

Integration of water quality in the habitat simulation approach of an Environmental Flow Assessment (EFA)

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Abstract

Determining environmental flow (EF) using the habitat simulation approach without considering water quality does not accurately reflect true ecosystem health. This study integrates water quality components into the determination of EF at Lata Sempeneh, Perak, upstream of the Kurau River. Six cross-sections were established and data on hydraulic variables, water quality parameters and aquatic insects were collected from October 2018 to September 2019. The mean annual flow (MAF) was 1.67 m³/s and aquatic insects (Ephemeroptera, Plecoptera, Trichoptera, and Odonata (EPTO)) were selected as the ecological indicators. Habitat Suitability Curves (HSCs) for velocity, water depth and substrate were developed and both slope and curvature methods were applied to determine the EF. The EPTO taxa showed the highest preference for velocities of 0.21–0.40 m/s, depths of 0.21–0.40 m and substrate sizes ranging from –2.01 phi to –4.00 phi. The EF values obtained from the slope and curvature methods were 0.73 m³/s and 1.03 m³/s, corresponding to 43.8% and 61.5% of the MAF, respectively. Water quality validation indicated that an EF of 61.5% of the MAF was most appropriate. This flow ensures that recreational water conditions at Lata Sempeneh comply with the National Water Quality Standards for Malaysia, specifically Class II. The inclusion of water quality in Environmental Flow Assessment (EFA) resulted in an EF that is closer to the MAF, thereby helping to maintain ecosystem integrity and ensure its continued functioning.

Keywords: EF, EFA, environmental flow, environmental flow assessment, EPTO, flow

Introduction

Flow is regarded as one of the key factors influencing river health and the capacity of river ecosystems to provide services (Norris & Thomas, 1999) and it is often identified as the primary variable governing riverine ecosystems (Power et al., 1995) because it shapes their ecological characteristics. Alterations to natural flow regimes reduce ecological integrity and negatively affect water quality, physical habitat availability and the diversity of macroinvertebrates, fish and riparian vegetation (Galat & Lipkin, 2000; Poff & Zimmerman, 2010).

Changes in flow can also affect the natural goods and services derived from rivers. Therefore, a sufficient amount of flow must be maintained to sustain ecosystem services and biodiversity. Flow plays a crucial role in maintaining biodiversity by creating aquatic habitats, transporting food from upstream, inundating floodplains during high flows and flushing sediments and degraded water quality through river systems (O’Keefe & Quesne, 2009). In addition, river flows shape channel morphology through sediment transport and deposition. Variations between high and low flows produce diverse riverbed conditions, such as rocky,

muddy, or sandy substrates which support a wide range of organisms due to the formation of heterogeneous physical habitats. Bunn and Arthington (2002) described flow as the major determinant of physical habitat in rivers, emphasizing that riverine species have evolved primarily in response to natural flow regimes. Connectivity throughout river channels and floodplains is essential for sustaining riverine populations, while altered flow regimes may facilitate the spread of invasive species.

With increasing development, society faces challenges in ensuring reliable water supplies while simultaneously protecting the ecological integrity of freshwater ecosystems (Walsh et al., 2012). The importance of preserving environmental flows has been widely recognized by scientists and water resource managers, making it a critical component of water resource management (Poff & Zimmerman, 2010). In recent years, governments have prioritized environmental flows to mitigate adverse impacts on aquatic ecosystems, leading to the development of various approaches for determining environmental flows in water resource projects (Yang et al., 2016).

There is growing awareness of the need to maintain natural flow regimes in rivers to support healthy freshwater ecosystems (Mohan et al., 2022). In addition to natural phenomena such as climate change and natural disasters, numerous hydraulic structures have been constructed for domestic, industrial, irrigation, hydropower and flood control purposes. These structures have altered natural flow variability, resulting in adverse impacts on water quality, aquatic organisms and ecological habitats. Consequently, environmental issues arise due to the gradual degradation of ecological functions (Liu et al., 2016).

Scientists have long recognized the need to maintain a minimum amount of water in rivers to support aquatic organisms (Tegos et al., 2018). Initially, the minimum flow concept linking river health primarily to low-flow conditions was used to protect ecosystems (Piniewski et al., 2011). However, the concept of environmental flow (EF) has since been adopted, as it incorporates scientific assessment and regulatory considerations (Li et al., 2009). Hirji and Davis (2009) defined EF as the quantity, quality and timing of water flows required to sustain the components, functions, processes and resilience of aquatic ecosystems that provide goods and services to people.

Another concept frequently discussed in river management is the Total Maximum Daily Load (TMDL), which represents the maximum amount of pollutants that can enter a water body without violating water quality standards (Adnan et al., 2022). While TMDL focuses on allowable pollutant loads from various sources, it differs from the environmental flow concept, which emphasizes the flow requirements necessary to sustain riverine habitats. Environmental flow assessments typically consider changes in flow under existing pollution levels, whereas TMDL studies are applied when new or increased pollutant inputs are introduced. Moreover, TMDL assessments rarely incorporate ecological components.

Research integrating water quality into environmental flow assessments remains limited. Most studies emphasize ecological components without concurrent empirical evaluation of water quality. Determining EF based solely on ecological targets may produce inconsistent results due to varying flow preferences among different organisms. Furthermore, environmental flow assessments often focus on only a small number of species, despite the presence of hundreds of species within river systems. As a result, the derived EF may not represent optimal conditions for the entire ecosystem. Underestimated EF values can lead to water quality degradation, which may jeopardize ecosystem health and result in the loss of sensitive species. Therefore, water quality should be evaluated concurrently with ecological and physical habitat components in EFAs.

Water quality has been identified as a crucial factor in EFAs (Chaudary et al., 2019), as anthropogenic pollution has constrained water quality improvements in many river systems (Huang et al., 2014). Previous studies have demonstrated that streamflow variations significantly influence water quality parameters, including dissolved oxygen and biochemical oxygen demand

(Walling et al., 2017). Additionally, significant correlations have been observed between flow and parameters such as total suspended solids and pH, supporting findings by Maharjan et al. (2016). These studies highlight the importance of integrating water quality into environmental flow assessments.

Environmental flow recommendations derived from habitat simulation approaches that neglect water quality may not accurately reflect the true condition of river systems under altered flow regimes. Reductions in flow can degrade water quality, potentially conflicting with national water quality policies and threatening aquatic organisms. Such impacts may be exacerbated in downstream reaches where reduced dilution capacity intensifies water quality deterioration. Given that most EFAs have not explicitly incorporated water quality alongside ecological inputs (Walling et al., 2017), this study proposes integrating water quality factors with ecological components within habitat simulation approaches. Tegos et al. (2018) supported the integration of hydrological, hydraulic, biological and water quality data to establish direct links between habitat availability and flow.

Flow alteration is one of the primary drivers of ecosystem disturbance in river systems. In addition to physical habitat changes, variations in water quality influence biological interactions among biotic and abiotic components and affect overall river functioning (Stein et al., 2021). Consequently, impaired water quality can reduce the ecosystem's ability to deliver essential services. This study aims to determine the optimal environmental flow required to sustain river ecosystem services by integrating water quality requirements into a habitat simulation methodology. The research addresses the following questions: (i) Does flow reduction impact water quality? (ii) To what extent does water quality change when flow is reduced for EF allocation? (iii) Does integrating water quality improve EF determination using habitat simulation? These questions lead to the hypothesis that environmental flow estimates are more effective when water quality is incorporated into environmental flow assessments.

Establishing an optimal environmental flow is necessary to minimize ecological disturbance resulting from flow alteration. Therefore, appropriate methods must be selected that are practical for policymakers, considering ease of application, technical expertise and cost. Tharme (2003) documented 207 environmental flow methods across 44 countries, a number that has likely increased in recent years. These methods vary according to management objectives, regional needs and constraints such as funding, time, data availability and technical capacity. Within the Instream Flow Incremental Methodology (IFIM), the United States Geological Survey developed the Physical Habitat Simulation System (PHABSIM), a hydraulic-habitat modeling tool used to evaluate the effects of flow changes on aquatic habitats, particularly fish. However, its application has declined in recent years, with Johnson et al. (2017) being among the most recent studies applying PHABSIM in the Godavari River, India. Another tool used in EFAs is CASiMiR-Fish, developed by the University of Stuttgart, Germany, for river and fish habitat assessment.

