

BRIDGING WATER ACCOUNTING AND THE WEFE NEXUS THROUGH AN INTERACTIVE WEB PLATFORM FOR CLIMATE-RESILIENT IRRIGATION MANAGEMENT AND PLANNING

ÉTABLISSEMENT D'UN LIEN ENTRE LA COMPTABILITÉ DE L'EAU ET LE LIEN ENTRE WEFE VIA UNE PLATEFORME WEB INTERACTIVE POUR UNE GESTION ET UNE PLANIFICATION DE L'IRRIGATION RÉSISTANTE AU CLIMAT

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ABSTRACT

In the face of increasing climate variability, population growth, and competing water demands, integrated approaches to water resources planning and management are more critical than ever. Traditional approaches often operate in sectoral silos, failing to account for the complex interactions between water, energy, food production, and ecosystems. This paper presents a novel, generic web-based geospatial Decision Support System for integrated Water Resources Planning and Management, grounded in Water Accounting and framed within the WEFE Nexus approach. A core design principle is the platform's applicability to any spatial management unit, making it a transferable tool for diverse hydrological and institutional contexts. Built with Django and open-source geospatial technologies, the system integrates both observed and satellite-derived data to construct comprehensive, multi-scale water balances. On the supply side, the platform integrates surface water, groundwater, and non-conventional resources (wastewater reuse, desalination, rainwater harvesting). On the demand side, it quantifies consumption across agricultural, urban, industrial, and environmental flow sectors. The energy dimension captures pumping energy, hydropower, solar and wind energy for irrigation, and the energy costs of desalination and wastewater treatment. Environmental impacts are assessed through ecosystem health indicators, aquifer overexploitation monitoring, and environmental flow quantification. A distinguishing feature is the participatory simulation module, enabling multi-stakeholder exploration of water management scenarios under different climate projections. Stakeholders collaboratively assess trade-offs across the WEFE nexus and evaluate agricultural strategies (agroecology, precision agriculture, intensive farming, greenhouse extension) with quantified effects on water saving, crop yields, energy consumption, and carbon sequestration. The platform was tested on the Loukkos river basin in northern Morocco, demonstrating its ability to produce spatially explicit water accounts, simulate cascading WEFE nexus effects under SSP2-4.5 and SSP5-8.5 climate pathways, and support participatory, evidence-based decision-making for climate-resilient irrigation management. The platform is open-source and readily transferable to other river basins and water-scarce regions worldwide.

Keywords: Water Accounting; WEFE Nexus; Decision Support System; Participatory simulation; Irrigation management; Climate resilience.

RESUME

Face à l'augmentation de la variabilité climatique, à la croissance démographique et à la concurrence pour l'accès à l'eau, les approches intégrées de planification et de gestion des ressources en eau sont plus essentielles que jamais. Les approches traditionnelles fonctionnent souvent en silos sectoriels, sans tenir compte des interactions complexes entre l'eau, l'énergie, la production alimentaire et les écosystèmes. Cet article présente un nouveau système d'aide à la décision géospatial générique basé sur le web pour la planification et la gestion intégrées des ressources en eau, fondé sur la comptabilité de l'eau et s'inscrit dans l'approche du lien entre WEFE (Eau-Énergie-Alimentation-Écosystèmes). Un

