

ENHANCING WATER USE EFFICIENCY UNDER CLIMATE VARIABILITY: A MULTI-SCALE REVIEW OF IRRIGATION SYSTEMS IN MALAYSIA

AMELIORATION DE L'EFFICIENCE D'UTILISATION DE L'EAU FACE A LA VARIABILITE CLIMATIQUE: UNE REVUE MULTI-ECHELLE DES SYSTEMES D'IRRIGATION EN MALAISIE

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ABSTRACT

Water is a critical resource for agricultural production and food security particularly in countries where irrigation supports intensive crop cultivation. In Malaysia, irrigation systems are central to paddy production within major granary areas that collectively contribute the majority of domestic rice supply. However, climate variability characterized by changing rainfall patterns, increasing temperatures, prolonged droughts and more frequent flood events is placing significant pressure on irrigation infrastructure and water resource management. This paper presents a multi-scale review of irrigation water use efficiency (WUE) in Malaysia examining irrigation performance from national, river basin, irrigation scheme and farm levels. The review synthesizes findings from irrigation performance assessments, climate impact studies, water productivity analyses, agricultural statistics and national policy frameworks. Evidence indicates that irrigation efficiency remains below international benchmarks in several major schemes, resulting in substantial conveyance and operational losses. Climate projections suggest increasing variability in water availability, requiring adaptive irrigation management strategies. Emerging technologies such as evapotranspiration-based irrigation scheduling, Internet of Things (IoT) sensors, remote sensing, automation and precision water management provide opportunities to improve irrigation performance and climate resilience. The paper proposes a climate-resilient irrigation framework integrating technological innovation, institutional strengthening and policy support to improve water productivity, reduce water losses and strengthen national food security. Findings provide insights for policymakers, irrigation managers and researchers seeking sustainable approaches for agricultural water management under future climate conditions.

Keywords: Water use efficiency, climate variability, irrigation systems, water productivity, climate adaptation, Malaysia.

RÉSUMÉ

L'eau est une ressource essentielle à la production agricole et à la sécurité alimentaire, en particulier dans les pays où l'irrigation soutient des cultures intensives. En Malaisie, les systèmes d'irrigation sont au cœur de la production de riz dans les principales zones de grenier à riz, lesquelles fournissent ensemble la majeure partie de l'approvisionnement national. Toutefois, la variabilité climatique, caractérisée par l'évolution des régimes de précipitations, la hausse des températures, des sécheresses prolongées et des inondations plus fréquentes, exerce une pression considérable sur les infrastructures d'irrigation et la gestion des ressources en eau. Cet article présente une revue multi-échelle de l'efficacité d'utilisation de l'eau d'irrigation (WUE) en Malaisie, en examinant les performances de l'irrigation aux échelles nationale, du bassin hydrographique, du périmètre irrigué et de l'exploitation. La revue synthétise les résultats d'évaluations des performances de l'irrigation, d'études d'impact climatique, d'analyses de la productivité de l'eau, de statistiques agricoles et de

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cadres politiques nationaux. Les données disponibles indiquent que, dans plusieurs grands périmètres, l'efficacité de l'irrigation demeure inférieure aux références internationales, ce qui entraîne d'importantes pertes lors du transport et de l'exploitation. Les projections climatiques laissent prévoir une variabilité accrue de la disponibilité en eau, nécessitant des stratégies adaptatives de gestion de l'irrigation. Des technologies émergentes, telles que la programmation de l'irrigation fondée sur l'évapotranspiration, les capteurs de l'Internet des objets (IoT), la télédétection, l'automatisation et la gestion de précision de l'eau, offrent des possibilités d'améliorer les performances de l'irrigation et la résilience climatique. L'article propose un cadre d'irrigation résilient au climat, intégrant l'innovation technologique, le renforcement institutionnel et l'appui des politiques publiques, afin d'améliorer la productivité de l'eau, de réduire les pertes et de renforcer la sécurité alimentaire nationale. Les résultats apportent des éclairages aux responsables des politiques publiques, aux gestionnaires de l'irrigation et aux chercheurs qui recherchent des approches durables pour gérer l'eau agricole dans les conditions climatiques futures.

