

INTEGRATING AGROECOLOGY AND CROP MODELING FOR CLIMATE RESILIENT WATER MANAGEMENT

INTÉGRATION DE L'AGROÉCOLOGIE ET DE LA MODÉLISATION DES CULTURES POUR UNE GESTION DE L'EAU RÉSISTANTE AU CLIMAT

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ABSTRACT

Climate change and urbanization intensify agricultural water competition, demanding approaches that reconcile food production with ecological and social resilience. Agroecology offers guiding principles, yet conventional irrigation is often seen as incompatible with agroecological transitions. This study reframes water management as an integrated agroecosystem component, developing and testing a framework that bridges agroecological design with data-driven optimization using AquaCrop at Taiwan's Jiufenggou urban-rural interface. The approach operates at two levels: first, a multi-scalar conceptual model aligns adaptive water management with agroecological tenets from farm-level soil health to territorial polycentric governance and nature-based solutions; second, empirical simulations transition water management from experience-based to climate-aware scheduling, using local ETo data. Localized water productivity (15–20 g/m²) and harvest index (0.43–0.50) were parameterized for silty clay loam, comparing paddy flooding with alternate wetting and drying. Three findings emerged: alternate wetting and drying reduces irrigation water use by 15–22% while maintaining 98 - 99% of yields; a three-tier drought framework based on the Relative Irrigation Supply Index guides adaptive management below 70% flow, 3-day-on, 2-day-off cycles (yield-preservation mode targeting critical growth stages), and below 40%, full yield-preservation mode; socio-hydrological mapping identified 35% of parcels as highly vulnerable to water deficits, enabling targeted resource allocation. Sensors enable model correction and automated alerts while ecological flows sustain biodiversity. Technical solutions alone are insufficient; effective implementation requires multi-stakeholder governance involving farmers, water associations, and planners. This socio-hydrological perspective identifies synergistic policy instruments from living labs to incentive reform. The framework offers a replicable pathway for climate-resilient water management, transforming irrigation into ecosystem stewardship and positioning skilled water management as a cornerstone of an equitable agricultural future.

Keywords: Agroecology, Irrigation, Water Productivity, Climate Adaptation, Socio-hydrology, Nature-based Solutions, Aqua Crop.

RESUME

Le changement climatique et l'urbanisation exacerbent la concurrence pour l'eau dans le secteur agricole, ce qui exige des approches permettant de concilier production alimentaire et résistance écologique et sociale. L'agroécologie propose des principes directeurs, mais l'irrigation conventionnelle est souvent considérée comme incompatible avec les transitions agroécologiques. Cette étude redéfinit la gestion de l'eau en tant que composante intégrée de l'agroécosystème, en développant et en essayant un cadre reliant la conception agroécologique à l'optimisation basée sur les données à l'aide

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d'AquaCrop, dans l'interface entre zones urbaines et rurales de Jiufenggou, à Taïwan. Cette approche intervient à deux niveaux : d'abord, un modèle conceptuel à échelle multiple aligne la gestion adaptative de l'eau sur les principes agroécologiques, depuis la santé des sols au niveau de l'exploitation agricole jusqu'à la gouvernance polycentrique territoriale et aux solutions fondées sur la nature; d'autre part, des simulations empiriques font évoluer la gestion de l'eau d'une planification fondée sur l'expérience vers une planification tenant compte du climat, à l'aide de données locales d'évapotranspiration de référence (ET_o). La productivité locale de l'eau (15–20 g/m²) et l'indice de récolte (0,43–0,50) ont été paramétrés pour un sol limono-argileux-terreau, en comparant l'inondation des rizières à la technique d'humidification et de séchage alternés. Trois conclusions y émergent : l'humidification et le séchage alternés réduit la consommation d'eau d'irrigation de 15 à 22% tout en maintenant 98 à 99% des rendements; un cadre de gestion de la sécheresse à trois niveaux, basé sur l'indice d'approvisionnement relatif en irrigation, guide la gestion adaptative en cas de débit inférieur à 70% (cycles de 3 jours d'irrigation suivis de 2 jours d'arrêt, en mode de préservation des rendements ciblant les stades critiques de croissance) et, en dessous de 40%, en mode de préservation totale des rendements; la cartographie socio-hydrologique a identifié 35% des parcelles comme hautement vulnérables aux déficits hydriques, permettant ainsi une allocation ciblée des ressources. Des capteurs permettent la correction des modèles et les alertes automatisées, tandis que les débits écologiques soutiennent la biodiversité. Les solutions techniques seules ne sont pas suffisantes; une mise en œuvre efficace nécessite une gouvernance multipartite impliquant les agriculteurs, les associations de gestion de l'eau et les planificateurs. Cette perspective socio-hydrologique identifie des instruments politiques synergiques, allant des laboratoires vivants à la réforme des incitations. Ce cadre propose une voie reproductible pour une gestion de l'eau résistante au changement climatique, transformant l'irrigation en gestion responsable des écosystèmes et positionnant une gestion de l'eau compétente comme un thème essentiel d'un avenir agricole équitable.

