leaf tissue and sap for nutrient status, soil analyses for nitrogen and salinity, and measurements of fertigation solution and drainage water to understand nutrient and salt dynamics. Such information was used to confirm that water savings were not achieved at the expense of crop stress, and to refine seasonal adjustment factors.

Fertiliser accounting

Fertiliser management differed among farms: Some farms fertilised by electrical conductivity (continuous or near-continuous injection at a target concentration), in which case fertiliser savings tended to be proportional to irrigation savings when concentrations were similar. Other farms fertilised by fixed daily quantities, in which case fertiliser savings depended on changes to the fertilisation plan rather than irrigation duration alone. Where complete fertilisation plans were not accessible, nutrient application and comparative trends were estimated from fertigation solution measurements and periodic sampling. Aggregate nutrient savings are therefore presented as the best available estimates, with attention to the underlying data quality.

Limitations

As a market-proximate demonstration, the work prioritised operational realism over perfect experimental control. Differences in field comparability, changes in farm staffing, pest events and water restrictions affected some datasets. These factors are discussed in the interpretation of results and inform recommendations for future deployments.

RESULTS

Across the demonstration farms, HIDRIX enabled a measurable reduction in irrigation volumes while maintaining production. On average, irrigation volumes in pilot areas were 15.8% lower than in the

corresponding reference areas (**table 1**). Yield was maintained, with an average increase of 0.7% across the farms with reliable production accounting.

Table 1: irrigation volume, yield and water productivity in the pilot farms (pilot and control)

		Surface (ha)	Irrigation applied (m3/ha)		Yield (Kg/ha)		Water productivity (Kg/m ³)
FARM A	PILOT (P)	3,7	5.049	-13,2%	61.046	0,0%	12,1
	REFERENCE (REF)	2,1	5.814		61.065		10,5
FARM B	P	4,3	3.400	-4,8%	52.085	4,5%	15,3
	REF	2,2	3.572		49.833		14,0
FARM C	P	2,7	6.645	-17,6%	41.771	-0,7%	6,3
	REF	2,5	8.061		42.055		5,2
FARM D	P	2,6	No drapo. / N.A.				
	REF	1,5	No drapo. / N.A.				
FARM E	P	2,7	6.809	-3,1%	55.154	1,5%	8,1
	REF	2,2	7.025		54.352		7,7
FARM F	P	3,9	5.352	-36,9%	40.793	-1,7%	7,6
	REF	4,5	8.487		41.503		4,9
FARM G	P	2,0	3.718	-19,1%	No drapo. / N.A.		
	REF	1,2	4.595		No drapo. / N.A.		
Average PILOT			5.162	-15,8%	50.170	0,7%	9,9
Average REFERENCE (CONTROL)			6.259		49.762		8,5

Combining these two outcomes, water productivity increased by 21.2% on average, with farm-level improvements ranging from modest gains to very large increases depending on baseline practice, soil behaviour and the degree of water restriction. The values represent averages across farms and seasons included in the analysis. In several cases, farms began with relatively advanced irrigation management, implying that further improvements required careful tuning and risk management. Moreover, the second project year (2022/2023) coincided with a drought year with water restrictions that obliged the farms to generally reduce their irrigation.

Nutrient and salinity management

Estimated fertiliser savings were observed alongside water savings. Aggregate reductions were 11.7% for nitrogen and 13.8% for phosphorus (expressed as P₂O₅) relative to reference areas (**table 2**). Beyond totals, monitoring highlighted how reductions in drainage events and better alignment between fertigation and crop demand can reduce nutrient losses.

In farms where irrigation water quality imposed salinity constraints, the roadmap incorporated explicit leaching fractions and seasonal adjustment factors. This helped avoid excessive salt accumulation while still reducing over-irrigation.

Farm-level observations and operational outcomes

The demonstrations generated operational insights relevant for scaling on-demand irrigation:

- Data quality matters: robust metering and consistent yield traceability are prerequisites for reliable evaluation and for building confidence in automation. Spending time to have a robust baseline is useful to demonstrate benefit and build trust with the farmer.
- Within-field variability is a key driver of efficiency: distributed sensing improved representativeness and reduced the risk of managing a heterogeneous sector based on a single point.

- Advisory support accelerates autonomy: farms moved faster toward confident use of on-demand control when supported by specialised agronomic guidance during early implementation.
- Co-benefits were observed: improved control of wet areas and better visibility of sector-level flows helped farms identify irrigation system issues (non-uniformity, clogging, pressure problems) and pursue corrective maintenance.

Table 2: Estimated fertilizer savings in the pilot farms (pilot and control)

		Surface (ha)	Nitrogen Fertilizer Units (kg/ha)		Phosphorus fertilizer units (kg/ha)	
FARM A	PILOT (P)	3,7	371,1	-7,0%	39,0	0,0%
	REFERENCE (REF)	2,1	399,2		39,0	
FARM B	P	4,3	140,0	-4,1%	111,0	-11,2%
	REF	2,2	146,0		125,0	
FARM C	P	2,7	298,1	0,0%	220,6	0,0%
	REF	2,5	298,1		220,6	
FARM D	P	2,6	No dispo. / N.A.			
	REF	1,5	No dispo. / N.A.			
FARM E	P	2,7	132,0	-10,2%	15,0	-21,1%
	REF	2,2	147,0		19,0	
FARM F	P	3,9	108,1	-36,9%	68,0	-36,9%
	REF	4,5	171,5		107,8	
FARM G	P	2,0	No dispo. / N.A.			
	REF	1,2	No dispo. / N.A.			
Average PILOT			209,9	-11,7%	90,7	-13,8%
Average REFERENCE (CONTROL)			232,4		102,3	

Commercial scaling after demonstration

Beyond the LIFE demonstration period, HIDRIX has been implemented in nine commercial farms. Several of these farms operate fully on-demand across large areas, using HIDRIX as the default irrigation management approach rather than a pilot tool. Since march 2026, three farms (in strawberry, blueberry and watermelon production) are operating completely on demand in Huelva.

