

ADAPTIVE AI-DRIVEN WATER MANAGEMENT FRAMEWORK FOR SHADEGAN WETLAND

CADRE DE GESTION DE L'EAU ADAPTATIF PILOTÉ PAR L'IA POUR LA ZONE HUMIDE DE SHADEGAN

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ABSTRACT

Wetland–agriculture systems are increasingly exposed to water scarcity, climatic variability, upstream hydraulic regulation, drainage inflows, and growing livelihood pressure. In such contexts, irrigation water management cannot be treated as a purely technical task because crop production, wetland condition, local livelihoods, and broader territorial resilience are affected simultaneously and often through competing demands. This challenge is particularly relevant in environmentally sensitive and institutionally complex territories, where static allocation rules are often unable to respond to rapid environmental and socio-economic change.

This paper proposes an adaptive AI-driven framework for water management using the Shadegan wetland–agriculture system in south-western Iran as a case study. The framework is designed to support more responsive and transparent decision-making under uncertainty and is organized around three integrated components. The first is a multi-purpose monitoring component based on satellite observations, meteorological records, environmental sensing, and contextual socio-economic information, enabling a more complete understanding of current territorial conditions. The second is a data-driven analytical and forecasting component intended for trend detection, crop water requirement estimation, environmental change screening, and scenario generation under uncertain future conditions. The third is a multi-criteria decision-support component used to compare and rank management options under agricultural, environmental, economic, livelihood, and institutional constraints. The study contributes a territorially oriented decision framework through which monitoring, forecasting, multi-criteria evaluation, feedback, and revision are linked within a single operational loop. This allows management options to be updated as field conditions, implementation constraints, and local priorities evolve. The framework is grounded in the Shadegan case and informed by the experience of the Conservation of Iranian Wetlands Project, including pilot villages associated with sustainable agriculture and wetland-compatible livelihood practices. A structured and operational basis is thus provided for the next phase of territorial water management in wetland–agriculture systems.

Keywords: adaptive irrigation management; artificial intelligence; remote sensing; decision support; Shadegan Wetland; conceptual framework

RESUME

Les systèmes agricoles des zones humides sont de plus en plus exposés à la rareté de l'eau, à la variabilité climatique, à la régulation hydraulique en amont, aux apports de drainage et à la pression croissante sur les moyens de subsistance. Les systèmes d'agriculture des zones humides sont de plus

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en plus exposés à la rareté de l'eau, à la variabilité climatique, à la régulation hydraulique en amont, aux apports de drainage et à la pression croissante sur les moyens de subsistance. Dans de tels contextes, la gestion de l'eau d'irrigation ne peut pas être traitée comme une tâche purement technique car la production agricole, l'état des zones humides, les moyens de subsistance locaux et la résistance territoriale plus large sont affectés simultanément et souvent par des demandes concurrentes. Ce défi est particulièrement pertinent dans les territoires écologiquement sensibles et institutionnellement complexes, où les règles d'allocation statiques sont souvent incapables de répondre aux changements environnementaux et socio-économiques rapides.

Cet article propose un cadre adaptatif piloté par l'IA pour la gestion de l'eau en utilisant le système des zones humides et agricoles de Shadegan au sud-ouest de l'Iran comme étude de cas. Le cadre est conçu pour soutenir une prise de décision plus réactive et transparente en situation d'incertitude et s'organise autour de trois composantes intégrées. Le premier est un composant de surveillance polyvalent basé sur des observations satellitaires, des relevés météorologiques, la détection environnementale et des informations socio-économiques contextuelles, permettant une compréhension plus complète des conditions territoriales actuelles. Le second est un composant analytique et de prévision fondé sur des données, destiné à la détection des tendances, à l'estimation des besoins en eau des cultures, au suivi des changements environnementaux et à l'élaboration de scénarios dans des conditions futures incertaines. Le troisième est un composant d'aide à la décision multicritères utilisé pour comparer et classer les options de gestion en fonction des contraintes agricoles, environnementales, économiques, institutionnelles et liées aux moyens de subsistance. L'étude contribue à un cadre décisionnel à l'échelle du territoire dans lequel le suivi, la prévision, l'évaluation multicritère, le retour d'information et la révision sont liés au sein d'une boucle opérationnelle unique. Cela permet d'actualiser les options de gestion à mesure que les conditions sur le terrain, les contraintes de mise en œuvre et les priorités locales évoluent. Le cadre est fondé sur le cas de Shadegan et éclairé par l'expérience du Projet de conservation des zones humides iraniennes, y compris les villages pilotes associés à une agriculture durable et des pratiques de subsistance compatibles avec les zones humides. Une base structurée et opérationnelle est ainsi fournie pour la prochaine phase de gestion territoriale des eaux dans les systèmes de zones humides-agricoles.

