

INTEGRATED TERRITORIAL IRRIGATION REFORM UNDER LOW EFFICIENCY AND CLIMATE-CONSTRAINED RIVER FLOWS: IADA SEBERANG PERAK, MALAYSIA

RÉFORME INTÉGRÉE DE L'IRRIGATION TERRITORIALE DANS LE CONTEXTE D'UNE FAIBLE EFFICACITÉ ET DES DÉBITS FLUVIAUX CONTRAINTS PAR LE CLIMAT : IADA SEBERANG PERAK, MALAISIE

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ABSTRACT

IADA Seberang Perak is one of Malaysia's twelve designated rice granary areas, supporting 8,568 ha of double-crop irrigated paddy under a gravity-fed system commissioned in the 1960s. The scheme depends on run-of-the-river abstraction from Sungai Perak at Teluk Sena Intake and contributes to national rice self-sufficiency targets under the National Agrofood Policy 2.0. However, irrigation efficiency is currently estimated at approximately 17%, well below national benchmarks. Combined with climate variability and increasing cross-sector abstraction, this low efficiency creates territorial-scale vulnerability in water allocation. This paper presents findings from the ongoing Irrigation Water Management Plan (IWMP), integrating crop water demand diagnostics, hydrological modelling and irrigation performance assessment to evaluate how agronomic water-use optimisation can strengthen territorial irrigation decision-making under flow-constrained conditions. Hydrological analysis used long-term discharge records (1960-2022) from Sungai Perak at Jambatan Iskandar to construct flow duration curves and derive low-flow thresholds. The 7Q50 discharge is 114.62 m³/s, while the net 7Q5 available at Teluk Sena Intake reduces to approximately 87.3 m³/s after upstream abstraction. Peak irrigation demand reaches about 30 m³/s, with an additional 27 m³/s abstracted upstream. Crop water demand analysis using FAO-based methods indicates that gross irrigation supply exceeds agronomic field requirement, mainly due to conveyance loss, distribution inefficiency and rigid scheduling. The study identifies three reforms: hydrologically triggered allocation, demand-responsive rotational supply and integrated basin-scale water balance modelling. The case demonstrates that climate resilience depends not only on water availability, but on allocation governance, operational flexibility and crop-responsive irrigation scheduling.

Keywords: Irrigation efficiency; crop water demand; flow duration curve; low-flow threshold; territorial governance; climate resilience; IADA Seberang Perak.

RESUME

IADA Seberang Perak est l'une des douze zones consacrées à grenier à riz en Malaisie, qui soutient 8 568 ha de récolte de riz irrigué à double culture, grâce à un système gravitaire mis en service dans les années 1960. Le périmètre dépend du prélèvement au fil de l'eau de Sungai Perak à prise d'eau de Teluk Sena et contribue aux objectifs nationaux d'autosuffisance en riz dans le cadre de la politique agroalimentaire nationale 2.0. Cependant, l'efficacité de l'irrigation est actuellement estimée à environ 17%, bien en dessous des références nationales. Combinée à la variabilité climatique et à l'augmentation des prélèvements intersectoriels, cette faible efficacité crée une vulnérabilité à l'échelle territoriale en matière de l'allocation de l'eau. Cet article présente les résultats du Plan de gestion de l'eau d'irrigation (PGEI) en cours, intégrant le diagnostic de la demande en eau des cultures, la

