



Original Research Article

An Extended Environmental Flow Assessment in Regulated Rivers: Integrating Hydraulic Modelling, Habitat Suitability, and Water Quality

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ABSTRACT

Environmental flow assessment in the regulated tropical river is often constrained by limited data and strong hydropower alteration. Conventional hydrological approaches based on fixed flow indices rarely account for the ecological complexity required for sustainable management. This study develops an extended species-centred environmental flow assessment framework by integrating hydrological analysis, hydraulic simulations, habitat suitability thresholds, and discharge-water quality analysis. The approach was applied to the downstream of Cirata Dam on the Citarum River, Indonesia. Habitat-based modelling identified an optimal discharge of 93.12 m³/s, maintaining 94% of suitable habitat area, while achieving good water quality conditions would require a discharge exceeding 500 m³/s, which is hydrologically unrealistic. The integrated results demonstrate that environmental flow determination in a regulated river must balance ecological and hydrological feasibility. Flow alone cannot ensure recovery with pollution control, illustrating the importance of combined flow regulation and watershed-scale water management policies.

KEYWORDS

Environmental flow, Extended assessment, Regulated river, Hydraulic-habitat suitability, Water quality

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INTRODUCTION

Riverine ecosystems are fundamental to both ecological integrity and human well-being, providing essential services such as habitat for aquatic life, water for consumption, agriculture, and industry. Several practical ways to identify riverine ecosystems include quantifying chemical, physical, and bacteriological properties [1] and classifying the quality into a water quality index (WQI) or water quality aptitude (WQA) [2] to assess the potential for water use. Recognising the critical link between river flow and ecosystem health, the concept of Environmental Flow (EF) has emerged as a cornerstone of sustainable water resource management [3]. One of the examples of water resource management case is the existence of dam or reservoir in the river. In that context, the dam's presence significantly altered flow duration, flood frequency, and magnitude [4]. Especially in Southeast Asia, the development of water resource management, such as irrigation and hydropower dams, deforestation, land degradation, mining, climate change, river flow diversion, and many more have led to the alteration of environmental flow [5]. As consequences from water resources development, the past work will have impacts on system rehabilitations, compensation costs and mitigating the new water resources developments in the future [6].

Environmental Flow is defined as the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems, and the human well-being that depends on them. Prioritising policies that take into account the importance of environmental flow will have an impact on low water security in meeting the target volume of water required to meet water needs, including environmental flows [7]. Thus, the policy framework will encourage better resource analysis in more appropriate water allocation management, especially during low-flow water availability [8], which can facilitate the formulation of relevant national policies [9]. The presence of the policies is vital for maintaining optimal environmental flow by guaranteeing the river's continuous availability of its native organisms while also regulating pollution and sedimentation levels. In this regard, the critical link between flow rates and water quality has been established, where sufficient discharge is necessary to regulate pollutant concentrations [10] and determine the overall water availability footprint [11]. Furthermore, the development of EF methodologies has evolved from desktop hydrological assessments in data-scarce regions [12] and comprehensive reviews of low-flow hydrology [13] to broad global surveys that categorise hundreds of assessment techniques [14]. The use of multi-criteria decision analysis frameworks offers a systematic approach for prioritising diverse EF components, providing support for complex hydrological decision-making [15].

The implementation of EF faces two primary challenges, particularly in developing countries. Firstly, regulated rivers, such as those controlled by a dam, exhibit highly disrupted natural flow regimes. Grown [16] demonstrated that such regulations significantly alter macroinvertebrate assemblages, while Lopez-Moreno et al. [17] highlighted how reservoir management creates artificial storage regimens. Furthermore, Pennock et al. [18] correlated these flow alterations directly with declining fish populations. In Indonesia, initial regulatory efforts utilised simple hydrological indices like the Q95 flow rate [19]. While these hydrological approaches are commonly used in a tropical region context [20]. The other approachment, define maintenance flows without directly accounting for ecological processes [21] or species-specific biological needs [22].

Secondly, advanced, ecological-rich assessment methods require extensive, species-specific microhabitat data. The foundational work on the In-Stream Flow Incremental Methodology (IFIM) by Bovee et al. [23] established the necessity for detailed hydraulic-biological integration. More recently, Hansen et al. [24] emphasised the importance of evolving these models for novel riverscapes. The complexity and cost of these methods have created a critical need for more streamlined and data-efficient techniques that provide reliable results with limited data availability, particularly where urgent conservation actions are needed. In this

context, Forcelini et al. [25] highlight the nuances of microhabitat selection, while Wegscheider et al. [26] advocate for combining expert opinion with hydrodynamic modelling to improve management efficiency.

Addressing these gaps requires a paradigm shift toward integrated and data-efficient methodologies. Recent research emphasises two critical components. The first is a species-centred habitat approach that overcomes data scarcity by adapting frameworks like IFIM [27]. Instead of relying on full Habitat Suitability Index curves, these methods can leverage generalised fish swimming performance databases to establish velocity thresholds [28]. This offers a scientifically grounded foundation for linking hydraulic simulations to habitat suitability [21]. The second, equally crucial component is the integration of water quality [29], [30]. The ecological health of riverine systems is intricately linked to both the magnitude and the quality of flows [31], yet flow assessment and water quality evaluation often remain separate, representing a critical gap in holistic ecosystem-based river management [32].

This study utilises the Citarum River, West Java, Indonesia, as a critical case study to test the integrated approach. As the longest river in West Java, the Citarum is harnessed by a cascade of three large multi-purpose dams (Saguling, Cirata, Jatiluhur) [33], which regulate its flow for essential benefits like hydropower and irrigation [34]. The operation of the cascade system, particularly the multi-objective optimisation for hydroelectric exploitation, has been a key research topic [35]. The downstream section of the Cirata Dam exemplifies a regulated river where outflow patterns are highly influenced by hydropower operations [36]. Consequently, the river faces several serious problems, including severe pollution from industrial and domestic waste, habitat degradation, and sedimentation [37]. Addressing these complex conditions requires special attention from various stakeholders, including government agencies, local communities, industries, and non-governmental organisations, prompting the government to issue strategic regulations for its rehabilitation [38]. Therefore, evaluating the existing Q95 maintenance flow against comprehensive ecological criteria is crucial for informed water management and the long-term health of the river.

The objectives of this research are: (1) To evaluate the performance of the existing maintenance flow rate (Q95) based on integrated habitat suitability and water quality criteria in the Citarum River downstream of the Cirata Dam. (2) To compare the hydrological approach (e.g. Q95) with the proposed integrated hydraulic-habitat-water quality approach to determine the most appropriate EF assessment strategy for regulated river conditions. (3) To formulate an integrated environmental flow rate recommendation that supports the sustainability of the aquatic ecosystem while considering both flow quantity and water quality dynamics.

The significance of this study lies in proposing and testing a novel, integrated environmental flow (EF) assessment framework specifically designed for data-scarce and highly regulated river systems like the Citarum River cascade. This dual-faceted methodology advances the state-of-the-art by combining an adapted hydraulic-habitat simulation (utilising species-specific fish swimming performance data) with a statistical water quality assessment. This integration provides enhanced ecological realism compared to conventional hydrological methods (e.g., Q95). The reported work's impact is the formulation of a practical, scientifically rigorous EF recommendation that addresses both flow quantity and water quality dynamics, enabling water resource managers to make more sustainable decisions for the long-term health of aquatic ecosystems in critical hydropower-regulated rivers.

Despite significant advances in Environmental Flow Science, a persistent gap remains in the development of ecologically meaningful EF assessment methods for highly regulated, data-scarce river systems, particularly in tropical regions. Existing approaches are still dominated by hydrology-based indices (e.g., fixed percentile flows), which implicitly assume stationary flow-ecology relationships and neglect the compounded effects of hydraulic habitat alteration and deteriorating water quality downstream of reservoirs. While process-based and habitat simulation models have been widely applied in data-rich temperate rivers, their transferability to regulated tropical rivers is constrained by limited biological data and complex operational

controls. This study addresses this gap by proposing an integrated environmental flow assessment framework that couples adapted hydraulic-habitat simulations, informed by species-specific fish swimming performance, with statistical water quality constraints. By testing this framework in a representative reservoir-regulated river cascade, the study advances EF methodology beyond flow-quantity paradigms and provides a transferable, ecologically grounded approach for sustainable river management under hydropower regulation.