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principe de conception fondamental est l'applicabilité de la plateforme à toute unité de gestion spatiale, ce qui en fait un outil transférable pour divers contextes hydrologiques et institutionnels. Construit avec Django et des technologies géospatiales «open-source», le système intègre à la fois des données observées et issues de satellites pour élaborer des bilans hydriques complets à multi-échelles. Sur le plan de l'offre, la plateforme intègre les eaux de surface, les eaux souterraines et les ressources non conventionnelles (réutilisation des eaux usées, dessalement, collecte des eaux pluviales). Du côté de la demande, il quantifie la consommation par les secteurs agricoles, urbains, industriels et environnementaux. La dimension énergétique englobe l'énergie de pompage, l'hydroélectricité, l'énergie solaire et éolienne pour l'irrigation, ainsi que les coûts énergétiques du dessalement et du traitement des eaux usées. Les impacts environnementaux sont évalués à l'aide d'indicateurs de la santé des écosystèmes, du suivi de la surexploitation des aquifères et de la quantification des débits environnementaux. Une caractéristique distinctive est le module de simulation participative, permettant aux diverses parties prenantes d'explorer des scénarios de gestion de l'eau sous différentes projections climatiques. Les parties prenantes évaluent de manière collaborative les compromis à travers le lien entre WEFE et analysent les stratégies agricoles (agroécologie, agriculture de précision, agriculture intensive, extension des serres) avec des effets quantifiés sur l'économie d'eau, les rendements des cultures, la consommation d'énergie et la séquestration du carbone. La plateforme a été testée sur le bassin versant de Loukkos, au nord du Maroc, démontrant sa capacité à produire des comptes de l'eau spatialement explicites, à simuler les effets en cascade du lien entre WEFE sous les trajectoires climatiques SSP2-4.5 et SSP5-8.5, et à soutenir une prise de décision participative fondée sur des preuves pour une gestion de l'irrigation résistante au climat. La plateforme est «open-source» et facilement transférable à d'autres bassins fluviaux et régions du monde où l'eau se fait rare.

Mots clés : Comptabilité de l'eau; Lien entre WEFE; Système d'aide à la décision; Simulation participative; Gestion de l'irrigation; Résistance climatique.

1. INTRODUCTION

Water resources worldwide are under unprecedented pressure from climate variability, population growth, and intensifying competition among agricultural, domestic, industrial, and environmental uses. In Morocco, intensive development has accelerated basin closure while chronic aquifer overexploitation underscores the need for shared, accountable water management systems (El Meknassi Youssoufi et al., 2023; El Meknassi Youssoufi et al., 2025). The Water-Energy-Food-Ecosystems (WEFE) Nexus Framework advocates for integrated cross-sectoral analysis to identify synergies and manage trade-offs (Hoff, 2011; FAO, 2014), while Water Accounting (WA) provides the systematic empirical foundation for evidence-based decision-making (Karimi et al., 2013).

Recent literature demonstrates that web-based GIS decision-support systems are increasingly used to operationalize the WEFE nexus by integrating spatial data indicator-based assessment, scenario analysis, and stakeholder communication into a single platform. GIS is particularly valuable in this context because WEFE interactions are spatially distributed and must be analyzed across multiple scales, while water accounting provides the quantitative basis for tracking supply, demand, use, and allocation. Platforms such as iWEG 1.0 (Taguta et al., 2023) show that combining maps, dashboards, and multi-criteria decision tools into a geospatial web environment improves the speed, accessibility, and interpretability of nexus analysis. Complementing this, water management guidance from the Global Water Partnership emphasizes that DSSs bridge science and policy by supporting data management, model integration, and inclusive planning (GWP, 2009).

Existing Decision Support Systems such as WEAP (Yates et al., 2005) and RiverWare (Zagona et al., 2001) offer robust hydrological modelling but lack full WEFE nexus integration, web-based accessibility, and participatory capabilities. Together, these limitations and the scientific rationale outlined above motivate the development of an open-source, web-GIS platform that combines rigorous Water Accounting with comprehensive WEFE analysis while enhancing collaboration, knowledge sharing, and governance.

This paper presents a novel, generic web-based geospatial DSS – *water-hub.net* – for integrated water resources planning and management, grounded in Water Accounting and framed within the WEFE Nexus approach. Built with Django and open-source geospatial technologies, the platform integrates observed and satellite-derived data to construct comprehensive, multi-scale water balances while providing interactive participatory simulation capabilities. The system is designed to be applicable to any spatial management unit, ensuring transferability across diverse hydrological and institutional contexts. The platform was tested on the Loukkos River basin in northern Morocco, where it was used to model the WEFE nexus and to quantify the combined effects of planned interventions in the water, energy, and agricultural sectors on the four nexus dimensions.

