

A MULTI-SCALE ASSESSMENT OF IRRIGATION GOVERNANCE AND SMART ALLOCATION MECHANISMS FOR ENHANCING WATER USE EFFICIENCY UNDER CLIMATE VARIABILITY IN MALAYSIA

UNE ÉVALUATION A ECHELLE MULTIPLE DE LA GOUVERNANCE DE L'IRRIGATION ET DES MÉCANISMES D'ALLOCATION INTELLIGENTE POUR AMÉLIORER L'EFFICACITÉ DE L'UTILISATION DE L'EAU FACE À LA VARIABILITÉ CLIMATIQUE EN MALAISIE

Y. Hj Mohd Sani ¹, M.A.A. Jamaari²

ABSTRACT

Water security and agricultural sustainability have become increasingly interconnected policy concerns as climate variability intensifies across Southeast Asia. In Malaysia, irrigated paddy cultivation remains central to national food security strategies, yet the sector faces growing pressure from competing water demands, aging irrigation infrastructure, institutional fragmentation, and increasing hydrological uncertainty. Although the country receives abundant annual rainfall, temporal and spatial variability in water availability continues to affect irrigation reliability, particularly within major granary areas that account for most domestic rice production. Simultaneously, Malaysia's rice self-sufficiency ratio (SSR) has remained below strategic national targets despite decades of investment in irrigation infrastructure and agricultural modernization.

This paper critically examines irrigation governance and smart water allocation mechanisms through a multi-scale analytical framework encompassing national, basin, irrigation-scheme, and farm-level dimensions. A systematic review methodology was employed, synthesizing evidence from peer-reviewed literature, government policies, irrigation master plans, climate adaptation studies, and recent agricultural water management reports. Particular emphasis is placed on evaluating institutional arrangements, governance effectiveness, technological innovation, and climate resilience within Malaysia's irrigation sector.

The analysis demonstrates that while Malaysia has established a relatively comprehensive policy framework for integrated water resources management, significant governance challenges remain. Fragmented institutional responsibilities, limited integration of climate information into operational decision-making, inadequate data interoperability, and constrained stakeholder participation continue to reduce water allocation efficiency. The findings further indicate that smart irrigation technologies, digital water accounting systems, remote sensing platforms, and adaptive governance arrangements offer substantial opportunities to improve water productivity while strengthening resilience to climate variability.

The paper proposes a Smart Multi-Scale Irrigation Governance Framework that integrates climate-informed decision-making, digital technologies, participatory governance, and adaptive water allocation mechanisms. The framework contributes to current debates on irrigation modernization by demonstrating that governance reform and technological innovation must progress simultaneously if Malaysia is to achieve long-term water security, agricultural productivity, and food system resilience. The proposed framework is further aligned with the Kuala Lumpur Joint Declaration on Irrigation and Infrastructure for Food Security (2025), which recognizes irrigation modernization, climate-smart

¹ Ministry of Agriculture and Food Security, Division of Irrigation and Agriculture Drainage, Putrajaya, Malaysia, mail: yuslina@water.gov.my

² Ministry of Agriculture and Food Security, Division of Irrigation and Agriculture Drainage, Putrajaya, Malaysia Email: aliifaimran@water.gov.my

technologies, integrated water resources management (IWRM), and strengthened stakeholder participation as essential pillars for achieving resilient food systems under climate change.

Keywords: Irrigation governance, climate variability, water use efficiency, smart irrigation, rice self-sufficiency, adaptive governance, Malaysia.

RESUME

La sécurité de l'eau et la durabilité agricole sont devenues des préoccupations politiques de plus en plus interconnectées à mesure que la variabilité climatique s'intensifie dans toute l'Asie du sud-est. En Malaisie, la riziculture irriguée reste au cœur des stratégies nationales de sécurité alimentaire, mais le secteur est confronté à une pression croissante en raison de la concurrence des demandes en eau, du vieillissement des infrastructures d'irrigation, de la fragmentation institutionnelle et de l'incertitude hydrologique croissante. Bien que le pays reçoive des précipitations annuelles abondantes, la variabilité temporelle et spatiale de la disponibilité en eau continue d'affecter la fiabilité de l'irrigation, en particulier dans les principales zones de greniers qui représentent la partie majeure de la production nationale de riz. Simultanément, le taux d'autosuffisance de la Malaisie en riz (SSR) est resté inférieur aux objectifs stratégiques nationaux malgré des décennies d'investissements dans les infrastructures d'irrigation et la modernisation agricole.

Cet article examine de manière critique la gouvernance de l'irrigation et les mécanismes d'allocation intelligente de l'eau à travers un cadre analytique à échelle multiple englobant les dimensions nationales, de bassin, de périmètre irrigué et d'exploitation agricole. Une méthodologie de d'analyse systématique a été utilisée, synthétisant les preuves issues de la littérature évaluée par des pairs, des politiques gouvernementales, des plans directeurs d'irrigation, des études d'adaptation au climat et des rapports récents sur la gestion de l'eau en agriculture. Un accent particulier est mis sur l'évaluation des dispositifs institutionnels, de l'efficacité de la gouvernance, de l'innovation technologique et de la résistance climatique au sein du secteur de l'irrigation malaisien.