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modélisation hydrologique et l'évaluation des performances d'irrigation afin d'évaluer la manière dont l'optimisation agronomique de l'utilisation de l'eau peut renforcer la prise de décision territoriale en matière dans des conditions de contraintes de débits. L'analyse hydrologique a utilisé des relevés de débit à long terme (1960-2022) provenant de Sungai Perak à Jambatan Iskandar pour construire des courbes de durée d'écoulement et dériver les seuils de faible débit. Le débit du 7Q50 est de 114,62 m³/s, tandis que le débit net du 7Q5 disponible à la prise d'eau de Teluk Sena se réduit à environ 87,3 m³/s après prélèvement en amont. La demande maximum d'irrigation arrive à environ 30 m³/s, à laquelle s'ajoutent 27 m³/s prélevés en amont. L'analyse de la demande en eau des cultures à l'aide de méthodes basées sur la FAO indique que l'approvisionnement brut d'irrigation dépasse les besoins agronomiques de la parcelle, principalement en raison de la perte de transport, de l'inefficacité de la distribution et de la programmation rigide. L'étude identifie trois réformes : une allocation provoquée par des facteurs hydrologiques, une distribution par rotation adaptée à la demande et une modélisation intégrée du bilan hydrique à l'échelle du bassin. Le cas démontre que la résistance climatique ne dépend pas seulement de la disponibilité de l'eau, mais aussi de la gouvernance des allocations, de la flexibilité opérationnelle et d'une programmation de l'irrigation adaptée aux besoins des cultures.

Mots clés : Efficacité de l'irrigation; Demande en eau des cultures; Courbe de durée des débits; Seuil de faible débit; Gouvernance territoriale; Résistance climatique; IADA Seberang Perak.

INTRODUCTION

Irrigated rice systems in humid tropical basins are increasingly exposed to a management paradox. Annual rainfall and river discharge may appear adequate, yet operational reliability declines during critical dry-season periods because water delivery is constrained by ageing infrastructure, rigid scheduling, poor field control and competing abstraction. In paddy systems, this problem is sharpened by the fact that water demand is not constant. It changes with land preparation, establishment, tillering, panicle initiation, flowering and grain filling. Irrigation therefore has to be treated as an agronomic input as well as a hydraulic service.

IADA Seberang Perak is one of Malaysia's national rice granary areas. It supports approximately 8,568 ha of double-crop paddy and is supplied mainly by run-of-the-river abstraction from Sungai Perak through Teluk Sena Intake (G&P Dams & Water Services, 2025a; G&P Dams & Water Services, 2025c). The system was developed in the 1960s and remains important to national rice self-sufficiency. However, current project assessment indicates low irrigation performance, with system efficiency estimated at about 17% (G&P Dams & Water Services, 2025a; G&P Dams & Water Services, 2025b). At the same time, the lower Sungai Perak corridor must accommodate potable water abstraction, non-granary irrigation abstraction and agricultural demand from the granary scheme.

This paper argues that Seberang Perak's irrigation vulnerability should not be interpreted simply as water shortage. The stronger diagnosis is that the scheme has a low-efficiency allocation system operating under low-flow timing constraint. Its resilience depends on whether crop water diagnostics, river-flow thresholds, hydraulic control and governance coordination are integrated into the Irrigation Water Management Plan (IWMP). The objective of this paper is therefore to demonstrate how agronomic water-use optimisation can strengthen territorial irrigation decision-making under climate-constrained river flow.

STUDY AREA AND PROBLEM CONTEXT

The Seberang Perak irrigation scheme is supplied from Sungai Perak at Teluk Sena (G&P Dams & Water Services, 2025a; G&P Dams & Water Services, 2025c). The intake commands a large regulated river catchment and distributes water through main, secondary and tertiary canal systems serving the paddy command area. The production system follows a double-cropping calendar, producing two seasonal peaks in demand. Irrigation requirement is especially sensitive during land preparation and reproductive growth stages, but effective demand is moderated by rainfall, evaporation, field depth and actual crop stage.

The study area is not a simple field-scale irrigation problem. It is a territorial allocation problem. The intake is located downstream of several water supply and non-granary abstraction points. River flow is influenced by hydropower release regulation. Canal performance is affected by sedimentation, leakage, ageing control structures and limited telemetry integration. Field-level water use is also shaped by farmer practice, drainage condition and uneven planting sequence.

For these reasons, the IWMP must move beyond a rehabilitation list. It must become a decision system that links river status, canal control and paddy water demand. The fundamental question is: when river flow is sufficient on paper, why does the scheme still behave as vulnerable? The answer lies in the compression of operational margin, not in annual water volume alone.

