

LEVERAGING ARTIFICIAL INTELLIGENCE AND DATA GOVERNANCE FOR RESILIENT AGRICULTURAL WATER MANAGEMENT: THE SAUDI ARABIAN EXPERIENCE

OPTIMISER L'INTELLIGENCE ARTIFICIELLE ET LA GOUVERNANCE DES DONNÉES POUR UNE GESTION RÉSISSANTE DE L'EAU AGRICOLE : L'EXPÉRIENCE DE L'ARABIE SAOUDIENNE

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ABSTRACT

In an era defined by acute water scarcity and the intensifying impacts of climate change, sustainable water management has become a critical pillar for agricultural resilience. Saudi Arabia, facing significant challenges in its semi-arid environment where agriculture accounts for the largest share of water consumption, has embarked on a transformative journey led by the Saudi Irrigation Organization (SIO). This journey aims to redefine irrigation practices through technological innovation and data-driven governance, aligning directly with Saudi Vision 2030 and the national data strategy. This paper explores the strategic integration of Artificial Intelligence (AI), advanced analytics, and robust data management frameworks to optimize water use efficiency and ensure long-term water security. The methodology centres on a comprehensive structural reform that transitioned from project-based management to a unified national entity responsible for irrigation, dams, and treated sewage effluent (TSE). A key milestone was the establishment of a dedicated Data Management Office (DMO) in 2022, mandated to ensure compliance with Saudi Data and AI Authority (SDAIA) standards. Central to this approach is the creation of a National Irrigation Database (NIDB), which serves as a centralised single source of truth for water resource planning. Several flagship initiatives operationalize this data foundation, foremost among them the Irrigation Calculator—a smart platform designed to calculate precise crop water requirements for 896 different crop types across 29 cities. The paper further details a centralised Business Intelligence (BI) platform, AI-driven anomaly detection for TSE reuse and dam safety, satellite-based consumption monitoring, and collaborative predictive modelling with KAUST. Findings demonstrate that this successful transition to smart irrigation is not merely a technological achievement but a governance-driven outcome. The study concludes by proposing a GCC-wide collaboration framework for data interoperability, offering a scalable model for other arid regions seeking to harmonise technological innovation with sustainable agricultural policy.

Keywords: irrigation practices; technological innovation; water resource planning; crop water requirements; sustainable agricultural policy.

RESUME

Dans une époque caractérisée par une grave pénurie d'eau et l'intensification des impacts du changement climatique, la gestion durable de l'eau est devenue essentiel pour la résistance agricole. L'Arabie saoudite, confrontée à des défis importants dans son environnement semi-aride où l'agriculture consomme la grande partie de l'eau, a entrepris une transformation profonde menée par l'Organisation saoudienne de l'irrigation (SIO). Cette transformation vise à redéfinir les pratiques d'irrigation grâce à l'innovation technologique et à la gouvernance axée sur les données, en s'alignant directement sur la Vision saoudienne 2030 et la stratégie nationale des données. Ce document explore l'intégration stratégique de l'intelligence artificielle (IA), des analyses avancées et des cadres robustes de gestion des données afin d'optimiser l'efficacité de l'utilisation de l'eau et d'assurer la sécurité hydrique à long

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terme. La méthodologie repose sur une réforme structurelle globale permettant de passer d'une gestion par projet à une entité nationale unifiée responsable de l'irrigation, des barrages et des eaux usées traités (TSE). Une étape clé était la mise en place d'un bureau dédié à la gestion des données (DMO), en 2022, chargé d'assurer la conformité aux normes de l'Autorité saoudienne des données et de l'intelligence artificielle (SDAIA). Au cœur de cette approche se trouve la création d'une base de données nationale sur l'irrigation (NIDB), qui sert de source unique et centralisée de vérité pour la planification des ressources en eau. Plusieurs initiatives phares concrétisent cette base de données, au premier rang desquelles se trouve la calculatrice d'irrigation — une plateforme intelligente conçue pour calculer avec précision les besoins en eau des cultures pour 896 types de culture différents répartis dans 29 villes. Le document détaille davantage la plateforme d'intelligence d'affaires (BI) centralisée, le système de la détection des anomalies pilotée par l'IA pour la réutilisation des eaux usées traités (TSE) et la sécurité des barrages, la surveillance de la consommation par satellite et la modélisation prédictive collaborative avec KAUST. Les résultats démontrent que cette transition réussie vers l'irrigation intelligente ne constitue pas seulement une réussite technologique, mais un résultat axé sur la gouvernance. L'étude conclut en proposant un cadre de collaboration à l'échelle du Conseil de coopération du Golfe (CCG) pour l'interopérabilité des données, offrant un modèle évolutif pour d'autres régions arides cherchant à harmoniser l'innovation technologique avec une politique agricole durable.