In this study, inflection point methods specifically the slope and curvature methods were applied. Two inflection points (lower and upper) were identified from the relationship between flow and weighted usable area (WUA). These methods assume that food availability is a primary factor influencing river carrying capacity and the sustainable abundance of aquatic organisms (Nelson, 1989). Inflection point methods have been widely applied in EFAs because they effectively describe the relationship between flow and hydraulic variables, where physical habitat availability is represented by WUA. This approach is consistent with the principles of IFIM, making the use of slope and curvature methods appropriate for determining environmental flow in this study.

Method and research area

Research area

The Sempeneh Recreational Area, also known as Lata Sempeneh, is a well-known tourist destination in Perak, Malaysia. It is located at 4.920069°N and 100.830803°E at the foothills of the Bintang Range, which forms part of the headwaters of the Kurau River. The area extends several hundred meters upstream, transitioning from large boulders in the upper reaches to undulating terrain downstream, where Sempeneh Village is located.

Within the recreational area, facilities include two small resorts, a retail outlet selling dry food items and public toilets for visitors. Further upstream, a campsite is accessible via a hiking trail. A water intake structure is located approximately two kilometres upstream and operates at a capacity of 3,000 m³/day. Agricultural activities are present in the vicinity, however unlikely to contribute to river pollution. Most likely, the recreational activities by visitors represent the only identifiable source of pollution. The site was selected for this study due to its minimal anthropogenic disturbance, aside from tourism-related activities, which aligns with the criteria of this research. Additionally, the site features a variety of flow types and remains accessible and safe throughout the sampling period.

The Kurau River is the main drainage artery of the basin, draining an area of approximately 682 km² that is predominantly low-lying (Zorkeflee et al., 2005). The river originates partly in the Bintang Range and partly in the Main Range. The upper reaches are characterized by steep, mountainous terrain, while the river ultimately discharges into the Melaka Strait at Kuala Kurau. The mid-valley sections consist of low to undulating terrain, transitioning into broad and flat floodplains downstream.

Ground elevations at the river headwaters reach approximately 1,200 m at Batu Besar and 900 m at Batu Ulu Trap. Slopes in the upper 6.5 km of the river average 12.5%, whereas slopes in the lower reaches range from approximately 0.25% to 5%. A dam constructed approximately 65 km downstream of the headwaters forms the Bukit Merah Reservoir, which primarily serves irrigation demands for downstream paddy cultivation. Upstream of the reservoir, two main river subsystems are present, of which the Kurau River subsystem and the Merah River subsystem. Both drain undulating to steep terrain before discharging into the reservoir.

Land use within the Kurau River subsystem is dominated by tree crop agriculture, while the Merah River subsystem is largely covered by the Pondok Tanjong Forest Reserve. The upper portion of the Kurau River basin lies within the District of Larut, Matang and Selama, while the downstream reaches fall within the Kerian District where both districts are located in the state of Perak. The basin is predominantly rural, with numerous riverine villages distributed from the mid to lower reaches of the river. The Kurau River and the study sub-catchment are shown in Figure 1, with the latter highlighted in yellow.

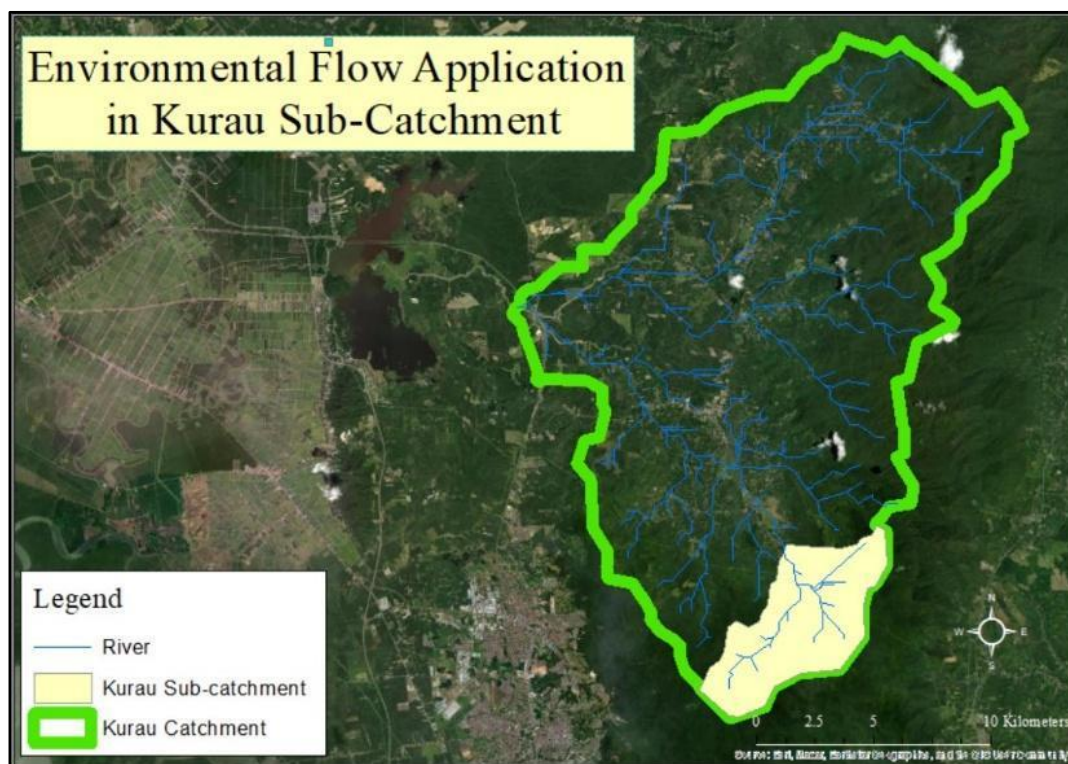


Figure 1. Kurau River Basin

Bukit Merah Lake is regulated by a dam constructed in the early 1900s. According to the Department of Irrigation and Drainage (DID), water releases downstream into the Kurau River occur only under emergency conditions, specifically when the lake water level reaches a designated safety threshold. Such releases take place through two outlets located at the northern and southern spillways and typically occur during the rainy season. Under normal operating conditions, water is released daily into the Selinsing Channel to meet irrigation demands.

The upstream Kurau Catchment is divided into four sub-catchments: the Kurau, Ara, Jelai, and Ayer Hitam sub-catchments. These sub-catchments cover areas of 159 km², 114 km², 32 km² and 39 km², respectively. The focus of this study is the Kurau sub-catchment.

Site preparation

Lata Sempeneh extends for several hundred meters, characterized by a series of stepped waterfalls that transition into an undulating downstream reach where tourists typically congregate. The total length of the recreational reach is approximately 540 m, with most sections dominated by large boulders, particularly within the waterfall zones. The undulating downstream reach is less than 100 meter in length, however, certain sections contain large boulders and high-velocity currents, which pose challenges for field sampling and measurements.

Six transects were established along the study reach, extending from one riverbank to the opposite bank. Each transect had a width of two meters and consisted of three sampling stations. Every transect encompassed at least two flow types, including run, run-pool or riffle habitats. Substrate composition varied across transects, ranging from clay to boulder sized materials, reflecting the importance of substrate heterogeneity as a primary factor influencing aquatic insect habitats (Brooks et al., 2005).

The first three transects were located in areas with relatively low canopy cover, while the remaining three upstream transects were situated under denser vegetation cover. Transect selection was based on three primary criteria, flow type (run, run-pool and riffle), substrate

composition (range of grain sizes) and shading condition. Additionally, flow variability was considered by conducting continuous sampling over twelve consecutive months, thereby capturing both low and high flow conditions.

Hydraulic variables

For each transect, a measuring tape was stretched across the river from one bank to the opposite bank at the water's edge, corresponding to the water level at the time of sampling. The measured distance represented the surface water width of the transect and varied between sampling events due to changes in water level. The total width was divided into three equal sections to establish three sampling stations.

Water depth was measured at each sampling station using a graduated ruler. Three depth measurements were taken along the transect line at each station and averaged. Depth was measured vertically from the riverbed surface to the water surface.