METHODOLOGY

Hydrological threshold assessment

Hydrological assessment used long-term discharge records for Sungai Perak at Jambatan Iskandar and water availability assessment at Teluk Sena Intake, as compiled in the IWMP technical reporting (G&P Dams & Water Services, 2025b; G&P Dams & Water Services, 2025c). Flow duration analysis was used to classify river discharge across exceedance probabilities and identify low-flow behaviour. Annual 7-day low-flow series were analysed to derive 7Q5 and 7Q50 thresholds. These thresholds were compared with upstream abstraction and monthly peak irrigation demand to evaluate intake-level operational buffer.

Crop water demand diagnostics

Crop water demand was assessed using reference evapotranspiration, effective rainfall and crop-stage coefficients consistent with FAO water requirement methodology (Allen et al., 1998). The analysis compared field-level agronomic water requirement against gross irrigation supply and design supply. This comparison was used to identify whether high abstraction is driven by crop demand or by distribution inefficiency. Particular attention was given to paddy growth stages because water deficit during reproductive periods can affect yield more severely than deficit during less sensitive periods.

Irrigation performance and governance diagnosis

Irrigation performance was reviewed using field observations, flow measurement, canal condition, control gate performance and distribution scheduling. Governance diagnosis examined how water allocation is coordinated across irrigation operations, upstream abstraction and basin-scale planning, consistent with integrated water resources management and basin-allocation principles (Global Water Partnership, 2000; Molden, 2007). The analytical framework therefore links three levels: plot-level crop water requirement, scheme-level hydraulic delivery and territorial-scale allocation governance.

Analytical integration

The paper does not treat hydrology, agronomy and irrigation operation as separate chapters. They are integrated as a single diagnostic chain. River-flow indicators define the outer boundary of water availability. Crop-stage water requirement defines the biological demand at field level. Irrigation efficiency indicates how much water is lost or misallocated between intake and crop root zone. Governance analysis determines whether threshold signals are translated into operational decisions. This integration is important because a high river discharge value alone does not guarantee field-level irrigation reliability, and a high gross supply volume does not guarantee crop-stage adequacy.

Table 1. Analytical components used in the irrigation resilience assessment

Component	Primary purpose	Decision relevance
Flow duration and low-flow analysis	Identify river-flow reliability and low-flow thresholds	Defines trigger points for dry-season abstraction management
Crop water demand estimation	Estimate stage-specific paddy water requirement	Separates real crop demand from system loss
Irrigation supply and efficiency review	Compare gross supply, design supply and beneficial demand	Identifies where abstraction reduction is possible
Canal and structure assessment	Assess hydraulic control weaknesses	Prioritises rehabilitation and telemetry
Governance review	Assess coordination among irrigation and upstream users	Supports basin-scale allocation decisions

RESULTS AND DISCUSSION

River flow regime and operational buffer

The flow duration curve indicates that Sungai Perak remains a substantial regulated river source, based on the long-term hydrological records assessed for the IWMP (G&P Dams & Water Services, 2025c). The 95% and 99% exceedance flows at Jambatan Iskandar are approximately 119.92 and 102.09 m³/s, respectively, showing continued dry-season flow support. Low-flow frequency analysis gives a 7Q50 discharge of 114.62 m³/s (G&P Dams & Water Services, 2025c). After upstream LAP and JPS non-granary abstraction of approximately 27.32 m³/s, the net 7Q5 availability at Teluk Sena is about 87.3 m³/s (G&P Dams & Water Services, 2025c).

Peak monthly irrigation demand for Seberang Perak reaches about 30.10 m³/s during seasonal demand peaks (G&P Dams & Water Services, 2025c). Numerically, this remains below net low-flow availability. However, this does not mean the system is risk-free. The key finding is that the hydraulic buffer narrows during low-flow windows. If low-flow conditions coincide with upstream abstraction, sedimentation, gate inefficiency, leakage and imprecise scheduling, the scheme loses operational flexibility. Hence, the risk is not absolute annual scarcity; it is low-flow timing combined with weak delivery control.