Mots-clés : Efficacité de l'utilisation de l'eau; Variabilité climatique; Systèmes d'irrigation; Productivité de l'eau; Adaptation au climat; Malaisie.

1. INTRODUCTION

Agriculture remains one of the largest consumers of freshwater resources worldwide. Irrigated agriculture accounts for approximately 70 percent of global freshwater withdrawals and plays a critical role in ensuring food security, supporting rural livelihoods and sustaining economic development. In Malaysia, irrigation systems are particularly important for paddy cultivation, which forms the backbone of the national rice industry. Rice is the staple food for the Malaysian population and remains a strategic commodity under the National Agrofood Policy 2021–2030 (NAP 2.0), which seeks to strengthen food security through modernization and technological transformation of the agrofood sector.

Malaysia's paddy production system relies heavily on irrigation infrastructure developed over several decades. Major granary areas including MADA, KADA, IADA Kerian, IADA Seberang Perak, IADA Barat Laut Selangor and other integrated agricultural development areas support double-cropping systems and contribute substantially to national rice production. These irrigation schemes were designed to ensure stable water supplies, improve farmer incomes and reduce dependence on imported rice.

Despite substantial investments in irrigation infrastructure, several challenges continue to affect irrigation performance. Many irrigation schemes experience conveyance losses, aging infrastructure, sedimentation, inefficient water distribution and limited operational flexibility. Recent assessments have revealed relatively low irrigation efficiency in some schemes. For example, the IADA Seberang Perak irrigation system recorded irrigation efficiency of only 22.14 percent and a water productivity index of 0.30 kg/m³, highlighting substantial opportunities for improvement.

Climate variability further compounds these challenges. The impacts of climate change are increasingly evident through changing rainfall patterns, higher temperatures, prolonged droughts and more frequent extreme weather events. These changes affect water availability, crop water requirements and irrigation scheduling. The Water Sector Transformation 2040 (WST2040) report identifies climate change as one of the most significant threats to water security in Malaysia and emphasizes the need for adaptation strategies to strengthen resilience.

Enhancing water use efficiency has therefore become a critical priority. Water use efficiency refers to the ability to maximize agricultural output while minimizing water consumption and losses. Improvements in irrigation efficiency can contribute directly to increased productivity, reduced operational costs, improved environmental sustainability and enhanced resilience to climate variability. This paper aims to review irrigation water use efficiency in Malaysia from a multi-scale perspective and identify pathways for improving irrigation performance under future climate conditions. Specific objectives are to:

1. Examine the status of irrigation systems and water use efficiency in Malaysia
2. Assess climate variability impacts on irrigation performance and water productivity
3. Evaluate emerging technologies and management approaches for improving water use efficiency
4. Propose a multi-scale climate-resilient framework for sustainable irrigation development.

2. LITERATURE REVIEW

2.1 *Water Use Efficiency and Irrigation Performance*

Water use efficiency is widely recognized as a key indicator of irrigation performance and agricultural sustainability. Traditional irrigation efficiency metrics focus on the proportion of water delivered to crops relative to water diverted from sources. However, modern approaches increasingly emphasize beneficial water consumption, water productivity and integrated water management.

Reinders (2022) argues that irrigation efficiency should be evaluated through a water balance framework encompassing water sources, conveyance systems, irrigation schemes and farm-level operations. Under this framework, the objective is to maximize beneficial water use while minimizing non-beneficial losses. The study highlights that efficient irrigation requires water to be delivered in the correct quantity, at the appropriate time and with minimal losses throughout the system.

Water productivity is closely linked to water use efficiency and is generally expressed as crop yield per unit volume of water consumed. Higher water productivity indicates more effective utilization of water resources and is increasingly used to evaluate irrigation performance under water-scarce conditions.

2.2 *Climate Change and Agricultural Water Resources*

Climate change poses significant risks to agricultural water management. Rising temperatures, altered precipitation patterns and increasing frequency of extreme events influence both water supply and crop water demand. In tropical regions such as Malaysia, shifts in monsoon behavior and rainfall variability can significantly affect irrigation scheduling and reservoir operations.