Mots-clés : Agroécologie; Irrigation; Productivité de l'eau; Adaptation au climat; Socio-hydrologie; Solutions fondées sur la nature; AquaCrop.

1. INTRODUCTION

Climate change, population growth, and urbanization increasingly strain global freshwater resources. Agriculture accounts for roughly 70% of global freshwater withdrawals, yet faces mounting competition from domestic, industrial, and environmental users (FAO, 2020). The Intergovernmental Panel on Climate Change projects that by 2050, nearly half the world's population will live under severe water scarcity, with agricultural systems most vulnerable to hydrological variability (Douville et al., 2021).

This challenge is acute in Asian monsoon regions, where rice, a highly water-intensive staple dominates production. Traditional continuous flooding consumes 1,500–2,000 mm of water per growing season (Bouman et al., 2007). Climate change disrupts rainfall, increases drought and flood frequency, and reduces surface water reliability (Mirza, 2011). Conventional responses emphasize technological fixes such as efficient pumps and precision irrigation. While valuable, these often neglect broader ecological and social dimensions. Leauthaud et al. (2025) identify a “scientific mismatch” between irrigation science and agroecological principles, noting that most irrigation research remains narrowly biophysical.

Agroecology offers an alternative paradigm prioritizing ecological processes, social equity, and adaptive governance (Altieri et al., 2015). The IPES-Food (2016) outlines thirteen principles including resource recycling, soil health, biodiversity, co-creation of knowledge, and participatory governance. When applied to water management, these principles shift focus from engineered control toward stewarding water as integral to agroecosystem functioning (Mitsch, 2012). Water flows through agricultural landscapes are embedded in social-ecological systems where human decisions, ecological processes, and hydrology interact (Sivapalan et al., 2012).

Despite theoretical promise, operationalising agroecology for water management remains difficult. Grassroots evidence from India shows local communities can develop alternative water systems challenging conventional governance (Tozzi, 2024). Likewise, institutional continuity in China's Honghe

Hani Rice Terraces offers lessons: sustainable management must rebuild local agency, not just apply technical fixes (Sun et al., 2026).

Successful transitions require attention to social organisation alongside biophysical interventions. Nature-based solutions (NbS) are gaining attention as complementary approaches. NbS work with ecological processes to regulate water and provide ecosystem services (Mitsch, 2012).

Key NbS in agriculture include constructed wetlands, riparian buffers, agroforestry, and soil conservation (WATERAGRI Project, 2025). These landscape-level interventions buffer hydrological variability and offer co-benefits such as water quality improvement, biodiversity habitat, and carbon sequestration. Innovative, crop models such as AquaCrop help evaluate alternative irrigation strategies. AquaCrop developed by the FAO is simpler and offers advantages: a water-driven growth engine, simplified canopy cover, conservative parameters, and user-friendly design (Steduto et al., 2009).

It simulates soil water balance, crop development, yield, and evapotranspiration. Validation studies confirm reliability for rice, maize, wheat, and vegetables (Vanuytrecht et al., 2014). For rice, the model has been calibrated for both continuous flooding and alternate wetting and drying (Maniruzzaman et al., 2015).

The tension between agroecology and conventional irrigation reflects divergent assumptions. Conventional irrigation follows command-and-control logic: fixed schedules based on crop water requirements, efficiency measured by delivery performance and yield (Molden et al., 2010). Agroecological management views landscapes as connected hydrological systems. Water productivity is assessed not only by yield per unit water but also by ecosystem services and social equity (Kijne et al., 2003).