The principal advantage of the proposed environmental flow assessment framework lies in its high adaptability to regulated, data-scarce river systems. By integrating hydraulic-habitat simulations based on generic fish swimming performance traits with statistically derived water quality constraints, the method reduces dependence on long-term ecological datasets while retaining ecological relevance. This modular structure allows the framework to be adjusted to different river types, species assemblages, and management objectives, making it transferable beyond the specific case study. Moreover, the approach explicitly accounts for operational flow regulation and water quality degradation, factors often overlooked by conventional hydrology-based methods. However, the method also has limitations. Its accuracy depends on the representativeness of selected hydraulic indicators and proxy biological traits, which may oversimplify complex ecological responses. In addition, the approach requires hydraulic modelling and water quality data of sufficient resolution, which may limit straightforward in systems with extremely sparse monitoring. Despite these constraints, the framework offers a pragmatic balance between scientific rigour and practical applicability, particularly in regions where traditional ecohydrological methods are either infeasible or ecologically inadequate.

MATERIALS AND METHODS

This research utilises a comprehensive set of datasets to support hydrological analysis, hydraulic modelling, habitat suitability, and water quality analysis for environmental flow assessment in the downstream reach of the Cirata Dam. An overview of all datasets is provided in Table 1. Daily discharge data from 1996 to 2022 were obtained from the Research Institute for Water Resources Development under the Ministry of Public Works and Housing, and were used to characterise the long-term flow regime and derive low-flow statistics, which are relevant to current river management practices in Indonesia [39]. Topographic data were derived from an eight meter resolution Digital Elevation Model (DEM) provided by the Geospatial Information Agency of Indonesia. These data were supplemented with field surveyed river cross-sections at three monitoring stations to improve the representation of channel geometry for hydraulic modelling. Fish population information, including species composition and basic morphological characteristics, was collected through interviews with local fishers and community members, supplemented by local studies [40]. Target indicator species were then identified, and their swimming performance parameters were obtained from the Fish Swimming Performance Database [28] to support habitat suitability simulation. Water quality data covering the period from 2014 to 2022 were obtained from Perum Jasa Tirta II, provides additional insight into habitat conditions by tracking critical parameters such as dissolved oxygen, temperature, and turbidity. Furthermore, discharge observation data including field measurements of velocity and depth were gathered specifically during the survey campaign. to calibrate and validate hydraulic simulations, ensuring accurate assessments of flow-habitat interactions in the study area.

Table 1. Datasets Parameter

Data Parameter	Type of Data	Source
Cirata Outflow	Daily discharge data from Cirata Hydropower Outlet (1996 – 2022)	Research Institute for Water Resources Development Agency or Research and Development, Ministry Public Works

Topography	Digital Elevation Model (DEM)	Geospatial Information Agency (BIG) of Indonesia
Fish Population	Species, morphology, characteristics	Interview data and [40]
Water Quality	Monthly water quality data from Cirata Hydropower Outlet (2014 – 2022)	PJT II (Perum Jasa Tirta II)
Discharge Observation Data	Velocity and depth of river flow	Observed Data

Methods

This study employed an integrated, species-centred assessment framework tailored for regulated and data-scarce rivers. The methodology was designed to link hydrological variability, hydraulic modelling, adapted habitat suitability assessment, and water quality evaluation.

The overarching goal is to determine an environmental flow magnitude that optimally balances the physical habitat requirements of indicator fish species with the necessity of maintaining river water quality standards. The analytical steps are structured to ensure that ecological realism is maximised despite data limitations, specifically by linking the hydraulic parameters (velocity and depth) with ecological criteria (fish swimming performance database) and statistically modelling the flow-quality relationship. The following sub-sections detail the specific analyses, moving from the baseline hydrological characterisation to the final integrated environmental flow recommendation.

Hydrological analysis and flow scenarios. Hydrological index methodologies were applied to characterise the flow regime and identify a set of discharge scenarios relevant for subsequent hydraulic and ecological determination. These methods utilise daily outflow data from the Cirata Dam (1996 – 2022) to understand the long-term variability and critical low-flow thresholds under the regulated river conditions. Two complementary analyses were conducted are Flow Duration Curve (FDC) method to describe long term flow variability and Low Flow Index method to identify critical discharge threshold under regulated river conditions.

The FDC is a graphical representation that provides a statistical representation of the relationship between streamflow magnitude and its exceedance probabilities over a specified period. This analysis was conducted using daily outflow data from Cirata Dam, which were sorted and analysed using the Weibull plotting position to estimate exceedance probabilities [41].

$$P = m / (n + 1) \times 100\% \tag{1}$$

Where m is the sorted data rank and n is the total length of the data series. Key discharge indices were extracted from the FDC to represent maintenance flows currently utilised in Indonesia and potential environmental flow thresholds. The selected flows were Q97.5, Q95 (representing the existing regulatory maintenance flow), and Q90. These indices form the potential flow scenarios for the hydraulic modelling phase.

Low Flow Frequency (LFF) analysis was performed to identify the ecologically critical low-flow discharges that represent baseflow conditions during prolonged dry periods, ensuring a robust evaluation of habitat sustainability. This analysis focused on the annual minimum 7-day average discharges (Q7), based on its established relevance for baseflow conditions that sustain aquatic habitats [13], [42]. Both the Gumbel minimum and Weibull minimum distributions were evaluated to estimate low flow quantiles for return periods of 2, 5, and 10 years (7Q2, 7Q5, and 7Q10). These low-flow quantiles serve as additional, extreme low-flow scenarios for hydraulic and ecological testing.

The final set of discharge scenarios, encompassing the FDC-derived indices (Q90, Q95, and Q97.5) and the LFF-derived quantiles (7Q2, 7Q5, and 7Q10), was collectively used as input for the hydraulic modelling to evaluate the corresponding habitat suitability and water quality criteria.

The lowest average discharge of 7 consecutive days from 1996 to 2022 has sample mean and standard deviation are assumed as good estimates for $E[Z]$ and $\sigma[Z]$, respectively are $80.93 \text{ m}^3/\text{s}$ and $22.02 \text{ m}^3/\text{s}$. Solutions to the system formed give $\alpha = 17.18$ and $\beta = 90.84$. With these results and $\gamma = -1.1396$ also by making the return periods are 10, 5, and 2 years, estimate value of the 7Q10, 7Q5, and 7Q2 Gumbel_{min} models are $z(T = 10) = 52.19 \text{ m}^3/\text{s}$, $z(T = 5) = 62.08 \text{ m}^3/\text{s}$, and $z(T = 2) = 84.55 \text{ m}^3/\text{s}$. From the same $E[Z]$ and $\sigma[Z]$, it follows that $CV_Z = 0.272$. Furthermore, $\alpha = 4.13$, $A(\alpha) = 0.91$, and $\beta = 89.11$. Finally, with these results and by making return periods are 10, 5, and 2 years, value of the 7Q10, 7Q5, and 7Q2 with Weibull_{min} model are $z(T = 10) = 51.69 \text{ m}^3/\text{s}$, $z(T = 5) = 61.99 \text{ m}^3/\text{s}$, and $z(T = 2) = 81.55 \text{ m}^3/\text{s}$.

Hydraulic modelling. Hydraulic modelling for flow analysis was conducted using the HEC-RAS software (version 6.3.1). This model is used to obtain flow parameters such as flow velocity and flow depth based on different discharge scenarios. In this study, the simulation conducted uses one-dimensional (1D) steady flow approach, which is flow considered constant over time, with the aim of analysing flow conditions over a specific period. It is used when flow changes are considered insignificant during the analysed period. Thus, the simulation results are simpler and focus on a more stable flow distribution. The model domain was constructed using the Digital Elevation Model (DEM), supplemented by field-surveyed cross-sections at the three monitoring points (STA 1100, 3450, 5200) to ensure accurate river bathymetry.

The model setup for hydraulic simulation includes the definition of both upstream and downstream boundary conditions. The upstream boundary condition is represented by fixed discharge scenarios (Q90, Q95, Q97.5, 7Q2, 7Q5, and 7Q10) which were obtained from the results of hydrological analysis. Meanwhile, the downstream boundary condition is defined using the Normal Depth method, calculated based on the average bed slope of the modelled river reach. This approach assumes that the flow at the downstream end is uniform and unaffected by the dam's backwater influence.

In the context of steady gradually varied flow ($\frac{\partial h}{\partial t} = 0$), the Saint-Venant equations reduce to a simplified set of partial differential equations. The continuity equation becomes:

$$h \frac{\partial V_x}{\partial x} + V_x \frac{\partial h}{\partial x} = 0 \quad (2)$$

and the momentum equation is expressed as

$$V \frac{\partial V}{\partial x} + g \frac{\partial h}{\partial x} + g(S_f - S_0) = 0 \quad (3)$$

Where x is the space coordinate along the channel axis, h is the depth, V_x is the flow velocity in the x direction, g is the acceleration due to gravity, S_f is the frictional slope, and S_0 is the bed slope.

The phenomenon of critical flow is indicated by the water surface elevation (WSE) being very close to or aligned with the critical depth line. This condition indicates that the Froude number (Fr) approaches one, which signifies a transition between subcritical and supercritical flow.