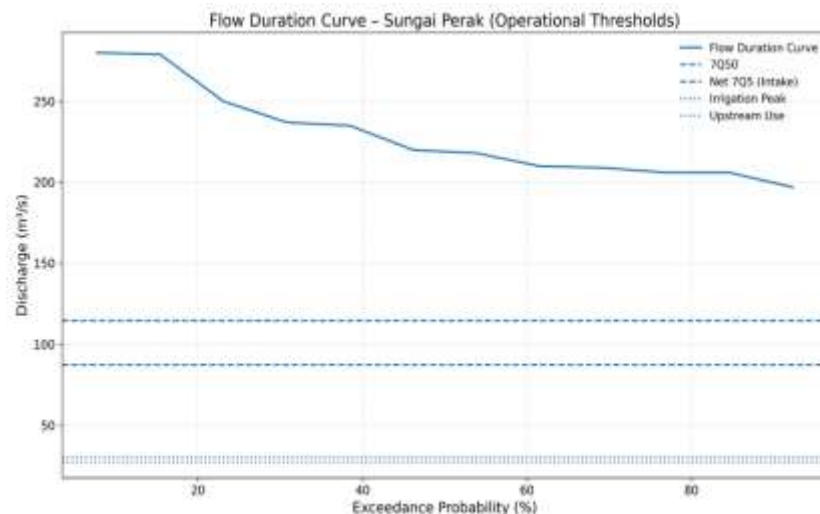


Figure 1. Flow Duration Curve of Sungai Perak with operational low-flow and abstraction thresholds at Teluk Sena Intake.

Agronomic water demand versus gross irrigation supply

The crop water demand assessment shows that field-level agronomic requirement is lower than gross irrigation supply, consistent with the comparison of field-level demand, effective rainfall and irrigation

design supply in the IWMP assessment (Allen et al., 1998; G&P Dams & Water Services, 2025c). This is the decisive agronomic finding. High abstraction cannot be explained by crop physiology alone. It reflects conveyance loss, rigid scheduling, control leakage and mismatch between water delivery and crop stage. Paddy does not require uniform water delivery throughout the season; it requires controlled water availability at the correct depth and timing.

This distinction matters because reducing abstraction is often misunderstood as reducing crop security. In this case, the stronger strategy is to reduce non-beneficial water movement while protecting water availability during yield-sensitive stages. Oversupply during land preparation and less critical vegetative stages increases drainage burden and can mask poor water productivity. Conversely, weak precision during panicle initiation, flowering and grain filling can affect yield even when total seasonal supply appears adequate. The agronomic target is therefore crop-stage water productivity, not simply lower abstraction.

The practical implication is that irrigation performance should be evaluated using two questions simultaneously. First, does the crop receive adequate water at the correct phenological stage? Second, how much gross abstraction is required to deliver that beneficial field water? A scheme can appear secure under gross supply statistics but still perform poorly if water arrives too early, too late or at excessive depth. This is why crop water diagnostics must be treated as a core component of irrigation governance, not as a secondary agronomic calculation.

Meaning of low-flow buffer

The low-flow buffer is the remaining operational margin after upstream abstraction and irrigation demand are considered. In a conventional water balance, a positive margin may be interpreted as sufficient. In an operating irrigation scheme, however, the margin must absorb uncertainty from rainfall timing, intake level, gate condition, canal roughness, sedimentation, farmer access and unexpected upstream demand. Therefore, the buffer must be managed as a risk reserve, not as surplus water.

This distinction is central to climate resilience. Climate variability increases the probability of irregular rainfall, delayed planting, compressed land preparation windows and higher evaporative demand. These stresses do not always appear as annual deficit. They appear as sharper timing pressure within a planting season. A threshold-based allocation system is therefore more useful than a static seasonal water sufficiency statement.

Infrastructure and hydraulic control constraints

Field assessment identified constraints that directly reduce hydraulic precision (G&P Dams & Water Services, 2025b; G&P Dams & Water Services, 2025c). These include sedimentation along canals, ageing gates, leakage at outlets, continuous discharge to drains at damaged structures and uneven tertiary delivery. Some flow measurement locations also posed access and safety constraints, requiring cautious interpretation of measured efficiency. Nevertheless, the pattern is clear: significant water is lost or poorly controlled before it becomes beneficial crop water.