Leauthaud et al. (2025) conclude irrigation and agroecology remain disconnected, citing four gaps: scale mismatch, disciplinary silos, difficulty combining quantitative models with participatory methods, and governance barriers. This study addresses these gaps through three objectives. Firstly, to develop a multi-scalar conceptual framework aligning adaptive water management with agroecological principles, from farm-level practices to territorial governance. Secondly, to empirically test this framework using AquaCrop in a contested socio-hydrological system at Taiwan's urban-rural interface, evaluating yield and water productivity under varied irrigation scenarios.

Thirdly, to quantify water savings and yield impacts of alternate wetting and drying compared to continuous flooding for rice and leafy vegetables, and to identify governance mechanisms and policy instruments that can accelerate adoption of resilient water-agroecology systems.

2. MATERIALS AND METHODS

2.1 Study Site Description

The primary research area is the Jiufenggou region under the jurisdiction of the Chising Management Office in Taipei, Taiwan. The total irrigated area is approximately 15 to 20 hectares, including scattered peripheral agricultural lands and ecological zones.

Geographically, the core area is located in the Zhoumei section of the Beitou District, centered at **25°06'23.6"N, 121°30'20.8"E (WGS84)**. The primary source of irrigation water is diverted from the Wufenggang Creek (Figure 1).

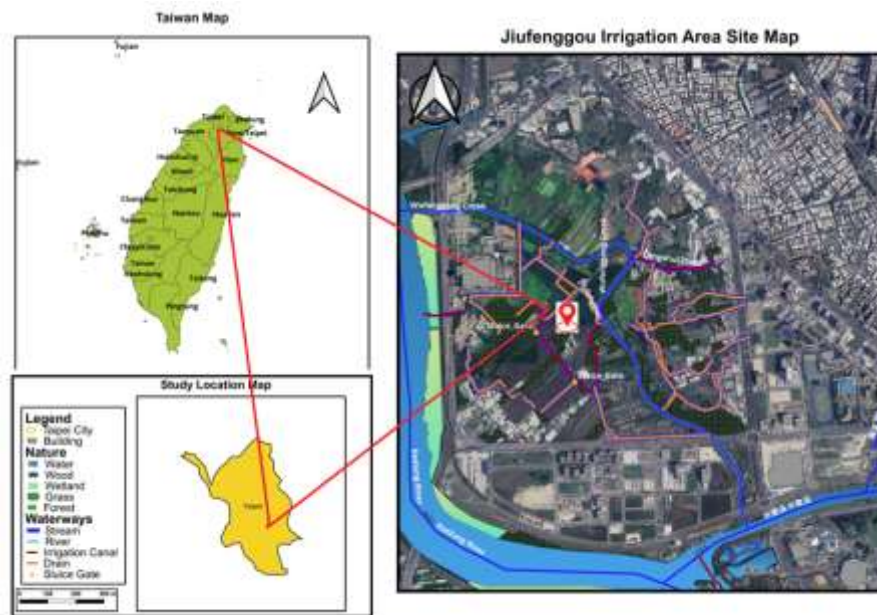


Figure 1. Location map of the Jiufenggou irrigation area

Due to ongoing urban planning modifications, specifically the development of the Beitou Shilin Technology Park, land parcel numbers and land use zoning have undergone significant adjustments. The region faces three intersecting challenges: water instability, water quality degradation, and sectoral water competition. Upstream urban development has drastically reduced surface runoff during the dry season (January to March), leading to severe water insecurity. River water quality is increasingly compromised by inflows of domestic sewage and polluted urban runoff. Intensifying competition exists between water required for agricultural irrigation and the ecological base flow necessary to maintain minimum water levels for habitat preservation.

To systematically address these challenges, the Jiufenggou irrigation area was categorized into three distinct management zones, as detailed in Table 1.

