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Tropical Climate Effects on Sustainable Water Supply, Demand, and Hydro-Economics: A Review

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ABSTRACT. As tropical regions face intensifying climatic shifts, the traditional management of water resources is becoming increasingly inadequate. In Malaysia, the transition from an agrarian economy to a high-technology industrial hub has significantly elevated the economic value of water security. This review explores the integration of the Modern Hydro-Economic Model (HEM) as a proposed strategic framework to navigate the complexities of water supply and demand within a tropical climate framework from 2000 to 2025, with a forward-looking application pathway toward 2026. Following the PRISMA 2020 guidelines, 1,240 records were identified; after duplicate removal, title/abstract screening, and full-text eligibility assessment, 310 studies were included. The systematic review synthesizes hydrological data (precipitation and recharge) with socio-economic indicators (GDP per m³ and operational expenditure). The review provides a proposed Modern HEM framework that would use optimization algorithms to balance ecosystem equilibrium with industrial and domestic requirements. The review identifies a critical shift in Malaysia's water portfolio, moving toward Conjunctive Use (rivers, TAPS, and groundwater) to mitigate "Economic Shutdown" risks. The synthesized literature indicates that as urbanization degrades river quality, the marginal cost of treatment rises, making alternative groundwater sources economically viable. Furthermore, the reviewed evidence suggests that the economic impact of water shortages in 2024 is substantially higher than in 2000 due to the growth of water-intensive tech sectors. The study concludes that a Modern HEM may provide a useful decision-support framework, subject to future empirical implementation and validation, for tropical water sustainability. It is intended to translate climatic uncertainty into predictable economic strategies, supporting resilience of Malaysia's water-energy-food nexus against future environmental shifts.

Keywords: *Hydro-economics, Tropical climate, Water security, Optimization modelling, Sustainable water management*

1. INTRODUCTION

Tropical climate change is increasingly recognized by many countries as a major factor affecting water resource sustainability, water demand and supply, and hydro-economic dynamics in countries with hot and humid climates such as Malaysia, Indonesia, Thailand, and Singapore. Although tropical regions generally receive substantial annual rainfall, increasingly erratic precipitation patterns, prolonged droughts, intense storms, and rising temperatures have significantly altered their hydrological balance over the past two decades (Nimma et al., 2025; Ab Rashid, Abd Rahman and Abdul Rashid, 2024). According to the latest report by United Nations World Water Assessment Programme (WWAP, 2024), tropical countries will see an increase in water demand of 30 – 40 % by 2035 due to population growth, industrialization, and land-use change. At the same time, climate uncertainty is occurring unnoticed and it is expected to reduce natural water storage capacity, affect river flows, and alter groundwater recharge, thus creating a gap between water supply and demand. This phenomenon not only affects the availability

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of surface and groundwater, it also affects the efficiency of water supply infrastructure, economic productivity, and the cost of national water management.

The conceptual framework in Figure 1 shows how tropical climate change is driven by a major factor, namely the increase in greenhouse gas emissions for every year, which has a major impact on the global hydrological cycle. This climate change has included variation in rainfall patterns, increased severity of drought and floods, higher evapotranspiration rates and direct deterioration in water quality that has affected accessibility of groundwater and freshwater resources (Bolan et al., 2024). These changes will impact key sectors in the country that rely on water as a critical resource such as (i) agriculture, (ii) energy, (iii) ecosystems, and (iv) domestic use.

In Asian nations like Malaysia, Indonesia, Thailand and Singapore, agriculture is a key sector due to its reliance on access to sufficient water resources. One of the major issues caused by climate change is limiting water supply, which in turn, limits productivity in agriculture and compromises food security. In the energy industry, for example, shifts in the flow of the rivers could impact the generation of hydroelectric power and reliability of energy. Meanwhile, for natural ecosystems, these changes will disrupt the water cycle, habitats, and natural biodiversity. For domestic use, the decline in water quality and availability threatens public health and the well – being of the global community. The interaction of these has emphasized the urgent need for adaptation approaches such as Integrated Water Resources Management (IWRM), Sustainable Land Use Practices (SLP), and Climate Resilient Policies (CRP) (Wicaksono et al., 2024). This framework will further link climate change, modern hydrological variability, water resources, sectoral dependencies and modern adaptive governance policies to ensure long-term resilience in the Global Economic Hydrological System (GEHS) with tropical climates especially for Malaysia, Indonesia, Thailand, and Singapore.