Mots-clés : Pratiques d'irrigation; Innovation technologique; Planification des ressources en eau; Besoins en eau des cultures; Politique agricole durable.

1. INTRODUCTION

Water scarcity stands among the most pressing resource challenges of the twenty-first century, and nowhere is its urgency more sharply felt than in the Arabian Peninsula. Saudi Arabia receives an average annual rainfall of less than 100 mm across much of its territory, yet supports an agricultural sector that consumes approximately 88 per cent of total national water withdrawals (Gabr et al., 2020). The kingdom relies almost exclusively on non-renewable fossil groundwater and desalinated seawater to sustain irrigated agriculture—a supply structure that is inherently finite and increasingly stressed by population growth, food security demands, and accelerating climate variability (Multsch et al., 2017).

This structural vulnerability has long been recognised at the policy level. Early computerised irrigation management models were proposed for large Saudi schemes by Abderrahman et al. (2001), and various remote-sensing approaches have since been applied to monitor agricultural water use at field and regional scales (López Valencia et al., 2020; Johansen et al., 2021). Yet the gap between data collection and operational decision-support remained wide. Irrigation allocations continued to rely on generalised seasonal rates—typically fixed at 40 m³ per hectare in winter and 80 m³ per hectare in summer—that took no account of crop type, growth stage, soil conditions, or local climate. The consequence was systematic over- or under-irrigation, wasted water, and an inability to enforce or audit allocation at the farm level.

Saudi Vision 2030 created the institutional impetus to close this gap. The Saudi Irrigation Organization (SIO) was restructured from a project-based body into a unified national entity with responsibility for irrigation infrastructure, dams, and treated sewage effluent (TSE) reuse. Simultaneously, the National Data Strategy and the Saudi Data and AI Authority (SDAIA) established governance standards that made data quality and AI readiness mandatory for public organisations (SDAIA, 2022). The SIO response was to build, from the ground up, an integrated data and AI ecosystem for agricultural water management.

This paper documents that ecosystem. It describes the governance architecture, the National Irrigation Database, the Irrigation Calculator platform, the centralised BI environment, and the advanced AI applications deployed for TSE monitoring, dam safety, and satellite-based consumption auditing. The central argument is that technological sophistication alone does not produce sustainable water management: governance, data quality, and institutional reform must come first. Saudi Arabia's

experience offers a replicable model for other arid regions confronting the same convergence of scarcity, demand, and climate risk.

2. LITERATURE REVIEW AND RESEARCH GAP

2.1 *Water Scarcity and Irrigation Management in Saudi Arabia*

The severity of Saudi Arabia's water challenge is well-documented. Groundwater abstractions for agriculture have far exceeded natural recharge rates for decades; in the Al Jawf region alone, total abstraction in 2015 was estimated at approximately 5.5 billion cubic metres, vastly outpacing any sustainable yield (López Valencia et al., 2020). Satellite gravimetric studies using GRACE data show a persistent declining trend in groundwater storage across multiple regions, with average annual declines in the order of -6.7 mm per year in areas such as Madinah (Badaoud et al., 2024). Meanwhile, agricultural evapotranspiration from irrigated fields routinely exceeds precipitation by factors of seven or more in some catchments (Gabr et al., 2020).

Efforts to quantify and reduce this demand have followed two broad tracks. The first involves improved estimation of crop water requirements (CWR). Studies using CROPWAT 8.0 across the Qassim region established that irrigation water requirements range from around 308 mm per decade for barley to nearly 1,480 mm per decade for citrus (Khan et al., 2021), highlighting the enormous variability that uniform allocation rules cannot accommodate. Haq and Khan (2022) demonstrated that combining high-resolution PlanetScope satellite data with FAO CROPWAT achieves strong temporal correlation ($r = 0.83$) in CWR estimation, opening the path towards real-time, field-level guidance. The second track focuses on demand-side governance. Multsch et al. (2017) evaluated a suite of water-saving strategies for Saudi irrigation agriculture, while Napoli et al. (2018) examined policy options for reducing agricultural withdrawals, concluding that technical fixes without complementary institutional reform deliver limited sustainable impact.