Mots-clés : Gestion adaptative de l'irrigation; Intelligence artificielle; Télédétection; Aide à la décision; Zone humide de Shadegan; Cadre conceptuel.

1. INTRODUCTION

Water scarcity is no longer an episodic threat in arid and semi-arid regions but a structural condition that increasingly shapes land, water, and livelihood systems. The challenge is especially acute in wetland–agriculture settings, where environmental preservation, agricultural production, and local livelihoods depend on the same limited and variable water base. Under such conditions, water management cannot be reduced to fixed seasonal allocation. It is more appropriately understood as a territorial governance problem shaped by ecological thresholds, agricultural demand, institutional capacity, and socio-economic trade-offs (Ramsar Convention Secretariat, 2021).

Shadegan Wetland in south-western Iran provides a clear example of this condition. Available project materials indicate that the wetland has been affected by upstream water regulation, irrigation development in adjacent plains, drainage inflows, and recent climatic drying. These pressures influence not only wetland condition but also the agricultural land, orchard systems, and village livelihoods connected to the wider Shadegan socio-ecological system. Water allocation in this context therefore cannot be treated as a fixed technical exercise. Responsiveness to evolving environmental and implementation conditions is required.

An institutional basis for such a transition has already been established through the Conservation of Iranian Wetlands Project (CIWP), implemented with national institutions and international partners. Through this program, participatory wetland management, sustainable agriculture, livelihood diversification, institutional coordination, and regular monitoring have been promoted. The project factsheet states that CIWP has played a leading role in wetland restoration in Iran since 2005, that

Shadegan was added as a replication site after earlier experience in Lake Urmia, and that the project's main themes include improved land and water management, wetland-friendly livelihoods, stronger institutional collaboration, and awareness and capacity-building activities. Regular monitoring and the embedding of decision-support systems in water and wetland management are also listed among the expected results (CIWP, n.d.).

At the same time, recent developments in agricultural water management indicate that more integrated digital approaches are becoming increasingly relevant. Remote sensing is now used not only for observation, but also for irrigation accounting, crop water-demand estimation, and management support (Calera et al., 2017; Benli et al., 2025). Adaptive irrigation decision-support systems, along with recent reviews on AI, IoT, and digital water management, point toward a broader shift from fixed scheduling to more dynamic and feedback-informed decision structures (Conde et al., 2024; Colizzi et al., 2025; Parra-López et al., 2025; Huang et al., 2026).

The remaining gap in Shadegan therefore lies not simply in the availability of data or the existence of management programs. It lies in the absence of a structured decision architecture through which heterogeneous evidence can be translated into revisable and transparent management choices. This interpretation is consistent with evidence from Iranian wetland-related livelihood studies, in which long-term project sustainability has been shown to depend not only on environmental goals, but also on market access, capacity building, financial support, and institutional support (Safa et al., 2025).

An adaptive AI-driven water management framework for the Shadegan wetland–agriculture system is therefore proposed in this paper. At the territorial scale, irrigation water management is shaped by interacting agricultural, environmental, economic, and regulatory pressures, which require a more explicit and revisable decision process. The paper contributes a structured decision framework that links monitoring, forecasting, multi-criteria evaluation, and adaptive revision in order to support more transparent and operationally grounded decision-making in the Shadegan context.

2. SHADEGAN CASE STUDY AND DECISION CONTEXT

The study area is defined as the Shadegan wetland–agriculture system in Khuzestan Province, southwestern Iran. A territorial scale is adopted because irrigation decisions in this setting are shaped by the interaction of wetland condition, agricultural demand, climatic variability, and local livelihood requirements. Within the Conservation of Iranian Wetlands Project, selected villages around Shadegan Wetland were identified as pilot locations for sustainable agriculture and wetland-compatible livelihood activities (Conservation of Iranian Wetlands Project, 2025a). Figure 1 shows the location of Shadegan Wetland and the surrounding pilot villages used in the CIWP implementation context.

