

THE ROLE OF IRRIGATION AND DRAINAGE IN MALAYSIA'S AGRO- ECOLOGICAL TRANSITION UNDER CLIMATE CHANGE: A COMPREHENSIVE ANALYSIS OF ADAPTIVE MANAGEMENT AND TECHNOLOGICAL INTEGRATION

RÔLE JOUE PAR L'IRRIGATION ET LE DRAINAGE DANS LA TRANSITION AGRO-ÉCOLOGIQUE DE LA MALAISIE FACE AU CHANGEMENT CLIMATIQUE : ANALYSE COMPLÈTE DE LA GESTION ADAPTATIVE ET DE L'INTÉGRATION TECHNOLOGIQUE

Nor Hafizah Mohd Suhadis¹, Yuslina Hj Mohd Sani², Muhamad Aliif Aimran Jamaari³

ABSTRACT

This paper presents a comprehensive framework for Malaysia's agro-ecological transition in rice cultivation to address climate vulnerabilities and achieve the 80% self-sufficiency target under the National Agrofood Policy 2.0. With global climate models projecting a 21% decrease in dry-season irrigation supply, and diagnostics at the IADA Seberang Perak scheme revealing an average overall irrigation efficiency of just 22.14%, systemic upgrades are urgently required. By synthesizing recent case studies, this analysis evaluates interventions across multiple scales: catchment-level agro-hydrological modeling (HEC-HMS/HEC-RAS), tertiary efficiency diagnostics, automated Internet of Things (IoT) water gates and methane-mitigating irrigation regimes. Key findings demonstrate that hydrological modeling at the Tanjung Karang Irrigation Scheme (TAKRIS) highlights severe temporal water mismatches, necessitating off-river storage infrastructure to capture wet-season surpluses for dry-season deficits. Concurrently, deploying ESP32-based IoT automated water gates significantly reduces localized distribution waste by providing real-time precision control and preventing tailwater runoff. Environmentally, implementing Alternate Wetting and Drying (AWD) reduces cumulative methane emissions by 57.81% without compromising crop yields. The study concludes that navigating climate uncertainties requires a multidisciplinary approach. It recommends constructing off-river storage, deploying tertiary-level IoT water gates and broadly adopting safe-AWD regimes. Ultimately, these adaptive management strategies should be unified under an Integrated Water Sector Data Centre (IWSDC) to establish a resilient, data-driven agricultural sector in line with the Water Sector Transformation 2040 agenda.

Keywords: Irrigation Efficiency, Climate Change, HEC-RAS Modeling, IoT Automation, Methane Mitigation, Rice-Microbe Nexus, National Agrofood Policy 2.0, Malaysia.

RESUME

Ce document présente un cadre complet de la transition agro-écologique de la Malaisie dans la riziculture afin de remédier aux vulnérabilités climatiques et d'atteindre l'objectif d'autosuffisance de 80% dans le cadre de la politique agroalimentaire nationale 2.0. Alors que les modèles climatiques mondiaux prévoient une diminution de 21% de l'approvisionnement en irrigation pendant la saison sèche, et que les diagnostics du périmètre irrigué IADA Seberang Perak révèlent une efficacité moyenne

¹ Head of Assistant Director, Division of Irrigation and Agriculture Drainage, Ministry of Agriculture and Food Security Malaysia, Putrajaya, Malaysia, E-mail: norhafizah@water.gov.my

² Director, Division of Irrigation and Agriculture Drainage, Ministry of Agriculture and Food Security Malaysia, Putrajaya, Malaysia, E-mail: yuslina@water.gov.my

³ Assistant Director, Division of Irrigation and Agriculture Drainage, Ministry of Agriculture and Food Security Malaysia, Putrajaya, Malaysia, E-mail: aliifaimran@water.gov.my