Flow velocity was measured using a Seba current meter. At each sampling station, velocity measurements were taken three times at the same locations as the depth measurements. The current meter was positioned at one-third of the total water depth below the water surface, following standard practice (Herschy, 1993). Velocity readings were recorded once the meter display had stabilized.

Water quality parameters

A YSI multiparameter probe was used to measure dissolved oxygen (DO), temperature, pH, total dissolved solids (TDS) and electrical conductivity. At each sampling station, three readings were recorded on every sampling date and the probe was calibrated prior to field deployment.

Water samples were collected using the grab sampling method. At each station and sampling event, a 1,000 mL polyethylene container was used to collect water samples for laboratory analysis of total suspended solids (TSS) and total nitrogen (TN). For total phosphorus (TP) analysis, water samples were also collected at each station. All samples were preserved by the addition of 2 mL of hydrochloric acid (HCl) and stored at 4 °C until analysis.

For biochemical oxygen demand (BOD) and ammoniacal nitrogen (AN) analyses, 1,000 mL water samples were collected at each station on every sampling date. A separate 500 mL sample was collected for chemical oxygen demand (COD) analysis, to which 0.5 mL of hydrochloric acid (HCl) was added for preservation, following USEPA guidelines (USEPA, 1982).

Total suspended solids (TSS) were determined using the gravimetric method based on EPA Method 160.2. Three replicate samples of 250 mL each were filtered through a 47 mm glass fibre membrane filter using a vacuum filtration system. Prior to filtration, the membrane filters were dried in an oven at 103–105 °C for one hour, cooled in a desiccator and weighed. After filtration, the filters containing retained solids were dried again at 103–105 °C for 24 hours, cooled in a desiccator and reweighed. TSS concentrations were calculated using Equation 1, and the final TSS value for each station was obtained by averaging the three replicate measurements.

$$\text{TSS (mg/L)} = \{(A - B) \times 1000\} / C \quad (1)$$

Where,

A = weight of filter + filtrate in mg

B = weight of filter in mg

C = volume of sample filtered in ml

Chemical oxygen demand (COD) was determined following APHA Method 5220 D, known as the closed reflux colorimetric method (APHA, 2005). COD concentrations (mg/L) were measured using a colorimeter.

Total phosphorus (TP) analysis was conducted in accordance with EPA Method 365.3 (APHA, 2005), which quantifies all forms of phosphorus, including orthophosphates, condensed phosphates and organic phosphorus in both dissolved and particulate phases. Measurements were performed using a PerkinElmer Lambda 25 spectrophotometer at a wavelength of 880 nm. Total phosphorus was expressed as the concentration of orthophosphate measured after digestion.

Total nitrogen (TN) was analysed using APHA Method 4500 (APHA, 2005), specifically the cadmium reduction method, which measures both organic and inorganic forms of nitrogen. Absorbance was measured using a PerkinElmer Lambda 25 spectrophotometer at a wavelength of 543 nm.

Biochemical oxygen demand (BOD) was determined following APHA Method 5210 B, with dissolved oxygen measurements conducted in accordance with APHA Method 4500-O G (APHA, 2005).

Ammoniacal nitrogen (AN) was analysed using APHA Method 4500-F, known as the phenate method (APHA, 2005).



Plate 1. Water quality in situ parameters recorded using a YSI multi probe

Geological variables

Substrate distribution was observed and recorded at each sampling station during every sampling event. Grain-size classification was based on the Wentworth scale (Wentworth, 1922). At each station, the percentage cover of boulders, cobbles and other substrate types on the riverbed surface was visually estimated and recorded. The category other included grain sizes ranging from pebbles to clay.

For example, at a sampling station with a surface area of 2 m × 4 m, substrate composition may consist of 10% boulders, 20% cobbles and 20% other grain sizes. To further quantify the composition of the other category, approximately 0.5 kg of substrate material was randomly collected from each station and transported to the laboratory for grain-size analysis.

Laboratory analysis was conducted using the Folk and Ward (1957) method, employing sieve grain size analysis in accordance with the Standard Test Method for Particle-Size Analysis of Soils (ASTM D422; ASTM, 2002). The final output of the analysis was expressed as the

percentage composition of boulder, cobble, pebble, granule, sand and silt–clay fractions occupying the surface area of each sampling station.



Plate 2. Mechanical shaker used in particle size analysis

Macroinvertebrates

Aquatic insects were sampled at each station using the kick sampling technique (Barbour et al., 1999), a widely employed method for collecting benthic macroinvertebrates from riverbeds. At each station, substrate within a 2 m × 4 m area was disturbed by kicking in front of a D-frame net, oriented with the net mouth facing the flow. Each station was kicked nine times and the dislodged organisms were captured by the net, transferred to three plastic containers per station and transported to the laboratory for further analysis.

The D-frame net used had a conical shape, a mesh size of 500 µm, a width of 30 cm and a length of 60 cm, fitted to a long handle. Collected aquatic insects, specifically Ephemeroptera, Plecoptera, Trichoptera and Odonata (EPTO), were visually sorted using forceps and preserved in universal bottles containing 80% ethyl alcohol (EtOH) (Che Salmah et al., 2001). In the laboratory, the abundance of each order of EPTO was counted and recorded.

Aquatic insects were selected over fish as target organisms for several reasons. First, literature reviews of the study area indicated that aquatic insects were abundant (Suhaila et al., 2016; Suhaila et al., 2017; Siti Hamidah et al., 2017). Second, the study area represents a microhabitat in the upper reach of the Kurau River, where fish mobility makes them unsuitable for assessing local habitat limitations, whereas aquatic insects are sedentary and reflect site-specific conditions. Third, the upper reach exhibits higher insect abundance compared to downstream sections (Danehy et al., 2017; Abebe et al., 2021). In environments where fish are scarce, aquatic insects serve as reliable surrogates for fish in Environmental Flow Assessments (EFAs), indirectly representing the ecological integrity and water quality of the river. Fish are generally more tolerant of water quality changes and are mobile in response to flow alterations. Moreover, aquatic insects constitute a key component of fish diets (Daheny et al., 2017) and Orth et al. (1987) reported that a 10% reduction in aquatic insect assemblages can reduce prey fish populations by 88%, highlighting their ecological importance.



Plate 3. Sampling of aquatic insects using D-frame net

River use classification

The study area is a recreational site, which is supposed to fall under Class II for recreational use with body contact, as shown in Table 1 (Department of Environment, 2017).

Table 1. River classes and uses

Class	Uses
Class I	Conservation of natural environment. Water Supply I - Practically no treatment necessary. Fishery I - Very sensitive aquatic species.
Class IIA	Water Supply II - Conventional treatment required. Fishery II - Sensitive aquatic species.
Class IIB	Recreational use with body contact.
Class III	Water Supply III - Extensive treatment required. Fishery III - Common of economic, value and tolerant species; livestock drinking.
Class IV	Irrigation
Class V	None of the above.

Source: Department of Environment, 2017

Habitat Suitability Index (HSI)

The Habitat Suitability Index (HSI) is a quantitative tool used to represent the preferences of aquatic organisms for various instream variables (Li et al., 2009). It indicates the response of target organisms to a given variable, reflecting either avoidance or preference (Conallin, 2010). In this study, three key physical habitat variables; velocity, water depth and substrate type, were used to develop the HSI. The HSI for each sampling station was calculated as the geometric mean of the suitability index (SI) scores for n environmental variables, as expressed in Equation

2 (Inglis et al., 2006). Subsequently, the Habitat Suitability Curves (HSCs) were generated from the calculated HSI values to represent the preference patterns of the target organisms.

$$HSI = \left\{ \sum_{i=1}^n SI_i \right\}^{1/n} \quad (2)$$

Where,

n – number of variables from $i=1$ to n

SI – Suitability index of a variable

The Suitability Index (SI) for each environmental variable was derived from the Habitat Suitability Curve (HSC). Prior to developing the HSC, the SI for each variable; velocity, water depth and substrate, was calculated by dividing the range of each variable into discrete intervals. For each interval, the frequency of habitat use by aquatic insects and the availability of habitat were determined. This approach follows the habitat preference model, in which the preference for each interval is estimated from the relative frequencies of habitat utilization and availability (Johnson et al., 2017). The corresponding Equation 3 and 4 for the habitat preference model is presented below.

$$P_i = \frac{U_i}{A_i} \quad (3)$$

Where,

P_i – relative preference value of a target organism for a specific interval of the measured variables

U_i – the proportion of utilization of the specific interval of the measured variables

A_i – the proportion of the specific interval of the measured variables in the studied river reach at the time the target organisms were sampled

The result of the ratio from the above equation was normalized to a preference scale from 0 to 1 using the next equation.

$$P_n = \frac{P_i}{P_{max}} \quad (4)$$

Where,

P_n – the normalized index of preference at each interval of the variable

P_i – relative preference value of a target organism for a specific interval of the measured variables

P_{max} – the maximum index of preference for a variable

Slope method

Gippel and Stewardson (1998) stated that the environmental flow represents a critical minimum flow, corresponding to the breakpoint in the relationship between flow and a measured variable, in this case, the Weighted Usable Area (WUA). One method to identify this breakpoint is the slope method, where the slope of the curve, expressed as the first derivative (dy/dx), equals 1 (Gippel & Stewardson, 1998; Liu et al., 2006; Shang, 2008).