In the Khuzestan phase of the project, pilot villages were specified for both livelihood-oriented and agriculture-oriented interventions. For livelihood-related activities, the listed villages include Masir, Salahaviyeh, Geydari, and Beit Obeid. For sustainable agriculture, the listed villages include Maleki, Emam Seh, Abu Arabid, Deymeh Yaghoob, and Mansoureh Bozorg (Conservation of Iranian Wetlands Project, 2025b). These locations show that the conceptual case developed here is rooted in an actual implementation geography rather than an abstract landscape.

From a decision-making perspective, Shadegan may be described as a multi-driver system. Wetland sensitivity must be considered because ecological processes can be affected by agricultural withdrawals and upstream hydrological changes. Agricultural demand is variable over time and depends on climatic conditions, crop patterns, and irrigation timing. Livelihoods are part of the same system because both farming and wetland-compatible activities depend on water availability and management rules. Institutional feasibility must also be considered because implementation depends on intersectoral coordination, local capacity, and continuity of support mechanisms.

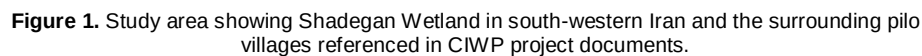


Table 1 shows that water-related decision-making in Shadegan is not shaped by hydrology alone, but by the interaction of environmental sensitivity, agricultural demand, livelihood dependence, institutional feasibility, and regulatory constraints. This confirms that territorial irrigation management in the case study must be treated as a multi-driver decision process rather than a single-objective allocation problem.

Component	Shadegan-specific relevance	Decision implication
Wetland condition	Wetland exposed to hydrological alteration and drying pressure	Irrigation management must consider wetland-sensitive thresholds
Agricultural pressure	Irrigated agriculture and orchard systems around the wetland	Water allocation affects both production and environmental stress
Climate variability	Seasonal and interannual variability in weather conditions	Forecasting is required for forward-looking management
Socio-economic setting	Pilot villages linked to agriculture and livelihood activities	Options must be screened for livelihood feasibility
Institutional context	CIWP-linked implementation environment	Recommendations must remain operationally realistic

The proposed framework is organized around three integrated components connected in an adaptive operational loop. It is designed to be operationalized using data sources and analytical tools that are currently available or feasibly deployable in the Shadegan context. The logic and methodological structure of a system suitable for phased implementation are defined.

3.1 Monitoring component

The monitoring component is intended to provide continuous, multi-source situational awareness of the wetland–agriculture system. The proposed input layers include satellite imagery, meteorological data, environmental sensing, and socio-economic context.

Satellite imagery from Sentinel-2 and Landsat 8/9 is proposed for vegetation indices, land-condition monitoring, surface temperature screening, and wetland inundation assessment. Meteorological records are required for reference evapotranspiration and seasonal demand estimation. Environmental sensing provides local water-level and water-quality observations. Socio-economic and institutional context is supplied through CIWP pilot-village documentation and related project records. These streams are not assumed to be naturally compatible. Their use requires a preprocessing layer through which spatial resampling, temporal aggregation, and territorial harmonization can be performed so that environmental, agricultural, and contextual variables may be interpreted within the same decision units.

3.2 Data fusion and analytical engine

The analytical engine is designed to transform heterogeneous observations into decision-relevant indicators. The proposed sequence includes preprocessing and harmonization, extraction of environmental and agricultural indicators, machine-learning-based estimation and forecasting, and scenario generation for decision support.

Crop water requirements are estimated using the FAO-56 formulation:

$$ET_c = K_c \times ET_0 \quad (1)$$

where ET_c is crop evapotranspiration, K_c is the crop coefficient, and ET_0 is reference evapotranspiration (Allen et al., 1998).

To complement demand estimation, water productivity indicators are used:

$$WP_{I+P} = \frac{Y}{I+P} \quad (2)$$

$$WP_{ET} = \frac{Y}{ET} \quad (3)$$

where Y is crop yield, I is irrigation supply, P is precipitation, and ET is evapotranspiration.