globale de l'irrigation de seulement 22,14%, des améliorations systémiques doivent être établies d'urgence. En synthétisant des études de cas récentes, cette analyse examine les interventions à plusieurs échelles : modélisation agro-hydrologique au niveau du bassin versant (HEC-HMS/HEC-RAS), diagnostics d'efficacité tertiaire, vannes automatisées basées sur l'Internet des objets (IoT) et régimes d'irrigation atténuant les émissions de méthane. Les principales conclusions démontrent que la modélisation hydrologique du périmètre irrigué de Tanjung Karang (TAKRIS) met en évidence de graves disparités temporelles dans l'approvisionnement en eau, nécessitant des infrastructures de stockage hors rivière pour capturer les excédents de la saison des pluies et combler les déficits de la saison sèche. Parallèlement, le déploiement de vannes automatisées IoT basées sur ESP32 réduit considérablement les déchets de distribution localisés en offrant un contrôle de précision en temps réel et en empêchant le ruissellement d'eau aval. Sur le plan environnemental, la mise en œuvre de la technique d'humidification et de séchage alternés (AWD) réduit les émissions cumulées de méthane de 57,81% sans compromettre les rendements des agriculteurs. L'étude conclut que la gestion des incertitudes climatiques nécessite une approche multidisciplinaire. Elle recommande de construire des installations de stockage hors rivière, de déployer des vannes IoT au niveau tertiaire et d'adopter largement des régimes sûrs pour les AWD. Finalement, ces stratégies de gestion adaptative devraient être centralisées au sein d'un centre intégré de données du secteur de l'eau (IWSDC) afin d'établir un secteur agricole résilient et axé sur les données, conformément au programme de transformation du secteur de l'eau à l'horizon 2040.

Mots-clés : Efficacité de l'irrigation; Changement climatique; Modélisation HEC-RAS; Automatisation IoT; Réduction des émissions de méthane; Lien entre riz-microorganismes; Politique agroalimentaire nationale 2.0; Malaisie.

INTRODUCTION

Malaysian agriculture is undergoing a fundamental shift from highly input-intensive monocultures to ecologically sound, resource-efficient management practices. Under the National Agrofood Policy 2.0 (NAP 2.0, 2021–2030), the federal government has set ambitious targets to stabilize local food supply and enhance rural livelihoods, specifically targeting an 80% rice self-sufficiency level (SSL) and elevating the average monthly income of granary smallholders to RM3,500 by 2030. Concurrently, the Economic Planning Unit (EPU), along with the Academy of Sciences Malaysia (ASM), has championed the Water Sector Transformation 2040 (WST 2040) agenda. WST 2040 aims to transform the nation's water sector from a mere economic enabler into a self-sustaining growth engine, heavily relying on the Water-Food-Energy (WFE) Nexus to balance resource trade-offs.

However, achieving these milestones is increasingly threatened by severe climate risks. High-resolution Global Climate Models (GCMs) project that Peninsular Malaysia will experience a warming trend of up to 1.97°C by 2100. While overall precipitation may remain high, changing monsoon patterns will cause severe temporal and spatial rainfall distribution mismatches. This is particularly evident in critical agricultural catchments like the Upper Bernam River Basin—the primary hydrological source for the Tanjung Karang Rice Irrigation Scheme (TAKRIS). Driven by Representative Concentration Pathway (RCP) 8.5 high-emission projections, available streamflow in the basin is projected to decrease by 21%, translating to major dry-season shortages from January to June.

To build resilience, Malaysian researchers are redesigning irrigation and drainage systems. No longer viewed as simple concrete pipes for water delivery, they are treated as sophisticated ecological interfaces. This paper presents a comprehensive synthesis of recent domestic case studies. We analyze watershed-scale hydrological modeling, tertiary efficiency diagnostics, IoT gate automation, methane-mitigating water regimes, rhizosphere microbiology, and biodiverse rice-fish polycultures. Together, they form an integrated framework for Malaysia's agro-ecological transition.

CATCHMENT-SCALE AGRO-HYDROLOGICAL MODELING: THE TAKRIS CASE STUDY

To manage seasonal supply volatility and optimize canal delivery under climate change, researchers at Universiti Putra Malaysia (UPM) developed a coupled predictive modeling framework utilizing HEC-HMS

and HEC-RAS. Focused on the Bernam-Tengi River basin within the Tanjung Karang Rice Irrigation Scheme region (TAKRIS), this case study evaluated how future climate scenarios impact river discharge and subsequent water allocation across the scheme.

Model Construction and Calibration Metrics

Continuous sub-catchment runoff was simulated in HEC-HMS using simulated discharge values, which were subsequently routed into HEC-RAS to solve one-dimensional unsteady flow equations along the canal network. Channel geometry was extracted from a high-resolution 30 m x 30 m Digital Elevation Model (DEM) and processed using HEC-GeoRAS. Channel resistance was parameterized using Manning's roughness coefficient (n), which was initially estimated from land-use maps and adjusted during calibration. The model was calibrated using daily discharge data from 2001 to 2003 and validated using daily records from 2004.