Studies reviewed in the WST2040 Climate Change Impact and Adaptation report indicate that climate-related risks to water resources are expected to intensify under future warming scenarios. These risks include increased drought frequency, greater flood occurrence, changes in river flows and challenges to reservoir reliability. For irrigated agriculture, climate variability may result in increased uncertainty regarding planting schedules, water allocation and crop productivity. Adaptive management approaches are therefore essential to maintain irrigation performance and food security.

2.3 *Climate Water Productivity under Climate Variability*

Recent research has examined how climate change may influence agricultural water productivity. A study conducted in the Northwest Selangor Rice Irrigation Scheme utilized the FAO AquaCrop model to evaluate future climate impacts on irrigated rice production. Results indicated that actual crop evapotranspiration may decrease by approximately 10 percent in future climate scenarios, while water productivity may increase by 14–29 percent depending on management conditions and emissions scenarios. These findings suggest that adaptive irrigation strategies could potentially offset some adverse climate impacts and improve resource efficiency.

2.4 *Emerging Irrigation Technologies*

Technological innovations provide new opportunities to improve water use efficiency. Recent reviews emphasize the potential of smart irrigation systems incorporating sensors, automation, weather forecasting and remote monitoring. These systems enable more precise water application and support adaptive management under variable climatic conditions.

Evapotranspiration-based irrigation scheduling has demonstrated particular promise. Research on oil palm nurseries found that irrigation based on actual evapotranspiration achieved higher water use efficiency than fixed irrigation schedules, suggesting broader applicability across agricultural systems.

3. METHODOLOGY

This study adopts a qualitative and quantitative review approach to synthesize information from multiple sources relevant to irrigation performance and climate adaptation in Malaysia. The methodology consists of four analytical scales: national, river basin, irrigation scheme and farm levels.

At the national scale, agricultural statistics, policy documents and sectoral reports are reviewed to assess irrigation development trends, food security priorities and water resource challenges. Particular attention is given to the National Agrofood Policy 2021–2030 and Agrofood Statistics reports. At the river basin scale, climate adaptation and water resource management studies are examined to understand basin-level vulnerabilities and adaptation requirements.

At the irrigation scheme scale, performance assessments from major granary areas including Seberang Perak, Kerian and Northwest Selangor are analyzed. Indicators include irrigation efficiency, water productivity, infrastructure condition and climate sensitivity. At the farm scale, studies evaluating irrigation scheduling, evapotranspiration management and precision irrigation technologies are reviewed to identify practical interventions for improving water use efficiency.

The review further integrates findings from climate modeling studies, water balance assessments and technology evaluations to develop a climate-resilient framework for irrigation management. The framework emphasizes integration across scales, recognizing that irrigation efficiency is influenced by interactions between policy, infrastructure, institutional arrangements and on-farm practices.

4. MALAYSIAN IRRIGATION LANDSCAPE AND GRANARY SYSTEMS

Malaysia's irrigated agriculture sector has evolved significantly since the 1960s through large-scale investments in irrigation infrastructure, rural development, and agricultural modernization. Irrigation development was primarily driven by the need to improve rice self-sufficiency, increase farmer incomes, and reduce rural poverty. Today, irrigation remains fundamental to national food security, particularly for paddy production.

The country's paddy cultivation system is concentrated within designated granary areas. These granaries receive priority support in terms of irrigation infrastructure, agricultural services, mechanization, and government assistance programs. According to the Ministry of Agriculture and Food Security, granary areas contribute the majority of Malaysia's domestic rice production and remain central to national food security objectives.