For operationalization, Random Forest is proposed for supervised land-cover and crop-condition classification, Support Vector Regression for crop water-demand modelling, and Long Short-Term Memory networks for time-series forecasting of water demand and environmental change. These are introduced as candidate analytical approaches, with final selection to be guided by local data quality, calibration performance, and operational feasibility.

3.3 Multi-criteria decision support

The third component converts monitored and predicted conditions into ranked management options. In a wetland–agriculture system such as Shadegan, an option cannot be selected on the basis of water saving alone. A technically efficient option may still be environmentally risky, economically weak, socially unacceptable, or institutionally difficult to apply.

To structure decision support, a weighted multi-criteria score is used:

$$Score_i = \sum_{j=1}^n w_j s_{ij} \quad (4)$$

where $Score_i$ is the composite score for management option i , w_j is the weight assigned to criterion j , and s_{ij} is the performance score of option i against criterion j .

The criteria proposed for the Shadegan case are agricultural performance, environmental compatibility, economic feasibility, livelihood compatibility, and institutional feasibility. At the conceptual stage, equal weights may be used as a neutral baseline in order to demonstrate the logic of the decision structure. Final weights, however, should be calibrated during implementation through stakeholder consultation, expert scoring, and regulatory priorities, and should be revised between seasonal cycles based on field feedback and observed implementation outcomes.

3.4 Feedback and revision

A defining feature of the framework is its feedback loop. In conventional static planning, recommendations are often fixed at the beginning of the season and revised only after serious mismatch becomes visible. In the present method, recommendations are treated as provisional and may be updated when new information becomes available. Updated wetland status, field conditions, implementation outcomes, and newly identified constraints are reintroduced into the same cycle of monitoring, analytics, and option ranking. In operational terms, this cycle is intended to support territorial decision-makers in reviewing allocation rules, irrigation scheduling priorities, environmentally sensitive restrictions, and support measures in response to updated evidence.

Figure 2 summarizes the operational structure of the framework, while Table 2 lists the proposed variables, indicators, and outputs associated with each module.

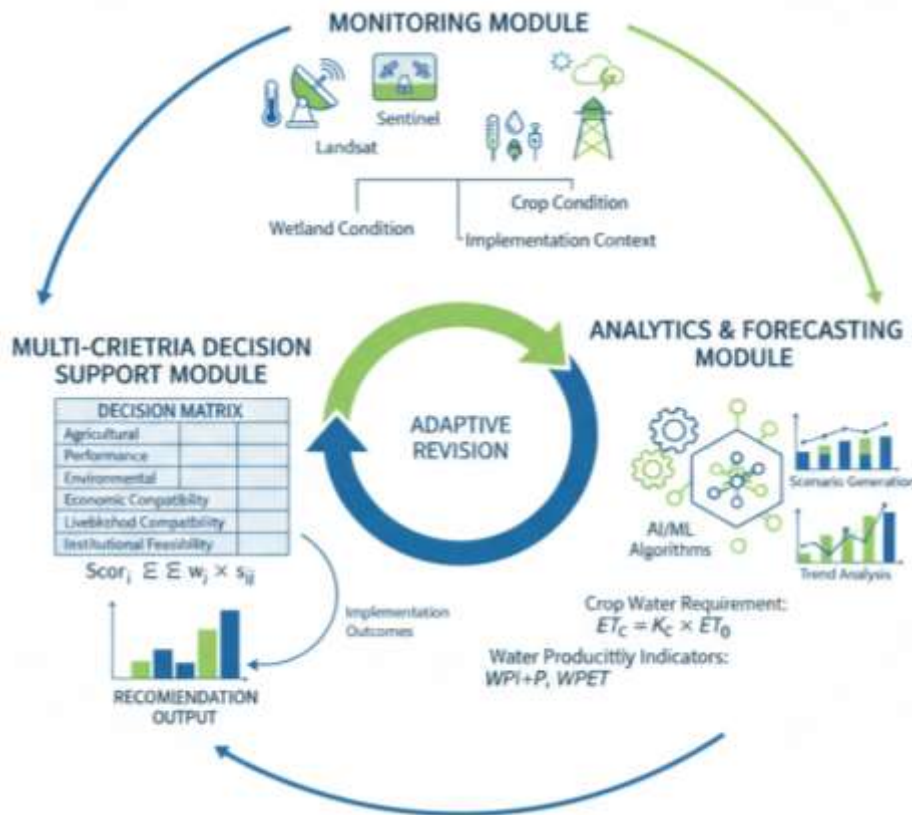


Figure 2. Operational structure of the proposed adaptive framework showing the three integrated components and the feedback-revision loop.