L'analyse démontre que, malgré la mise en place par la Malaisie d'un cadre politique relativement complet pour la gestion intégrée des ressources en eau, d'importants défis de gouvernance persistent. La fragmentation des responsabilités institutionnelles, l'intégration limitée des informations climatiques dans la prise de décision opérationnelle, l'interopérabilité insuffisante des données et la participation restreinte des parties prenantes continuent de réduire l'efficacité de l'allocation de l'eau. Les résultats indiquent en outre que les technologies d'irrigation intelligentes, les systèmes numériques de comptabilité de l'eau, les plateformes de télédétection et les dispositifs de gouvernance adaptative offrent des opportunités substantielles pour améliorer la productivité de l'eau tout en renforçant la résistance à la variabilité climatique.

Le document propose un cadre de gouvernance d'irrigation à échelle multiple intelligent qui intègre la prise de décision éclairée par le climat, les technologies numériques, la gouvernance participative et des mécanismes adaptatifs d'allocation de l'eau. Le cadre contribue aux débats actuels sur la modernisation de l'irrigation en démontrant que la réforme de la gouvernance et l'innovation technologique doivent progresser simultanément pour que la Malaisie puisse atteindre la sécurité hydrique à long terme, la productivité agricole et la résistance du système alimentaire. Le cadre proposé est en outre aligné sur la Déclaration conjointe de Kuala Lumpur sur l'irrigation et les infrastructures de la sécurité alimentaire (2025), qui reconnaît la modernisation de l'irrigation, les technologies intelligentes face au climat et la gestion intégrée des ressources en eau (GIRE), et a renforcé la participation des parties prenantes en tant que piliers essentiels pour parvenir à des systèmes alimentaires résistants dans le cadre du changement climatique.

Mots-clés : Gouvernance de l'irrigation; Variabilité climatique; Efficacité de l'utilisation de l'eau; Irrigation intelligente; Autosuffisance en riz; Gouvernance adaptative; Malaisie.

1. INTRODUCTION

Water resources management has emerged as one of the most pressing development challenges of the twenty-first century. Rapid population growth, urbanization, industrial expansion, environmental degradation, and climate change are exerting unprecedented pressure on freshwater systems worldwide. Agriculture remains the largest consumer of freshwater resources, accounting for approximately 70% of global withdrawals and exceeding 80% in many developing economies. Consequently, the future sustainability of food production systems depends largely on the ability of governments and water managers to improve water use efficiency while simultaneously enhancing resilience to climatic uncertainty.

Historically, irrigation development focused primarily on engineering solutions designed to increase water supply through reservoirs, canals, diversion structures, and conveyance networks. While such investments substantially increased agricultural productivity during the Green Revolution, growing evidence suggests that infrastructure alone is insufficient to address contemporary water challenges. Increasingly, attention has shifted toward governance arrangements that determine how water is allocated, managed, monitored, and distributed among competing users.

Recent international experience demonstrates that governance quality often has a greater influence on irrigation performance than infrastructure investment alone. Countries such as Australia, Spain, Israel, and China have achieved significant improvements in water productivity through the integration of digital technologies, adaptive management approaches, stakeholder participation, and climate-informed decision-making. These developments have stimulated renewed interest in Integrated Water Resources Management (IWRM), adaptive governance frameworks, and smart water allocation systems capable of responding dynamically to changing environmental conditions.

The growing recognition that water governance influences agricultural productivity, environmental sustainability, and economic development has led to its incorporation within Sustainable Development Goal 6, which emphasizes integrated management of water resources at all levels. However, translating these principles into operational reality remains a significant challenge, particularly in countries where institutional responsibilities are fragmented across multiple agencies and administrative scales.

1.1 Malaysian Context

Malaysia occupies a unique position within the global water security landscape. Despite receiving annual rainfall ranging between 2,500 mm and 3,000 mm, the country continues to experience localized water shortages, periodic droughts, and increasing competition among agricultural, domestic, industrial, and environmental water users. This apparent paradox reflects the fact that water availability is influenced not only by total precipitation but also by temporal distribution, storage capacity, institutional effectiveness, and governance arrangements.

Rice remains the most strategically important food crop in Malaysia and occupies a central role in national food security policy. National paddy cultivation covers more than 600,000 hectares, producing approximately two million metric tonnes of paddy annually. Nevertheless, domestic production has not been sufficient to meet total national demand, resulting in continued reliance on rice imports. According to recent agricultural statistics, Malaysia's rice self-sufficiency ratio has fluctuated between approximately 56% and 70% over the last decade, highlighting persistent structural challenges within the sector.

The majority of domestic rice production originates from a limited number of irrigated granary areas include:

- (a). MADA (Muda Agricultural Development Authority)
- (b). KADA (Kemubu Agricultural Development Authority)
- (c). IADA Kerian

- (d). IADA Barat Laut Selangor
- (e). IADA Ketara
- (f). IADA Seberang Perak

These granaries represent strategic national assets because they contribute disproportionately to domestic rice supply while supporting thousands of farming households. Their continued productivity depends heavily on reliable irrigation services and effective water allocation systems.