2. CONCEPTUAL FRAMEWORK

2.1 Water Accounting as the methodological backbone

The platform's quantitative foundation rests on the WA framework (Karimi et al., 2013), extended here to encompass all WEFE nexus dimensions. A core design principle is spatial unit flexibility: the same accounting logic applies whether the unit of analysis is a river basin, sub-basin, irrigated perimeter, or administrative region, ensuring broad transferability. Supply integrates surface water (dams, rivers), groundwater, and non-conventional sources (desalination, wastewater reuse, rainwater harvesting), while demand is quantified across irrigation, urban, industrial, and environmental flow sectors. Water transfers are computed through spatial overlay of infrastructure networks and administrative boundaries.

2.2 The WEFE Nexus as the analytical lens

The platform operationalizes the WEFE Nexus through four interconnected dimensions (Figure 1): (i) Water-Energy: pumping, desalination, hydropower, and solar/wind irrigation; (ii) Water-Food: crop water requirements, irrigation efficiency, and multi-crop accounting; (iii) Water-Ecosystems: environmental flow compliance, aquifer overexploitation, and land cover change; and (iv) Energy-Food-Ecosystem feedbacks: how intensification affects energy demand and ecosystem services. Thirty-two aggregated KPIs track performance across all dimensions per simulation turn.

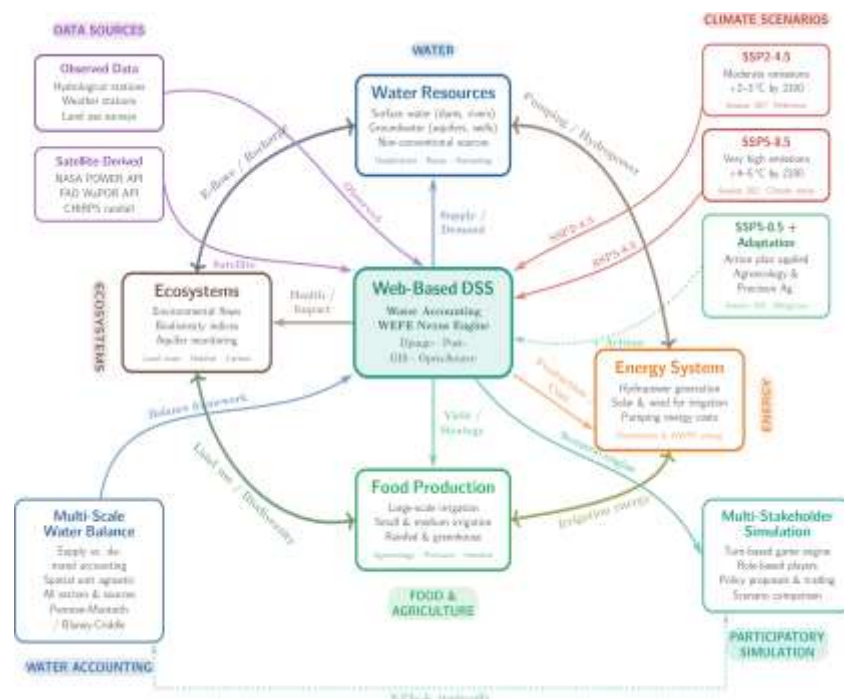


Figure 1. Conceptual framework of the web-based DSS integrating Water Accounting and the WEFE Nexus.

2.3 Participatory Scenario Simulation

Grounded in companion modelling and multi-agent systems theory (Bousquet et al., 2002), the participatory module builds on Moroccan experience in role-playing games for water governance (Dionnet et al., 2008). Stakeholders, water authorities, irrigation agencies, agricultural managers, energy planners, and environmental regulators, interact through a turn-based simulation engine that propagates collective decisions across the WEFE system under user-selected climate projections.

3. SYSTEM ARCHITECTURE AND TECHNOLOGY STACK

The platform is built entirely on open-source technologies (zero licensing costs) following a five-layer design: external data sources → backend logic → geospatial processing → spatial databases → interactive web frontend. The server side is implemented in Django with over 35 asset data models, a WEFE nexus metrics engine, the Action-Impact agricultural strategy module, and a REST API (Django REST Framework) exposing GeoJSON endpoints. Internationalization covers English, French, Spanish, and Arabic.