2.2 *AI and Data-Driven Water Management*

Globally, the convergence of AI, Internet-of-Things sensors, and cloud analytics has created new possibilities for precision water management. Dai et al. (2025) propose a five-layer smart-water architecture—sensing, transmission, processing, intelligent analysis, and decision support—showing how Singapore and Chinese city pilots achieved measurable reductions in non-revenue water and improved system resilience. Dada et al. (2024) review IoT-AI integration in water and wastewater treatment, identifying predictive maintenance and real-time quality monitoring as particularly high-value applications. In the agricultural domain, Razavi et al. (2026) synthesise the interconnections among watershed models, optimisation algorithms, AI surrogates, and decision-support systems, arguing that scalability constraints and data inconsistencies remain the primary barriers to operational deployment. For the Saudi context specifically, Sharma (2021) proposed a multi-criteria optimisation and intelligent water demand forecasting framework, achieving demand-prediction accuracy above 98 per cent in simulation. Albaroudi et al. (2025) examined AI opportunities aligned with Vision 2030, identifying precision irrigation and ML-based monitoring as priority applications. The empirical evidence from Hamdouni (2026a) confirms that AI-compatible smart irrigation is positively and significantly associated with improvements in water-use efficiency and crop water productivity across 13 Saudi regions and six major crops over 2010–2024, with AI adoption increasing water-use efficiency by approximately 8–10 per cent. A complementary study by Hamdouni (2026b) found that AI-enabled monitoring significantly improves cultivated land quality and productivity, with effects persisting over time.

2.3 *The Research Gap*

Despite this accumulation of evidence, a critical gap persists: virtually no published work documents a complete, operational, institutionally embedded AI and data governance framework for national-scale irrigation management in an arid public-sector context. Remote-sensing studies focus on monitoring but rarely connect their outputs to operational allocation workflows. AI modelling papers propose

frameworks but lack implementation detail. Governance studies address policy without engaging the technical architecture. The present paper addresses this gap directly by describing SIO's end-to-end transition from fragmented data management to an AI-ready national platform—from the establishment of data governance structures to the deployment of operational tools used in daily irrigation decisions.

3. METHODOLOGY AND SYSTEM DESIGN

3.1 Institutional Reform and Structural Transition

The foundation of SIO's digital transformation was organisational rather than technological. The transition from a project-based management model to a unified national entity consolidated responsibility for surface irrigation networks, dam operations, and TSE reuse under a single governance structure. This consolidation eliminated the data silos that had previously made integrated analysis impossible: regional offices collected incompatible metrics, operational sectors used different terminologies, and no common platform existed for cross-domain queries.

The establishment of a dedicated Data Management Office (DMO) in 2022 formalised this shift. The DMO was mandated to achieve compliance with SDAIA's National Data Governance Standards, a requirement that drove systematic attention to data quality, metadata management, and interoperability across all SIO operational sectors (SDAIA, 2022). The DMO operates across four primary data domains, each designed to support AI readiness (Table 1).

Table 1. SIO Data Governance Framework: Four Primary Domains and AI Readiness Outcomes

Data Domain	Primary Function	Key Components	AI Readiness Outcome
Data Domain Definition	Scope & ownership mapping	Irrigation, dams, TSE, groundwater	Unified semantic model
Governance Framework	Policy, stewardship & compliance	SDAIA standards alignment	Audit-ready data lineage
Architecture Roadmap	Infrastructure planning	Centralised NIDB platform	Scalable ML-ready pipelines
Business Glossary	Shared vocabulary & definitions	Standardised crop & water terms	Interoperable cross-agency queries

3.2 The National Irrigation Database

The National Irrigation Database (NIDB) is the technical centrepiece of SIO's data strategy. Designed as a centralised single source of truth, the NIDB integrates data streams from irrigation networks, pumping stations, treatment plants, meteorological stations, and field reporting systems across all SIO regions. A standardised business glossary ensures that terms such as "crop water requirement," "irrigation duty," and "treated sewage effluent" carry identical meanings across operational sectors, enabling reliable cross-domain aggregation and query.