Recognising that the bed slope $S_0 = -\frac{\partial z}{\partial x}$, the equation can be reformulated into a total energy gradient form. The following energy equation is used to calculate the water surface elevation between cross-sections in the context of HEC-RAS modelling:

$$V \frac{\partial V}{\partial x} + g \frac{\partial h}{\partial x} + g \frac{\partial z}{\partial x} = 0 \quad (4)$$

Among these, the first term, which reflects the gradient of the velocity head, becomes dominant as the flow approaches a critical condition. At this point, the flow velocity increases significantly relative to the flow depth, causing the Froude number to approach unity ($Fr = 1$).

Thus, the velocity term serves as the key indicator in identifying and characterising critical flow transitions within the hydraulic model. Hence, this phenomenon of critical flow often occurs in channels with a high gradient [43]–[45].

The Manning's roughness coefficient (n) is the critical parameter influencing flow velocity and depth. The initial values of n were estimated based on channel characteristics (e.g., riverbed material and vegetation) [46]. The final value was determined through a calibration process by comparing simulated velocity and depth profiles against field measurement data collected at the three monitoring points (STA 1100, 3450, and 5200) during a specific measured discharge.

The calibration procedure involved iteratively adjusting the Manning's n until the simulation results aligned with the measured values. The performance of the calibration was quantitatively evaluated using statistical metrics, specifically the Root Mean Square Error (RMSE) and the Coefficient of Determination (R^2), calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (S_i - O_i)^2}{N}} \quad (5)$$

$$R^2 = 1 - \frac{\sum_{i=1}^N (O_i - S_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (6)$$

Where S_i is the simulated value, O_i is the observed value, \bar{O} is the mean observed value, and N is the number of observations. A final set of Manning's n values was adopted when the resulting RMSE was below 0.1 and the R^2 was above 0.85, indicating an acceptable fit for the subsequent habitat simulation.

Habitat parameter assessment. The In-stream Flow Incremental Methodology (IFIM) is a widely recognised framework used to assess the relationship between stream flows and aquatic habitats. Developed in the late 1970s, IFIM integrates hydraulic engineering models with empirical habitat data to evaluate how changes in water flow affect the availability and quality of habitats for aquatic organisms, particularly fish [23], [47]. Habitat suitability criteria are used to represent microhabitat requirements in IFIM. Given the limitation of empirically derived Habitat Suitability Criteria (HSC) for local fish populations in the Citarum River, this study adopted an adapted, species-centred approach to derive the critical hydraulic criteria (velocity and depth).

Principles of the Fish Swimming Performance Database was utilised to determine the optimal flow parameters for habitat simulation [28]. This method links hydraulic variables (velocity) directly to the physiological capability of fish, specifically focusing on endurance and swimming speed.

Based on local ecological knowledge and interview data [40], *Cyprinus carpio*, *Hampala macrolepidota*, *Oreochromis niloticus*, *Hemibagrus nemurus* was selected as the key indicator species for the downstream Citarum River reach. This species represents a economically important group in the area.

The criteria for flow velocity (V) and depth (D) were derived by linking the indicator species' morphological data to the generalised principles of the Fish Swimming Performance Database [28]. The dimensionless equations relating velocity, swimming distance, and fish length were utilised to translate physiological limits into hydraulic thresholds.

$$X_* = M(V_*)^a \quad (7)$$

where:

$$X_* = X/l \quad (8)$$

and:

$$V_* = V/\sqrt{gl} \quad (9)$$

Where:

X_* = dimensionless swimming speed

- X = swimming distance (m)
- V_* = dimensionless water velocity
- V = water velocity (m/s)
- l = fish length (meters)
- g = gravitational acceleration = 9.81 m/s²
- M and a are coefficients derived from dimensionless speed vs. Time regression, see Table 2.

Table 2. Grouped data dimensionless swim distance equations and prediction interval coefficient derived from fatigue regressions [28]

Group	X• vs. V•		95% Prediction Interval				75% Prediction Interval			
			Upper Boundary		Lower Boundary		Upper Boundary		Lower Boundary	
	M	a	M	a	M	a	M	a	M	A
Catfish & Sunfish	3.89	-3.95	31.67	-3.95	0.48	-3.96	13.32	-3.95	1.14	-3.96
Eel	5.98	-1.72	25.02	-1.72	1.43	-1.72	13.85	-1.72	2.58	-1.72
Herring	59.34	-1.49	102.93	-1.49	34.24	-1.49	81.97	-1.49	42.97	-1.49
Salmon & Walleye	26.92	-2.99	374.99	-2.99	1.93	-2.99	126.33	-2.99	5.74	-2.99
Sturgeon	0.01	-6.67	0.06	-6.67	0.001	-6.67	0.02	-6.67	0.002	-6.67
Pike (derived)	8.51	-2.04	33.16	-2.04	2.19	-2.04	18.84	-2.04	3.85	-2.04

The HSC_V was established by calculating the predicted maximum velocity that the indicator fish can maintain. The upper velocity threshold was defined by the velocity corresponding to the 50% percentile limit of the sustained swimming performance derived from the equations. Any cell in the hydraulic model with a velocity exceeding this threshold was assigned a habitat suitability index of 0 (Unsuitable), while velocities equal to or below this threshold were assigned 1 (Suitable). This approach ensures minimum energy expenditure for daily activities while simplifying the assessment for data-scarce conditions. The HSC_D was based on the minimum requirements for the indicator species' morphology. The minimum depth threshold was set at 0.5 meters. Cells with depths below this minimum were assigned $HSC_D=0$, and cells above were assigned $HSC_D=1$.

The simulated velocity and depth outputs were combined using the minimum rule to determine the final composite habitat suitability index ($HSC_{Composite}$) for each cell, where $HSC_{Composite} = \min(HSC_V, HSC_D)$. The Weighted Usable Area (WUA) was then calculated as the total wetted surface area where the $HSC_{Composite}$ equals 1 (Suitable). This method effectively determines the total available habitat area that simultaneously meets the minimum velocity (50% sustained swimming) and depth requirements for the indicator species. The flow scenario that yields the maximum WUA ($HSC_{Habitat}$) is identified as the hydraulically optimal flow, serving as one of the primary inputs for the final integrated EF recommendation.

Before determining the swimming speed of fish species, the fish populations in the Cirata downstream were grouped according to the grouping in [28]. For fish species not included in the reference list, the grouping process involved adjusting the taxonomy of the fish species of relevance to align with the taxonomy of the fish group listed. Fish species classifications are in Table 3.

Table 3. Fish population group and classification

Local	Name	Order	Families	Group	Size (min)	Size (max)
	Scientific					
Mas	<i>Cyprinus carpio</i>	Cypriniformes	Cyprinidae	Salmon & Walleye	25	36
Hampal	<i>Hampala macrolepidota</i>	Cypriniformes	Cyprinidae	Salmon & Walleye	12	40
Nila	<i>Oreochromis niloticus</i>	Perciformes	Cichlidae	Salmon & Walleye	4	60
Tagih	<i>Hemibagrus nemurus</i>	Siluriformes	Bagridae	Catfish	38	38

Water quality assessment. The other essential component of the integrated environmental flow framework is the water quality assessment, which addresses the pollution constraints prevalent in the Citarum River. The determination of water quality status at each point is achieved through the implementation of the STORET method, in accordance with the Decree of the Minister of Environment of the Republic of Indonesia Number 115 of 2003 concerning Guidelines for Determining Water Quality Status [48]. Furthermore, the quality standard reference, as outlined in Government Regulation Number 22 of 2021 Class II, is utilised to categorise water based on its suitability for specific purposes. These purposes include infrastructure/facilities, water recreation, freshwater fish farming, livestock, agriculture irrigation, and other similar uses that require water of a comparable quality [49]. Critical parameters analysed include Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS). This assessment establishes the current environmental condition and provides the quality standard that the minimum environmental flow must satisfy. The method to determine water quality status is using the rating system from the "US-EPA (Environmental Protection Agency)" by classifying water quality into four classes.

Several studies have employed statistical methods such as Pearson's correlation coefficient to analyse the relationship between water discharge and water quality parameters. For instance, a study reported significant correlations among various physico-chemical parameters, including dissolved oxygen (DO), biochemical oxygen demand (BOD), and total dissolved solids (TDS) with changes in water discharge levels [50]. Furthermore, flow variability has been shown to affect water quality significantly because seasonal changes, which lead to higher concentrations of suspended solids and nutrients due to erosion and runoff [32] [31]. This established relationship justifies the use of empirical modelling to determine the minimum flow required to maintain water quality standards.

To determine the minimum flow required to maintain water quality above the regulatory standard, a statistical modelling approach such as Pearson's Correlation Coefficient (r) was employed to quantify the strength and direction of the relationship between the historical annual discharge data (Q) and corresponding water quality index status (WQIS) data (2014 – 2022).