Under tropical climates, high rainfall intensity often leads to the risk of flooding, river overflow and soil erosion, while longer dry seasons cause droughts, depletion of dam levels and stress on Water Treatment System (WTS) (Ab Rashid et al., 2024). In general, water is the main medium through which climate change is felt, with changing precipitation regimes, increased evapotranspiration, and more frequent extreme events altering the hydrological balance worldwide. Global water withdrawals have tripled in the past 50 years, now exceeding 4600 km³ per year, with agriculture accounting for about 69% of global use, industry 19%, and urbanization 12% (WWAP, 2024; Zhu, Hou, and Wei, 2024). The combination of population growth, urbanization, and industrial expansion is further increasing pressure on water resources, particularly in developing regions that are already vulnerable to resource scarcity and variability.

The implications of climate change also have a direct impact on hydro-economics – the relationship between water resources, economic value, management costs, and government policy decisions. Water supply instability leads to increased production cost, disruption of industrial supply chains, and pressure on water tariffs and the national budget (Ismail & Al-Amin, 2021). For example, Malaysia has faced several water supply disruptions in Selangor, Kedah, and Kelantan due to pollution of raw water resources and reduced dam capacity during extreme summers (SPAN,

2014; SPAN, 2008–2023). These challenges demonstrate that water-related problems are not merely technical but also have significant implications for economic development. Furthermore, the impact of tropical climate on water resources is increasingly complex due to anthropogenic factors such as rapid urbanization, land exploration, intensive agricultural activities, and the release of pollutants into rivers and lakes (Bolan et al., 2024). Rapidly growing urban areas increase the “urban heat island” phenomena, change micro – rainfall patterns, and accelerate evapotranspiration rates, thus reducing the ability of soil to store water. This adds further pressure on water catchment systems and hydrological infrastructure.

Since various climatic, human and economic factors interact in tropical water crises, there is a need for a comprehensive review to elucidate the relationships between climate change, water-supply sustainability, domestic and industrial demand, and hydro-economics of the region, reducing bias in economic evaluation, allocation and water-resource management. Researchers have taken the approach of using hydro-economic analysis by providing tools such as optimization models, computable general equilibrium (CGE) model, econometric demand functions, and cost-benefit assessments to support policies (Bouzidi & Dionisio, 2025; Hossen, 2021; Harou et al., 2009) towards solutions to tropical water crises involving these interactions. However, many of these frameworks are still poorly integrated with non-stationary climate dynamics, fail to reflect extreme events, socio – political constraints, and regional inequalities. This gap limits the ability of such models to guide adaptive water governance, especially in areas increasingly vulnerable to droughts, floods, and water quality degradation. Therefore, the integration of climate – hydrological models with hydro-economics frameworks is needed to address uncertainty, fairness, and trade – off between sectors.

This review paper aims to synthesize the latest evidence on the impacts of climate change on water supply and demand, critically assess its integration into hydro-economics, and develop a conceptual framework that links climate drivers, hydrological changes, demand responses, and economic exchanges. This study provides a systematic review of 310 included records from 2000–2024 and proposes research and policy priorities to advance climate-resilient water governance and presents strategic directions for more sustainable water management.