DISCUSSION

Enabling continuous improvement

Continuous improvement in irrigation requires more than performance at a single point in time; it requires a repeatable process that learns from measured outcomes. HIDRIX operationalises this through an iterative cycle:

- Define a seasonal strategy. A roadmap is agreed based on weather forecasts, crop coefficients, field constraints and risk appetite.
- Execute and monitor. Irrigation events are executed autonomously or semi-autonomous; monitoring captures both actions and responses.
- Diagnose deviations. Differences between expected and observed behaviour (e.g., faster drying in a zone, unexpected flow patterns, rising salinity) are detected early.

- Recalibrate. Thresholds, adjustment factors and sector priorities are updated, typically on a weekly basis during the campaign and more substantially between seasons.
- Consolidate learning. Parameter sets and lessons are stored and reused, shortening the learning curve in the following campaign and enabling gradual tightening of safety margins.

This structure helps explain why yield benefits may increase after multiple years of use. Early seasons often emphasise risk control and confidence building, especially in sensitive crop stages. As trust grows and the farm's irrigation system issues are corrected, the roadmap can be refined to capture larger efficiency gains while protecting crop performance.

Delivering traceability

Traceability is achieved when a farm can reconstruct the full chain from data to decision to action to outcome. HIDRIX provides this by design. Each irrigation event can be linked to:

- The forecast and crop parameters used to establish the target.
- The sensor state and thresholds that triggered or modified the event.
- The actual executed duration, volume and sector allocation.
- Associated fertigation settings and, where available, quality indicators (e.g., conductivity).
- Subsequent crop and soil responses captured in monitoring.

This creates an auditable "irrigation ledger" that can be used for internal management, advisory review and external reporting (for instance in the value chain). It is especially relevant since the monitoring is conducted at irrigation unit level, where the filtration and fertilization usually occur, with limited risk of altering data. In area where illegal water pumping is or has been an issue such as the Doñana area in Spain where the LIFE4DOÑANA project stands, this transparency is of the utmost importance.

Risk management and adoption

Two practical factors strongly influence adoption. First, many farms operate under time pressure, with irrigation decisions concentrated in a small number of people. Automation can reduce workload, but only if the system is trustworthy. The demonstration highlighted the importance of conservative initial settings, clear visualisation of what the system is doing, and rapid support during early anomalies. Second, infrastructure quality conditions achievable gains. Poor filtration, pressure instability or clogged emitters can dominate crop response and undermine confidence.

HIDRIX can help reveal such issues through flow monitoring, but farms may need an initial technical upgrade path to fully benefit from on-demand control. It has to be noted that carefully identifying these issues is critical otherwise the farmer often link the irrigation management problems that occur with the new system, when it really only highlights those problems.

Implications for irrigation services

The results support a shift in how irrigation services are conceived. Traditional decision support tools often end at the recommendation stage. HIDRIX extends the service to execution and verification, enabling consistent application and creating traceable evidence of performance. This is particularly relevant in basins with allocation limits, where compliance depends on measured volumes, and in supply chains where sustainability claims increasingly require documentation. The combination of efficiency, traceability and reduced workload suggests that on-demand systems can be a practical lever for scaling water productivity improvements in high-value irrigated agriculture.

CONCLUSIONS

HIDRIX demonstrates how on-demand irrigation and fertigation management can improve water use efficiency while creating the traceability needed for modern irrigated agriculture. Commercial-scale

demonstrations achieved an average 15.8% reduction in irrigation volumes while maintaining yields (+0.7%), leading to a 21.2% increase in water productivity. Estimated nutrient savings (−11.7% N and −13.8% P₂O₅) indicate additional environmental benefits when fertigation practices are aligned with optimised irrigation.

Beyond quantified indicators, HIDRIX embeds a continuous improvement workflow: seasonal planning, near real-time adjustment through distributed sensing, systematic diagnostics and recalibration, and consolidation of learning across campaigns. The same workflow produces an auditable record linking inputs, decisions, actions and outcomes, supporting transparency for farm management, advisors and external stakeholders.

Post-demonstration deployment in nine commercial farms, including several operating fully on-demand, confirms scalability and highlights an additional value proposition: reduced workload and decision pressure for key farm personnel. For future deployments, the main success factors are robust metering and traceability, adequate irrigation infrastructure (filtration, pressure stability, emitter uniformity), and structured advisory support during early implementation to accelerate autonomy.

These findings reinforce the role of innovative irrigation management services that move beyond recommendations to traceable execution, enabling verified efficiency gains at scale in water-scarce basins.

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