Table 2. Proposed variables, indicators, and outputs of the framework

Module	Variable / indicator	Unit	Source	Role in decision-making
Monitoring	Wetland and crop condition indicators	map / index	satellite data	current spatial condition
Monitoring	ET_0	mm day ⁻¹	meteorological data	climatic demand
Monitoring	Contextual livelihood information	descriptive	project / local data	implementation context
Analytics	ET_c	mm day ⁻¹	computed	crop water requirement
Analytics	WP_{I+P}	kg m ⁻³	computed	productivity relative to supplied water
Analytics	WP_{ET}	kg m ⁻³	computed	productivity relative to consumed water
Analytics	Forecast scenarios	Categorical/continuous	prediction module	early warning and planning

As described in Table 2, the proposed framework links monitoring variables, derived analytical indicators, and forecast outputs within a single operational structure, thereby clarifying how raw observations are progressively translated into decision-relevant information.

4. DATA SOURCES AND SYSTEM INPUTS

The framework draws on data sources that are either openly available or linked to existing CIWP project operations.

Sentinel-2 provides 10 m multispectral imagery with high revisit frequency suitable for vegetation and land-cover monitoring. Landsat 8/9 provides multispectral and thermal information useful for surface temperature screening and wetland extent assessment. FAO WaPOR offers a relevant regional framework for evapotranspiration and water productivity assessment in data-scarce environments (FAO, n.d.). OpenET is cited here only as an international example of operational ET-based water management rather than as a direct input source for the Shadegan case (Volk et al., 2024).

Agro-meteorological data are required in order to estimate reference evapotranspiration and support demand forecasting. Their integration with remote sensing and sensor data follows recent literature on crop water-demand estimation and digital water management (Fuentes-Peñailillo et al., 2025; Garcia et al., 2025). Field and environmental observations, including water-level and soil-moisture information where available, are necessary for ground reference and for linking remotely sensed conditions to operational decisions. Socio-economic and institutional inputs are supplied through CIWP pilot-village records, sustainable agriculture activity reports, and livelihood-related project documentation.

5. EVALUATION FRAMEWORK AND IMPLEMENTATION ARCHITECTURE

Because the paper presents a conceptual framework, evaluation is defined as a future validation plan rather than reported performance.

5.1 Proposed validation plan

Validation is proposed at two levels. At the algorithm level, candidate models such as RF, SVR, and LSTM would be calibrated and tested using historical satellite, hydro-climatic, and field data from the Shadegan region. Performance measures should be defined before deployment and may include classification accuracy for spatial mapping tasks and RMSE, MAE, and R2 for regression and forecasting tasks. For the decision framework itself, evaluation should also consider transparency of option ranking, responsiveness to updated field conditions, consistency with regulatory constraints, and usability for territorial water management actors.

At the field level, management-option rankings and irrigation recommendations should be assessed against observed outcomes in CIWP pilot villages across multiple seasonal cycles. Validation dimensions should include wetland-related indicators, crop-condition responses, and livelihood compatibility feedback.

5.2 Implementation architecture

The proposed system architecture is modular. A data ingestion layer is envisaged through which satellite platforms, meteorological feeds, and field observations are linked. An analytical processing layer is intended for classification, estimation, and forecasting. A decision-support layer is included for the ranking of options and the documentation of trade-offs. A stakeholder interface is also proposed for water managers, agricultural extension services, wetland governance actors, and project coordinators, so that ranked options can be reviewed, adapted, and translated into territorially relevant management actions.

Table 3 translates this architecture into proposed management options and evaluation dimensions for the Shadegan case. The institutional feasibility of livelihood-compatible adjustment packages is not fixed, because program continuity, local coordination, and implementation capacity are likely to influence their practical viability.