Table 1. Current status and zoning of the Jiufenggou irrigation area

Management zone	Land ownership	Irrigation patterns / crops	Remarks
Upstream segment of Jiufenggou	Coexistence of public and private	Vegetables, horticultural crops	Adjacent to Technology Park; waterways heavily impacted by engineering projects
Core ecological waterway area	Taipei City Government	Ecological maintenance, landscape	Must maintain essential ecological base flow
Downstream Wufenggang Creek confluence area	Private agricultural land	Rice, water bamboo	Influenced by tidal actions and water backflow from Wufenggang Creek

2.2 Crop Productivity Model Configuration

The quantitative analysis employed the AquaCrop crop growth model (Version 6.1). The model requires comprehensive input data, including meteorological station data (temperature, rainfall, reference evapotranspiration ET_0), soil texture profiles (predominantly silty clay loam), and specific management practices (continuous flooding or irrigation thresholds for alternate wetting and drying).

The model calculates above-ground biomass from normalized water productivity (WP). This enables analysis of water use efficiency (WUE) and crop yield across irrigation scenarios. The governing equation in this process is:

$$B = WP \times \sum (Tr/ET_0) \quad (1)$$

Where:

B is Biomass (kg/m²), WP is normalized water productivity (g/m²), Tr is crop transpiration (mm), and ET_0 is reference evapotranspiration (mm).

The crop productivity model incorporates a refined response mechanism for elevated atmospheric carbon dioxide (CO₂) concentrations. For the Wufenggang Creek irrigation area, the model was calibrated specifically for rice and short-term leafy vegetables using the following localized configurations. Reference crop evapotranspiration ET_0 is calculated using the globally standard Penman-Monteith equation. Meteorological data were sourced from the nearest reliable observatories: the Taipei Meteorological Station (Station ID: 466920) and the Shilin Automatic Observation Station. The baseline CO₂ concentration is set at approximately 410 ppm. Using local rice varieties as the baseline, key physiological parameters were calibrated to reflect Taipei's specific agroclimatic conditions. The Base Temperature was set at 10°C. The reference Harvest Index (HI₀) for rice was calibrated between 0.43 and 0.50. Normalized water productivity (WP) was established at 15 to 20 g/m². Canopy Expansion acts as the primary indicator influencing overall water transpiration. Based on data from the Taiwan Geological Survey Institute (2020), the soil profile surrounding Wufenggang Creek is predominantly silty clay loam with the following characteristics: bulk density 1.35 g/cm³, field capacity 0.32 cm³/cm³, permanent wilting point 0.15 cm³/cm³, and saturated hydraulic conductivity 2.5 cm/day.

2.3 Irrigation Management Scenarios

Two primary irrigation management scenarios were established to assess adaptation strategies.

Scenario A (Baseline): Continuous Flooding (CF) (Paddy Field) - Maintaining a constant standing water depth of 3 to 5 cm throughout the growing season, representing conventional practice in the study region.

Scenario B (Adaptation): Alternate Wetting and Drying (AWD) - A water-saving technique where irrigation is applied only when soil water content drops below 20% of the readily available water threshold. This threshold was selected based on published AWD guidelines for rice (Bouman et al., 2007) and preliminary local calibration.

Net irrigation requirement was calculated using the soil water balance equation:

$$I_{net} = \sum (ET_c - P_e - G_e - \Delta SW) / E_f \quad (2)$$

Where:

ET_c is crop evapotranspiration, P_e is effective rainfall, G_e is groundwater capillary rise contribution (particularly relevant when the Wufenggang Creek water level is high), ΔSW is change in soil water storage, E_f is irrigation efficiency (accounting for the discrepancy in water loss rates between traditional earth canals and concrete-lined channels in Jiufenggou).

3. RESULTS AND DISCUSSION

3.1 Simulated Water use and Yield under Alternative Irrigation Scenarios

AquaCrop simulations revealed consistent water savings under alternate wetting and drying (AWD) compared to continuous flooding (CF) across both rice and vegetable production systems (Table 2). For rice, AWD reduced seasonal irrigation water use by 17.3% on average (range: 15.2-22.1% depending

on rainfall variability), while maintaining yields at 98-99% of CF levels with no statistically significant reduction.

For leafy vegetables, water savings ranged from 15.8% to 19.4% across planting cycles, with no statistically significant yield reduction ($p > 0.05$, paired t-test).