Geospatial processing relies on GDAL, Shapely, GeoPandas, Rasterio, and PyProj. All geometries are stored in WGS 84. A dual PostgreSQL/PostGIS architecture separates the simulation database from the water accounting database, linked by a custom router. The frontend uses Tailwind CSS, HTMX for partial page updates, Leaflet.js for interactive GeoJSON maps, and Plotly and Charts.js for WEFE dashboard charts.

4. DATA INTEGRATION

Water balances are constructed from three complementary streams harmonized in a unified framework. Observed data include dam inflows, reservoir levels, river discharge, piezometric records, meteorological stations (temperature, rainfall, humidity, wind, radiation), population statistics, sectoral consumption figures, and infrastructure specifications. Satellite-derived products extend spatial coverage: the NASA POWER API supplies gridded climate variables at 0.5° from 1981 (NASA, 2023); FAO WaPOR provides actual evapotranspiration (AETI), land cover, and biomass water productivity at 100–250 m (FAO, 2023); and CHIRPS delivers gridded rainfall at 0.05° (Funk et al., 2015). In the Loukkos case study, 15 variable types yield over 6,650 monthly records per asset (1981–2025).

Climate projections use the NASA NEX-GDDP GFDL-ESM4 model (Thrasher et al., 2022), storing monthly temperature, precipitation, and reference ET over 2026–2050 under SSP2-4.5 and SSP5-8.5. Under SSP5-8.5, mean annual precipitation declines 18% compared to SSP2-4.5 (42.96 vs. 52.16 mm/month). Evapotranspiration is computed via FAO Penman-Monteith (Allen et al., 1998) in data-rich settings or Blaney-Criddle in data-scarce environments, with WaPOR AETI serving as independent validation.

5. WATER BALANCE AND WEFE NEXUS MODULES

5.1 Water supply and demand accounting

Surface water supply is computed from calibrated dam inflow models using SCS Curve Number and Rational method. Under SSP2-4.5 (S1), total dam inflow reaches 1,385 Mm³/yr; under SSP5-8.5 (S2) it drops to 961 Mm³/yr (–31%), driven by reduced precipitation (539 vs. 819 mm/yr) and higher evapotranspiration. Irrigation demand is disaggregated across large-scale, small and medium-scale irrigation, and private irrigation perimeters, applying irrigation efficiency factors (surface 0.60, sprinkler 0.75, drip 0.90). Table 1 summarises comparative WEFE indicators across scenarios.

Table 1. Comparative WEFE indicators across the three Loukkos basin scenarios (Turn 26 / year 2050).

Indicator	S1: SSP2-4.5	S2: SSP5-8.5	S3: SSP5-8.5 + Adaptation
Dam inflow (Mm ³ /yr)	1,385	961	950
Dam water supply (Mm ³ /yr)	700	705	625
Irrigation consumption (Mm ³ /yr)	561	564	526
Irrigated area (ha)	76,059	76,059	76,059
Crop production (10 ³ t/yr)	2,291	2,291	2,310
Environmental flow (Mm ³ /yr)	126.1	109.9	126.1

5.2 Energy, food, and ecosystem dimensions

The six WEFE nexus indicators displayed in Figure 2 reveal consistent and interconnected responses across the three climate scenarios, illustrating both the magnitude of climate stress and the effectiveness of adaptation measures.

Hydropower generation peaks sharply under S2 (SSP5-8.5, Climate stress) at 90.5 GWh/yr, driven by increased dam releases under high-stress conditions, compared to 49.8 GWh/yr under the S1 reference. However, adaptation measures under S3 reduce releases to meet downstream demands more efficiently, bringing generation down to 43.5 GWh/yr, a Water-Energy nexus trade-off that prioritizes water security over power production.