The National Agrofood Policy 2021–2030 (NAP 2.0) identifies irrigation modernization, climate resilience, digital agriculture, and sustainable resource management as critical priorities for strengthening food security and improving agricultural competitiveness. Similarly, the Water Sector Transformation 2040 (WST2040) initiative emphasizes the importance of integrated water governance, technological innovation, and data-driven decision-making in addressing future water challenges. Together, these policy frameworks reflect growing recognition that irrigation modernization must extend beyond infrastructure rehabilitation toward broader institutional transformation.

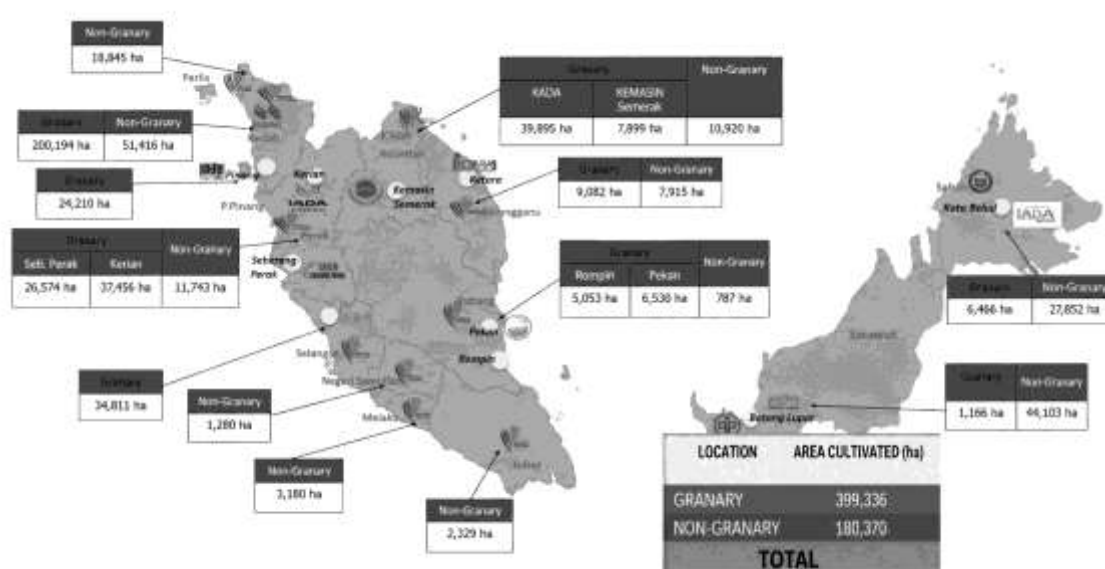


Figure 1. Granary and Non - Granary Areas in Malaysia

1.2 Emerging Global Commitment Towards Irrigation Modernization

Recent international policy developments further reinforce the urgency of irrigation transformation. During the Third High-Level Advisory Group (HLAG) Meeting of the International Commission on Irrigation and Drainage (ICID) held in Kuala Lumpur in September 2025, member countries adopted the Kuala Lumpur Joint Declaration on Irrigation and Infrastructure for Food Security. The declaration recognizes that climate change, aging irrigation infrastructure, water scarcity, and increasing food demand represent interconnected threats to global food security and emphasizes that modernization of irrigation systems guided by Integrated Water Resources Management (IWRM) principles is indispensable for ensuring sustainable agricultural production.

The declaration is particularly relevant to Malaysia because it explicitly highlights many of the challenges currently confronting the national irrigation sector, including deteriorating infrastructure, growing competition for water resources, and the need for climate-resilient agricultural systems. It further advocates the adoption of water-efficient technologies, digital innovations, public–private partnerships, and participatory water management approaches that closely align with the objectives of the National Agrofood Policy 2021–2030 and Water Sector Transformation 2040.

1.3 Problem Statement

Although Malaysia possesses relatively abundant water resources, irrigation performance remains constrained by institutional fragmentation, aging infrastructure, insufficient real-time monitoring and weak integration between climate information and operational decision-making.

Governance responsibilities are distributed among federal agencies, state governments, irrigation authorities, river basin organizations and local users. This multi-layered governance structure frequently results in coordination challenges, delayed decision-making and inconsistent water allocation practices. Previous studies have highlighted governance weaknesses including overlapping jurisdictions, inadequate stakeholder participation and limited data sharing among institutions.

Climate variability further complicates irrigation management by increasing uncertainty regarding water availability during critical cropping periods.

1.4 Research Objectives

This study aims to:

- (a). Review the current state of irrigation governance and water allocation in Malaysia.
- (b). Assess governance challenges across multiple spatial and institutional scales.
- (c). Examine emerging smart irrigation and water allocation technologies.
- (d). Identify gaps in existing governance frameworks.