Table 1. Calibration and Validation Metrics for the Catchment-Scale Agro-Hydrological Model (TAKRIS Case Study)

Evaluation Phase	R ²	NSE	PBIAS (%)	RSR
Calibration (2001–2003)	0.66	0.64	0.94	0.60
Validation (2004)	0.65	0.59	1.77	0.64

A critical technical finding from the UPM research team was the importance of continuous loss methods (such as the Deficit and Constant method or the Soil Moisture Accounting method) in HEC-HMS for long-term climate projections. Traditional event-based loss methods, such as the Soil Conservation Service Curve Number (SCS-CN), are mathematically restricted because they do not account for soil moisture recovery during dry spells. Conversely, continuous loss methods simulate long-term water movement across vegetative, surface, and groundwater layers. The Deficit and Constant method are particularly useful because it allows the initial loss to recover after extended dry periods. However, UPM's reviews highlighted that despite the high accuracy and simplicity of this method, climate change impact studies utilizing it remain very limited in Malaysia, identifying a critical gap for future hydrological research.

Hydrological Mismatch and Infrastructure Requirements

The HEC-RAS unsteady flow simulations uncovered severe temporal water imbalances within TAKRIS, highlighting a major mismatch between seasonal precipitation and crop irrigation requirements.

- **Off-Season Dynamics (January to June):** During the off-season, the scheme faces a critical dry-season water deficit of 52.46 Mm³ from January to March. However, from April to June, the system receives an excess supply of 40.10 Mm³ due to increased seasonal rainfall.
- **Main-Season Dynamics (July to December):** The early phase of the main season (July to September) is under-supplied, with a deficit of 53.14 Mm³. In contrast, the later phase (October to December) experiences a substantial surplus of 52.40 Mm³.

These findings demonstrate that the primary challenge for Malaysian rice granaries is not a physical lack of water, but rather a temporal misalignment between seasonal precipitation and crop irrigation requirements. To address this mismatch, the UPM researchers concluded that structural upgrades are essential. Specifically, implementing off-river storage (ORS) facilities and retention reservoirs would allow managers to capture and store excess wet-season flows for redistribution during critical dry-season deficits, thereby stabilizing water supply and protecting crop yields.

TERTIARY-LEVEL IRRIGATION EFFICIENCY DIAGNOSTICS: THE IADA SEBERANG PERAK CASE STUDY

While basin-scale water availability is shaped by climate and storage infrastructure, overall water security is heavily constrained by tertiary-level distribution efficiency. To analyze these localized losses, the River Engineering and Drainage Research Centre (REDAC) at Universiti Sains Malaysia (USM) conducted a diagnostic study at the IADA Seberang Perak Irrigation Scheme in Perak.

Spanning over 8,500 hectares, IADA Seberang Perak is one of Malaysia's key rice granaries. Water is sourced from Sungai Perak via the Teluk Sena intake and delivered through primary, secondary, and tertiary canals. Despite upgrading 65% of its primary and secondary canals to concrete, the scheme has historically underperformed, with prior benchmarking studies reporting an overall irrigation efficiency of only 17%. To investigate the sources of these losses, USM researchers analyzed a 185-hectare representative plot in Block E of the Right Branch Canal (RBC) zone under FELCRA supervision. This block was chosen because over 90% of its tertiary canals had been upgraded to concrete, allowing researchers to isolate operational inefficiencies from physical channel seepage.

The system's overall irrigation efficiency (E_p) was modeled using the following multiplicative formula, where E_c is Conveyance Efficiency, E_d is Distribution Efficiency, and E_a is Field Application Efficiency:

$$E_p = E_c \times E_d \times E_a$$

Seasonal Efficiency and Water Balance Analysis

The diagnostic, conducted over two distinct planting seasons, revealed significant operational inefficiencies.

Main Season (Season 2/2022)

During the main season, high rainfall supplemented irrigation inputs. However, this led to substantial over-irrigation and uncontrolled runoff. Total drainage from the plot (1296.1mm) exceeded the total irrigation input (1248.4mm), indicating poor flow regulation and scheduling. The component efficiencies were calculated as:

- $E_c = 84.62\%$
- $E_d = 47.95\%$
- $E_a = 33.98\%$

Applying the efficiency formula:

$$E_p = 0.8462 \times 0.4796 \times 0.3398 = 13.87\%$$

This low overall efficiency (13.87%) reflects severe water losses due to unmanaged application during high-rainfall periods.