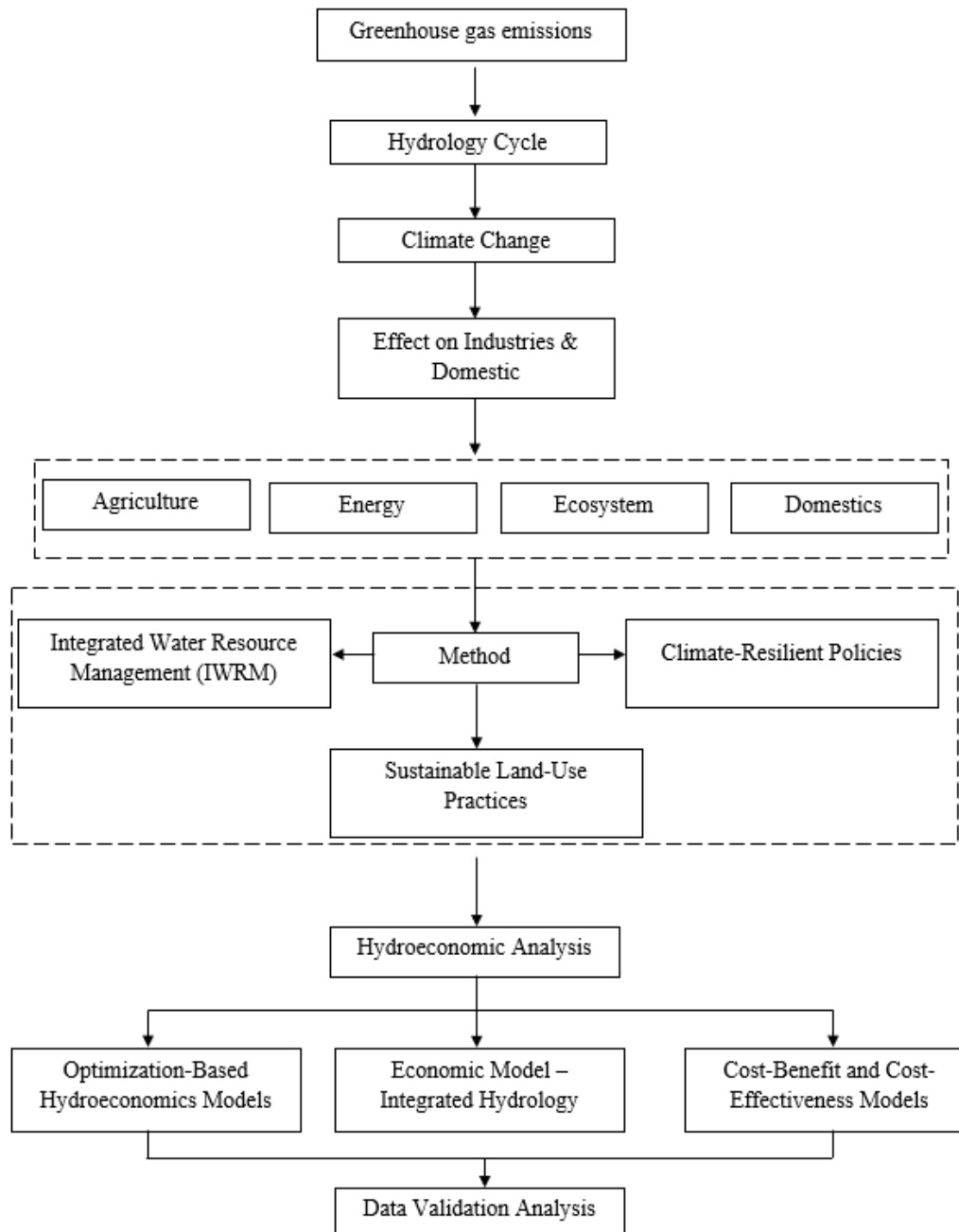


Figure 1. Conceptual framework of tropical climate effects sustainable water supply, demand, and hydro-economics.