4.1. Major Irrigation and Granary Areas

Malaysia currently maintains eight major granary regions:

Table 1. Major Granary Areas in Malaysia

Granary Area	State(s)	Approximate Area (ha)	Main Water Source
MADA	Kedah, Perlis	96,000	Muda River
KADA	Kelantan	26,000	Kelantan River
IADA Kerian	Perak	24,000	Bukit Merah Reservoir
IADA Seberang Perak	Perak	8,500	Sungai Perak
IADA Barat Laut Selangor (NSRIS)	Selangor	18,000	Tengi River System
IADA Pulau Pinang	Penang	12,000	Local Rivers
KETARA	Terengganu	15,000	Terengganu River
IADA Kemasin Semarak	Kelantan	9,000	Kemasin Basin

The largest irrigation authority, MADA, manages approximately 96,000 hectares and contributes nearly 40% of Malaysia's rice production. MADA is often regarded as the country's most advanced irrigation system due to continuous modernization efforts and relatively higher operational efficiency.

However, many irrigation schemes continue to face challenges related to aging infrastructure, canal seepage, inadequate maintenance, sedimentation, and inefficient water allocation. These challenges become increasingly significant under climate variability.

4.2. National Paddy Production and Food Security

Rice remains strategically important because it constitutes the primary staple food for Malaysia's population. National food security targets emphasize maintaining adequate domestic rice production while reducing vulnerability to international market disruptions.

The National Agrofood Policy 2021–2030 highlights the need to increase productivity, improve resource efficiency, and enhance climate resilience across the agro food sector. The policy identifies technological modernization and smart agriculture as critical enablers of future food security. Despite government support, rice self-sufficiency remains challenged by increasing production costs, limited land expansion opportunities, labor shortages, and water management constraints. Climate variability further complicates these issues by increasing uncertainty in water availability and crop performance.



Figure 1. Relationship between Irrigation Performance and Food Security

The figure illustrates how irrigation performance directly influences agricultural productivity and national food security outcomes.

5. RESULTS AND DISCUSSION

5.1 Irrigation Efficiency Assessment

Irrigation efficiency remains one of the most important indicators of irrigation system performance. Efficient irrigation systems maximize beneficial water use while minimizing losses associated with conveyance, seepage, evaporation, and operational inefficiencies.

Recent assessments of irrigation schemes in Malaysia reveal substantial variation in performance levels. The case study of IADA Seberang Perak provides an important example. The scheme recorded irrigation efficiency of only 22.14 percent and a Water Productivity Index (WPI) of 0.30 kg/m³. Such values indicate significant losses occurring throughout the water delivery system. Major contributing

factors include canal deterioration, sediment accumulation, degraded control structures, and delays in water distribution.

Although approximately 65 percent of irrigation canals have been upgraded to concrete-lined channels, tertiary distribution systems remain vulnerable to inefficiencies. The study concluded that considerable opportunities exist to improve irrigation performance through infrastructure modernization and improved operational management.

Table 2. Comparison of Irrigation Performance

Indicator	FAO Benchmark	Seberang Perak
Irrigation Efficiency (%)	>60	22.14
Water Productivity (kg/m ³)	>1.0	0.30
Canal Condition	Good	Moderate
Climate Resilience	High	Moderate-Low

The comparison demonstrates a substantial gap between current performance and international best practices.

5.2 Water Productivity under Climate Change Efficiency Assessment

Water productivity has emerged as a critical metric for evaluating agricultural sustainability. Unlike conventional efficiency measures, water productivity directly links crop production with water consumption.

The Aqua Crop study conducted within the Northwest Selangor Rice Irrigation Scheme provides valuable insights into future climate impacts. The research utilized downscaled climate projections under RCP4.5, RCP6.0 and RCP8.5 scenarios to evaluate future water productivity trends. Results indicated that actual crop evapotranspiration could decrease by approximately 10 percent under future climatic conditions. Simultaneously, water productivity could increase significantly depending on management practices.