2. LITERATURE REVIEW

2.1 Evolution of Irrigation Governance

The concept of irrigation governance has evolved considerably over the past four decades. Early approaches were primarily concerned with the design, construction, and operation of hydraulic infrastructure. Success was generally measured through engineering indicators such as canal efficiency, irrigated area coverage, and water delivery reliability. While these metrics remain important, contemporary scholarship increasingly recognizes that irrigation performance is fundamentally shaped by institutional arrangements, stakeholder interactions, and governance processes.

This shift reflects growing awareness that water allocation decisions involve complex trade-offs among economic, social, environmental, and political objectives. As a result, irrigation governance is now commonly understood as the set of formal and informal institutions, policies, rules, and relationships that influence how water resources are managed and distributed among competing users.

The emergence of Integrated Water Resources Management (IWRM) represented a significant milestone in this evolution. Developed through international policy dialogues during the 1990s, IWRM advocates coordinated management of water, land, and related resources in ways that maximize economic and social welfare without compromising environmental sustainability. The framework emphasizes integration across sectors, administrative boundaries, and stakeholder groups while promoting participatory decision-making and adaptive management.

Malaysia formally adopted many IWRM principles through national water policies and strategic plans. However, implementation challenges persist due to institutional fragmentation, differing administrative capacities among states, and the complexity of coordinating multiple agencies with overlapping responsibilities. Recent assessments suggest that while policy commitment remains strong, operational integration continues to lag behind strategic aspirations.

2.2 Theoretical Perspectives on Smart Irrigation Governance

Contemporary irrigation governance literature increasingly draws upon adaptive governance theory, socio-ecological systems thinking, and the water-energy-food nexus framework. Adaptive governance is particularly relevant under conditions of climatic uncertainty because it emphasizes flexibility, learning, experimentation, and institutional responsiveness. Rather than relying on fixed allocation rules, adaptive systems continuously adjust management strategies based on new information and changing environmental conditions.

The water-energy-food nexus perspective further highlights the interconnected nature of resource management challenges. Agricultural production depends on water and energy inputs, while water management itself often requires significant energy resources. Decisions affecting one sector therefore have important implications for others. The nexus framework has gained increasing prominence within Malaysian policy discussions, particularly through WST2040 and related sustainability initiatives.

Simultaneously, advances in digital technology are transforming possibilities for irrigation management. Remote sensing, Internet of Things (IoT) sensors, automated control systems, cloud-based platforms, and artificial intelligence are enabling unprecedented levels of monitoring, forecasting, and decision support. These technologies form the foundation of what is increasingly described as “smart irrigation governance,” whereby data-driven systems support more adaptive and efficient water allocation decisions.

2.3 Knowledge Gap

While there is substantial literature on the hydrological impacts of climate change in Malaysia, there is a distinct lack of interdisciplinary research bridging financial governance (budget allocations) with operational technology (smart allocation mechanisms). The mechanisms through which national-level policies translate into flexible, decentralized decision-making for Water User Groups (WUGs) remain inadequately modeled.

Table 1. Summary Literature on Irrigation Governance and Smart Water Allocation

Author(s) / Policy Document	Core Theme / Focus Area	Key Findings and Practical Implications	Identified Knowledge Gaps / Challenges
Zulkafli et al. (2017); N. W. Chan (2009)	Institutional Challenges & Irrigation Governance	Malaysia's water vulnerabilities stem largely from fragmented, top-down governance and mismanagement rather than absolute physical water scarcity. Traditional centralized, “supply-driven” governance frameworks are proving insufficient for equitable water distribution under emerging climate pressures.	Lack of coordination between government agencies, political interference, and inadequate inclusion of local stakeholders (e.g., NGOs and civil society) hinder holistic water management.
Rasviah Md. Khalid (2018)	Water Security & Demand Management vs. Supply Management	Recurrent water stress and droughts (exacerbated by climate change) require an urgent shift in management approaches. Recommends transitioning from traditional Water Supply Management (WSM)—such as building dams—to proactive Water Demand Management (WDM).	Bureaucratic friction persists due to jurisdictional divisions between federal and state governments over water resources, complicating holistic river basin management and tariff restructuring.

Rowshon et al. (2019); Alam et al. (2020)	Smart Irrigation Systems & Water Productivity	Transitioning from conventional to smart irrigation systems significantly improves water productivity in Malaysian rice granaries. Scenario-based simulations indicate that real-time monitoring and automated systems can improve Water Use Efficiency (WUE) by up to 25–35% .	Misaligned budgeting and rigid, top-down decision-making limit the adoption of smart irrigation technologies. High adoption barriers remain for local paddy farmers.
Grigg (2024); Global Water Partnership (GWP) (2000)	Integrated Water Resources Management (IWRM) Frameworks	IWRM promotes coordinated development of water, land, and related resources to maximize social and economic welfare without compromising ecosystems. It serves both as a governance framework and a practical process for multi-objective problem solving.	Global implementation of IWRM remains slow, often constrained by vague definitions, disconnects between policy and practice, and difficulties integrating socio-economic needs into management decisions.
WST2040; NAP 2.0 (2021–2030); NWRP (2012)	Strategic Modernization & Industrial Revolution 4.0 (IR 4.0)	National strategies advocate transforming the water and agriculture sectors through IR 4.0 technologies, precision water-demand management, and data integration to ensure long-term food and water security.	Significant technological deficits remain at the local level. For example, 86.2% of paddy farmers in granary areas use machinery valued at less than RM10,000 , highlighting a substantial gap between national policy ambitions and on-the-ground farming realities.