Irrigation water consumption remains nearly stable between S1 (561 Mm³/yr) and S2 (564 Mm³/yr), reflecting sustained agricultural demand despite declining inflows (1,384 to 961 Mm³/yr). Under S3, the adoption of precision agriculture and agroecology reduces consumption to 526 Mm³/yr, a saving of 38 Mm³/yr (–6.7% relative to S2), with a corresponding direct reduction in pumping energy of 6.0 GWh/yr (–5.1%), a measurable Water–Energy nexus synergy. Crop production remains resilient across all scenarios: 2,291 × 10³ t/yr under both S1 and S2, rising marginally to 2,310 × 10³ t/yr under S3 (+0.8%), despite consuming 38 Mm³/yr less water. This demonstrates that the adaptation package maintains and even slightly improves food security under the most severe climate pathway.



Figure 2. Comparative WEFE nexus indicators across the three scenarios.

Environmental flow allocation is the most sensitive indicator to climate stress, declining from 126 Mm³/yr under S1 to 110 Mm³/yr under S2 (–13%), falling below the minimum thresholds of 3.0 m³/s at Oued El Makhazine and 1.0 m³/s at Dar Khroufa. Under S3, environmental flows are fully restored to 126 Mm³/yr, illustrating a central nexus synergy: water saved through precision agriculture simultaneously safeguards food production and ecosystem health, closing the adaptation loop across the WEFE dimensions

6. PARTICIPATORY SIMULATION MODULE

6.1 Scenario construction and asset configuration

Each simulation defines a spatial boundary, a climate pathway, and a geospatially referenced asset inventory. Three scenarios were constructed for the Loukkos basin (Table 2): S1 (Session 287, SSP2-4.5, 14 assets) represents the reference trajectory; S2 (Session 292, SSP5-8.5, 14 assets) applies the same plan under high emissions and adds a desalination plant; S3 (Session 293, SSP5-8.5, 17 assets) augments S2 with a floating solar farm, a second wastewater treatment plant, and agricultural adaptation strategies.

Table 2. Overview of the three Loukkos simulation scenarios.

Attribute	S1 (Session 287)	S2 (Session 292)	S3 (Session 293)
Climate pathway	SSP2-4.5	SSP5-8.5	SSP5-8.5
Adaptation actions	None	None	Agroecology + Precision Ag.
Total assets	14	14	17
Desalination plant	No	Yes	Yes
Solar farm	No	No	Yes (floating)

6.2 Agricultural strategy simulation (Action-Impact)

The Action-Impact module parameterizes adaptation strategies by impact codes specifying direction and magnitude. In S3, two strategies are combined: agroecology (25% water saving, 40% input reduction, 2 tC/ha/yr carbon sequestration, –30% mechanization, +20% labor, +15% product price) and precision agriculture (20% water saving, +15% yield, –20% inputs and labor). Table 3 shows how S3 intensifies these strategies compared to S1.

Table 3. Action-Impact parameters for S1 (reference) and S3 (adaptation).

Strategy	Impact	Unit	S1	S3
Agroecology	Water saving	%	10	25
	Carbon sequestration	tC/ha/yr	2.0	2.0
	Input reduction	%	–	40
	Product price increase	%	15	15
Precision Ag.	Water saving	%	10	20
	Yield increase	%	–	15
	Input decrease	%	–	20

6.3 Multi-dimensional simulation outcomes

The simulation engine propagates action impacts across all WEFE dimensions (Figure 3). Compared to S2, S3 achieves higher water saving and input reduction (radar chart), adds three infrastructure assets, improves water productivity at IP Loukkos from 31.2 to 37.2 kg/m³, and reduces pumping energy by 6.0 GWh/yr (5.1%). These multi-dimensional visualizations allow stakeholders to negotiate balanced, nexus-aware strategies.