The NIDB architecture is explicitly designed for machine learning readiness: structured schema, consistent temporal granularity, automated quality checks, and documented lineage from source to analytical layer. This design philosophy reflects the recognition that data quality problems are not merely a technical inconvenience—they directly undermine the reliability of AI-generated recommendations. An AI model that predicts irrigation demand from poor-quality data may produce results that are worse than the manual processes it was intended to replace (Razavi et al., 2026).

3.3 The Irrigation Calculator: Design and Calculation Logic

The Irrigation Calculator is SIO's most directly operational decision-support tool. It was developed to overcome the inadequacy of fixed seasonal allocation rates by providing crop-specific, location-specific,

and system-specific water requirement estimates to both internal allocation staff and external users including farmers and agricultural technicians.

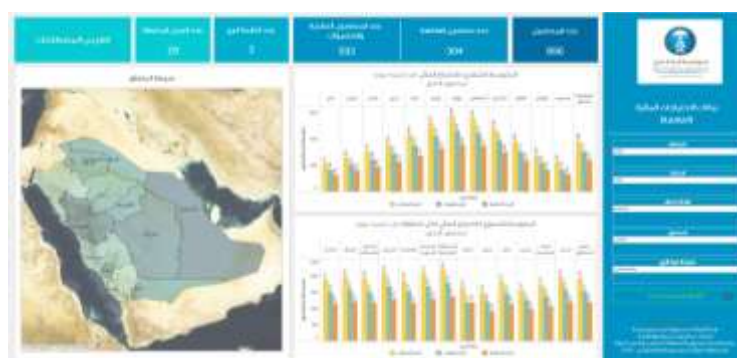
The calculator was built using Tableau as its core platform for data integration, calculation logic, and interactive visualisation. Its reference data foundation is the KACST Crop Water Requirement Study, conducted in cooperation with the Ministry of Agriculture and the Ministry of Environment, Water and Agriculture (MEWA), which provides empirically validated water requirements for Saudi conditions. Table 3 summarises the platform's coverage parameters. The core calculation logic translates daily crop water requirements (derived from the reference dataset) into monthly totals based on user inputs. For fruit crops, the monthly water requirement (m³) is calculated as:

Monthly WR (m³) = (Daily CWR × Crop-growth days in month × Number of trees) / 1000 or, where area is the input: Monthly WR (m³) = (Daily CWR × Days × Area in ha × Trees per ha) / 1000 For field and vegetable crops, the formula simplifies to: Monthly WR (m³) = Daily CWR × Crop-growth days × Area in hectares. The platform implements these calculations as computed fields within Tableau, with branching logic that handles the distinction between tree crops and field crops, accommodates both area-based and tree-count-based inputs, and incorporates salinity correction factors appropriate to four water quality classes. The interactive dashboard (as illustrated in Figure 1) allows users to select region, city, crop group, crop, irrigation system, and salinity level, then displays results in both monthly tabular form and graphical seasonal profiles, supplemented by crop-specific irrigation guidance notes.



[Figure 1. Smart Irrigation Calculator Dashboard — interactive Tableau interface showing monthly and annual crop water requirements for Palm Trees across regions and irrigation systems]

Figure 1. Smart Irrigation Calculator Dashboard (Source: SIO, 2025)



[Figure 2. Crops Water Requirements Dashboard — regional overview with interactive map, monthly bar charts, and filter dimensions for region, city, crop type, and water salinity]

Figure 2. Crops Water Requirements Dashboard (Source: SIO, 2025)

3.4 *Business Intelligence Platform and Operational Integration*

Parallel to the Irrigation Calculator, SIO deployed a centralised BI platform that aggregates real-time operational data from all regional offices. The platform integrates metrics from pumping stations, distribution networks, water quality sensors, and field reporting systems into a unified operations dashboard accessible to both field teams and executive decision-makers. Automated data pipelines replace manual data collection and compilation processes, eliminating transcription errors and enabling same-day situational awareness across SIO's entire operational footprint.