2. METHODOLOGY

This study used a systematic review methodology based on the PRISMA 2020 guidelines. Four major databases: Scopus, Web of Science, ScienceDirect, and Google Scholar; were searched for the period 2000–2024. The terms were linked across the three main themes: climate change, water supply/water demand, and hydro-economics, with combinations of “climate change”, “water supply”, “water demand”, “hydro-economic”, and “adaptation”. The review followed four PRISMA stages: identification, screening, eligibility, and inclusion. During identification, 1,240 records were retrieved. After removing 420 duplicates, 820 records remained for title and abstract screening. A further 410 records were excluded because they did not address the climate–water–economics relationship, leaving 410 full-text reports for eligibility assessment. Full texts were assessed against the following criteria: refereed publication,

English language, publication during 2000–2024, and an explicit focus on water supply, water demand, or hydro-economics under climate change. This step excluded 100 articles that did not provide sufficient methodological clarity or climate–economic integration. The final systematic-review sample therefore comprised 29 studies, which were coded according to hydrological focus (e.g., aquifers, soils, and surface water), demand sector (agriculture, energy, and domestic), economic method (optimization, CGE, econometrics), and adaptation strategy (including water pricing, infrastructure, and governance reform). Studies published in 2025 cited elsewhere in the manuscript were used as supplementary contextual literature, but they are not included in the 310-study PRISMA sample. Figure 2 presents the detailed study-selection flow.

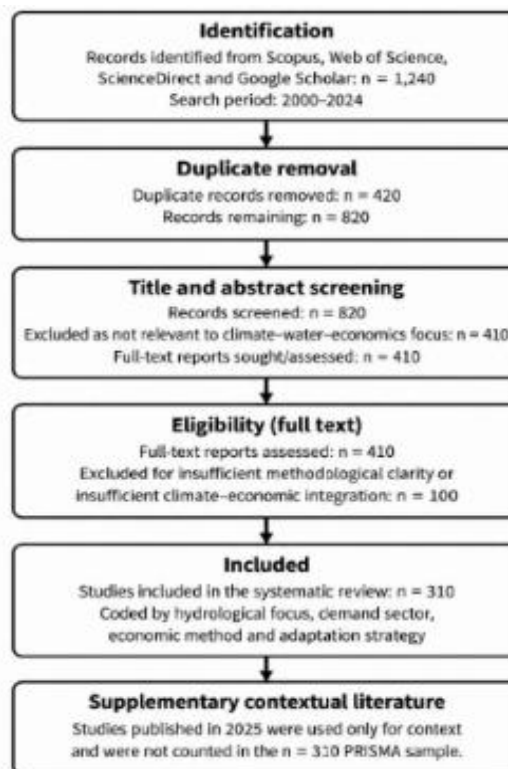


Figure 2. PRISMA 2020 study-selection flow diagram, showing the reported screening counts.

3. RESULTS AND DISCUSSION

The review shows continued growth in this field over the past two decades, with a significant increase after 2010, in line with increased international attention to climate change and water security. Geographically, most studies are concentrated in Asia and North America, while research from Africa and small island states remains limited despite their high vulnerability to global climate impacts. In terms of sector coverage, agriculture accounted for more than half of all studies, followed by the domestic water-supply and energy sectors. From a hydrological perspective, surface water systems were the focus, while soil and surface water–groundwater interactions were underrepresented in the PRISMA 2020 review. Thus, this imbalance further highlights regional and thematic gaps that require more focused attention for future research. Table 1 presents selected studies from the 310 studies included through PRISMA 2020, linking geographical focus to dominant themes and methodological choices in the study area especially tropical climatic effect in sustaining water supply, demand, and hydro-economics.

The reviewed literature also indicates that research has grown steadily over the past two decades with a surge after 2010. As stated in the explanation above, Asian and North American countries remain the most studied regions, while African countries and small island states receive less attention. Additionally, more studies combining economics and hydrology are required in Asian nations, particularly Malaysia, Indonesia, Thailand and Singapore, where the use of agricultural water resources is important. The agricultural sector is the main sector in these countries especially in Malaysia, followed by domestic supply and energy. Meanwhile, groundwater and integrated systems studies have received less attention and need to be pursued with new economic modeling studies on water, agriculture, energy, and land.