In this study, a graph of the relationship between flow and WUA was plotted, with both axes normalized as percentages. A logarithmic function was fitted to the data and the first derivative (dy/dx) was calculated. A second graph plotting normalized flow against slope was then generated and the environmental flow was determined at the point where the slope equals 1, following the logarithmic equation.

Weighted Usable Area represents the amount of habitat available for organisms and evaluates the impact of flow changes on habitat (Li et al., 2009). WUA integrates physical habitat changes caused by flow alteration with habitat suitability criteria of the target organisms to estimate environmental flow. Its unit is area per unit reach length, where the WUA of each cell describes habitat use. Higher WUA values indicate better habitat availability. This index is a key variable in the Instream Flow Incremental Methodology (IFIM).

According to Payne (2003), WUA is calculated as the product of the area and the Habitat Suitability Index (HSI) of the measured variables, normalized to area per unit length (e.g., m²/1000 m). In this study, the HSI for velocity, water depth and substrate was multiplied by the area at each station. The WUA values for all stations were then plotted against flow to determine the environmental flow. Equation 5 presents the WUA calculation.

$$WUA = \sum F [f(V_i) + f(WD_i) + f(S_i)] \times A_i \quad (5)$$

Where;

F[] - composite suitability factor (CSF);

$f(V_i)$ - HSI for velocity in station i ;

$f(WD_i)$ - HSI for water depth in station i ;

$f(S_i)$ - HSI for substrate in station i ; and

A_i - subsurface area for station i .

Curvature method

The curvature method is an alternative approach for determining the minimum environmental flow by identifying the maximum curvature point on the relationship between flow and Weighted Usable Area (WUA) (Gippel & Stewardson, 1998). Liu et al. (2006) noted that the breakpoint identified using the curvature method is unique.

In this method, the logarithmic function fitted to the flow–WUA data (as used in the slope method) is differentiated a second time to obtain the second derivative (d^2y/dx^2). This derivative, together with the first derivative (dy/dx), is used in Equation 6 to calculate the curvature parameter k . The minimum flow is then identified as the flow corresponding to the maximum k value, which is determined by plotting normalized flow against the calculated k values.

The curvature method provides an alternative assessment of environmental flow, complementing the slope method and is particularly useful for identifying critical points in the habitat–flow relationship where habitat gains per unit increase in flow begin to diminish.

$$k = \frac{[-a/Q^2]}{[1+(\frac{a}{Q})^2]^{3/2}} \quad (6)$$

Results and discussion

Development of Habitat Suitability Index (HSI)

a) HSI of velocity

While the utilization model describes the occurrence of insects within a specific range of a variable without considering the contribution of area size, habitat preference represents an index of area-based density that reflects the suitability of a space for insect habitation. In other words, it quantifies the degree to which an insect prefers a given area for living. Habitat preference

values range from 0.00 to 1.00, where 1.00 indicates the highest suitability and 0.00 indicates the lowest suitability. According to Zhu et al. (2021), the Habitat Suitability Index (HSI) is classified into four categories, as described in Table 2.

Table 2. Habitat quality classes

Classes	HSI	Habitat Quality
1	0.75 - 1.00	Highly suitable habitat
2	0.50 - 0.74	Moderately suitable habitat
3	0.25 - 0.49	Generally suitable habitat
4	0.00 - 0.24	Poorly suitable habitat

Source: Adjusted from Zhu et al., 2021

To determine habitat preference of aquatic insects with respect to water velocity, velocity measurements were first grouped into classes at 0.20 m/s intervals. Based on the observed data, velocities were classified into six categories, 0.00, 0.20, 0.40, 0.60, 0.80 and 1.00 m/s, each representing a 0.20 m/s increment. For each velocity class, relative frequencies were calculated for both habitat availability and aquatic insect utilization.

The highest Habitat Suitability Index (HSI) for water velocity was observed at 0.40 m/s, corresponding to the interval between 0.21 m/s and 0.40 m/s. The Habitat Suitability Curve (HSC) derived from these values is presented in Figure 2. Highly suitable habitat (Class 1), defined as having a suitability index greater than 0.75, occurred within the velocity range of 0.20–0.60 m/s. In contrast, the lowest preference by aquatic insects was observed at velocities between 0.61 m/s and 0.80 m/s.

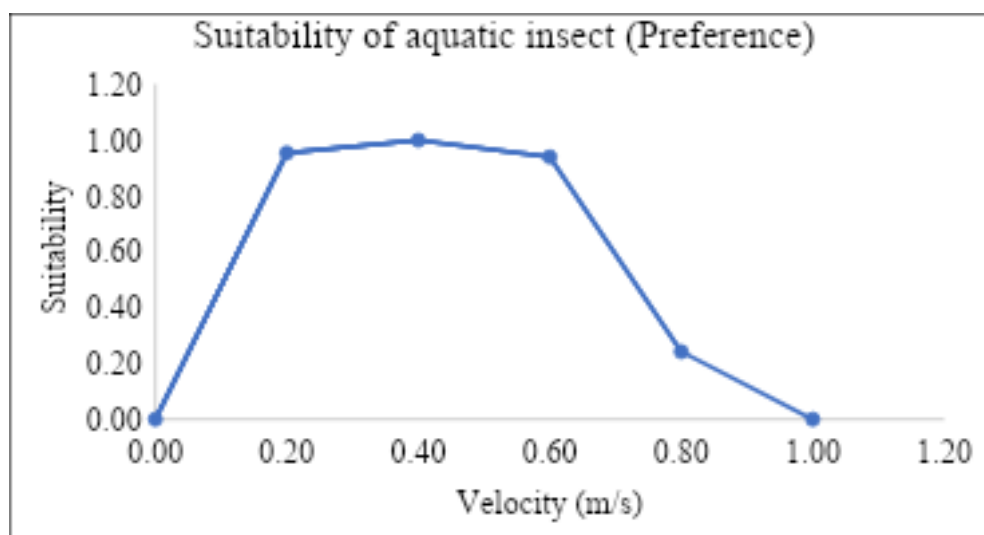


Figure 2. Habitat Suitability Curve (velocity)

Although the most preferred velocity interval was 0.21–0.40 m/s, the overall suitable velocity range for aquatic insects extended from 0.01 m/s to 0.60 m/s, as this range exhibited Habitat Suitability Index (HSI) values greater than 0.75 (Zhu et al., 2021). This suitable range accounted for 98.6% of the total aquatic insects collected, indicating that the study area provided highly suitable habitat conditions in terms of velocity. In contrast, only 1.4% of individuals were found within the 0.60–0.80 m/s range, which was therefore classified as poorly suitable habitat.

Despite the broad suitable range, the optimum velocity preference during the study period was identified as 0.21–0.40 m/s. This interval supported 44.9% of the total aquatic insect abundance while occupying 43.2% of the total habitat area. Comparable findings have been reported in previous studies for example, Szalkiewicz et al. (2022) reported velocity HSI values ranging from 0.02–0.60 m/s for macroinvertebrates, including Ephemeroptera, Plecoptera and Trichoptera (EPT), in the Flinta River, Poland, while Li et al. (2009) observed a preferred velocity range of 0.30–0.70 m/s for *Baetis* spp. in the Xiangxi River, China. The results of the present study fall within the ranges reported in these earlier studies, indicating consistency and ecological validity.