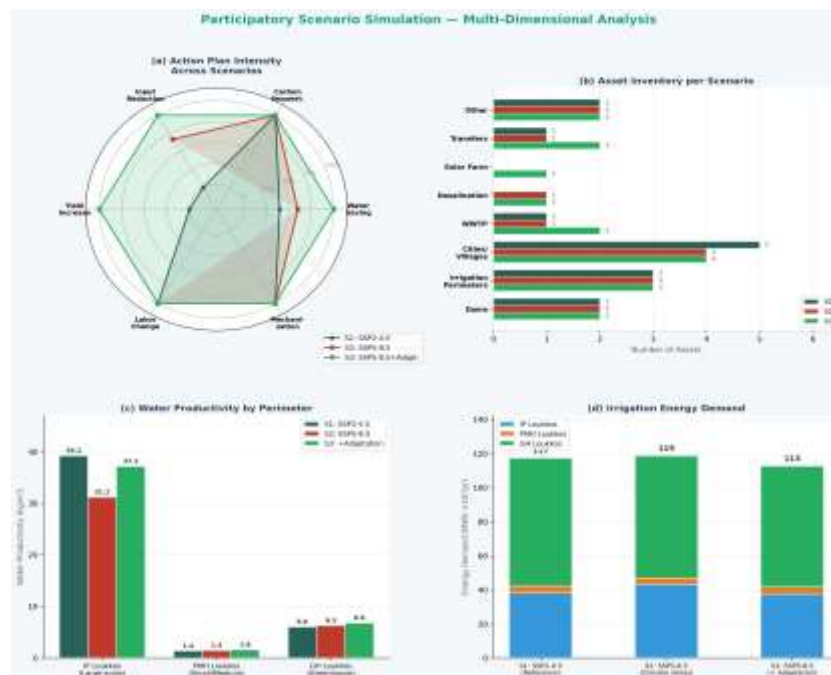


Figure 3. Participatory simulation outcomes. (a) Radar chart of action plan intensity; (b) asset inventory comparison; (c) water productivity by perimeter type; (d) energy demand reduction under S3.

7. CASE STUDY: LOUKKOS RIVER BASIN, MOROCCO

7.1 Study area

The Loukkos river basin (6.21–5.24°W, 34.75–35.40°N) has a semi-arid Mediterranean climate (17.4 °C mean annual temperature, 758 mm/yr rainfall). Two major dams anchor the system: Oued El Makhazine (672.9 Mm³, 2,700 km², 36 MW hydropower) and Dar Khroufa (480.3 Mm³, 653 km²). The basin serves ~765,000 inhabitants and three irrigation systems: IP Loukkos (14,322 ha), GH Loukkos greenhouse perimeter (25,323 ha), and PMH Loukkos (4,038 ha). Figure 4 shows the spatial water flux model of the basin, illustrating the geospatially referenced asset network and water transfer connections as represented in the platform.

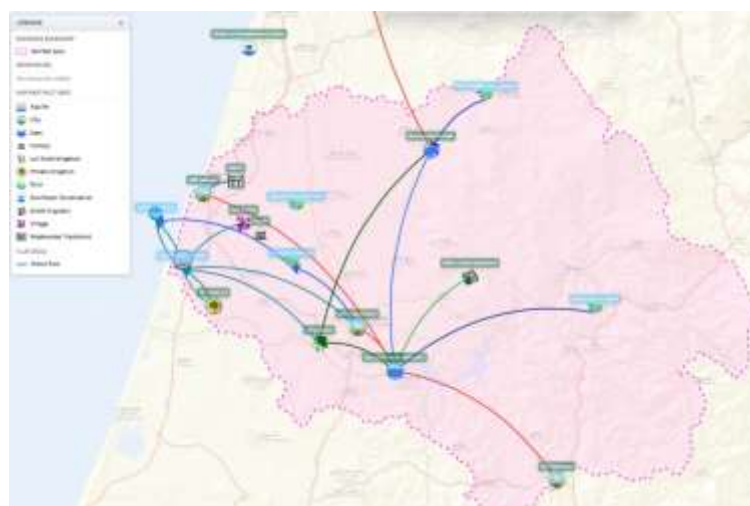


Figure 4. Spatial water flux model of the Loukkos river basin.