In South Asia, the dual challenges of groundwater management and increasing agricultural water demand under climate change have been studied through the integration of satellite observations (GRACE) using hydrological modeling. According to Shamsudduha and Taylor (2020), GRACE-derived groundwater storage anomalies are used to monitor groundwater dynamics in major aquifer systems. This has revealed a pattern of ongoing depletion and significant spatial heterogeneity in storage decline. This finding has important hydro-economic implications such as groundwater depletion affects irrigation costs, inter-sectoral water allocation, and the long-term sustainability of agricultural livelihoods. By linking physical evidence of groundwater stress to the economic dimensions of resource scarcity and allocation, such studies provide an important basis for policy interventions in balancing water security, agricultural productivity, and climate resilience.

A South Asian study on groundwater resilience using the Mapping Groundwater Resilience to Climate Change and Human Development in Asian Cities method (Neupane et al., 2023), is also relevant. The study combines climate change projections (through RCP scenarios), urbanization/land-use change, and groundwater abstraction to model future groundwater recharge and levels in cities such as Bangkok, Lahore, Kathmandu, and Ho Chi Minh City. Findings from this study show that peri-urban or less developed areas are likely to maintain or increase groundwater recharge under moderate development, while inner-city areas experience groundwater depletion and loss of resilience under high levels of urbanization and warming. The study also introduces a resilience metric that measures the percentage of recovery relative to depletion and maps the most vulnerable zones, thus offering policy guidance on where interventions are most critical.

In Sub-Saharan Africa, water-related research has largely focused on rainfed agriculture, reflecting the high dependence of rural communities on rainfall for their livelihoods. Studies in the region have mostly been based on case studies and household-level analyses, which provide insights into local realities and adaptation practices (Schroeter et al., 2025; Thomas and Nanteza, 2023). However, these approaches have had a micro-scale impact that has not translated into broader impacts. In contrast, studies in North America have been shaped by the importance of hydropower and irrigation. Both of these methods are used for energy security and agricultural productivity. Researchers in this field often use computable general equilibrium (CGE) models to capture macroeconomic relationships and simulate underlying outcomes for new findings. While providing a broader economic picture, these approaches sometimes ignore local diversity and nuances (Levizzani and Cattani, 2019; Grogan et al., 2022).

In Europe, research has focused more on flood risk and governance, reflecting the historical impact of floods and the strength of established research institutions. Research methods in this region using risk assessment and scenario modelling dominate the field. Nevertheless, technical risk analysis does not automatically translate into effective governance action (European Commission, 2024). In East Asia, reflecting the pressures of rapid urbanization with increasing domestic and industrial water demand, research priorities have emerged. Econometric studies in this region have yielded empirical evidence of the elasticity of demand and consumption patterns (Müller and Levy, 2019). However, such a quantitative focus may ignore the deeper sociopolitical dynamics that influence water allocation.

Table 1 highlights not only differences in regional vulnerability but also different methodological biases. Local case studies provide depth of analysis, while large-scale economic and statistical models offer breadth. Looking ahead, a more integrated approach, combining econometric rigor with a governance perspective, and linking scenario modeling with participatory field evidence, could provide a more comprehensive understanding of the multi-scale water challenges driven by climate change. Therefore, new studies should focus more on Malaysia, Indonesia, Thailand, and Singapore by integrating new research frameworks for economic hydrology modeling of the Asian region in these countries for the future.

Table 1. Selected studies across regions, research focuses, and methods; 2025 sources provide supplementary context. Note: Literature from 2025 is discussed as supplementary contextual evidence and is not included in the formal 2000–2024 PRISMA sample (n = 310).