Table 3. Proposed territorial management options and evaluation criteria for the Shadegan case

Option	Agricultural effect	Water effect	Environmental implication	Livelihood implication	Regulatory feasibility
Improved irrigation scheduling	Better irrigation timing	Lower non-beneficial application	Positive if coordinated with wetland needs	Generally compatible	Moderate to high
Deficit irrigation strategy	Possible water saving with yield risk	Lower irrigation demand	Potentially positive if controlled	Crop- and income-dependent	Moderate
Wetland-sensitive allocation rule	Possible restriction during peak demand	Supports environmental allocation	Strongly positive	May require adaptation support	Moderate
Livelihood-compatible adjustment package	Reduced direct pressure from water-intensive practice	Indirect water saving	Positive if sustained	Depends on market and skills support	Dependent on regulatory support

Table 3 illustrates that no management option is uniformly optimal, since each alternative involves trade-offs across water saving, agricultural performance, environmental implications, livelihood compatibility, and regulatory feasibility. This comparison reinforces the need for a multi-criteria territorial decision process rather than single-objective water management.

DISCUSSION

The proposed framework addresses a structural gap in wetland–agriculture management at territorial scale: the absence of an explicit decision process capable of integrating agricultural, environmental, economic, and regulatory drivers, together with uncertainty, implementation constraints, and feedback from real conditions, into one coherent revision cycle. The Shadegan case illustrates why this gap matters. In projects of this kind, interventions may underperform not only because of technical limitations, but also because plans are not sufficiently revised when environmental or implementation conditions change. The framework proposed here is intended to address that deficit by linking evidence generation, predictive analysis, option ranking, and management revision within a transparent territorial decision process.

Several implementation challenges remain. Institutional coordination is required in order to connect environmental, agricultural, and local project data. The economic burden of water reallocation may fall unevenly on local farmers unless livelihood consequences are explicitly considered. Algorithm selection and calibration will also depend on the quality and continuity of locally available data.

Table 4 compares the logic of the proposed framework with conventional and partial approaches. The comparison concerns capability structure rather than measured performance and is therefore consistent with the conceptual status of the paper.

A technically structured and practically oriented method is thus presented through which irrigation-related decisions in wetland–agriculture systems may be documented, analyzed, compared, and revised more systematically. The comparison highlights that the proposed framework differs primarily in its combination of multi-source monitoring, forecasting, decision ranking, feedback-based revision, and socio-economic integration.

Table 4. Conceptual comparison of water-management approach logic

Capability Dimension	Conventional Static Planning	Monitoring-Only Approach	Modelling-Based Approach	Proposed Adaptive Framework
Multi-source monitoring	Absent	Present	Present	Present
Demand forecasting	Absent	Absent	Present	Present
Multi-criteria decision ranking	Absent	Absent	Partial	Present
Feedback-based revision	Absent	Partial	Partial	Present
Socio-economic integration	Partial	Partial	Partial	Present

CONCLUSIONS

An adaptive AI-driven framework for water management in the Shadegan wetland–agriculture system has been proposed. The framework integrates three components — multi-purpose monitoring, data-driven analytics and forecasting, and multi-criteria decision support — into an operational loop capable of adaptive revision based on updated information and implementation feedback.

The main contribution lies in the decision logic through which satellite-based monitoring, predictive modelling, multi-criteria scoring, and adaptive revision are connected within a single territorial decision cycle. In this way, trade-offs may be documented, options may be ranked, and recommendations may be updated as conditions change. The framework is grounded in the Shadegan case and informed by CIWP project experience and recent advances in digital water management.

The methodological foundation for a system that can be operationalized, validated, and progressively improved through phased deployment is provided. In Shadegan and similar wetland–agriculture systems, such a framework may support more proactive, evidence-based, and institutionally coherent water management under climate stress.

Author Contributions

Khoshnaz Payandeh contributed to project coordination, field-context definition, supervision of local implementation documentation, and integration of Shadegan pilot information. Mehdi Forouzanfar contributed to the AI-driven analytical, forecasting, and decision-support structure of the framework. Anna Pinnarelli contributed to the scientific framing, adaptive management logic, manuscript organization, and integration of the territorial decision-support perspective. All authors contributed to manuscript review and approved the submitted version.

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