Due to the non-linear nature of the dilution mechanism (where pollutant concentration decreases as discharge increases), Simple Non-Linear Regression was performed. Several common functions were tested. The Logarithmic function was selected as the final model due to its highest Coefficient of Determination (R^2), which ensures the best statistical fit for the observed data:

$$WQIS = \beta_0 + \beta_1 \ln(Q) + \epsilon \tag{10}$$

Where $WQIS$ is the predicted pollutant Water Quality Index Status, Q is the discharge (m^3/s), $\ln(Q)$ is the natural logarithm of discharge, β_0 and β_1 are the regression coefficients, and ϵ is the error term.

The selected model's validity was confirmed based on the high R² value. Using the validated Logarithmic regression equation, the required minimum quality flow (Q_{Quality}) was calculated by setting the predicted concentration ($C_{\text{Pollutant}}$) equal to the regulatory standard defined in Government Regulation No. 22 of 2021 Class II, and then solving the equation for Q. This Q_{Quality} value represents the minimum flow required to maintain water quality standards through dilution.

RESULTS AND DISCUSSION

The Cirata reach forms part of the Citarum River cascade system in West Java, Indonesia, which consists of the Saguling, Cirata, and Jatiluhur reservoirs [35], [51]. The Cirata Dam acts as the intermediate reservoir, receiving inflows from both natural tributaries and the regulated outflows of the upstream Saguling Dam, and subsequently releasing water toward the Jatiluhur Reservoir. This configuration makes the flow regime downstream of the Cirata Dam highly regulated, primarily influenced by hydropower generation and irrigation demands (Figure 1. a). The watershed draining into the Cirata Reservoir covers an area of approximately 1,500 km², with an average annual rainfall ranging from 1,500 to 3,000 mm/year and a mean discharge of around 165.01 to 194.19 m³/s at the dam outlet.

The study reach is a 2.6-3 km section immediately downstream of the Cirata Dam outflow. Measurements were conducted at three monitoring points along the downstream reach of the Cirata Dam (Figure 1. b), namely STA 1100, STA 3450, and STA 5200, to record flow velocity and water depth. Instantaneous discharge measurements were used to validate the Manning's roughness coefficient and to obtain representative cross-sectional profiles for hydraulic modelling.

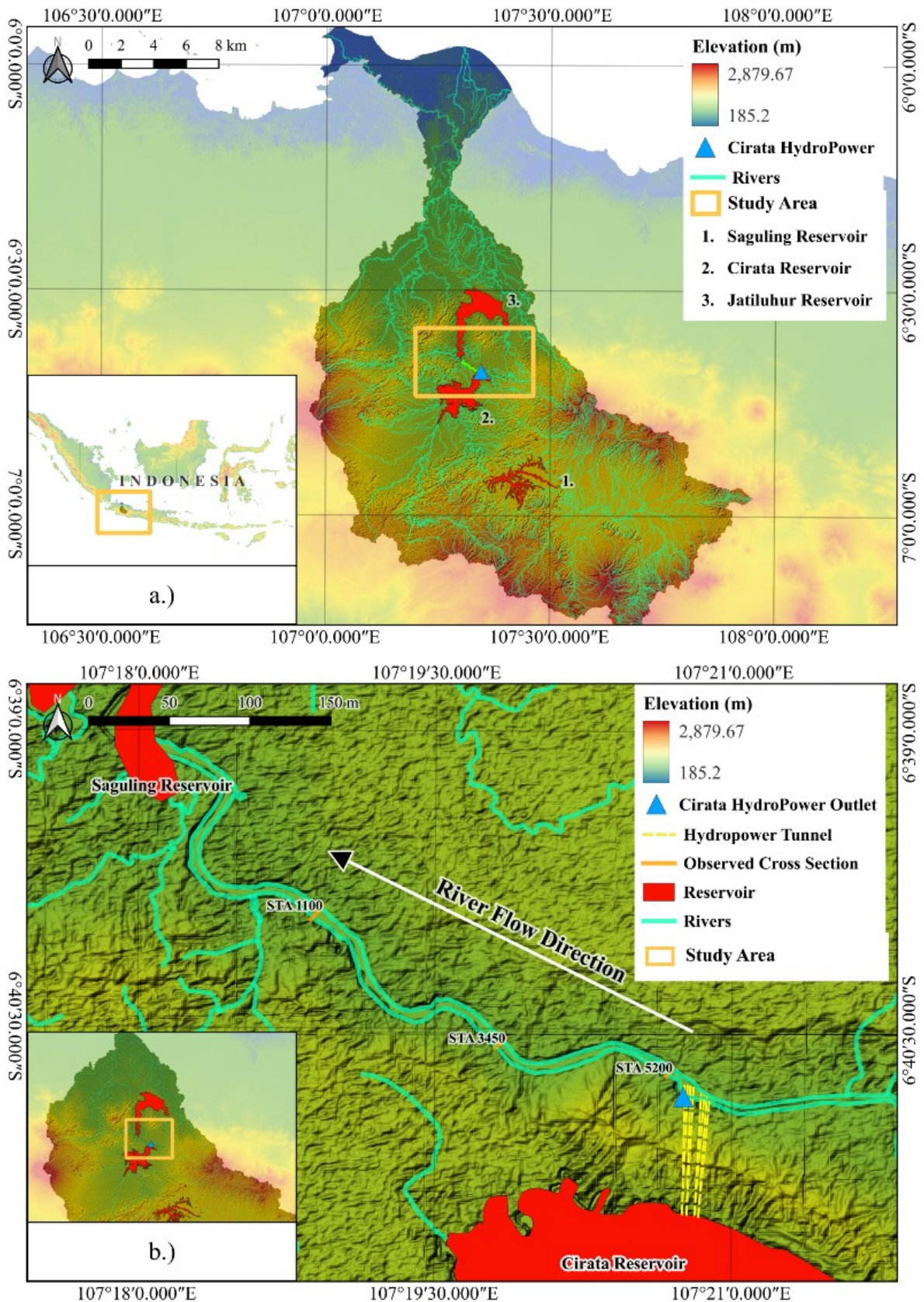


Figure 1. a.) Citarum watershed map showing the Saguling-Cirata-Jatiluhur cascade system b.) Measurement points and downstream study reach (STA 1100, STA 3450, and STA 5200)

The flow regime of the Cirata Dam was characterised by the Flow Duration Curve (FDC) analysis and the Low Flow Frequency (LFF) analysis. The discharge results of the Flow

Duration Curve and Low Flow Frequency calculations have different values. The results are visualised in Figure 2 and summarised in Table 4.

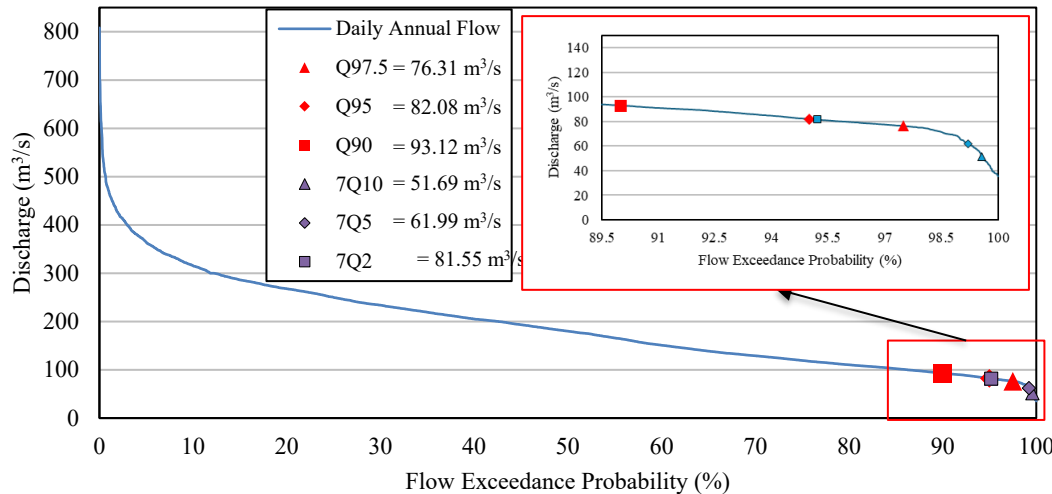


Figure 2. Flow Duration Curve of Cirata Dam Outflow

Table 4. Model discharge scenarios

Flow Duration Curve			Model Discharge (m ³ /s)					
			Low Flow Index					
			Gumbel Minima			Weibull Minima		
Q97.5	Q95	Q90	7Q10	7Q5	7Q2	7Q10	7Q5	7Q2
76.31	82.08	93.12	52.19	65.08	84.55	51.69	61.99	81.55

These discharge scenarios will be input as flow data into the HEC-RAS software for modelling the river's hydraulic flow, and thereafter, habitat simulations will be conducted to determine the suitability of the hydraulic flow depth and velocity parameters against the life requirements of each species.