Off-Season (Season 1/2023)

During the drier off-season, scarcer water supplies prompted tighter operational control. This improved field application efficiency (E_a) to 94.64%. However, distribution efficiency (E_d) remained low at 40.24%. The component efficiencies were calculated as:

- $E_c = 79.96\%$
- $E_d = 40.24\%$
- $E_a = 94.64\%$

Applying the efficiency formula:

$$E_p = 0.7996 \times 0.4024 \times 0.9464 = 30.40\%$$

Despite better field application, the system still lost more than two-thirds of its supplied water before reaching the crop root zones.

Table below shows that the multi-seasonal average overall efficiency was 22.14%, falling far short of the FAO's recommended threshold of 50% to 60% for gravity-fed irrigation schemes. This underperformance is reflected in a low Water Productivity Index (WPI) of 0.30 kg/m³.¹⁶ The USM researchers identified several physical and operational bottlenecks, including control structure degradation, sedimentation, and a lack of real-time monitoring. These findings demonstrate that physical concrete upgrades must be paired with modern, automated water-control systems to prevent resource waste and improve climate resilience.

Table 2. Tertiary-Level Irrigation Efficiency and Productivity Diagnostics (IADA Seberang Perak Case Study)

Diagnostic Parameter (IADA Seberang Perak Block E)	Season 2/2022 (Main Season)	Season 1/2023 (Off-Season)	Multi-Seasonal Average
Conveyance Efficiency (E_c)	84.62%	79.96%	82.29%
Distribution Efficiency (E_d)	47.95%	40.24%	44.10%
Field Application Efficiency (E_a)	33.98%	94.64%	64.31%
Overall Irrigation Efficiency (E_p)	13.87%	30.40%	22.14%
Water Productivity Index (WPI)	—	—	0.30 kg/m ³
Total Paddy Yield (within study plot)	608.81 tonnes	—	—
Harvested Study Area	148.12 hectares	—	—

MICRO-LEVEL MODERNIZATION: AUTOMATED IOT WATERGATE PROTOTYPING

To address the localized distribution and application losses identified in major granaries, researchers at the Malaysian Agricultural Research and Development Institute (MARDI) Seberang Perai developed a prototype automated IoT water gate system. Led by Mohammad Aafa Mhd Bookeri at the Engineering Research Centre, this study designed a low-cost, scalable solution to replace labor-intensive manual gate operations and improve irrigation efficiency.

System Architecture and Control Logic

The automated water gate prototype is built around an ESP32 microcontroller, which features integrated Wi-Fi and Bluetooth connectivity. The system's architecture includes:

- **Sensing Suite:** Three HC-SR04 ultrasonic sensors installed across the plot to measure water levels. The maximum measurement range for these sensors is calibrated to a 12 cm vertical threshold, representing the physical distance from the sensor to the water base.
- **Actuation:** A 12 V linear actuator mechanically coupled to a sluice gate.

- **Connectivity:** The ESP32 transmits real-time sensor data via cellular gateways to the Blynk IoT platform, allowing farmers to monitor water levels, view historical trends, and perform manual overrides via web or mobile interfaces.

The system's control logic is programmed to maintain optimal water levels based on specific crop growth phases. If the water level within the field falls below a critical threshold of 5 cm, the ESP32 triggers the 12 V linear actuator to open the water gate. Once the water level reaches the target depth, the controller commands the actuator to close the gate, preventing over-flooding and eliminating tailwater runoff.

Empirical Calibration and Technical Constraints

Field testing of the prototype identified key technical constraints and operational limits necessary for reliable field deployment:

1. Signal Stability and Sensor Distance: Wireless signal stability was evaluated by testing the sensors at distances of 5 meters, 10 meters, and 15 meters from the central ESP32 microcontroller. The sensors provided highly stable and reliable water level readings at distances of 5 and 10 meters. However, at 15 meters, the readings became highly unstable, exhibiting significant fluctuations due to signal attenuation and crop canopy interference. To ensure reliable data transmission, researchers recommend that sensor nodes be placed within a 10-meter radius of the central controller, ideally in the center of the plot to avoid micro-topographical errors.