Region	Focus	Methods	Study
South Asia	Groundwater & Agriculture	GRACE, Modeling	Shamsudduha and Taylor, (2020)
Sub-Saharan Africa	Rainfed Vulnerability	Case Studies	Schroeter <i>et al.</i> , 2025; Thomas and Nanteza, 2023
North America	Hydropower & Irrigation	Hydrological Models	Levizzani & Cattani, 2019; Grogan <i>et al.</i> , 2022
Europe	Flood Risk & Governance	Risk Assessment	European Commission, 2024
East Asia	Urban Demand	Econometrics	Müller and Levy, 2019
Malaysia	River, Groundwater, Freshwater	Hydro-Economics Model & Optimization	Proposed Modern HEM framework (future empirical validation)

Future research in Malaysia should prioritize the development of an integrated hydro-economic optimization model (HEM) that incorporates surface-water and groundwater resources. The proposed model would combine hydrological parameters, such as river discharge and groundwater recharge, with economic variables, including water-supply costs, sectoral demand, and the economic value of water. This integrated approach could support sustainable water allocation and inform national water-management policies under changing tropical climatic conditions. This proposed HEM optimization approach is intended for future empirical testing because it is for efficient distribution, conjunctive use and environmental sustainability. The purpose of using HEM is to change the narrative of more modern methods and models from finding new water supplies to managing existing supplies in the most valuable way in terms of water economics and environmental ecosystems. The HEM model is composed of five main phases: (i) data input / data

preparation, (ii) integration module / hydrology and economic model, (iii) optimization core, (iv) output phase / optimal mitigation strategy, and (v) decision and policy support.

The first phase of the proposed HEM framework involves collecting and preparing hydrological and socioeconomic data. Hydrological inputs include river discharge, precipitation patterns, and groundwater recharge rates. Meanwhile, in socio-economic data, the information collected is infrastructure costs, water demand by sector, and the economic value of each cubic meter of water used. The second phase involves hydrological and economic models. From this phase, the hydrological model in this phase will simulate the physical availability of river water which will be taken as a study sample and aquifer. The economic model will calculate the costs, treatment and economic losses if there is a shortage of water supply due to climate change in a country. The third phase comprises the optimization core, in which mathematical algorithms would be applied to optimize water allocation by maximizing economic benefits or minimizing operational costs, subject to hydrological and environmental constraints. These constraints would ensure that water abstraction remains within sustainable limits. The next phase is the output phase which involves an optimal distribution strategy. The results of this economic mathematical calculation can determine the best conjunctive distribution ratio for the use of river water and groundwater and freshwater against changes in the tropical season in a country and provide guidance to the sectors involved that need to be prioritized during climate change or the tropical season based on the impact on the water economy and climate economy. Finally, the decision and policy support phase would translate the model outputs into actionable recommendations, including equitable water-pricing strategies, tariff adjustments, and national water-management policies. Figure 3 shows the framework for the integration of the hydro-economics Optimization model for sustainability and management of water resources in Malaysia.