3.5 *Advanced AI Applications: TSE, Dam Safety, and Satellite Monitoring*

SIO's responsibility for over 500 dams and a growing TSE reuse programme created demand for AI-driven monitoring that extends beyond irrigation scheduling. For TSE quality assurance, AI anomaly detection models monitor sensor readings along the full treatment-to-application chain, flagging deviations from quality thresholds in near-real-time and triggering inspection workflows before non-compliant water reaches irrigated fields. For dam safety, collaborative modelling with KAUST applies ML-based hydrological analysis to early-warning flood prediction and optimised reservoir operation scheduling.

The QIAS initiative addresses a different but complementary challenge: verifying that actual field-level water consumption matches the quantities allocated. Using satellite imagery from Landsat and Sentinel platforms and applying machine-learning classification approaches (consistent with the methodology of Ebrahim and Elmanadely, 2023, and López Valencia et al., 2020), QIAS estimates consumption at national scale without relying on self-reported farm data. This provides SIO with an independent audit layer that supports policy enforcement and, crucially, generates the empirical evidence needed to evaluate whether the Irrigation Calculator recommendations translate into actual consumption reductions.

4. RESULTS AND ANALYSIS

4.1 *Data Governance: From Silos to Integrated Platform*

The establishment of the DMO and the NIDB produced measurable structural changes in SIO's information environment. Prior to reform, data resided in incompatible regional systems with no shared metadata schema, making cross-regional analysis a manual, time-intensive process requiring weeks of compilation. Following implementation of the four-domain governance framework, all primary data streams feed into the NIDB under a consistent schema. The business glossary eliminates semantic ambiguity in cross-domain queries. Data lineage documentation ensures that any figure presented to decision-makers can be traced back to its source, a requirement for both regulatory compliance and AI model validation.

Compliance with SDAIA standards was achieved across all four governance domains by the end of 2023, enabling SIO to participate in national data-sharing frameworks and position its datasets as potential inputs to GCC-wide interoperability initiatives. This outcome is consistent with the argument of Dai et al. (2025) that cross-sectoral data sharing and national standards are prerequisites for sustainable smart-water governance at scale.

4.2 *Irrigation Calculator: Operational Uptake and Coverage*

The Irrigation Calculator entered live operation on 5 December 2024, following a development process that moved from problem identification in Q2 2024 through brainstorming and design thinking sessions with operational users in Q3 2024, to solution design and deployment in Q4 2024. This rapid nine-month cycle from problem definition to live deployment reflects both the maturity of the NIDB data foundation and the effectiveness of the Tableau-based development environment for rapid prototyping.

Table 3 summarises the coverage parameters of the deployed platform. In its initial configuration the calculator covers 896 crop varieties across 29 cities, accommodates four irrigation system types and four salinity classes, and presents results in both monthly and annual formats with graphical seasonal profiles. The scope represents a categorical improvement over the previous allocation regime. Where allocation staff previously applied two seasonal rates regardless of crop or location, they now have access to differentiated recommendations grounded in empirically validated reference data.

Table 3. Irrigation Calculator: Coverage and Technical Parameters

Parameter	Value / Description
Geographic coverage	29 cities across all administrative regions of Saudi Arabia
Total crop categories covered	896 crop varieties (304 fruit crops; 592 vegetable and field crops)
Irrigation systems modelled	4 systems: surface, bubbler, drip, and sprinkler
Salinity classification	4 levels plus average; integrated into all CWR calculations
Output units – fruit crops	Litres per tree per day (monthly and annual views)
Output units – field crops	Cubic metres per hectare per day (monthly and annual views)
Reference data source	KACST Crop Water Requirement Study (MEWA / Ministry of Agriculture)
Platform development tool	Tableau (data integration, calculation logic, interactive dashboards)
Live operational date	5 December 2024

The calculator's dual audience—internal allocation staff and external field users—is a structural strength. Internal users benefit from standardised, auditable allocation calculations that replace ad hoc manual estimates. External users, including farmers and technicians, receive crop-specific irrigation guidance that converts the numerical water requirement into practical management instructions. The platform thus acts simultaneously as a water-management instrument and a knowledge-transfer mechanism, compressing the gap between institutional decision-making and field practice. This dual function aligns with findings by Alotaibi and Kassem (2021), who found that farmer awareness and access to technical guidance are significant predictors of sustainable water management adoption in Saudi Arabia.