Overall, the study area can be characterized as a high quality habitat for aquatic insects with respect to velocity, with an optimum preference occurring between 0.21 m/s and 0.40 m/s. Flow velocity was therefore identified as an important factor influencing aquatic insect habitat suitability and shelter availability (Hasmi et al., 2021).

In addition to velocity, multiple environmental factors including water depth, canopy cover, substrate composition and water quality also influence aquatic insect habitat preference. Aquatic insects are known to inhabit a wide range of flow conditions, from slow to moderate and even fast-flowing waters (Ortho et al., 1987; Merritt & Cummins, 1995; Yule & Sen, 2004; Abebe et al., 2021; Hasmi et al., 2021). This broad velocity tolerance reflects the presence of multiple families with differing hydraulic preferences. For example, Suhaila et al. (2016) reported 25 families and 31 genera of EPTO in the Kurau River, demonstrating the taxonomic diversity associated with varying flow conditions.

b) HSI of water depth

To determine the habitat preference of aquatic insects with respect to water depth, depth measurements were initially grouped into classes at 0.20 m intervals. Based on the observed data, water depth was classified into seven categories: 0.00, 0.20, 0.40, 0.60, 0.80, 1.00 and 1.20 m, each representing a 0.20 m increment. For each depth class, relative frequencies were calculated for both habitat availability and aquatic insect utilization.

The Habitat Suitability Index (HSI) for water depth was illustrated using a Habitat Suitability Curve (HSC), as shown in Figure 3. Water depths ranging from 0.20 m to 0.60 m exhibited HSI values greater than 0.75 and were therefore classified as highly suitable habitat. In contrast, the lowest preference for water depth was observed within the 0.81–1.00 m interval.

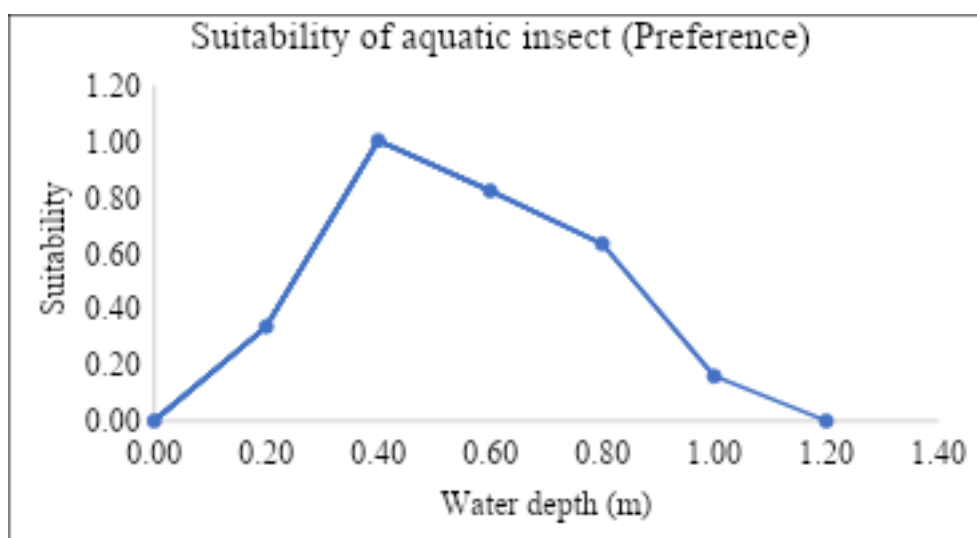


Figure 3. Habitat Suitability Curve (water depth)

Analysis of water depth indicated that the highest abundance of aquatic insects occurred within the 0.41–0.60 m interval, accounting for 54.3% of the total individuals collected and 55.9% of the available habitat area. In contrast, the lowest utilization was recorded in the 0.81–1.00 m depth interval, where only 0.7% of individuals were collected, corresponding to 1.3% of the total habitat area.

A clear habitat preference was observed at depths of 0.21–0.40 m, where aquatic insects comprised 33.4% of the total individuals while occupying 28.3% of the available habitat area. Depths with Habitat Suitability Index (HSI) values greater than 0.75 (Zhu et al., 2021) ranged from 0.21 m to 0.60 m, within which 88.1% of all individuals were collected and 84.2% of the total habitat area was represented. The least suitable habitat occurred at depths between 0.81 m and 1.00 m, occupying only 1.3% of the available habitat.

Comparable results have been reported in previous studies. Szalkiewicz et al. (2022) identified a tolerable water depth range of 0.03–0.60 m for macroinvertebrates, while Li et al. (2009) reported preferred depths of 0.10–0.30 m for *Baetis* spp. These findings support the present results and indicate that water depth is a critical factor influencing aquatic insect distribution. Furthermore, Hasmi et al. (2021) demonstrated a positive relationship between aquatic insect abundance and dissolved oxygen concentration, as well as the importance of lower water temperatures, both of which are closely associated with depth.

c) HSI of substrate

To determine the habitat preference of aquatic insects with respect to substrate composition, sediment grain size was initially grouped into classes at 2.00 phi intervals. Based on grain size measurements, substrates were classified into seven categories, 0.00, –2.00, –4.00, –6.00, –8.00, –10.00 and –12.00 phi, with each class representing a 2.00 phi increment. For each substrate class, relative frequencies were calculated for both habitat availability and aquatic insect utilization.

The Habitat Suitability Index (HSI) for substrate was used to construct the Habitat Suitability Curve (HSC), as shown in Figure 4. Substrate grain sizes ranging from –2.00 phi to –8.00 phi exhibited HSI values greater than 0.75 and were therefore classified as highly suitable habitat. In contrast, the lowest preference was observed for the –10.00 phi class, corresponding to the –8.01 to –10.00 phi interval.

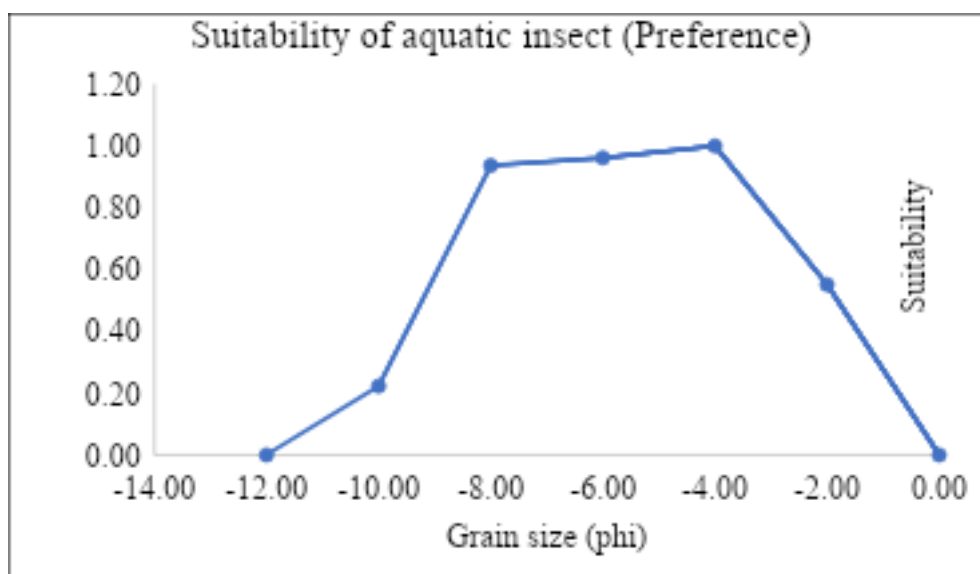


Figure 4. Habitat Suitability Curve (substrate)

Aquatic insects exhibited a strong preference for substrates within the -2.00 to -8.00 phi range, where approximately 95.7% of the total individuals were recorded. Within this range, the optimum substrate class was identified as -2.01 to -4.00 phi, which accounted for 29.6% of the available habitat and supported 31.3% of the total aquatic insect abundance. According to Zhu et al. (2021), high quality habitat corresponds to suitability values greater than 0.75, which in the present study encompassed 95.2% of the available substrate habitat.