Table 2. Simulated water use, yield, and water productivity under continuous flooding (CF) and alternate wetting and drying (AWD) scenarios

Crop	Scenario	Irrigation water use (mm)	Yield (t/ha)	Water productivity (kg/m ³)	Water saving (%)	Yield change (%)
Rice	CF	1,420	6.85	0.68	—	—
Rice	AWD	1,175	6.72	0.82	17.3	-1.9
Leafy vegetables	CF	285	9.65	2.41	—	—
Leafy vegetables	AWD	232	9.58	2.93	18.6	-0.7

Note: Values represent means across 10 simulation years (2016-2025).
Vegetable values are per cropping cycle (approximately 45 days).

Water productivity increased substantially under AWD. Rice water productivity improved from 0.68 kg/m³ under CF to 0.82 kg/m³ under AWD, representing a 20.6% increase. Vegetable water productivity showed similar improvement, increasing from 2.41 kg/m³ to 2.93 kg/m³ (21.6% increase).

These findings align closely with published field studies. Meta-analyses of AWD experiments in Asia report average water savings of 15-30% with minimal yield impacts when water thresholds are maintained above 15-20% of saturated soil moisture (Bouman et al., 2007; Carrijo et al., 2017; Phoeurn et al., 2024). The results from Jiufenggou fall within this range, supporting the validity of the AquaCrop parameterization for local conditions.

The observed increase in water productivity under AWD stems from two mechanisms. First, percolation and seepage losses are reduced during dry periods when the soil is not continuously saturated. Second, evaporative losses decrease when the soil surface dries between irrigation events. These findings have practical implications for the Chising Management Office, suggesting that AWD adoption could partially offset declining water supplies without sacrificing agricultural output.

However, several caveats warrant attention. The simulations assumed perfect implementation of AWD thresholds by farmers. In practice, adoption may be incomplete due to risk aversion, lack of technical knowledge, or infrastructure constraints. Additionally, the model did not account for potential weed pressure changes under AWD, which some studies report as a challenge in aerobic rice systems. Finally, the simulations used historical climate data (2016-2025); under future climate scenarios with increased rainfall variability, water savings might differ.

The timing of water savings varied across crop growth stages. For rice, the largest reductions occurred during the vegetative stage (tillering), where AWD allowed soil drying between irrigation events without yield penalty. During the reproductive stage (panicle initiation to flowering), AWD maintained soil moisture above the 20% readily available water threshold to protect yield formation. This stage-specific response informed the development of the drought adaptation framework described below.

3.2 Dynamic Rotational Irrigation Framework for Drought Adaptation

Based on the simulation results and local hydrological data, a three-tier dynamic rotational irrigation framework was developed for the dry season (January to March). Table 3 presents the alert levels and corresponding adaptation measures.

Table 3. Drought adaptation and alert levels for Jiufenggou

Alert level	Water source status	Rotational irrigation / adaptation measures
Green (Normal)	Wufengang Creek flow is sufficient	Maintain parallel ecological and irrigation functions; Jiufenggou maintains normal water level (approximately 40-60 cm)
Yellow (Warning)	Flow drops to 70% of baseline observations	Initiate regional rotational irrigation: divide Jiufenggou irrigation area into upstream and downstream sections, implementing a cycle of 3 days of water supply followed by 2 days of suspension
Red (Severe)	Flow drops below 40% of baseline observations	Yield-protection priority mode: suspend non-essential landscape watering; utilize crop drought-stress critical points simulated by AquaCrop to provide precise, quantified watering (e.g., exclusively supplying water during rice flowering stage)

The yellow alert threshold (70% of baseline flow) corresponds to a Relative Irrigation Supply Index (RISI) value of approximately 0.75-0.80, consistent with the Irrigation Stress Zone definition. RISI is calculated as actual water supply divided by crop water requirement, with values below 0.8 indicating moderate to severe stress. The red alert threshold (40% of baseline) corresponds to $RISI < 0.50$, where model simulations indicate yield losses exceeding 20% if full irrigation is not maintained during critical growth stages.

This three-tier framework provides an operational structure for translating model outputs into management actions. The green-yellow-red system is familiar to water managers and farmers in Taiwan, who already use similar systems for typhoon and flood warnings. The specific thresholds (70% and 40% of baseline flow) were derived from model simulations showing that yield losses remain below 5% when irrigation is reduced by up to 30% during non-critical stages, but exceed 15% when reductions exceed 60% during reproductive stages.