4.3 Business Intelligence: Operational Efficiency Gains

The centralised BI platform produced the most immediately quantifiable operational improvement. Reporting cycles that previously required weeks of manual data collection and compilation from regional offices were compressed to hours through automated data pipelines. Real-time dashboards enable SIO operations managers to identify anomalies in pumping station performance, distribution network pressure, or water quality metrics without waiting for periodic reports. Executive decision-makers can access current operational status across all regions simultaneously, enabling faster coordination during peak demand periods or emergency events.

This efficiency gain has a direct bearing on water use. Slow, inconsistent decision processes in large irrigation organisations are a recognised pathway for water loss (SIO, 2025): water that is not allocated correctly, or is allocated late, may be used suboptimally or simply wasted. By tightening the information-to-decision loop, the BI platform reduces this source of inefficiency independently of any improvement in allocation methodology.

4.4 Advanced AI Applications: TSE, Dam Safety, and Consumption Auditing

AI anomaly detection for TSE quality monitoring has enabled a shift from reactive to predictive quality management. Rather than discovering water quality failures after affected irrigation has occurred, SIO

can now intercept deviations before non-compliant TSE reaches the field. Predictive maintenance scheduling for pumping stations and treatment infrastructure, driven by operational data patterns in the NIDB, has reduced unplanned downtime and the associated disruption to irrigation supply schedules. The KAUST collaboration on dam safety applies ML-based hydrological models to the 500+ dams under SIO management, producing flood probability estimates and optimised release schedules that reduce both downstream flood risk and unnecessary water release. The QIAS satellite monitoring programme provides an independent verification layer: by estimating field-level water consumption from remote sensing data, SIO can compare actual use against calculator-recommended allocations, creating an evidence base for iterative improvement of both the tool and the governance framework surrounding it. Table 2 summarises outcomes across all five AI and data initiatives.

Table 2. SIO AI and Data Initiatives: Technical Mechanisms and Demonstrated Outcomes

Initiative	Technical Mechanism	Demonstrated Outcome
Irrigation Calculator	Crop-specific CWR model, 896 crops, 29 cities; Tableau DSS	Replaced fixed 40/80 m ³ /ha seasonal allocations; live since Dec 2024
Centralised BI Platform	Real-time integration of pumping stations, network metrics, field data	Reporting cycle compressed from weeks to hours
QIAS Satellite Monitoring	Landsat/Sentinel ML pipeline for field-scale consumption estimation	National-scale policy enforcement and allocation audit
TSE Quality Monitoring	AI anomaly detection, source-to-user chain surveillance	Predictive maintenance; reduced operational downtime
Dam Safety & Flood AI (KAUST)	ML-driven hydrological modelling; 500+ dams	Early-warning flood prediction; optimised reservoir releases

5. DISCUSSION

5.1 Governance as the Primary Enabler

The SIO experience offers a clear answer to a question that pervades the smart water management literature: what comes first, technology or governance? The answer, in this case, is unambiguously governance. The Irrigation Calculator is only as reliable as the KACST reference dataset it draws on and the NIDB that delivers it; the BI platform is only as useful as the data quality standards that ensure the metrics it aggregates are comparable; the QIAS satellite audit is only meaningful if there is an institutional framework that acts on its findings. Without the DMO and the four-domain governance architecture, each of these tools would operate in isolation, its outputs contested, its recommendations ignored.

This finding echoes the conclusions of Dai et al. (2025) and Hamdouni (2026a), both of whom identify integrated governance as a critical complement to technological adoption. It also confirms the theoretical argument of Abderrahman et al. (2001), who recognised more than two decades ago that water management reform in Saudi Arabia requires institutional coordination, not merely computational tools. What has changed is the scale of ambition and the quality of the enabling infrastructure.

5.2 The Irrigation Calculator as a Water-Saving Mechanism

The calculator's contribution to water saving operates through two distinct pathways. The first is estimation accuracy: replacing the two-rate seasonal allocation with crop-specific, region-specific, system-specific CWR calculations eliminates the systematic over-irrigation that occurs when a single rate is applied to crops with very different water needs. The literature is unambiguous on the magnitude of this potential—annual CWR values for date palm exceed 1,377 mm while those for barley are below 300 mm (Haq and Khan, 2022); applying the same allocation to both is guaranteed to waste water on one or under-supply the other.