The hydraulic modelling results on Figure 3 demonstrate successful calibration with Manning's value (n) is 0.037. The validation of this modelling result was carried out by comparing field test data and software prediction results, showing a high level of accuracy (Depth: R² = 0.973, RMSE = 0.479 m; Velocity: R² = 0.981, RMSE = 0.052 m/s).

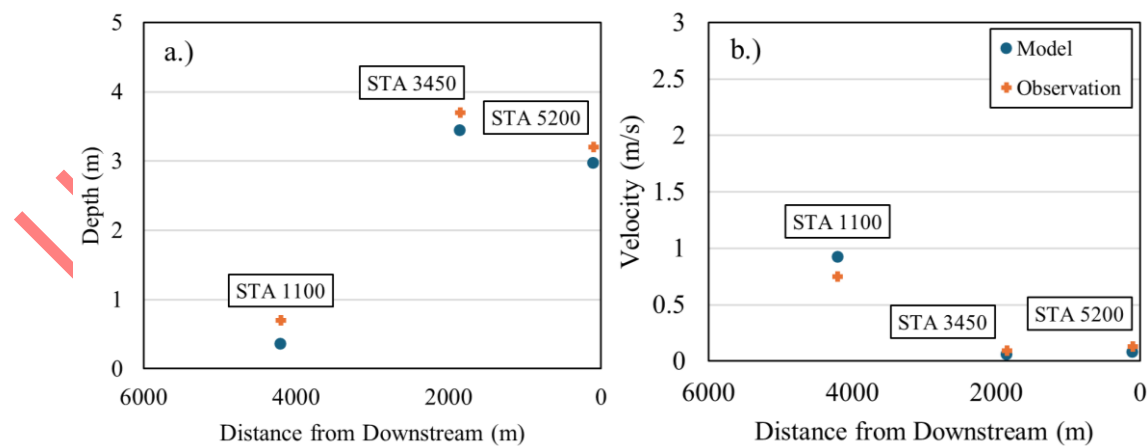


Figure 3. a.) Depth and b.) Velocity calibration data for the model and observation

Furthermore, hydraulic modelling is carried out by modelling each of the discharge scenarios calculated in the hydrological analysis for the steady flow model. Figure 4 shows the hydraulic modelling results indicate the flow pattern formed is consistent with the topographic

characteristics and the configuration of the analysed channel. Figure 4 also shows the highly variable riverbed morphology (dashed black line), with significant elevation changes. This morphological variation directly causes the flow to become irregular.

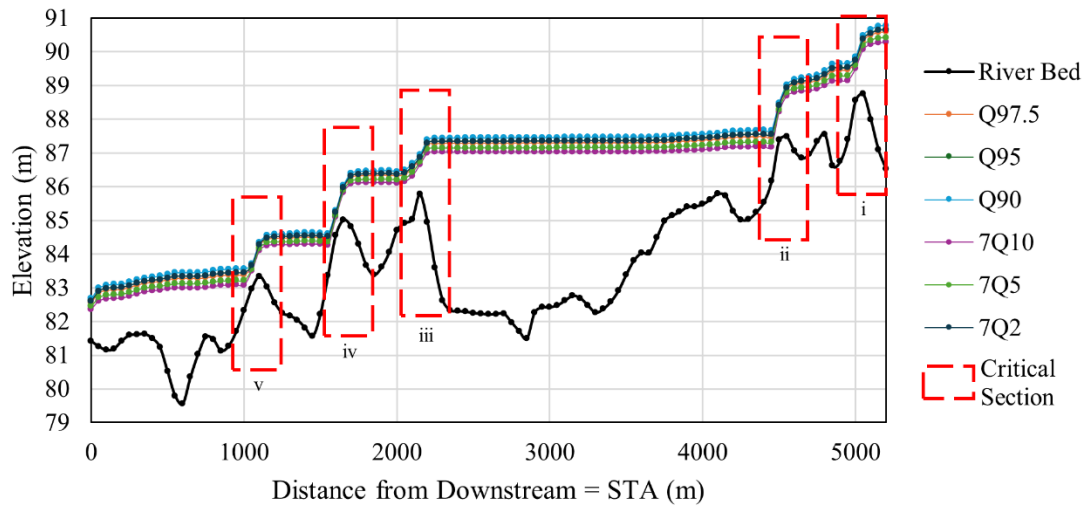


Figure 4. River longitudinal section with water surface elevation profile

Habitat Suitability Response to Discharge Variation

Habitat suitability parameter classification. Table 5 is the results of the calculation of flow velocity and depth parameter requirements for each fish species.

Table 5. Results of calculating speed and depth parameter requirements for each fish species

Name			Velocity Passage Estimation (m/s)					Min Depth Estimation (m)
Local	Scientific	Group	2.5%	12.50%	50%	87.50%	97.50%	
Mas	<i>Cyprinus carpio</i>	Salmon & Walleye	3.90	2.71	1.62	0.97	0.67	0.50
Hampal	<i>Hampala macrolepidota</i>	Salmon & Walleye	3.42	2.38	1.42	0.85	0.59	0.50
Nila	<i>Oreochromis niloticus</i>	Salmon & Walleye	4.06	2.83	1.69	1.01	0.70	0.75
Tagih	<i>Hemibagrus nemurus</i>	Catfish	2.02	1.63	1.19	0.87	0.70	0.50

After obtaining the parameter requirements for fish species, the matching process between the results of the hydraulic modelling that has been carried out with the parameter requirements of fish species. A 50 percent estimate was chosen as the upper limit of fish speed, considering that the result of the velocity passage estimation calculation represents the limit of the fish's ability to swim in the current.

Weighted usable area. Weighted Usable Area (WUA) analysis is conducted by matching the results of river flow hydraulic modelling with the living requirements parameters of each fish species. The results are visualised in the Figure 5 and Figure 6.



Figure 5. Weighted velocity usable area percentage for a.) *Cyprinus carpio*, b.) *Hampala macrolepidota*, c.) *Oreochromis niloticus*, d.) *Hemibagrus nemurus*

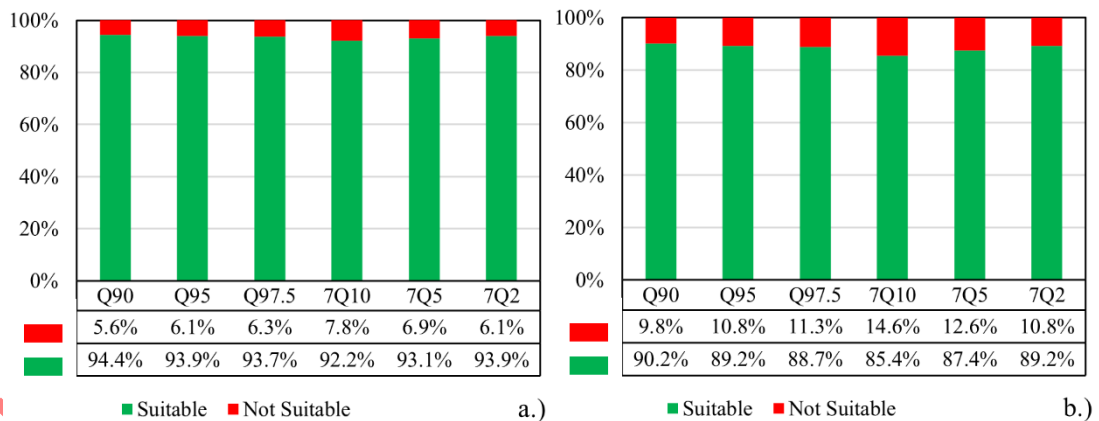


Figure 6. Weighted depth usable area percentage for a.) *Cyprinus carpio*, *Hampala macrolepidota*, *Hemibagrus nemurus*, and b.) *Oreochromis niloticus*

Figure 5 shows that the percentage of discharge area parameters indicates that increasing discharge can affect the presence of fewer fish due to the higher flow depth parameters. Otherwise, Figure 6 indicate that increasing discharge affects fewer fish due to the higher flow velocity parameters.

Hydraulic-habitat analysis. Figure 7 presents the hydraulic modelling results showing the relationship between flow velocity and water depth across multiple cross sections for each simulated discharge scenario. The figure aims to evaluate whether the hydraulic conditions at each modelled discharge fulfill the habitat requirements for fish species. In comparison to Figure 5 and Figure 6, which provide only the percentage of living fish species for each

modelled discharge, Figure 7 offers a more detailed perspective by directly comparing hydraulic parameters relevant to fish habitat sustainability.