Comparable findings have been reported in previous studies. Szalkiewicz et al. (2022) identified silt, sand and gravel as suitable substrates for macroinvertebrates, although specific grain-size dimensions were not reported. Similarly, Li et al. (2009) found cobble to be the most preferred substrate for *Baetis* spp. While these studies categorized substrates by general grain types rather than precise size classes, the present study provides a more detailed grain-size classification and identifies pebble sized substrates (-2.00 to -4.00 phi) as the optimum substrate for aquatic insects.

d) Composite suitability factor of HSI

A Pairwise Comparison Matrix (PCM) was constructed and scoring was conducted using the Analytic Hierarchy Process (AHP) to derive weighting factors for each habitat variable. Based on the PCM, the resulting weights were 0.26 for velocity, 0.11 for water depth and 0.63 for substrate. These weights were subsequently evaluated for consistency.

Consistency testing indicated a Consistency Index (CI) value of 0.02 and a Random Consistency Index (RCI) of 0.58 (Saaty, 1980). The resulting Consistency Ratio (CR) was 0.03, which is below the acceptable threshold of 0.10, indicating satisfactory consistency of the judgments (Saaty, 1980). As the consistency requirement was met, the derived weights were applied in the calculation of the Composite Suitability Factor (CSF), as shown in Equation 7.

$$CSF = 0.26*HSI(Velocity) + 0.11*HSI(Water\ depth) + 0.63*HSI(Substrate) \quad (7)$$

The Analytic Hierarchy Process (AHP) was applied to determine the relative weighting of habitat criteria influencing aquatic insect abundance. Three primary criteria were considered, velocity, water depth and substrate composition. Previous studies have demonstrated that substrate is the most influential factor affecting aquatic insect abundance compared to velocity and water depth (Li et al., 2009). Grain size is particularly important in providing suitable microhabitats for aquatic insects (Fanelli et al., 2022). Consistent with this, Pearson correlation analysis in the present study revealed significant relationships between aquatic insect abundance and the presence of boulders, pebbles and granules.

Velocity was identified as the second most important factor, as it plays a key role in structuring substrate composition by removing finer sediments and exposing coarser particles that are more suitable for aquatic insect habitation. In addition, velocity enhances dissolved oxygen availability within the water column, which is essential for aquatic insect survival (Abebe et al., 2021). Water depth was considered comparatively less influential, although it remains an important environmental variable. Accordingly, PCM scoring was assigned based on the relative importance of the criteria in descending order, substrate, velocity and water depth. The resulting AHP weights were 0.63 for substrate, 0.26 for velocity and 0.11 for water depth.

Development of environmental flow

a) Slope method

Data on flow and cumulative Weighted Usable Area (WUA) were used to examine the relationship between WUA and discharge. The resulting relationship was described by the

logarithmic equation, $y = 0.4376\ln(x) + 1.0544$ where y represents cumulative WUA and x represents flow. Taking the derivative of this equation produced $\frac{dy}{dx} = \frac{0.4376}{x}$. Setting $\frac{dy}{dx} = 1$ to determine the flow corresponding to the maximum rate of WUA increase, the calculated flow was $0.73 \text{ m}^3/\text{s}$, which represents 43.8% of the mean annual flow (MAF) for the study reach. The MAF was $1.67 \text{ m}^3/\text{s}$. The slope of the WUA curve (dy/dx) is illustrated in Figure 5.

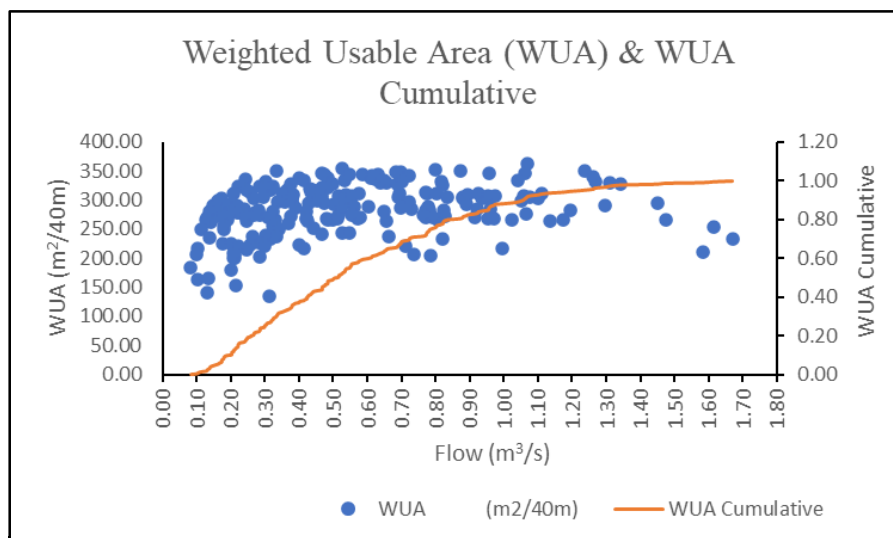


Figure 5. WUA in cumulative is overlaid with WUA distribution

The minimum flow that provides suitable habitat for aquatic insects, based on the slope method, was determined to be $0.73 \text{ m}^3/\text{s}$, corresponding to 43.8% of the mean annual flow (MAF). At this flow, the rate of change in habitat availability equals the rate of change in discharge, as described by Gippel and Stewardson (1998). Above $0.73 \text{ m}^3/\text{s}$, small variations in flow produce only minor changes in habitat availability. In contrast, flows below this threshold lead to rapid reductions in available habitat, even with small decreases in discharge. This occurs because habitat suitability declines, resulting in lower aquatic insect abundance due to altered habitat characteristics or reduced food availability (Tegos et al., 2018). Therefore, $0.73 \text{ m}^3/\text{s}$ represents the breakpoint for the lowest flow capable of sustaining aquatic insect habitat in the study reach.

b) Curvature method

The curvature method was used as an alternative approach to determine the minimum flow, where the maximum point of the curvature ($K_{\square\square\square}$) corresponds to the environmental flow (EF) for the study reach. Based on the slope method, the first derivative of the WUA-flow relationship was $\frac{dy}{dx} = \frac{0.4376}{x}$, and the second derivative was $\frac{d^2y}{dx^2} = -\frac{0.4376}{x^2}$. The curvature (K) was calculated using $K = \frac{-0.4376/x^2}{[1+(0.4376/x)^2]^{3/2}}$. The resulting K values were plotted against flow and the maximum curvature point ($K_{\square\square\square}$) was identified. These values were then overlaid on the WUA curve to show the corresponding flow, as shown in Figure 6.

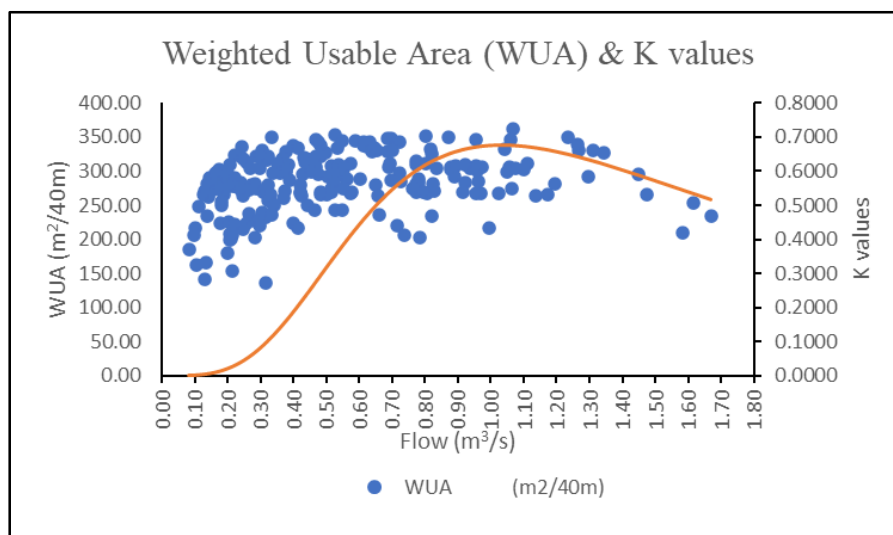


Figure 6. Curve of K values overlaid on WUA

Using the curvature method, the maximum curvature ($K_{\square\square\square}$) was 1.000, corresponding to a normalized flow of 0.61–0.62. The midpoint, 0.615, was selected, which equates to a flow of 1.03 m³/s or 61.5% of the mean annual flow (MAF). This value is 14% higher than the minimum flow determined using the slope method and represents a slope-to-curvature ratio of 0.71.