Projected increases include:

- (a). WPIrr+RF : 14–24%
- (b). WPIrr : 14–19%
- (c). WPETc : 17–29%

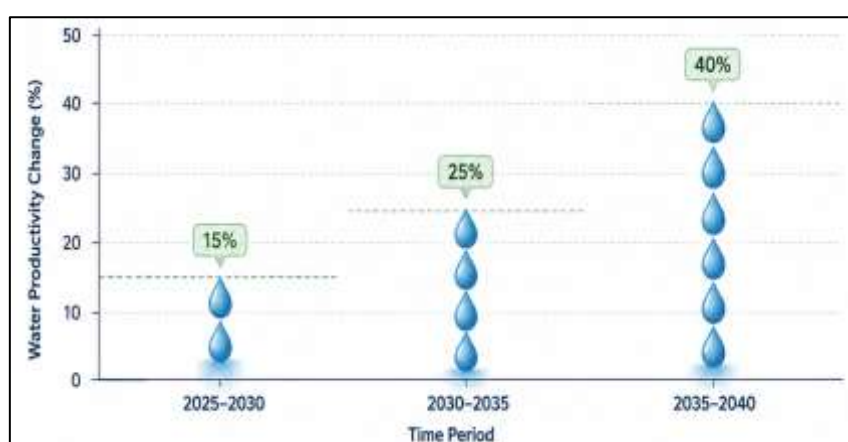


Figure 2. Projected Water Productivity Changes

Percentage increase under climate adaptation scenarios.

5.3 Climate Risks to Irrigation Systems

Climate change affects irrigation systems through multiple pathways:

(a). Drought Risk

Extended dry periods reduce river flows, reservoir storage and groundwater recharge. Water shortages can disrupt irrigation schedules and reduce crop yields.

(b). Flood Risk

Extreme rainfall events damage irrigation infrastructure, inundate agricultural land and increase sedimentation within canals.

(c). Temperature Increases

Higher temperatures increase evapotranspiration and alter crop water requirements.

(d). Water Quality Degradation

Climate variability can exacerbate water quality problems, including nutrient loading, algae growth and salinity intrusion.

The Water Sector Transformation 2040 report identifies climate adaptation as a critical component of future water resource planning. Integrated adaptation strategies are required to reduce vulnerability and improve resilience.

Table 3. Major Climate Risks Affecting Irrigation

Climate Hazard	Impact on Irrigation	Risk Level
Drought	Water shortage	High
Flooding	Infrastructure damage	High
Heat Stress	Increased water demand	Medium
Salinity Intrusion	Reduced water quality	Medium
Extreme Rainfall	Canal instability	High

These findings suggest that climate change does not necessarily lead to lower water productivity if adaptive management practices are implemented effectively.

5.4 Climate Risks to Irrigation Systems

Recent technological developments offer substantial opportunities for improving water use efficiency such as:-

(a). Evapotranspiration-Based Irrigation

Research demonstrates that irrigation scheduling based on actual evapotranspiration achieves higher water use efficiency than fixed irrigation schedules. ET-based irrigation ensures that water applications correspond closely with crop requirements, reducing waste and improving productivity.

(b). Smart Irrigation Systems

Smart irrigation systems integrate:

- Weather forecasting
- Soil moisture sensors
- Automated control systems
- Remote monitoring
- Decision support tools

These technologies enable real-time irrigation management and adaptive responses to changing climatic conditions.

(c). Remote Sensing

Satellite imagery and drone technologies provide accurate information regarding crop health, water stress and irrigation performance. These tools support precision agriculture and improve decision-making.

(d). Automated Canal Operations

Automation of gates and control structures can improve water distribution efficiency, reduce labor requirements and minimize operational losses.



Figure 3. Smart Irrigation System Architecture

5.5 Lessons from IADA Kerian

The recent IADA Kerian agricultural water resource management study highlights several emerging challenges facing Malaysian irrigation systems. These include increasing competition for water resources, changing land use patterns, climate variability, water quality concerns and infrastructure maintenance requirements.

The study emphasizes the need for integrated water resource management approaches that combine:

- (a). Hydrological assessment
- (b). Water balance analysis
- (c). Infrastructure modernization
- (d). Stakeholder participation
- (e). Climate adaptation planning

Kerian serves as an example of how future irrigation systems must evolve beyond traditional engineering approaches and incorporate broader environmental and socio-economic considerations.

5.5 Multi-Scale Analysis

Analysis of Malaysian irrigation systems indicates that irrigation efficiency is influenced by factors operating at multiple scales.