3. METHODOLOGY

This study employs a systematic literature review and policy analysis approach. The methodology integrates academic literature, government reports, irrigation studies, and policy documents to evaluate irrigation governance across multiple scales.

Databases and Sources Used The analysis integrates empirical data and policy directives from:

- Governmental Blueprints:** Water Sector Transformation 2040 (WST2040), National Agrofood Policy 2021-2030 (NAP 2.0) and the National Water Resources Policy (NWRP).
- Institutional Reports:** Department of Irrigation and Drainage (DID) Malaysia, National Hydraulic Research Institute of Malaysia (NAHRIM) and the Ministry of Agriculture and Food Security (MAFS).
- Academic Literature:** Scopus-indexed research focusing on IWRM, irrigation governance and climate change adaptation in Southeast Asia.

Analytical Framework The study utilizes a Multi-Scale Institutional Analysis framework, assessing the water sector across three levels:

Contemporary international discourse increasingly views irrigation modernization as a governance challenge rather than solely an engineering issue. The Kuala Lumpur Joint Declaration adopted by ICID member countries in 2025 explicitly recognizes irrigation infrastructure, climate-smart technologies, and integrated water governance as mutually reinforcing components of food security and climate resilience. This position supports emerging literature arguing that future gains in agricultural water productivity will depend on institutional innovation and governance reform as much as physical infrastructure investment.



Figure 2. Simplified Analytical Framework

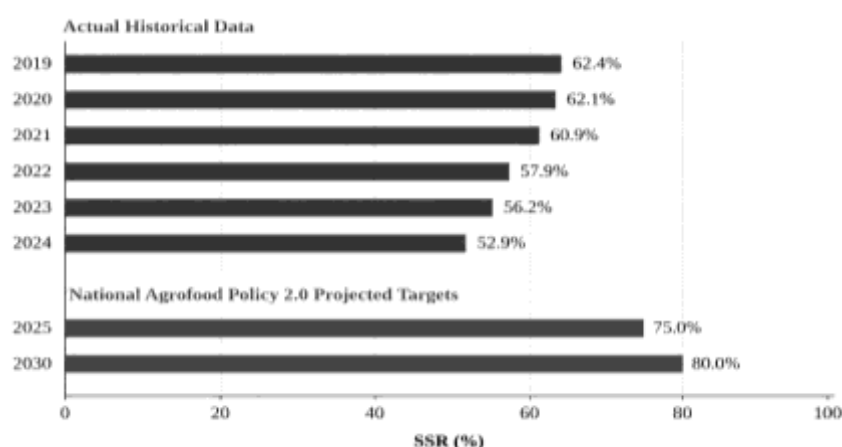


Figure 3. Self-Sufficiency Ratio (SSR) for Rice in Malaysia

The figure illustrates persistent fluctuations in rice self-sufficiency despite continued investment in irrigation infrastructure.

4. RESULTS AND DISCUSSION

4.1 Multi-Scale Assessment of Irrigation Governance in Malaysia

The analysis reveals that irrigation governance in Malaysia is characterized by a highly interconnected but institutionally fragmented system that spans multiple administrative and operational scales. While this structure has enabled the successful development of extensive irrigation infrastructure supporting national rice production, increasing climate variability and competing water demands have exposed weaknesses in coordination, data integration, and adaptive decision-making.

At the national level, irrigation development is guided by a range of policy instruments including the National Agrofood Policy 2021–2030 (NAP 2.0), the National Water Resources Policy, and the Water Sector Transformation 2040 agenda. Collectively, these frameworks emphasize food security,

sustainable water management, digital transformation, and climate resilience. However, policy coherence does not always translate into operational integration. Responsibilities for irrigation, water resources, river basin management, environmental protection, and agricultural development remain distributed across numerous federal and state institutions, creating overlapping mandates and fragmented accountability structures. Previous studies on Malaysian water governance have consistently identified institutional fragmentation as a major constraint to effective water management.

The challenge becomes particularly evident at the basin scale, where water allocation increasingly involves balancing agricultural requirements with domestic consumption, industrial development, ecosystem protection, and flood management. Although Integrated Water Resources Management (IWRM) principles have been adopted within national policy frameworks, implementation remains uneven across river basins. Differences in institutional capacity, financial resources, and political priorities among states often result in varying levels of effectiveness.

At the irrigation-scheme level, authorities such as MADA, KADA, IADA Kerian, Barat Laut Selangor, Seberang Perak, and KETARA have historically focused on maintaining reliable water deliveries for paddy cultivation. These organizations have accumulated substantial technical expertise and have contributed significantly to national rice production. Nevertheless, many schemes continue to operate using allocation procedures developed under assumptions of relatively stable hydrological conditions. Climate variability, increasing demand, and aging infrastructure are placing these systems under growing stress.