Ratios between slope and curvature methods vary across studies. For example, Liu et al. (2006) reported a ratio of 4.47, where the slope method produced a higher environmental flow, whereas Gippel and Stewardson (1998) found ratios of 0.64 for Starvation Creek and 0.69 for Armstrong Creek.

In the present study, the $K_{\square\square\square}$ flow of 1.03 m³/s (61.5% of MAF) represents the breakpoint at which WUA for aquatic insects begins to change in response to flow variations. Accordingly, this flow is considered the minimum required to sustain aquatic insect habitat based on the curvature method.

Water quality validation

Following the determination of minimum flows using both the slope and curvature methods, potential environmental flows (EFs) were evaluated for their effects on water quality. The objective was to ensure that selected minimum flows would maintain water quality at least at Class II according to the National Water Quality Standard for Malaysia (NWQS). The water quality parameters analyzed included pH, temperature, conductivity, total dissolved solids (TDS), dissolved oxygen (DO), total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (AN), total nitrogen (TN) and total phosphorus (TP). The Class II limits for these parameters are summarized in Table 3.

This analysis aimed to identify the greatest potential effects of flow reduction on water quality. Correlation and regression analyses were performed between flow and each water quality parameter using the Statistical Package for Social Sciences (SPSS), with significance assessed at $p < 0.05$.

Table 3. Class II limit of water quality parameters

Water quality parameters	Class II
pH	6.0- 9.0
Temperature	Normal + 2 °C
Conductivity	1000
TDS	1000
DO	5.0 - 7.0
TSS	25.0 - 50.0
BOD	3.0
COD	25.0
AN	0.1 - 0.3
TN	NOT MENTIONED IN NWQS
TP	0.2 - 0.1

Source: Department of Environment, 2017

Correlation between flow and water quality variables

Pearson correlation analysis was conducted using SPSS to assess the relationships between flow and each water quality parameter. Parameters with $p \geq 0.05$ were considered not significant and excluded from further analysis, while those with $p < 0.05$ were retained for regression analysis. In this study, BOD and COD were excluded at this stage because their correlations with flow were not significant ($p \geq 0.05$). The remaining parameters, pH, temperature, conductivity, TDS, DO, TSS, AN, TN and TP had significant correlations with flow ($p < 0.05$) and were therefore included in the subsequent regression analysis, as summarized in Table 4.

Table 4. Correlation between flow and water quality paramters

Water quality parameter	r	R ²	p
pH	0.343	0.118	0.047
Temperature	0.280	0.079	0.004
Conductivity	0.312	0.097	0.008
TDS	0.308	0.095	0.009
DO	0.196	0.038	0.044
TSS	0.322	0.104	0.007
AN	0.448	0.201	0.028
TN	0.302	0.091	0.006
TP	0.173	0.030	0.011

Regression between flow and water quality variables

Based on the significant correlations identified in the previous step, simple linear regression (SLR) analyses were performed between flow and each of the water quality parameters, pH, temperature, conductivity, TDS, DO, TSS, AN, TN and TP. The slope values of the regression lines, which indicate the sensitivity of each parameter to changes in flow, were recorded. The regression relationship is expressed in Equation 8, where M represents the slope and C represents the y-intercept.

$$\text{Water Quality parameter} = C + M \cdot \text{Flow} \tag{8}$$

Simple linear regression (SLR) analyses showed that flow significantly influenced several water quality parameters ($p < 0.05$), indicating that changes in flow can directly affect

aquatic habitat conditions. Flow was a positive predictor of pH, DO and TSS, whereas it was a negative predictor for temperature, conductivity, TDS, AN, TN and TP. The regression slopes indicate the expected change in each parameter per 1 m³/s change in flow. Since environmental flow is about a reduction in flow, specifically, a 1 m³/s reduction in flow would result in pH decrease by 1.222 units, temperature increase by 0.799 °C, conductivity increase by 3.761 µS/cm, TDS increase by 2.291 mg/L, DO decrease by 2.397 mg/L, TSS decrease by 2.171 mg/L, AN increase by 0.085 mg/L, TN increase by 0.266 mg/L and TP increase by 0.573 mg/L.

These results demonstrate that reductions in flow below the environmental flow threshold could negatively affect water quality, particularly pH, DO and TSS, which are critical for sustaining aquatic insects. While some parameters increase with flow reduction, others decline, highlighting the need to maintain minimum flows that preserve overall water quality within Class II standards. This explanation has answered the first research question.

Impact on water quality variables with flow changes

Based on the SLR results, conductivity was predicted to increase the most (3.761 units) and dissolved oxygen (DO) to decrease the most (2.397 units) per 1 m³/s reduction in flow. However, the actual flow reduction to 0.73 m³/s from the slope method corresponded to a decrease of 0.94 unit. Accordingly, the expected changes in water quality parameters were adjusted proportionally, pH (-1.149 units), temperature (0.751 °C), conductivity (3.535 µS/cm), TDS (2.154 mg/L), DO (-2.253 mg/L), TSS (-2.041 mg/L), AN (0.080 mg/L), TN (0.250 mg/L) and TP (0.539 mg/L).

Similarly, for the curvature method, a flow reduction of 0.64 unit to 1.03 m³/s yielded adjusted changes of pH (-0.782 units), temperature (0.511 °C), conductivity (2.407 µS/cm), TDS (1.466 mg/L), DO (-1.534 mg/L), TSS (-1.389 mg/L), AN (0.054 mg/L), TN (0.170 mg/L) and TP (0.367 mg/L).

The resulting water quality concentrations at 0.73 m³/s were pH (6.09), temperature (25.40 °C), conductivity (24.40 µS/cm), TDS (16.24 mg/L), DO (5.20 mg/L), TSS (1.53 mg/L), AN (0.15 mg/L), TN (0.48 mg/L) and TP (2.35 mg/L). All parameters met Class I or II standards according to the National Water Quality Standard for Malaysia, confirming that the slope method minimum flow maintains suitable water quality. The detailed concentrations for all parameters at 0.73 m³/s are summarized in Table 5.

Table 5. New concentration of water quality parameters when flow is reduced to 0.73 m³/s or 43.80% (from the slope method result)

Water quality parameter	Mean (concentration)	New concentration	Percentage increase or decrease	Class I	Class II	If EF equals to 0.73 m ³ /s
pH	7.24	6.09	-15.87	6.5 - 8.5	6.0- 9.0	II
Temperature	24.65	25.4	3.05		Normal + 2 °C	II
Conductivity	20.86	24.4	16.95	1000	1000	I
TDS	14.09	16.24	15.28	500	1000	I
DO conct	7.45	5.2	-30.24	> 7	5.0 - 7.0	II
TSS	3.57	1.53	-57.16	< 25	25.0 - 50.0	I
BOD	3.79	-	-	-	-	-
COD	10	-	-	-	-	-
AN	0.07	0.15	114.14	< 0.1	0.1 - 0.3	II
TN	0.23	0.48	108.71	NOT MENTIONED IN NWQS	NOT MENTIONED IN NWQS	
TP	1.81	2.35	29.76	NATURAL LEVEL	0.2 - 0.1	I

Under a reduced flow of 1.03 m³/s, the measured water quality parameters were pH (6.46), temperature (25.16 °C), conductivity (23.27 µS/cm), TDS (15.56 mg/L), DO (5.92 mg/L), TSS (2.18 mg/L), AN (0.12 mg/L), TN (0.40 mg/L), and TP (2.18 mg/L). All values complied with Class I or II water use standards. Using the curvature method, the new concentrations were calculated and are presented in Table 6. Both discussion and summary in Table 5 and Table 6 have answered research question number 2.