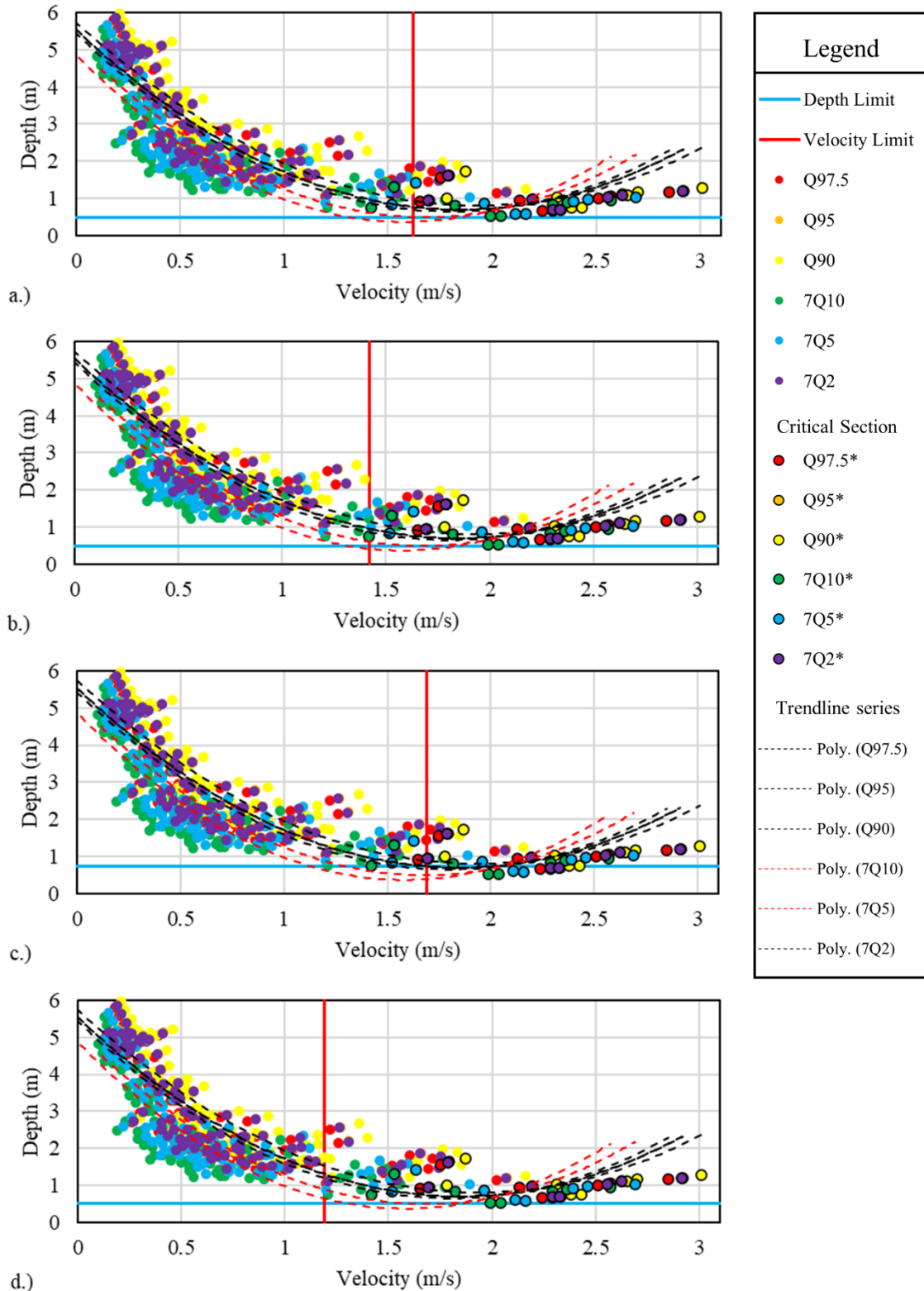


Figure 7. Model Discharge comparison with depth and velocity limit for a.) *Cyprinus carpio*, b.) *Hampala macrolepidota*, c.) *Oreochromis niloticus*, d.) *Hemibagrus nemurus*

Figure 7 serves as a fundamental reference for identifying hydraulic conditions that may pose risks to fish habitats. The outlined marker points indicate critical sections (i-v), showing locations where hydraulic conditions frequently exceed habitat thresholds. Data points located to the left of the velocity limit and above the depth limit represent suitable hydraulic conditions

for fish habitat. The dashed trendlines represent second-degree polynomial fits for each discharge scenario, demonstrating consistent velocity and depth relationships across the river reach with higher discharges. It generally shifting data points toward higher velocity and depth parameter regimes. These hydraulic stress zones are further examined spatially in Figure 8 and Figure 9, which identify the geographic locations that meet the habitat requirements based on the depth and velocity criteria established in this analysis.

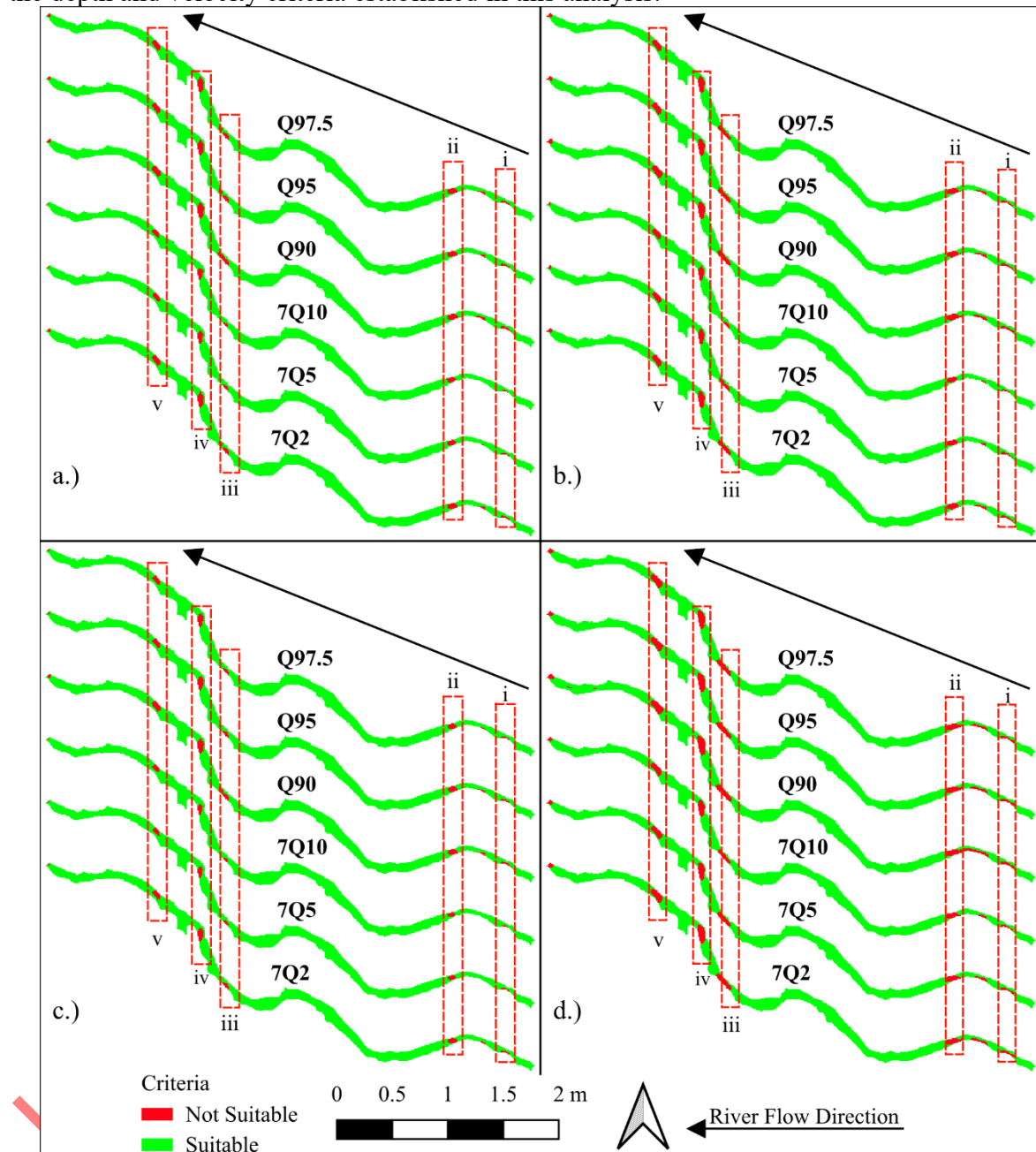


Figure 8. Weighted velocity usable area map for a.) *Cyprinus carpio*, b.) *Hampala macrolepidota*, c.) *Oreochromis niloticus*, d.) *Hemibagrus nemurus*

Figure 8 visualised the spatial distribution of velocity-based habitat suitability for different discharge scenarios. It complements the analysis shown in Figure 7 by highlighting critical sections (i-v), indicated by red stripe boxes, which is persistent of velocity limitations across multiple discharge scenarios. Critical sections ii and iv show the most extensive constraints, particularly at higher discharges. For each fish species, velocity limitations affect 3-11% of the reach across discharge scenarios, with the most severe constraints occurring at Q90 discharge.