1. At the national scale, policy frameworks determine investment priorities and food security targets.
2. At the basin scale, water allocation and climate impacts influence water availability.
3. At the scheme scale, infrastructure conditions and operational management affect delivery efficiency.
4. At the farm scale, irrigation scheduling and technology adoption determine actual water productivity.

These interactions highlight the importance of adopting integrated and multi-scale approaches to irrigation management.

6 CLIMATE-RESILIENT IRRIGATION FRAMEWORK FOR MALAYSIA

The findings of this review demonstrate that improving irrigation efficiency in Malaysia requires more than infrastructure upgrades alone. Climate variability, increasing water competition, changing agricultural practices and technological advancements necessitate a holistic and integrated approach. A climate-resilient irrigation framework should therefore combine engineering, management, policy, institutional and technological interventions across multiple scales. The proposed framework is based on four interconnected levels: national, river basin, irrigation scheme, and farm scales. These levels interact dynamically and collectively determine irrigation performance, water productivity and climate resilience.



Figure 4. Multi-Scale Climate-Resilient Irrigation Framework

The framework recognizes that interventions at a single scale are insufficient. For example, farm-level adoption of precision irrigation may yield limited benefits if basin-level water allocation remains inefficient or if irrigation infrastructure is incapable of delivering water reliably.

6.1 Multi-Scale Analysis

At the national scale, policy and governance provide the foundation for long-term irrigation sustainability. The National Agrofood Policy 2021–2030 identifies modernization, smart agriculture, sustainability, and food security as strategic priorities. The policy emphasizes technology adoption, productivity enhancement, and climate adaptation within the agrofood sector. Future national interventions should focus on:

(a). Climate-Smart Irrigation Policy

Development of a dedicated climate-smart irrigation policy incorporating:

- Climate risk assessments
- Drought management protocols
- Water productivity targets
- Digital irrigation standards

(b). National Irrigation Performance Benchmarking

Establishment of standardized performance indicators:

- Irrigation efficiency
- Water productivity
- Infrastructure condition
- Carbon footprint
- Climate resilience

(c). Digital Irrigation Transformation

National implementation of:

- IoT monitoring networks
- Remote sensing platforms
- National irrigation databases
- AI-assisted decision support systems

These initiatives align closely with Water Sector Transformation 2040 objectives.

6.2 River Basin-Level Interventions

River basins form the hydrological foundation of irrigation systems.

Climate change increasingly affects:

- River flows
- Reservoir storage
- Groundwater recharge
- Water quality

Integrated River Basin Management (IRBM) should therefore become a central component of future irrigation planning.

Recommended actions include:

(a). Basin Water Accounting

Implementation of comprehensive water accounting systems that quantify:

- Water availability
- Agricultural demand
- Environmental flow requirements
- Future climate impacts

(b). Reservoir Optimization

Use of climate-informed reservoir operation models to improve:

- Drought preparedness
- Flood mitigation
- Irrigation reliability

(c). Climate Forecast Integration

Seasonal climate forecasts should be incorporated into irrigation planning.

Benefits include:

- Improved planting schedules
- Better water allocation decisions
- Reduced drought vulnerability

6.3 Irrigation Scheme-Level Interventions

Most irrigation losses occur at scheme level due to conveyance inefficiencies, operational shortcomings and aging infrastructure.

Recent assessments of Seberang Perak and Kerian indicate substantial opportunities for performance improvement through modernization and operational optimization.

Recommended interventions include:

(a). Canal Modernization

Priority should be given to:

- Canal lining
- Leakage reduction
- Sediment management
- Infrastructure rehabilitation

(b). Automated Water Control

Automation technologies can significantly improve delivery efficiency through:

- Automated gates
- Remote monitoring
- Real-time flow regulation

(c). Digital Twins

Future irrigation schemes should adopt digital twin technologies that simulate:

- Canal hydraulics
- Water demand
- Climate impacts
- Operational scenarios

Digital twins enable proactive management and optimization.

6.4 Farm-Level Interventions

The farm scale ultimately determines actual water productivity.

Recommended interventions include:

(a). Alternate Wetting and Drying (AWD)

AWD has demonstrated substantial water savings in paddy cultivation while maintaining yields.