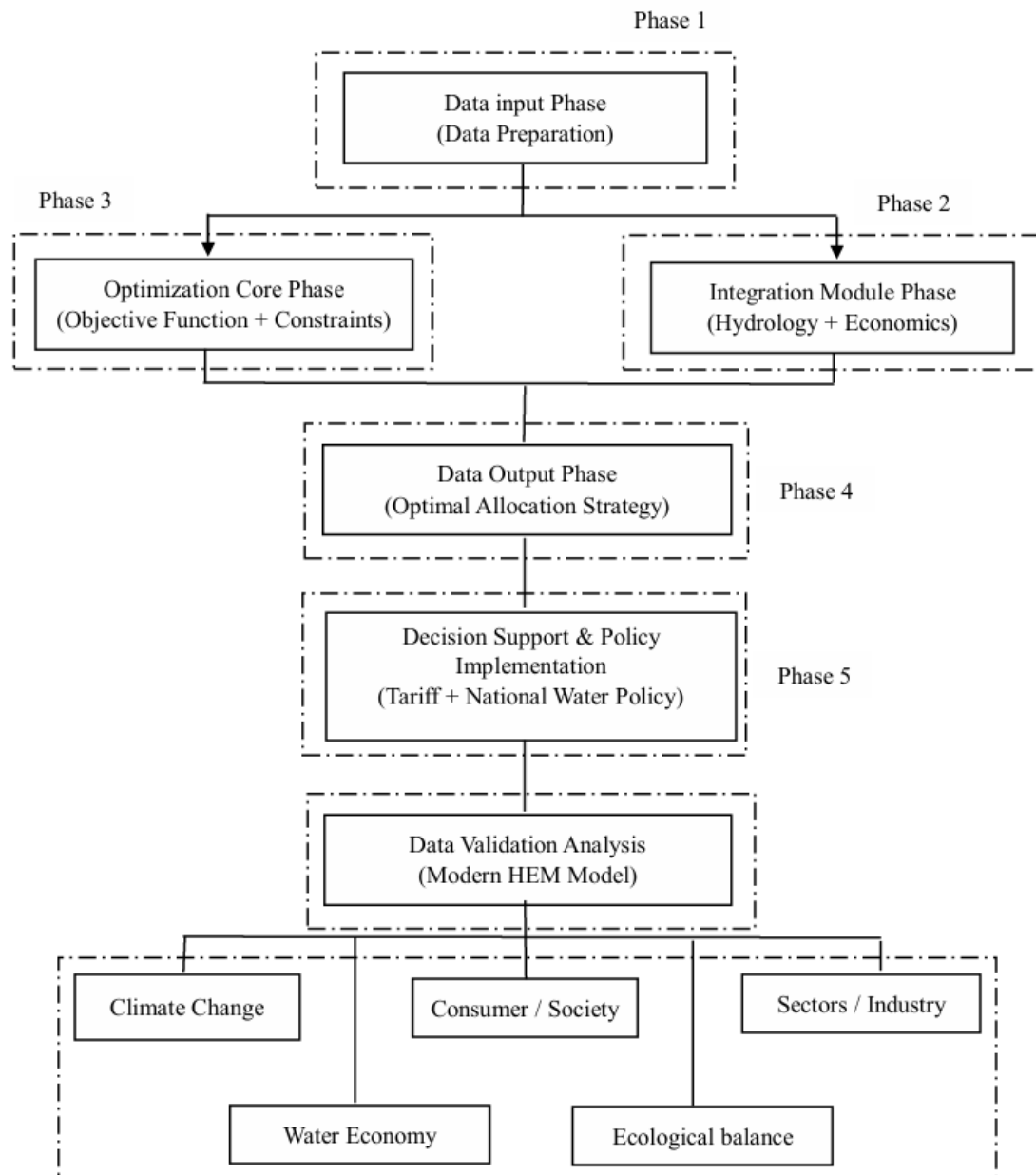


Figure 3. Proposed framework for integrating a hydro-economic optimization model (HEM) into sustainable water-resource management in Malaysia.

The PRISMA-based review indicates that development of a Hydro-Economic Model (HEM) for Malaysia requires integrated analysis of hydrological supply parameters and economic demand/cost parameters. The evidence presented for 2000–2024 was synthesized from published literature and national reports rather than generated using the proposed HEM framework. Table 2 summarizes these historical hydro-economic trends and qualitative classifications.

Table 2. Trends and qualitative synthesis of hydro-economic parameters in Malaysia (2000–2024).

Year	Dominant Water Source	Groundwater Utilization (%)	Marginal Cost of Treatment (RM/m ³)	Relative Economic Value of Water (Qualitative Category)	Hydro-economic Integration/Optimization Category	References
2000	Surface water 98%	Less than 1.0%	0.45	Low	Low	NWRS (2000-2050)
2008	Surface water 98%	1.5%	0.62	Moderate	Moderate	SPAN Statistics & JPS
2014	Surface Water + *ORS	2.2%	0.88	Moderate	Strategic	Selangor water Crisis
2020	Conjunctive Use *(S+G)	3.8%	1.15	High	High	Green Technology Master Plan
2024	HEM Integrated	More than 5.0%	1.52	Very High	Optimal	MyIPH 2023 & Water Transformation 2040
2025 - 2026	Modern HEM Model	NIL	NIL	NIL	NIL	Proposed Modern HEM framework (future empirical validation)

ORS = off-river storage; S + G = surface water and groundwater; NIL = not available or not applicable (the proposed framework has not yet been empirically validated).