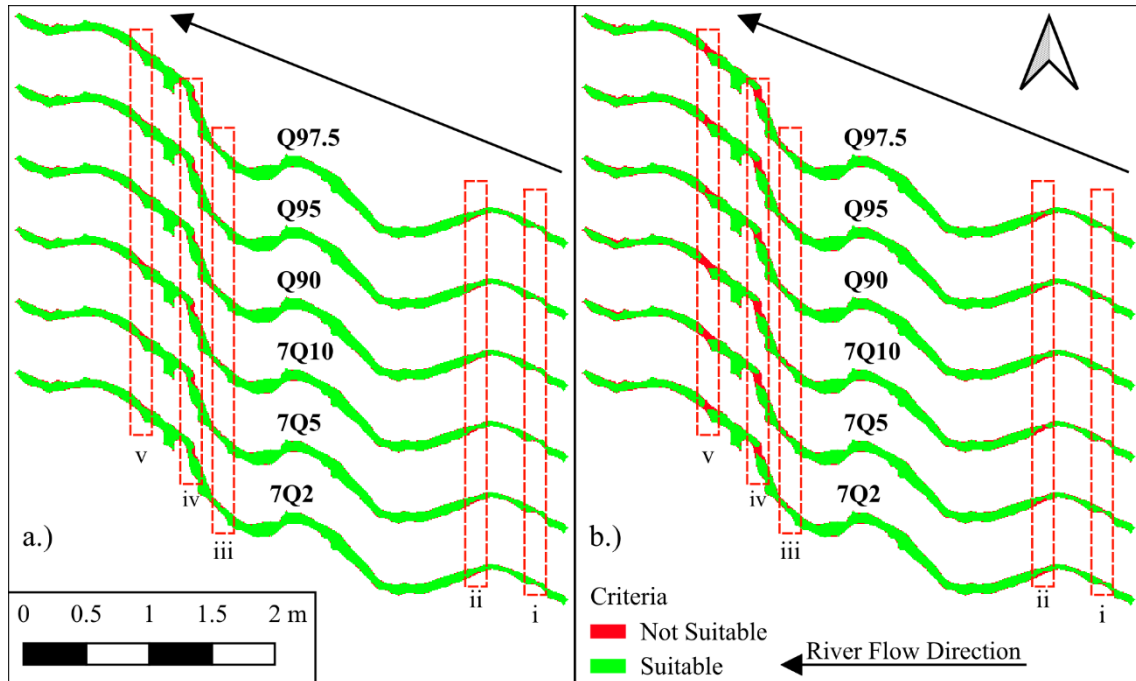


Figure 9. Weighted depth usable area map for a.) *Cyprinus carpio*, *Hampala macrolepidota*, *Hemibagrus nemurus*, and b.) *Oreochromis niloticus*

Figure 9 also shows spatial representation of the habitat simulation results based on flow depth. Green areas indicate zones where the depth supports fish habitat requirements, while red areas represent zones where the depth is insufficient. At Q90 discharge, approximately 90-94% of the study reach provides suitable depth conditions, decreasing to 85-92% at 7Q10 discharge.

Water Quality Modelling

Table 6 presents the annual water quality status and mean discharge data from 2014 to 2022. Water quality status, assessed using the STORET method, ranges from 16 (moderate pollution) to 34 (heavy pollution), while annual discharge varies from 80.69 to 291.49 m³/s. Figure 10 visualises the concurrent trends of both parameters over the nine-year period.

Table 6. Annual water quality and discharge data

Years	Water Quality Status	Discharge (m ³ /s)
2014	18	219.82
2015	18	161.65
2016	18	291.49
2017	16	245.29
2018	20	170.69
2019	18	170.93
2020	32	88.00
2021	34	80.69
2022	20	111.5

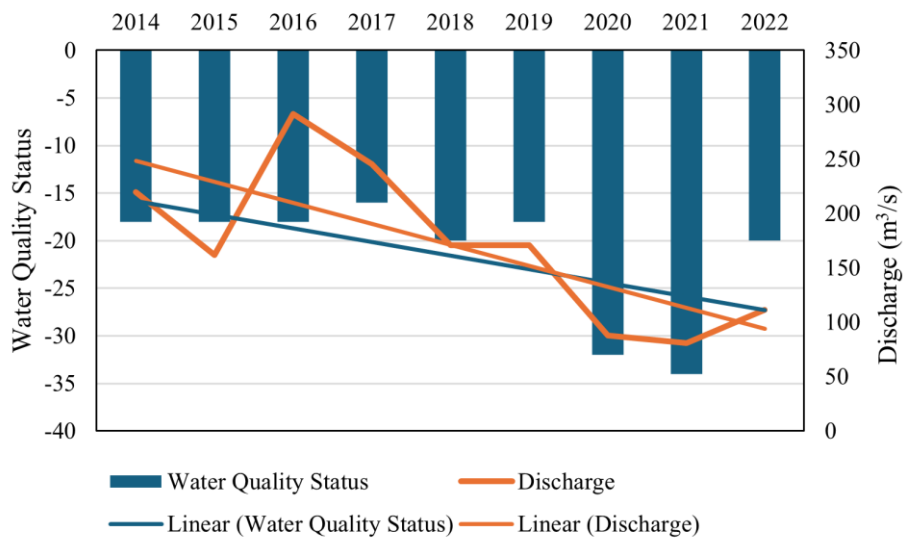


Figure 10. Water quality status and mean annual flow rate

Figure 10 shows the temporal variation of water quality status and mean annual discharge from 2014 to 2022. This pattern is observable across multiple years, where higher annual discharge values are associated with improved water quality status. The data reveal concurrent declines in both parameters in 2020-2021, with discharge decreasing to 80.69-88.00 m³/s and water quality status deteriorating to 32-34 (heavy pollution). Subsequent recovery is observed in 2022, with improved discharge (111.50 m³/s) and water quality status (20, moderate pollution), supporting the dilution principle: the more water released into the river, the more diluted the pollutant concentrations become.

The regression analysis was conducted to derive a predictive model that can estimate the discharge required to achieve a targeted water quality status, to further quantify the relationship observed in Figure 10. Specifically, the aim was to determine the discharge rate that would result in a water quality index of zero, classified as “very good” based on the STORET method. The resulting logarithmic regression is presented in Figure 11.

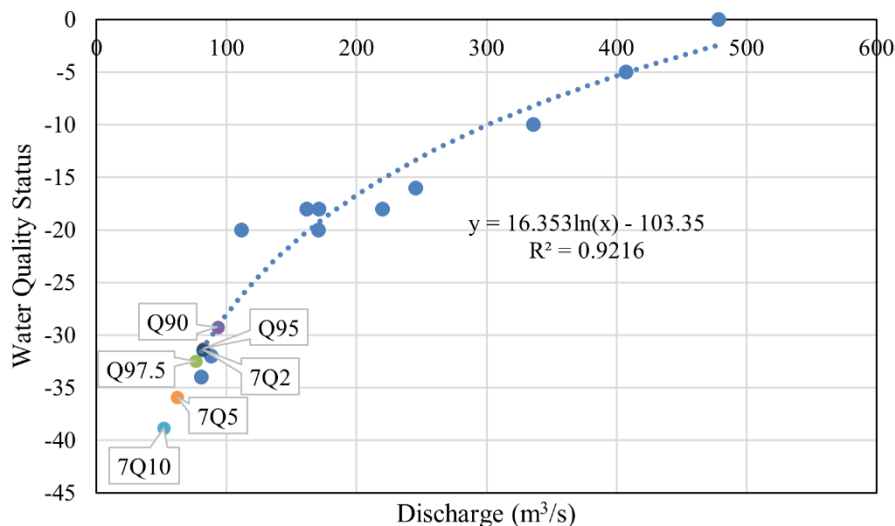


Figure 11. Correlation between water quality and discharge with logarithmic trendline equation

Figure 11 illustrates the correlation between water quality status and discharge using a logarithmic regression model. The regression analysis demonstrates a strong statistical relationship between discharge and water quality status ($R^2 = 0.9216$). However, the discharge required for 'very good' water quality (556.17 m³/s) represents an exceedance probability of less than 0.5% based on historical flow records.