Implementation of this framework requires institutional coordination across multiple actors. The Chising Management Office holds formal authority over water allocation but cannot compel farmers to adopt AWD practices without their cooperation. Conversely, farmers possess local knowledge of field conditions but lack access to real-time hydrological data and crop model outputs. Bridging this gap requires what socio-hydrology terms "co-production" of knowledge and decisions (Sivapalan et al., 2012).

3.3 Water Supply and Usage Trends

Analysis of water supply and usage data for the Zhoumei and Jiufenggou irrigation areas over the past decade (2016-2025), based on annual statistics from the Irrigation Agency and the Chising Management Office, reveals a clear transitional trend (Table 4).

The primary water source is the Shuangxi River weir, directing water into Wufengang Creek. Agricultural water use has steadily declined, while ecological and flood retention demands are now formally incorporated. Two implications emerge: remaining agriculture faces complex urban-ecological competition, and formal recognition of ecological demands creates opportunities for AWD to free water for dry-season habitat maintenance.

Table 4. Overview of water supply and usage trends (2016-2025)

Year period	Registered irrigated area (ha)	Annual total water supply (10 ⁴ m ³)	Main crop types	Remarks
2016-2018	110-125	1,200-1,400	Rice, vegetables, horticulture	Pre-development phase of Beitou Shilin Tech Park
2019-2021	85-100	950-1,100	Vegetables, rice (declining)	Impacted by zoning and land filling operations
2022-2024	50-75	600-800	Landscape horticulture, organic vegetables	Transitioning toward ecological waterways and smart irrigation
2025-2026	45-60	500-650	Urban farming, landscape maintenance	Ecological transition

3.4 Socio-Hydrological Vulnerability Mapping

To identify areas most at risk and enable targeted interventions, a socio-hydrological vulnerability assessment was conducted. Vulnerability was calculated as $V = (\text{Exposure} + \text{Sensitivity}) - \text{Adaptive Capacity}$, with indicators normalized to 0-1 scale. Exposure captured physical risks (terminus farmlands, higher elevations, no pumping). Sensitivity reflected farmer age and crop water stress sensitivity (rice > vegetables). Adaptive capacity measured group participation, technology acceptance, and alternative water sources.

Application identified three vulnerability zones (Table 5; Figure 2). Approximately 35% of parcels are highly vulnerable (water stress + limited adaptive capacity), 45% medium, and 20% low (near diversion point with alternative sources).

Table 5. Social vulnerability evaluation indicators

Dimension	Evaluation indicators	Link to social impact
Exposure	Terminus farmlands, higher elevations, no pumping	Identifies highest drought risk
Sensitivity	Farmer age, crop water sensitivity	Evaluates tolerance capacity against climate variations
Adaptive capacity	Group participation, tech acceptance, alternative water access	Measures resilience and recovery capability

The mapping approach identifies both where deficits occur and who is most susceptible. Two parcels with identical RISI may differ in vulnerability based on operator age and alternative water access. This enables precise resource allocation by prioritizing sensors and backup wells for high vulnerability zones operationalizing environmental justice.

Stakeholder engagement informed indicator selection. Interviews with elderly farmers documented drought years (2003, 2011, 2015) and traditional 5-day rotation practices, which are informal and contested. Younger farmers preferred sensor-based scheduling; older farmers wanted simple thresholds.

A 2025 workshop (comprising Chising Management Office, farmers, neighborhood office, NGO) revealed consensus: water shortage is worsening; farmers accept equitable rotational irrigation; ecological flows are legitimate. Divergence emerged on technology: agency favored automated sensors; farmers requested simple visual indicators (colored flags, staff gauges).