Recent investigations undertaken within IADA Kerian provide valuable insights into emerging governance challenges. The study identified increasing pressure on water resources due to changing climatic conditions, industrial expansion, water quality concerns, and competing demands across sectors. Importantly, the findings emphasized the need for integrated water balance modelling, stakeholder engagement, climate adaptation planning, and improved operational coordination.

At the farm level, irrigation management remains largely dependent on centralized delivery schedules. While Water User Groups (WUGs) and Kumpulan Pengguna Air (KPA) have been established in several irrigation schemes, their influence on strategic allocation decisions remains limited. Consequently, opportunities for localized adaptation and collaborative water management are not fully realized.

Table 2. Multi-Scale Governance Assessment of Malaysian Irrigation Systems

Governance Level	Existing Strengths	Key Constraints	Strategic Priority
National	Strong policy commitment and investment support	Fragmented institutional mandates	Governance integration
Basin	Increasing adoption of IWRM principles	Inter-state coordination challenges	Climate-responsive allocation
Irrigation Scheme	Established operational institutions	Aging infrastructure and rigid allocation systems	Digital modernization
Farm	Existing farmer organizations	Limited participation in decision-making	Participatory governance

4.2 Climate Variability and Emerging Water Allocation Challenges

Climate variability represents one of the most significant threats to the long-term sustainability of irrigated agriculture in Malaysia. Although the country is generally regarded as water-rich, the distribution of rainfall is becoming increasingly unpredictable. Variations in the timing, intensity, and duration of rainfall events have important implications for reservoir operations, river flows, irrigation scheduling, and

crop productivity.

The effects of climate variability are already visible across several major granary areas. Prolonged dry periods associated with El Niño events have periodically reduced reservoir inflows and increased irrigation demand during critical crop growth stages. At the same time, extreme rainfall events and flooding have disrupted agricultural operations, damaged infrastructure, and complicated water management planning. Climate projections indicate that these challenges are likely to intensify over coming decades.

Traditional irrigation allocation systems are often based on predetermined schedules and historical hydrological records. Such approaches assume a degree of predictability that is increasingly absent under contemporary climatic conditions. As a result, irrigation authorities frequently face situations in which allocation plans become misaligned with actual water availability.

This mismatch underscores the importance of adaptive allocation mechanisms capable of incorporating real-time hydrological information, seasonal climate forecasts, and dynamic demand assessments. Rather than relying solely on infrastructure expansion to address future water challenges, governance systems must become more flexible, data-driven, and responsive to changing environmental conditions.

4.3 Irrigation Modernization and Water Use Efficiency

One of the most significant findings emerging from recent international and Malaysian studies is that improvements in water use efficiency (WUE) depend not only on technological innovation but also on governance effectiveness. Modern irrigation systems increasingly integrate digital technologies such as remote sensing, automated gates, telemetry systems, Internet of Things (IoT) sensors, and decision-support platforms. These technologies enable irrigation managers to monitor water availability, crop requirements, and system performance with unprecedented accuracy.

The concept of water productivity has become particularly important in this context. Rather than maximizing water deliveries, contemporary irrigation management seeks to maximize agricultural output per unit of water consumed. This shift represents a fundamental transition from supply-oriented management toward efficiency-oriented management.

Malaysia's modernization agenda reflects this evolution. Both NAP 2.0 and WST2040 emphasize digital transformation, precision agriculture, and smart infrastructure as key pillars of future agricultural development. These initiatives recognize that future food security objectives cannot be achieved solely through increasing cultivated area or expanding water withdrawals. Instead, productivity gains must increasingly originate from more efficient resource utilization.

International evidence suggests that smart irrigation technologies can reduce water consumption by between 15% and 35% while maintaining or improving yields. Similar gains are potentially achievable within Malaysian irrigation schemes, particularly in areas where water losses, operational inefficiencies, and outdated control systems remain prevalent.

Yield (t/ha)

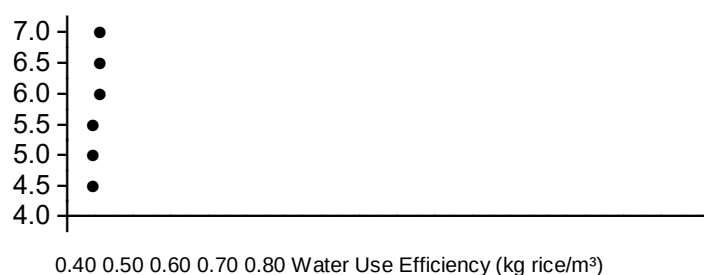


Figure 4. Relationship Between Paddy Yield and Water Use Efficiency in Malaysia (2019–2024)

Figure illustrates the positive relationship between improvements in water use efficiency and paddy productivity observed across irrigated systems undergoing modernization. The relationship suggests that water conservation and productivity enhancement should not be viewed as competing objectives. Instead, they are increasingly complementary outcomes of effective irrigation governance and technological innovation.