Novelty and Applicability of the Integrated Framework

Addressing the challenges of Environmental Flow (EF) assessment in regulated, data-scarce tropical rivers remains a critical research frontier. Most conventional EF methods are either too data-intensive (e.g., PHABSIM) or too simple (e.g., hydrological methods) to capture the ecological complexity driven by both water quantity and quality. The framework proposed herein, which integrates species-centred hydraulic-habitat modelling, flow-water quality regression, and an adaptive hydrological approach, offers a novel, multi-dimensional solution to this gap. This integrated approach fundamentally shifts the assessment from a single-focus analysis (e.g., only quantity) to a comprehensive ecological and physico-chemical evaluation, ensuring EF recommendations are based on the most limiting ecological factor.

The applicability of this framework is demonstrated through its ability to select the most contextually relevant hydrological scenarios for regulated systems. Our analysis compared flow duration curve (FDC) methods, such as Q90 and Q95, with low-flow indices, such as 7Q10. In determining the LFF method, Weibull Minima was chosen because it resulted lower value compared to the Gumbel Minima method, thus serving as the most conservative and extreme representation of the minimum water requirement for environmental flow. In a river segment downstream of a large dam, like the Citarum, flow availability is primarily dictated by reservoir releases and management decisions rather than natural drought extremes. Consequently, the Q90 method proves more relevant for establishing a reliable maintenance flow because it focuses on the availability of discharge over time, reflecting conditions under which flow is consistently managed. Conversely, relying solely on extreme indicators like 7Q10, which represents less frequent and extreme conditions, provides limited ecological and regulatory utility in a heavily regulated system, thereby underscoring the necessity of an adaptive hydrological choice within the framework tailored to managed rivers.

The Logic of Integration from Determining the Final Environmental Flow

The determination of the final Environmental Flow (EF) regime is rooted in the principle of the most restrictive limiting factor, which states that the overall ecological integrity of a river is constrained by the parameter that requires the highest flow. This principle necessitates integrating the two critical flow components derived from our framework: hydraulic-habitat flow (Q_{Habitat}) and water quality flow (Q_{Quality}). In this study, the Q_{Habitat} derived from species-specific suitability curves indicated an optimal flow of $93.12 \text{ m}^3/\text{s}$ to maximise available habitat for target species. Simultaneously, the Q_{Quality} analysis, based on the regression between discharge and water quality status, required a mean annual flow of $556.17 \text{ m}^3/\text{s}$ to achieve a "very good" status index ($WQIS = 0$).

A direct comparison reveals a significant conflict: the flow required for ideal water quality ($556.17 \text{ m}^3/\text{s}$) is orders of magnitude higher than optimal habitat flow ($93.12 \text{ m}^3/\text{s}$). More critically, the Q_{Quality} requirement corresponds to an annual exceedance probability of less than 0.5%, making it hydrologically unrealistic and unsustainable under normal river management conditions. Therefore, while water quality remains a severe ecological concern, the EF recommendation cannot be driven solely by the flow requirement for dilution. Instead, the final EF must be determined by the most stringent Q_{Habitat} that is simultaneously hydrologically reliable. Based on the adaptive hydrological analysis, the flow probability of ($Q90 = 93.12 \text{ m}^3/\text{s}$) was selected as the final, reliable EF recommendation.

represents a necessary eco-hydraulic trade-off. This flow rate is sufficient to maintain 94.1% of the optimal habitat area (i.e., maintaining ecological function) while remaining within a discharge level that is consistently available in a hydropower system. Furthermore, this choice aligns with Indonesian regulation (PP No. 38/2011), which mandates a minimum flow with Q95 for maintenance. By selecting Q90, the EF provides a buffer above the mandated minimum, offering better ecological security. This integrated determination highlights that when one ecological constraint (water quality) is driven by non-flow sources, the EF

recommendation serves primarily to maintain the physical-habitat integrity and river self-purification capacity, while pollution must be addressed through complementary watershed management policies.

Multi-Dimensional Constraints on Environmental Flow Determination

Although the Environmental Flow (EF) regime is established based on realistic flow availability, its effectiveness is severely limited by local flow dynamics and river morphology. Analysis shows that unsuitable habitat conditions in specific river segments are closely linked to flow characteristics, particularly the phenomenon of Gradually Varied Flow (GVF). Changes in riverbed morphology, such as narrowing, widening, and variations in slope (as illustrated in Figure 4), act as hydraulic controls creating GVF conditions.

According to GVF theory, an increase in riverbed slope results in a significant decrease in water depth. This decrease in depth directly reduces habitat suitability for aquatic species, as the water depth becomes less than the ecological threshold required for essential activities (such as foraging and shelter). Furthermore, the assumption of relatively constant discharge (Q) in areas experiencing a decrease in wetted cross-sectional area (due to shallow depth) will lead to an increase in flow velocity (based on the principle of continuity $Q = A \times V$). This increase in velocity, particularly at low flows such as $Q_{97.5}$ or $7Q_{10}$, can exceed the species' biological tolerance thresholds, making it the second limiting factor.

This finding emphasises that a comprehensive determination of EF cannot rely solely on bulk discharge values, but must consider the spatial distribution of flow characteristics (depth and velocity) which are directly influenced by local morphology. Failure to account for these species-specific hydraulic-habitat constraints can lead to EF recommendations that are theoretically adequate but ecologically ineffective in critical sections.

The second constraint limiting the effectiveness of EF is the condition of water quality, which necessitates interventions beyond flow management. Regression analysis shows that, although there is a strong statistical correlation between discharge and water quality status ($R^2 = 0.9216$), an increase in discharge alone is not sufficient to consistently ensure good water quality status.

As concluded in the section Water Quality Modelling, the discharge required to achieve "very good" water quality status approximately $556,168 \text{ m}^3/\text{s}$ is hydrologically unrealistic. These findings strongly indicate that the dominant factor influencing the decline in water quality downstream of the Cirata Dam is not hydrological factors, but rather non-flow pollution sources such as domestic waste, aquaculture waste, and other anthropogenic activities in the watershed.

Consequently, the role of environmental flow in the context of water quality has shifted from a controlling variable to a supporting factor. Maintaining a minimum flow rate is crucial to prevent further degradation due to pollutant accumulation and to support the river's self-purification capacity. However, for a substantial improvement in water status, EF recommendations must be complemented by complementary watershed governance policies that directly address and control the main sources of pollution.

Broader Implications for River Basin Management and Policy

The findings highlight a crucial paradigm shift required in the management of regulated tropical rivers: ecological sustainability demands more than simply meeting a minimum flow requirement. The proposed framework demonstrates that maintaining ecological integrity, particularly in systems facing multi-dimensional pressures, necessitates integrated, multi-disciplinary frameworks that simultaneously address hydrological, physical-habitat, and water quality needs. In general, this approach offers a transferable template for river basins in other tropical regions, particularly those regulated by hydropower infrastructure and facing similar data constraints, to adopt faster, species-based, and ecologically relevant EF assessment.

The main policy implications of this research centre on the need to bridge the gap between water quantity and water quality policies. The established EF decision (which is $Q_{90} = 93.12 \text{ m}^3/\text{s}$) is effective in maintaining the integrity of the physical habitat and supporting the river's self-purification capacity (as discussed in the The Logic of Integration from Determining the Final Environmental Flow section). However, this effectiveness is severely limited by the dominance of non-flow source pollutants. Therefore, environmental flow policies must be strengthened by complementary watershed management policies that actively target and control sources of domestic pollution, aquaculture, and industry upstream.

Although the proposed framework provides a robust solution for data-limited conditions, certain limitations must be acknowledged as future research directions. First, this framework can be improved by incorporating ecologically relevant short-term flow fluctuation analysis, which may be missed by FDC analysis based on monthly or annual averages. Second, future research should verify the modelling assumptions (e.g., fish swimming parameters) with actual field data to improve the representation of river system heterogeneity. Strengthening this aspect will increase the framework's robustness, ensuring that water management policies are context-sensitive and adaptive to achieve sustainable environmental governance.

CONCLUSION

This study successfully developed and applied a novel, integrated Environmental Flow Assessment framework for regulated and data-scarce tropical rivers by systematically combining species-centred hydraulic-habitat criteria and discharge-water quality analysis. The integrated approach demonstrated that establishing an EF regime, which is the selected Q_{90} flow discharge, is highly effective in maintaining the physical-habitat suitability for target fish species, even at lower discharge rates, provided the complex local constraints like Gradually Varied Flow (GVF) are acknowledged. However, the most critical finding is the empirical proof that the river's ecological health is ultimately limited by non-flow pollutant sources, which demand flow rates for dilution that are hydrologically unsustainable. This research study highlights key contributions and emphasises that environmental flow policies in regulated river systems must be closely linked to complementary watershed management policies to ensure ecological function, thus providing information for future sustainable watershed planning globally.

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