Table 2. Key hydrological and irrigation indicators for Seberang Perak

Indicator	Value	Interpretation
Command paddy area	8,568 ha	National rice granary scale
Current irrigation efficiency	about 17%	Low system performance and high loss risk
7Q50 at Jambatan Iskandar	114.62 m ³ /s	Severe low-flow threshold for river assessment
Net 7Q5 at Teluk Sena	about 87.3 m ³ /s	Available intake buffer after upstream abstraction
Upstream abstraction	about 27.32 m ³ /s	Competing potable and non-granary demand
Peak irrigation demand	about 30.10 m ³ /s	Seasonal irrigation demand peak
Efficiency reform target	17% to 30%	Moderate operational improvement scenario

An efficiency improvement from about 17% to 30% is therefore a realistic first reform target. It is not an aggressive modernisation claim. It represents a moderate operational recovery from leakage, conveyance loss and scheduling inefficiency. If achieved, seasonal gross abstraction could be reduced substantially while maintaining field-level crop water needs.

Diagnosis-to-reform logic

The diagnosis points to a clear reform logic. Hydrological analysis shows when the river system becomes operationally sensitive. Agronomic analysis shows when the crop truly needs water. Irrigation performance assessment shows where delivery control is lost. Governance analysis shows whether these signals are translated into decisions. The weak point is not any single component but the absence of an integrated decision loop.

Table 3. Diagnosis-to-reform logic for IWMP implementation

Observed condition	System meaning	IWMP response
Gross supply exceeds field-level demand	Abstraction includes non-beneficial losses	Adopt crop-stage water budgeting and block-level monitoring
Low-flow buffer narrows during dry periods	River sufficiency depends on timing and abstraction coordination	Use 7Q5 and 7Q50 as operational triggers
Static irrigation timetable	Delivery not matched to crop stage or rainfall	Implement demand-responsive rotational scheduling
Leakage, sedimentation and gate weakness	Hydraulic precision is reduced before field delivery	Prioritise control structures, desilting and telemetry
Multiple upstream users	Irrigation is part of basin allocation, not isolated scheme operation	Build shared basin water balance model

PROPOSED TERRITORIAL IRRIGATION REFORM FRAMEWORK

The proposed IWMP reform framework is built on three mutually reinforcing elements: hydrologically triggered allocation, demand-responsive rotational supply and integrated basin-scale water balance modelling. The structure is synthesized from crop water requirement science, IWRM principles and water productivity/allocation frameworks (Allen et al., 1998; Global Water Partnership, 2000; Molden, 2007). Figure 2 summarises the proposed decision pathway.



Figure 2. Decision logic for Integrated Water Management Plan (IWMP) implementation

Figure 2. Integrated decision logic for climate-resilient irrigation water management in IADA Seberang Perak. Source: Synthesized from FAO crop-water requirement principles, IWRM approaches and IWMP project findings (Allen et al., 1998; Global Water Partnership, 2000; Molden, 2007; G&P Dams & Water Services, 2025a, 2025b, 2025c).

Hydrologically triggered allocation

Irrigation scheduling should incorporate low-flow thresholds rather than rely only on historical crop calendars. The 7Q5 and 7Q50 indicators can serve as operational triggers for dry-season abstraction, intake monitoring and inter-agency coordination. When river flow approaches low-flow thresholds, the scheme should activate tighter gate control, reduced non-essential flushing, prioritised delivery to crop-critical blocks and closer communication with upstream abstractors.

Demand-responsive rotational supply

The irrigation calendar should move from broad fixed timetabling to sub-staggered rotational supply aligned with crop growth stage. This requires block-level mapping of planting stage, rainfall contribution, soil water condition and field access. The agronomic objective is to deliver the right depth at the right time, especially during panicle initiation and flowering, while reducing unnecessary oversupply during land preparation and non-critical stages.

Integrated basin-scale water balance modelling

A unified allocation model should integrate irrigation abstraction, potable demand, non-granary use, transfer scenarios, rainfall, evapotranspiration and climate variability. The model should not function only as a technical simulation. It should serve as a governance tool, creating shared understanding among agencies on demand timing, low-flow risk and allocation consequence.