The second pathway is management discipline. By standardising the calculation process and making its results auditable, the calculator removes the variability and inconsistency inherent in manual estimation. Allocation decisions that were previously opaque become transparent and repeatable. This matters for institutional accountability: when SIO sets a water allocation, it can now demonstrate that the figure derives from a validated model applied consistently across all users. The shift from "what we have always done" to "what the data shows is needed" is a governance achievement as much as a technical one.

It should be noted that final quantified figures for total hectares served and annual water saved are being consolidated following the December 2024 deployment. The recommended verification methodology is a before-and-after comparison of actual irrigation volumes under the former generalised allocation regime versus quantities recommended and applied following calculator adoption on a defined verifiable area. SIO anticipates completing this analysis for the first full operating season in 2025.

5.3 Scalability and Limitations

The SIO model is structurally replicable. The governance framework—DMO, NIDB, business glossary, SDAIA compliance—provides a template applicable to any national irrigation authority willing to invest in institutional reform before platform deployment. The Irrigation Calculator's calculation logic is universal: the need to estimate CWR more accurately and communicate results more clearly is not specific to Saudi Arabia. What varies across contexts is the reference data foundation; any replication would require locally validated CWR studies equivalent to the KACST dataset.

Limitations of the current implementation include the reliance on static reference CWR values rather than dynamically updated real-time estimates. As QIAS matures and satellite-based ET estimation achieves finer temporal resolution—following the approach demonstrated by Haq and Khan (2022)—there is a clear pathway to replace or calibrate the reference data with observed consumption patterns. A second limitation is the absence, at the time of writing, of completed quantified water-saving figures. Quantification is not merely a reporting formality; it is the evidence base that justifies the governance investment and guides future iterations of the platform. The ICID Management Award evaluation criteria explicitly require documented water-saving quantification, and SIO is actively addressing this gap.

5.4 GCC-Wide Collaboration Potential

The NIDB architecture and the governance standards aligned with SDAIA create a natural foundation for regional data interoperability. GCC member states share broadly similar hydrological conditions, crop portfolios, and irrigation system typologies. A shared data exchange framework—drawing on the interoperability principles articulated by Yang et al. (2024) for digital twin basin systems—could enable participating countries to pool CWR reference data, calibrate AI models against a larger evidence base, and respond collectively to shared climate vulnerabilities such as dust-storm impacts on evapotranspiration, transboundary aquifer depletion, and regional flood events. SIO has identified this as a medium-term institutional priority.

6. CONCLUSION

Saudi Arabia's experience with AI-driven irrigation management offers three substantive contributions to the global literature on water governance in arid regions. First, it demonstrates that the path from fragmented data management to operational AI is paved with governance reform, not technology procurement. The DMO, the NIDB, the business glossary, and the SDAIA compliance framework were preconditions for every technological initiative that followed. Second, it shows that crop-specific, location-specific water requirement estimation is achievable at national scale using a combination of validated reference data, structured calculation logic, and interactive decision-support tools. The Irrigation Calculator, covering 896 crops across 29 cities and live since December 2024, represents a concrete, operational proof of this principle. Third, it illustrates how multiple AI applications—BI dashboards, anomaly detection for TSE quality, dam safety modelling, and satellite consumption

auditing—can be integrated into a coherent operational ecosystem when they share a common data foundation and governance framework.

The transition from water management to smart water management is not a single technological leap. It is a sequence of institutional decisions, data investments, and operational integrations that compound over time. SIO's trajectory since 2022 illustrates this sequence clearly. The result is an organisation that is better equipped to allocate water efficiently, enforce policy, anticipate infrastructure failures, and respond to climate extremes—and that has created a replicable model for other arid-region irrigation authorities seeking to achieve the same.

Future work should focus on completing the quantification of water savings achieved following Irrigation Calculator deployment, expanding QIAS from pilot to full national coverage, and developing the data-sharing protocols that would enable GCC-wide application of these AI models. These steps will further consolidate the evidence base and extend the reach of an approach that has already demonstrated substantial operational value.

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