7.2 Simulation results (2025–2050)

The 26-year simulation (Figure 5, Table 4) shows that under SSP5-8.5, mean annual inflow at Oued El Makhazine drops from 910 Mm³/yr (S1) to 764 Mm³/yr (S2, –16%), driven by a 17% precipitation decline (525 vs. 631 mm/yr). A critical finding emerges: under S2, total irrigation demand (674.2 Mm³/yr) approaches total dam water supply (705.4 Mm³/yr), leaving minimal margins for other uses. The adaptation scenario S3 resolves this pressure: combined agroecology and precision agriculture reduce total irrigation demand to 597.1 Mm³/yr (saving 77.1 Mm³/yr) while maintaining equivalent irrigated area (76,427 vs. 76,059 ha). These results align with regional projections predicting significant runoff reductions under future climate in Morocco (Tramblay et al., 2012).

Table 4. Summary of the 26-year simulation (2025–2050) for the Loukkos river basin.

Indicator (26-yr mean)	S1: SSP2-4.5	S2: SSP5-8.5	S3: SSP5-8.5 + Adaptation
Dam inflow (Mm ³ /yr)	910	764	753
Min / Max inflow (Mm ³ /yr)	380 / 1,197	292 / 1,216	264 / 1,222
Dam supply (Mm ³ /yr)	420	434	404
Precipitation (mm/yr)	631	525	525
Irrigation consumption (Mm ³ /yr)	516	565	530
Hydropower (GWh/yr)	45.8	88.1	43.8
Environmental flow (Mm ³ /yr)	94.6	76.4	94.6

7.3 Key findings

The case study demonstrates four capabilities: (i) spatially explicit water accounts integrating 15 variable types and >6,650 records per asset; (ii) cascading climate impact simulation –a 17% precipitation decline propagates into a 16% inflow reduction, 31% hydropower loss, and 13% environmental flow deficit; (iii) quantified adaptation assessment– combined strategies reduce irrigation demand by 43% and restore full environmental flow compliance; and (iv) transferability, the entire scenario is constructed from generic asset models and globally available API data sources.

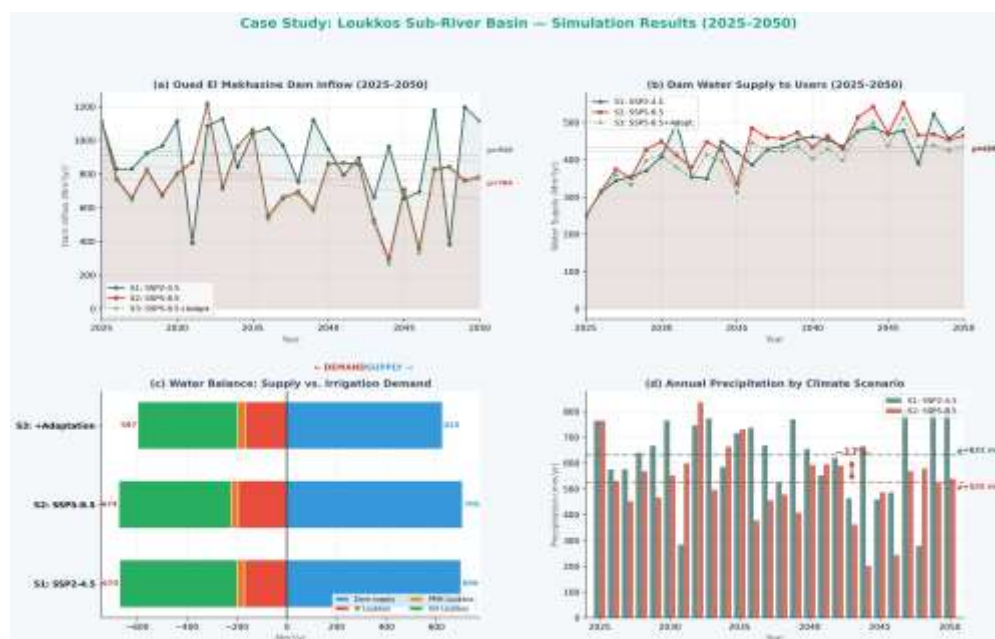


Figure 5. Loukkos basin simulation results (2025–2050). (a) Dam inflow time series under three scenarios; (b) dam water supply; (c) water balance—irrigation demand vs. supply; (d) precipitation trends under SSP2-4.5 vs. SSP5-8.5.