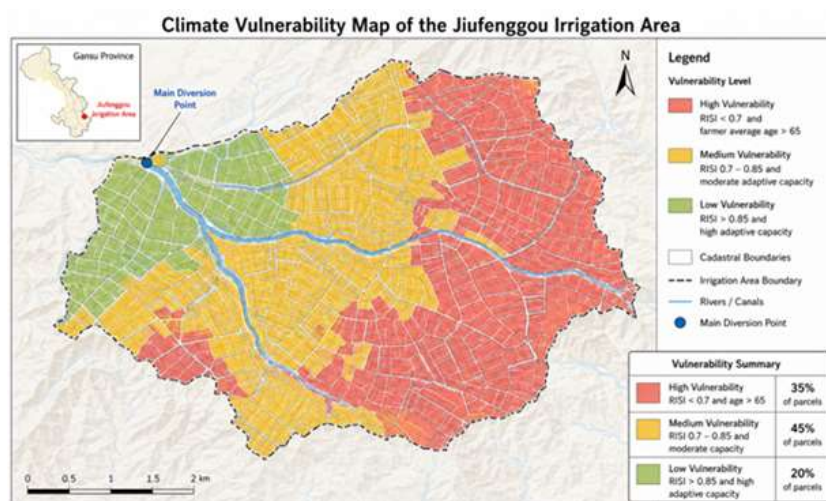


Figure 2. Climate vulnerability map of the Jiufenggou irrigation area, integrating physical water deficit (RSI) with social vulnerability indicators.

Figure 2. Climate vulnerability map integrating RSI with social indicators.

3.5 Synthesis: Connecting Results to Agroecological Principles

The results presented above operationalize several core agroecological principles. First, input reduction is achieved through AWD, which reduces irrigation water use by 15-22% without compromising yields. Second, synergy is demonstrated by the alignment between agricultural water savings and ecological flow maintenance: water not used for irrigation can sustain the Jiufenggou ecological waterway. Third, co-creation of knowledge is embedded in the stakeholder workshop process, where model outputs were discussed and refined with farmers and water managers. Fourth, land and water governance is addressed through the three-tier alert framework, which provides transparent, rule-based allocation procedures.

The framework also complements nature-based solutions (NbS) rather than competing with them. Upstream of the irrigation area, urban development has increased runoff variability and reduced dry-season baseflow. Restoring riparian vegetation and constructing small retention ponds in the upper catchment could moderate these hydrological fluctuations. Downstream, the ecological waterway requires minimum flows for habitat maintenance; AWD reduces agricultural withdrawals, freeing water for ecological purposes during critical dry periods. This synergy between on-farm efficiency and landscape restoration represents a tangible application of agroecological principles to peri-urban water management.

4. LIMITATIONS AND FUTURE RESEARCH

In this study three limitations are acknowledged. First, AquaCrop simulations lack field validation for local systems at present. Parameters (WP 15-20 g/m², HI 0.43-0.50) align with similar Taiwan environments (Lin, 2019), but local calibration would improve confidence. Second, vulnerability assessment used proxy indicators (e.g., farmer age) rather than direct measurements. Third, economic costs of AWD adoption (pumping energy, labour) remain unquantified.

Future research should prioritize: (1) field validation of AquaCrop with soil moisture sensors; (2) economic analysis under various water pricing scenarios; (3) weed and disease dynamics under AWD; (4) framework extension to other peri-urban areas in Taiwan.

5. CONCLUSIONS

This study developed an integrated framework bridging agroecological principles with data-driven irrigation optimization across farm-level practices (AWD, soil moisture monitoring) and landscape-level governance (rotational irrigation, ecological flow allocation). Applied to Taipei's Jiufenggou irrigation area, three findings emerged.

Firstly, AquaCrop simulations showed AWD reduces irrigation water use by 15-22% compared to CF while maintaining yields at 98-99% of baseline levels with no significant reduction. Water productivity increased approximately 20%.

Secondly, a three-tier drought framework based on the Relative Irrigation Supply Index was developed. Below 70% flow (yellow alert), irrigation follows a 3-day-on, 2-day-off cycle and below 40% (red alert), irrigation targets only critical crop growth stages to preserve yields.

Thirdly, socio-hydrological mapping identified 35% of irrigated parcels as highly vulnerable due to water deficits ($RISI < 0.8$) and limited adaptive capacity, enabling precise resource targeting.

This research discovered that, beyond technical solutions, effective implementation requires multi-stakeholder governance involving farmers, water associations, and planners. Stakeholder workshops so far revealed consensus on action and acceptance of equitable rotational irrigation, though divergence emerged on technology preferences.

The primary contribution of this work is a replicable framework combining AquaCrop parameterisation, RISI-based alert levels, and vulnerability mapping for peri-urban irrigation areas facing water scarcity. Immediate next steps include installing soil moisture sensors in high vulnerability zones, formally adopting the alert framework, and continuing stakeholder engagement.

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