Potential benefits include:

- 20–30% water savings
- Reduced methane emissions
- Improved water productivity

(b). Evapotranspiration-Based Irrigation

Studies demonstrate that ET-based irrigation scheduling improves water use efficiency compared with fixed irrigation schedules.

Precision Agriculture

Technologies include:

- Soil moisture sensors
- Drone monitoring
- Satellite imagery
- Variable-rate irrigation

These approaches optimize water application and reduce wastage.

Table 4. Recommended Adaptation Technologies

Technology	Water Saving Potential	Readiness Level
Alternate Wetting and Drying	High	High
ET-Based Irrigation	High	High
IoT Sensors	Medium-High	Medium
Remote Sensing	Medium	High
Automated Gates	Medium	High
AI Decision Support	Medium-High	Emerging
Digital Twin Systems	High	Emerging

7. NATIONAL ROADMAP FOR IRRIGATION TRANSFORMATION (2025–2050)

A phased implementation roadmap is proposed as follows:

Phase I: Foundation (2025–2030)

Objectives:

- Strengthen monitoring systems
- Improve water accounting
- Upgrade critical infrastructure

Targets:

- Irrigation efficiency >40%
- 50% digital monitoring coverage
- Pilot smart irrigation projects

Phase II: Expansion (2030–2040)

Objectives:

- Scale smart irrigation technologies
- Integrate climate forecasting
- Strengthen basin-level management

Targets:

- Irrigation efficiency >50%
- Water productivity >0.8 kg/m³
- Full climate forecasting integration

Phase III: Transformation (2040–2050)

Objectives:

- Achieve climate-resilient irrigation systems
- Implement digital irrigation ecosystems

Targets:

- Irrigation efficiency >60%
- Water productivity >1.0 kg/m³
- Nationwide smart irrigation coverage

8. POLICY IMPLICATIONS

The proposed framework supports several national and international policy objectives.

1. National Agrofood Policy 2.0

The framework contributes directly to:

- Food security enhancement
- Smart agriculture adoption
- Productivity improvement
- Sustainable resource management

2. Water Sector Transformation 2040

The framework addresses:

- Climate adaptation
- Data-driven governance
- Infrastructure resilience
- Sustainable water management

3. Sustainable Development Goals

The framework supports:

- SDG 2 (Zero Hunger)
- SDG 6 (Clean Water and Sanitation)
- SDG 9 (Industry, Innovation and Infrastructure)
- SDG 13 (Climate Action)

Table 5. Policy Alignment Matrix

Recommendation	NAP 2.0	WST2040	SDG 2	SDG 6	SDG 13
Smart Irrigation	✓	✓	✓	✓	✓
Climate Forecasting	✓	✓	✓	✓	✓
Automation	✓	✓	✓	✓	-
AWD Adoption	✓	-	✓	✓	✓
Basin Management	-	✓	✓	✓	✓

CONCLUSIONS

This study reviewed irrigation water use efficiency and climate adaptation challenges across Malaysian irrigation systems using a multi-scale perspective encompassing national, basin, irrigation scheme, and farm levels. The review revealed that irrigation efficiency remains below international benchmarks in several major irrigation schemes. The case of IADA Seberang Perak, with irrigation efficiency of only 22.14% and water productivity of 0.30 kg/m³, illustrates the magnitude of current inefficiencies. Simultaneously, climate variability is increasing uncertainty in water availability, irrigation scheduling, and agricultural productivity. Climate modelling studies indicate that adaptive management can significantly improve future water productivity despite increasing climatic pressures. Smart irrigation systems, evapotranspiration-based scheduling, automation, remote sensing, and precision agriculture represent promising pathways toward enhanced irrigation performance.

The proposed climate-resilient irrigation framework emphasizes integration across national, basin, scheme, and farm scales. Such integration is essential for achieving long-term water security, improving food production, and strengthening resilience under changing climatic conditions. Future investments should prioritize infrastructure modernization, digital transformation, climate-informed water management, and capacity building. By adopting these measures, Malaysia can significantly enhance irrigation efficiency, improve water productivity, and support national food security objectives through 2050 and beyond.

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