DISCUSSION

The Loukkos case study demonstrates that the *water-hub.net* platform can operationalize the WEFE Nexus through digital water accounting in a way that is both analytically rigorous and accessible to non-specialist stakeholders. Several aspects merit discussion.

Comparison with existing tools. Desktop-based DSS such as WEAP (Yates et al., 2005) and RiverWare (Zagona et al., 2001) offer more mature hydrological modelling capabilities, but they lack web-based accessibility, full WEFE nexus integration, and interactive multi-stakeholder simulation. The *water-hub.net* platform fills this gap by combining Water Accounting, nexus-wide impact quantification through the Action-Impact module, and a participatory scenario engine, all delivered through the browser with no software installation required. The open-source stack (Django, PostgreSQL/PostGIS, Leaflet) eliminates licensing barriers that restrict adoption in resource-constrained institutions.

The platform's spatial unit flexibility is a key design advantage: the same asset models, data pipelines, and simulation engine apply whether the unit of analysis is a river basin, a sub-basin, or a single irrigated perimeter. The integration of three complementary data streams –ground stations, satellite products (NASA POWER, WaPOR, CHIRPS), and downscaled climate projections (GFDL-ESM4)– ensures operational flexibility across data-rich and data-scarce environments. The Action-Impact module introduces a practical mechanism for quantifying agricultural adaptation trade-offs that is absent from most existing water planning tools.

The current implementation relies on a single climate model (GFDL-ESM4); multi-model ensembles would provide more robust uncertainty estimates. Dam inflow models (SCS-CN, Rational) are simplified and would benefit from calibration against longer observed records where available. Groundwater dynamics are represented at a conceptual level and do not yet incorporate physically-based aquifer modelling. The participatory module has been tested in a research setting; field validation with actual stakeholder panels is needed to assess its effectiveness for consensus-building.

The long-term viability of the DSS depends on its embedding within existing institutional frameworks. As argued by El Meknassi Yousoufi et al. (2023), water accounting must be institutionalized as a governance tool that holds all actors accountable for their water consumption and its downstream consequences. By design, the platform aligns its outputs with the mandates and planning processes of water, agriculture, and energy agencies. Capacity building targets institutional staff to foster internal ownership, while a data-sharing protocol ensures sustained multi-agency contributions. Furthermore, in basins approaching closure, the platform's ability to track return flows, non-conventional sources, and water circularity pathways (El Meknassi Yousoufi et al., 2025) provides the quantitative evidence base needed to negotiate water reallocation among competing users. Aligning the tool's outputs with mandatory regulatory and strategic instruments guarantees its operational relevance beyond the project lifecycle.

CONCLUSION

This paper presented a novel, open-source, web-based geospatial Decision Support System for integrated water resources planning and management, grounded in Water Accounting and framed within the WEFE Nexus approach. Built with Django and open-source geospatial technologies, the platform integrates observed data, satellite-derived products (NASA POWER, FAO WaPOR, CHIRPS), and downscaled climate projections to construct comprehensive, multi-scale water balances applicable to any spatial management unit.

The Loukkos river basin case study demonstrated the platform's capabilities through a three-scenario comparison over a 26-year horizon (2025–2050). Under SSP5-8.5, the basin faces a 17% precipitation decline, a 16% reduction in dam inflow, a 31% loss in hydropower generation, and a 13% environmental flow deficit compared to SSP2-4.5. The adaptation scenario showed that combining agroecology (25% water saving, 2 tC/ha/yr carbon sequestration) and precision agriculture (20% water saving, 15% yield increase) can reduce irrigation demand by 43% while restoring full environmental flow compliance and

maintaining equivalent irrigated area, illustrating the type of nexus-aware, evidence-based trade-off analysis that the platform enables.

Future work will focus on incorporating multi-model climate ensembles for robust uncertainty quantification, integrating physically-based groundwater modelling, and conducting field validation with stakeholder panels in the Loukkos basin and other pilot sites. The platform's generic design and reliance on globally available data sources and open standards ensure its readiness for transfer to other river basins, irrigated systems, and water-scarce regions worldwide.

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