4.4 Comparative International Experiences and Lessons for Malaysia

Experiences from other countries demonstrate that governance reform and technological modernization are most effective when implemented simultaneously. Australia's Murray–Darling Basin, for example, has pioneered the use of digital water accounting, market-based allocation systems, and basin-scale planning mechanisms that improve transparency and operational efficiency. Similarly, Spain's irrigation modernization programmes have successfully combined infrastructure upgrades with automated control systems and farmer participation mechanisms.

China has invested heavily in smart irrigation technologies, including remote sensing platforms, artificial intelligence, and precision water delivery systems. These initiatives have generated substantial improvements in agricultural water productivity while reducing pressure on freshwater resources.

The common lesson across these cases is that technology alone does not guarantee success. Instead, effective outcomes emerge when technological innovation is supported by strong institutions, clear accountability structures, stakeholder engagement, and adaptive governance arrangements.

For Malaysia, this implies that future irrigation modernization efforts should place equal emphasis on governance reform and technological investment. The effectiveness of smart irrigation systems will depend heavily on the institutional environments within which they operate. Figure illustrates the positive relationship between improvements in water use efficiency and paddy productivity observed across irrigated systems undergoing modernization. The relationship suggests that water conservation and productivity enhancement should not be viewed as competing objectives. Instead, they are increasingly complementary outcomes of effective irrigation governance and technological innovation.

4.5 Governance Network Analysis

The review highlights the importance of understanding irrigation governance as a network rather than a hierarchy. Water allocation decisions are influenced by interactions among ministries, state governments, river basin organizations, irrigation authorities, farmer organizations, and individual farmers. Consequently, improving system performance requires strengthening communication, coordination, and information exchange across institutional boundaries.

4.6 Proposed Framework: Multi-Scale Smart Allocation and Governance (MS-SAG)

To bridge the identified gaps, this paper proposes the Multi-Scale Smart Allocation and Governance (MS-SAG) framework. This conceptual model aligns federal budgeting with micro-level technological adoption to enhance WUE.

1. Macro Level: National Governance & Finance

At the highest tier, national policy establishes the fiscal and strategic architecture to drive structural reform:

- Performance-Linked Budgeting (Federal to State): Financial allocations from the federal government to state entities are tied directly to measurable water management benchmarks, ensuring accountability and fiscal efficiency.
- Strategic Policy Integration: Aligning national objectives by integrating the Water Sector Transformation 2040 (WST2040) blueprint—which leverages Fourth Industrial Revolution (IR

4.0) technologies—with the targets set under the National Agrofood Policy 2.0 (NAP 2.0).

2. Meso Level: State & Basin Management

The intermediate tier operationalizes national policy by managing resources at the regional and ecosystem level:

- **Institutional Oversight:** Executed by State Water Management Authorities, such as the Lembaga Urus Air Selangor (LUAS), to regulate and monitor basin-level water distribution.
- **Cross-Sectoral Nexus Planning:** Implementing a holistic Water-Food-Energy (WFE) nexus approach to minimize resource conflicts and maximize cross-sectoral synergies.
- **Decentralized Financial Subsidies:** Facilitating agrotech adoption through decentralized grant disbursement mechanisms, allowing localized funding for modern agricultural infrastructure.
- **Micro Level: Smart Allocation & Operations**
- The localized tier focuses on field-level execution, community empowerment, and real-time automated infrastructure:
- **Community Empowerment:** Strengthening Water User Groups (WUGs) to foster localized ownership, participatory management, and equitable distribution among farmers.
- **Data-Driven Agriculture:** Deploying Internet of Things (IoT) sensors to capture real-time soil moisture profiles and localized weather data for informed decision-making.
- **Precision Infrastructure:** Utilizing automated gate systems that dynamically adjust water flow based on real-time crop water requirements, minimizing tailwater losses.

The convergence of these macro, meso, and micro-level interventions is engineered to deliver high-impact results

Table 3. Target Outcome

Objective	Target Impact
Water Use Efficiency (WUE)	Realization of a 25–35% increase in water use efficiency across managed irrigation systems through improved allocation, monitoring, and smart irrigation technologies.
Climate Resilience	Enhanced capacity to mitigate and adapt to extreme climate events, particularly droughts and prolonged flooding, ensuring more reliable water availability for agriculture.
Agricultural Sustainability	Maintenance and safeguarding of the Self-Sufficiency Level (SSL) for staple crops, contributing to long-term national food security and sustainable agricultural production.

5. CONCLUSION

This study has examined irrigation governance and smart water allocation mechanisms through a multi-scale analytical framework encompassing national, basin, irrigation-scheme, and farm-level dimensions. The analysis demonstrates that climate variability, competing water demands, aging infrastructure, and institutional fragmentation are reshaping the challenges facing Malaysia's irrigation sector.

Although Malaysia has developed a comprehensive policy framework supporting sustainable water management and agricultural modernization, governance weaknesses continue to constrain operational performance. Existing allocation systems were largely designed for more predictable hydrological conditions and are increasingly challenged by climatic uncertainty. Consequently, future improvements in irrigation performance will depend not only on infrastructure investment but also on institutional adaptation.