2. Power Dynamics and Actuator Speed: Calibration tests evaluated the relationship between the state of charge (SoC) of the 12 V battery (from 100% to 0%) and the time required for the linear actuator to extend or retract. The results showed that as the battery's charge declines, the operational speed of the actuator decreases. This latency can delay gate closures and cause minor over-watering. To maintain consistent system performance, MARDI researchers highlighted the importance of keeping the battery sufficiently charged, recommending the integration of solar recharging units for long-term field use.

AGRO-ECOLOGICAL INTERVENTIONS: ALTERNATIVE WATER REGIMES AND METHANE MITIGATION

In tandem with physical and digital water-control modernizations, Malaysian research organizations have investigated the agronomic and environmental impacts of alternative irrigation regimes. Traditional continuous flooding (CF) maintains a standing water head of 5 cm to 10 cm throughout the growing season. This persistent inundation creates highly anoxic, oxygen-deprived soil conditions that encourage the proliferation of methanogenic archaea, making flooded rice fields a major source of greenhouse gas emissions. To address this, agronomy researchers at Universiti Putra Malaysia (UPM) have evaluated alternative water-saving techniques.

Methane Emissions Mitigation

A laboratory and tank-scale study led by Nur Fitriah Pauzai at UPM's Faculty of Agriculture evaluated the environmental impacts of Alternate Wetting and Drying (AWD) and Mid-season Drainage (MD). Utilizing the popular Malaysian rice variety *MR297* transplanted across 15 tanks in a randomized complete block design (RCBD), the study measured cumulative methane (CH₄) emissions over a full planting cycle.

The results demonstrated that introducing aerobic soil phases via AWD and MD dramatically reduces cumulative methane emissions without causing significant yield loss, providing a viable pathway for low-carbon rice cultivation in Malaysia.

Table 3. Methane Mitigation and Yield Performance Under Alternative Water Regimes (MR297 Case Study)

Irrigation Treatment Regime	Cumulative CH ₄ Emissions (g CH ₄ /m ² per cycle)	Methane Emission Reduction vs. CF	Statistical Impact on Final Grain Yield
Continuous Flooding (CF)	70.24	Baseline (0%)	Standard baseline yield
Alternate Wetting and Drying (AWD)	30.75	57.81%	No statistically significant loss
Mid-season Drainage (MD)	15.93	77.07%	No statistically significant loss

Field Validation of Safe-AWD

To validate these findings under actual field conditions, a team led by Wan Fazilah Fazlil Ilahi at UPM's Department of Agriculture Research and Development Platform conducted a field experiment in Padang Raja, Kelantan. The study used a direct-seeded wet-season variety, *Mardi Sempadan MR303*, grown from June to September in 46 m x 50 m plots separated by compacted clay bunds to prevent lateral seepage.

The "safe-AWD" protocol was implemented based on International Rice Research Institute (IRRI) guidelines:

- **Field Water Tube Installation:** A low-cost, 15 cm diameter and 30 cm tall PVC field water tube was deployed to monitor sub-surface water levels. The lower 15 cm of the tube was perforated with holes to allow water flow, while the upper 15 cm remained solid. The tube was buried in the soil with the solid half protruding above the surface, and the interior soil was cleared.
- **Operational Management:** The field was kept under a standard 5 cm to 10 cm water head until 30 days after sowing (DAS) to suppress weeds and ensure healthy seedling establishment. From 30 DAS onward, irrigation was withheld, allowing the water table to drop to 15 cm below the soil surface (monitored via the PVC tube) before re-irrigating to a depth of 5 cm above the ground. This alternate wetting and drying cycle were maintained until the harvest stage.

Table 4: Agronomic Performance Metrics of Safe-AWD Under Field Conditions (Mardi Sempadan MR303 Case Study)

Agronomic Parameter (Mardi Sempadan MR303)	Continuous Flooding (CF) Control Plot	Safe-AWD Experimental Plot	Statistical Significance (p<0.05)
Mean Plant Height (at harvest)	99.78 ± 4.15 cm	95.00 ± 4.53 cm	No Significant Difference
Mean Panicle Length	24.17 ± 0.55 cm	22.31 ± 0.58 cm	No Significant Difference
Mean Number of Filled Grains	121.93 ± 8.80	94.40 ± 5.35	No Significant Difference
Mean Number of Unfilled Grains	14.00 ± 2.96	10.93 ± 2.10	No Significant Difference
Total Grain Number per Panicle	135.93 ± 6.17	105.33 ± 4.90	No Significant Difference