IMPLEMENTATION PRIORITIES

The proposed reform should be implemented in phases. Immediate actions should focus on low-cost control improvements and decision rules rather than waiting for full infrastructure modernisation. Medium-term actions should improve telemetry, canal control and block-level scheduling. Longer-term actions should institutionalise basin-scale allocation modelling and inter-agency data sharing.

Table 4. Priority actions for implementation

Timeframe	Priority action	Expected effect
Immediate	Use 7Q5 and 7Q50 thresholds in seasonal operation meetings	Creates shared low-flow awareness before stress occurs
Immediate	Map crop stage by block before major irrigation release	Improves match between water delivery and biological demand
Short term	Repair leakage points, missing boards and critical control gates	Reduces non-beneficial discharge and improves delivery control
Short term	Introduce sub-staggered rotation by crop stage	Reduces oversupply and protects reproductive-stage demand
Medium term	Install telemetry at strategic intake and canal points	Enables flow-responsive scheduling and audit
Medium term	Develop integrated water balance model with upstream users	Supports transparent basin-scale allocation

Risk safeguards

Efficiency improvement must not be implemented as blunt water reduction. The first safeguard is agronomic: water saving should come from reducing losses and unnecessary supply, not from creating crop stress. The second safeguard is hydrological: restrictions or rotation tightening should be triggered by river-flow status and intake condition, not by calendar date alone. The third safeguard is institutional: operational changes must be coordinated with irrigation managers, upstream abstractors and field-level users so that water saving does not shift risk to farmers.

IMPLICATIONS FOR AGRICULTURAL RESILIENCE

The main contribution of this case is the demonstration that climate resilience in rice irrigation cannot be achieved by infrastructure rehabilitation alone. It requires agronomic intelligence. Crop water demand diagnostics identify where water is biologically required and where delivery losses are being misread as demand. Hydrological thresholds identify when the river system becomes operationally vulnerable. Governance reform determines whether these two signals are translated into allocation decisions.

For Seberang Perak, the practical pathway is staged reform: rehabilitate control structures, monitor flow and field response, implement sub-staggered delivery, adopt crop-stage water budgeting and institutionalise threshold-based allocation. This approach protects yield while reducing abstraction pressure. It is also transferable to other tropical granary systems where total annual water availability remains substantial but operational reliability is eroded by climate variability and weak allocation control.

LIMITATIONS AND FURTHER WORK

This paper is based on project-level hydrological assessment, crop water demand diagnostics and field observations available during the IWMP study period. Several limitations remain. First, irrigation efficiency estimates should be refined with repeated flow measurement across more tertiary locations and water levels. Second, the crop water demand analysis should be updated with season-specific rainfall, evaporation and actual planting dates as additional planting seasons are completed. Third, the proposed basin-scale allocation model should be tested under future climate and demand scenarios, including changes in upstream abstraction and operational release from Chenderoh Dam.

These limitations do not weaken the main finding. They define the next stage of scientific and operational refinement. The immediate conclusion remains robust: water allocation decisions should be driven by crop demand, low-flow thresholds and measured system performance rather than by legacy timetable alone.

CONCLUSION

The IADA Seberang Perak case shows that the central irrigation challenge is not merely absolute river water availability, but the governance and operational capacity to allocate water precisely under low-flow and climate-variable conditions. The combined evidence from flow duration analysis, crop-water diagnostics and irrigation performance assessment indicates that resilience can be strengthened through hydrologically triggered allocation, demand-responsive rotational supply and basin-scale water balance modelling. These reforms would reduce non-beneficial abstraction, widen the low-flow operational buffer and protect paddy yield targets without treating increased abstraction as the default solution.

The study shows that agronomic water-use optimisation can strengthen territorial irrigation governance. By linking crop water demand, 7Q5 and 7Q50 hydrological thresholds, irrigation efficiency diagnostics and basin-scale allocation modelling, the IWMP can shift the scheme from infrastructure-centred supply to adaptive, flow-responsive water management. Improving efficiency from 17% to 30% is a credible immediate target that would widen low-flow buffer without compromising yield. This provides a practical model for climate-constrained irrigated rice systems in tropical river basins.

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