The evidence reviewed in this study indicates that smart irrigation technologies, climate-informed decision-support systems, digital monitoring platforms, and participatory governance arrangements offer significant opportunities to enhance water use efficiency while strengthening resilience. However,

technological innovation alone is insufficient. Lasting improvements require complementary governance reforms that improve coordination, transparency, accountability, and stakeholder engagement.

The proposed Smart Multi-Scale Irrigation Governance Framework provides a pathway for integrating these elements within a coherent management approach. By linking climate intelligence, digital technologies, adaptive governance, and stakeholder participation, the framework offers a practical strategy for addressing emerging water challenges while supporting national food security objectives.

The significance of these findings extends beyond Malaysia's national context. The recommendations developed in this study directly support the commitments endorsed by ICID member countries through the Kuala Lumpur Joint Declaration on Irrigation and Infrastructure for Food Security. By promoting irrigation modernization, climate-smart water management, participatory governance, and integrated resource planning, Malaysia has the opportunity to position itself as a regional leader in climate-resilient irrigation development and sustainable food production.

As Malaysia advances toward the goals articulated in the National Agrofood Policy 2021–2030 and Water Sector Transformation 2040, irrigation governance will play an increasingly important role in determining the sustainability and resilience of the agricultural sector. The future of rice production will therefore depend not only on how much water is available, but also on how effectively that water is governed, allocated, and utilized under conditions of growing uncertainty.

REFERENCES

- Alam, M. M., Siwar, C., Murad, M. W., & Toriman, M. E. (2020). Climate change adaptation and water management in agricultural systems: Emerging challenges and opportunities. *Agricultural Water Management*, 228, 105892.
- Food and Agriculture Organization. (2017). *Water for sustainable food and agriculture*. FAO.
- Food and Agriculture Organization. (2023). *The state of the world's land and water resources for food and agriculture: Systems at breaking point*. FAO.
- Global Water Partnership. (2000). *Integrated water resources management (TAC Background Paper No. 4)*. Global Water Partnership.
- Grigg, N. S. (2024). Framework and function of integrated water resources management in support of sustainable development. *Sustainability*, 16(13), 5441. <https://doi.org/10.3390/su16135441>
- International Commission on Irrigation and Drainage. (2025). *Kuala Lumpur Joint Declaration on Irrigation and Infrastructure for Food Security*. 3rd High-Level Advisory Group (HLAG) Meeting, Kuala Lumpur, Malaysia, September 8, 2025. International Commission on Irrigation and Drainage.
- International Commission on Irrigation and Drainage. (2026). *A multi-scale assessment of irrigation governance and smart allocation mechanisms for enhancing water use efficiency under climate variability in Malaysia (ICID 2026 Abstract No. 289)*. ICID 2026 Conference Proceedings.
- Khalid, R. M. (2018). Review of the water supply management and reforms needed to ensure water security in Malaysia. *International Journal of Business and Society*, 19(S3), 472–483.
- Ministry of Agriculture and Food Industries. (2021). *National Agrofood Policy 2021–2030 (NAP 2.0): Agrofood modernisation safeguarding the future of national food security*. Ministry of Agriculture and Food Industries, Malaysia.
- Ministry of Agriculture and Food Security. (2025). *Perangkaan agromakanan Malaysia 2024*. Policy and Strategic Planning Division, Ministry of Agriculture and Food Security, Malaysia.
- Ministry of Agriculture and Food Security. (2025). *Kajian pengurusan sumber air pertanian di skim pengairan dan saliran IADA Kerian, Perak: Final report (Volume I)*. Bahagian Pengairan dan Saliran Pertanian (BPSP), Ministry of Agriculture and Food Security, Malaysia.
- Ministry of Agriculture and Food Security. (2025). *Cadangan kerja-kerja menaiktaraf infrastruktur pengairan di kawasan penanaman padi dalam dan luar jelapang di seluruh negara*. Bahagian Pengairan dan Saliran Pertanian (BPSP), Ministry of Agriculture and Food Security, Malaysia.
- National Water and Climate Development Programme. (2019). *Development of national water and climate development programme (WACDEP Malaysia Report)*. Universiti Putra Malaysia.
- United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations.
- UN-Water. (2024). *Summary progress update 2024: SDG 6—Water and sanitation for all*. United Nations.

- Van der Zaag, P., & Savenije, H. H. G. (2015). Principles of integrated water resources management. UNESCO-IHE Institute for Water Education.
- Water Sector Transformation 2040 Secretariat. (2022). Water Sector Transformation 2040 (WST2040): Executive summary. Government of Malaysia.
- Chan, N. W. (2009). Issues and challenges in water governance in Malaysia. *Iranian Journal of Environmental Health Science & Engineering*, 6(3), 143–152.
- Sukereman, A. S., & Suratman, R. (2014). A review on integrated water resource management (IWRM) in Malaysia. In *Proceedings of the International Graduate Conference on Engineering, Science and Humanities (IGCESH 2014)*, Universiti Teknologi Malaysia, Johor Bahru, Malaysia.