Grain Filling %	89.48 ± 2.65%	89.58 ± 2.09%	No Significant Difference
1,000-Grain Weight (g)	71.15 ± 4.51 g	83.42 ± 7.83 g	No Significant Difference
Harvest Index	0.46 ± 0.03	0.47 ± 0.03	No Significant Difference
SPAD Chlorophyll Content	Comparable high values across stages	Comparable high values across stages	No Significant Difference

Statistical analysis using a standard t-test ($P < 0.05$ at a 95% confidence level) confirmed no significant differences in growth and yield performance metrics between the AWD and CF treatments. This demonstrates that safe-AWD can be implemented in Malaysian fields to achieve substantial water savings and reduce greenhouse gas emissions without compromising crop yields.

STRATEGIC POLICY ALIGNMENT

The integration of these modern water management practices directly aligns with the strategic targets set by the Ministry of Agriculture and Food Security (KPKM) and the Economic Planning Unit (EPU). First, the National Agrofood Policy 2.0 (NAP 2.0) has set the target of achieving an 80% national self-sufficiency level (SSL) for rice by 2030, while simultaneously elevating the average monthly income of granary smallholders to RM3,500. Deploying automated IoT watergate systems resolves localized distribution losses, immediately maximizing water productivity and stabilizing crop yields. This technological modernization is directly supported by NAP 2.0's Policy Thrust 1, which advocates smart agricultural modernization and rapid technological diffusion.

Second, the Water Sector Transformation 2040 (WST 2040) agenda, facilitated by the Academy of Sciences Malaysia (ASM), seeks to establish an evidence-based, data-driven water sector. Volume III of WST 2040 strongly recommends the development of an **Integrated Water Sector Data Centre (IWSDC)**. This platform is designed to serve as a single-point reference repository, integrating basin-scale runoff projections (such as UPM's HEC-HMS datasets) and real-time field-scale telemetry (such as MARDI's ESP32 water level networks) into a unified dashboard. Establishing the IWSDC allows water managers to make real-time, proactive allocation decisions, addressing the dry-season deficits projected under the RCP 8.5 high-emission climate scenarios.

Third, implementing alternative irrigation regimes (AWD and MD) and multi-trophic rice-fish polycultures directly supports the circularity, sustainability, and biodiversity goals of both NAP 2.0 and WST 2040.

CONCLUSION AND STRATEGIC RECOMMENDATIONS

The synthesis of research across Malaysian organizations demonstrates that navigating climate uncertainties requires an integrated, multi-disciplinary approach. Combining predictive hydrological modeling, digital water-control automation, alternative irrigation regimes, and biodiverse polycultures offers a robust path forward for Malaysia's primary rice granaries.

To operate these findings and accelerate the agro-ecological transition, the following strategic recommendations are proposed:

1. **Construct Off-River Storage (ORS) Infrastructure:** To address the temporal water mismatches identified by UPM's HEC-RAS modeling, regional water authorities should construct dedicated off-river storage and retention basins.¹¹ These structures will capture and store wet-season excess flows (such as the 52.40 Mm³ main-season surplus) and redistribute them during critical dry-season deficits (such as the 52.46 Mm³ off-season shortage).

2. **Deploy Automated IoT Watergates at the Tertiary Level:** To improve the low (22.14%) average irrigation efficiency identified by REDAC/USM, irrigation schemes should integrate automated water gate systems utilizing ESP32 microcontrollers and ultrasonic sensors. These systems can prevent localized water waste and tailwater runoff through real-time monitoring and automated water level control.
3. **Broadly Adopt Safe-AWD Regimes:** Given that agronomic trials by UPM demonstrate no yield loss under safe-AWD, agricultural extension agencies should promote the widespread adoption of this practice. Utilizing low-cost PVC monitoring tubes to implement AWD can reduce methane emissions by up to 57.81%, conserve water, and stimulate the beneficial "Rice-Microbe Nexus" to enhance natural soil fertility.
4. **Establish an Integrated Water-Food-Energy Nexus Data Center:** In line with the WST 2040 Agenda, Malaysia should establish the Integrated Water Sector Data Centre (IWSDC) as a centralized, data-driven reference platform. Integrating basin-scale HEC-HMS hydrological models, tertiary-level efficiency audits, and real-time IoT sensor networks into a single platform will enable coordinated, proactive resource management across the water, food, and energy sectors.

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