Note: Historical values and categories were synthesized from national reports and the peer-reviewed sources cited in the table; they are not outputs from the proposed HEM. Reported marginal treatment costs (RM/m³) are indicative only because the source studies did not use a uniform costing method. Relative economic value (REV) is presented as a qualitative category rather than a directly measured or nationally comparable indicator.

Previous research and national planning documents for 2000–2024 show a historical dependence on surface-water systems, alongside increasing attention to groundwater and Tasek Takungan Pinggiran Sungai (TAPS) as complementary sources. Recent 2025 studies are used here only as supplementary context and are not part of the PRISMA count. Source diversification can reduce exposure to supply interruption caused by river pollution or hydrological stress (Ismail & Al-Amin, 2021). Urbanization and declining raw-water quality can also raise treatment and pumping costs (Bolan et al., 2024). Hydro-economic studies use economic functions to compare supply alternatives and evaluate the conditions under which one source may become more cost-effective than another

(Crespo et al., 2025). In this review, the economic value of water is qualitatively assessed in relation to water-dependent economic productivity and the potential economic losses associated with supply disruptions. Water-supply disruptions may have had greater economic consequences in 2024 than in 2000, given the expansion of high-value economic activities that depend on reliable water supplies. However, this interpretation is based on the reviewed literature and has not been quantitatively validated using the proposed HEM framework.

The review was supplemented with literature published in 2025 to reinforce the currency of the review material without changing the formal search period of the PRISMA review period (2000–2024). This recent research on hydro-economic valuation, conventional and non-conventional water-source management, water-resource quality and trends, and the incorporation of physical water constraints with economic and governance aspects further supports the need to combine physical water constraints with economic and governance considerations (Crespo et al., 2025; Dashkevych & Housh, 2025; Schroeter et al., 2025; Roy et al., 2025). These sources contain up-to-date context but are not included in the 310 study systematic-review count.

For future implementation, this research proposes developing a proposed hydro-economic model (HEM) tailored specifically to the Malaysian context, as illustrated in the integration framework of Figure 3. This proposed next phase would use a multi-dimensional validation process to evaluate the model's efficacy in balancing tropical climate volatility with socio-economic imperatives. Empirical studies in the future, through the synthesis of data obtained from the three areas of ecosystem's equilibrium, industrial demand and society's needs, would allow the identification of the impact of the proposed HEM optimization approach on the cost-efficiency of the operations and on the distribution of the marginal values. Ultimately, the research will assess whether the HEM can function as a decision-support tool for ensuring national water security and sustainable economic resilience amidst 21st-century environmental shifts.

4. CONCLUSION

This review traces the evolution of water-resource management in Malaysia from conventional hydrological monitoring toward more integrated hydro-economic thinking. Based on the 2000–2024 PRISMA review, the literature highlights rising treatment pressures associated with urbanization and increasing economic exposure as water-dependent, high-value sectors expand. The HEM integration framework proposed for 2026 provides a conceptual roadmap for linking tropical climate variability, water availability, sectoral demand, economic costs, and policy decisions. Since the proposed framework has not yet been put into practice or tested under real-world conditions, efficiency gains and exact surface-water/groundwater “switch points” are not asserted within this review. Future application would require testing of the optimization process for identifying context-specific thresholds, cost-efficiency gains and policy-relevant trade-offs. The proposed HEM therefore represents a future decision-support framework rather than a validated operational model, with its contribution lying in the structured integration of hydrological, economic, and governance considerations for climate-resilient water management in Malaysia.

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Nur Muhammad Mohamad Zaki : Conceptualization, Methodology, Investigation. Writing – Original draft; **Nurul Nadiyah Mohd Firdaus Hum**: Methodology, Resources, Supervision, Writing – Review & Editing.

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The authors used ChatGPT for formatting purposes. All outputs were reviewed and validated by the authors.

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Not applicable.

COMPETING INTEREST

The authors declare that there are no competing interests.

COMPLIANCE OF ETHICAL STANDARDS

Not applicable.

SUPPLEMENTARY MATERIAL

Not applicable.

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