Table 6. New concentration of water quality parameters when flow is reduced to 1.03 m³/s or 61.50% (from the curvature method result)

Water quality parameter	Mean (concentration)	New concentration	Percentage increase or decrease	Class I	Class II	If EF equals to 1.03 m ³ /s
pH	7.24	6.46	-10.8	6.5 - 8.5	6.0- 9.0	II
Temperature	24.65	25.16	2.07		Normal + 2 °C	II
Conductivity	20.86	23.27	11.54	1000	1000	I
TDS	14.09	15.56	10.41	500	1000	I
DO conct	7.45	5.92	-20.59	> 7	5.0 - 7.0	II
TSS	3.57	2.18	-38.92	< 25	25.0 - 50.0	I
BOD	3.79	-	-	-	-	-
COD	10	-	-	-	-	-
AN	0.07	0.12	77.71	< 0.1	0.1 - 0.3	II
TN	0.23	0.4	74.02	NOT MENTIONED IN NWQS	NOT MENTIONED IN NWQS	
TP	1.81	2.18	20.26	NATURAL LEVEL	0.2 - 0.1	I

Environmental flow determination

The minimum flows derived from both the slope and curvature methods were acceptable, as both satisfied Class II water use standards. To determine the most suitable environmental flow (EF) for the Kurau River sub-catchment, results from both methods were verified using water quality samples collected upstream of Lata Sempeneh. The measured water quality data were analyzed through correlation and regression with the reduced flows calculated by the slope and curvature methods.

Analysis of the upstream data was conducted to assess whether 43.8% or 61.5% of the mean annual flow (MAF) was more suitable as the environmental flow, complementing Class II of river uses. The mean flow at the upstream site was 1.33 m³/s. The results indicated that all water quality parameters remained within Class II limits for both flow reductions, except for pH.

(a) Scenario 1: When flow was reduced to 43.8% of MAF, the pH dropped from 5.83 (Class III) to 4.91 (Class V), indicating acidic conditions.

(b) Scenario 2: When flow was reduced to 61.5% of MAF, the pH decreased slightly from 5.83 to 5.20 (Class III), which did not affect the overall water quality classification.

Based on these findings, a flow reduction of 61.5% of MAF is recommended as the environmental flow for the Kurau River sub-catchment.

A comparable study in the Xiangxi River, China (Li et al., 2009), used *Baetis* spp. as a biological target and produced an EF of 42.91% of MAF. Both studies applied the slope method, and the results are similar, demonstrating the robustness of the approach.

Comparison with the Tennant Method (Tennant, 1976) further supports this recommendation. According to Tennant, 30% of MAF is considered satisfactory for aquatic insects, 0.73 m³/s corresponds to Good and 1.03 m³/s corresponds to Outstanding environmental flow. Both values are acceptable, but the 1.03 m³/s (61.5% of MAF) is more aligned with maintaining ecological standards. With the results and comparison between slope method and curvature method, showed that the EF determination was more appropriate with the water quality integration in response to research question 3.

Benefits of the study:

1. Provides guidance for local authorities (e.g., *Pihak Berkuasa Tempatan*, Forestry Department) in managing recreational areas to meet Class II water quality standards as defined in the National Water Quality Standards for Rivers in Malaysia (NWQSM) (Department of Environment, 2022).
2. Supports river basin management and development planning by helping State Governments to consider EF before water intakes, mini-hydro projects, or dams are constructed upstream.
3. Assists the State Water Authority or Department of Irrigation & Drainage (DID) in implementing EF as a measure of river carrying capacity for future development or conservation.
4. Provides a public health guideline for recreational areas, as Class II water quality helps prevent waterborne diseases.
5. Offers a model ecological methodology for Environmental Impact Assessments (EIAs), allowing the consideration of both water quality and flow alterations, rather than relying solely on water quality parameters. This approach can define threshold values for maximum flow reduction based on ecological criteria.

Conclusion

Two methods were applied to determine a reasonable environmental flow (EF) at Lata Sempeneh in the Kurau River sub-catchment, resulting in EF values of 43.8% and 61.5% of the mean annual flow (MAF). Both values are ecologically acceptable, as preserving at least 30% of river flow is generally sufficient to maintain aquatic ecosystem function.

The results indicated that flow reductions to both 43.8% and 61.5% of MAF maintained water quality within Class II, as specified in the National Water Quality Standards for Rivers in Malaysia (NWQS). However, verification with additional water quality data suggested that an EF of 61.5% of MAF would better support river recreational use at Lata Sempeneh and the upstream segments. This implies that the ecological integrity of the Kurau River from Lata Sempeneh to the headwaters would remain within Class II even after reducing the flow to 61.5% of MAF.

Therefore, the recommended EF for the Kurau River sub-catchment is 1.03 m³/s, corresponding to 61.5% of MAF. Incorporating water quality into the environmental flow assessment (EFA) produced a more meaningful and optimal EF, closer to the original mean annual flow, than methods based solely on hydrology or biology. This research has managed to answer all the research questions and the hypothesis.

This study has some limitations. Only four orders of aquatic insects were used as target organisms, yet additional insect orders could provide a more comprehensive understanding of the relationship between flow and biological components. A longer data collection period that accounts for variability and potential climate change impacts would also improve the robustness of the water quality modelling. Finally, the results are most applicable to upstream rivers with low pollution levels and generally clean water quality.

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References

- Abebe, W. B., Tilahun, S. A., Moges, M. M., Wondie, A., Dersseh, M. G., Assefa, W. W., Mhired, D. A., Adem, A. A., Zimale, F. A., Abera, W., Steenhuis, T. S., & McClain, M. E. (2021). Ecological status as the basis for the holistic environmental flow assessment of a tropical highland river in Ethiopia. *Water*, 13(14), 1913.
- Adnan, M. S., Roslen, H., & Samsuri, S. (2022). The application of Total Maximum Daily Load (TMDL) approach in water quality assessment for the Batu Pahat River. *IOP Conference Series: Earth and Environmental Science*, 1022, 012074.
- American Public Health Association (APHA). (2005). *Standard Methods for the Examination of Water and Wastewater* (Vol 21). American Public Health Association.
- ASTM International. (2002). ASTM D422-63: Standard test method for particle-size analysis of soils.
- Barbour, M. T., Gerritsen, J., Snyder, B. D., & Stribling, J. B. (1999). *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish* (2nd ed.). U.S. Environmental Protection Agency.

- Brooks, A. J., Haeusler, T., Reinfelds, I., & Williams, S. (2005). Hydraulic microhabitats and the distribution of macroinvertebrate assemblages in riffles. *Freshwater Biology*, 50(3), 331–344.
- Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, 30(4), 492–507.
- Chaudhary, S., Dhanya, C. T., Kumar, A., & Shaik, R. (2019). Water quality-based environmental flow under plausible temperature and pollution scenarios. *Journal of Hydrologic Engineering*, 24(5).
- Che Salmah, M. R., Amelia, Z. S., & Abu Hassan, A. (2001). Preliminary distribution of Ephemeroptera, Plecoptera, and Trichoptera (EPT) in Kerian River Basin, Perak, Malaysia. *Pertanika Journal of Tropical Agricultural Science*, 24(2), 101–107.
- Conallin, J., Olsen, M., Boegh, E., Jensen, J. K., & Pedersen, S. (2010). Habitat suitability indices development in Denmark: Are international indices applicable under small lowland stream conditions? *International Journal of River Basin Management*, 8(2), 151–160.
- Department of Environment Malaysia. (2017). Environmental Quality Report 2017. Ministry of Energy, Science, Technology, Environment & Climate Change.
- Department of Environment, Malaysia. (2022). Environmental Quality Report 2022. Ministry of Natural Resources, Environment and Climate Change, Malaysia.
- Fanelli, R. M., Cashman, M. J., & Porter, A. J. (2022). Identifying key stressors driving biological impairment in freshwater streams in the Chesapeake Bay watershed, USA. *Environmental Management*, 70(6), 926–949.
- Folk, R. L., & Ward, W. C. (1957). Brazos River bar: A study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27(1), 3–26.
- Galat, D. L., & Lipkin, R. (2000). Restoring ecological integrity of great rivers: Historical hydrographs aid in defining reference conditions for the Missouri River. *Hydrobiologia*, 422/423, 29–48.
- Gippel, C. J., & Stewardson, M. J. (1998). Use of wetted perimeter in defining minimum environmental flows. *Regulated Rivers: Research & Management*, 14(1), 53–67.
- Hasmi, N. A., Norazlimi, N. A., & Abd-Latip, N. F. (2021). Abundance of aquatic insects in the spatial variation of two rivers in Perak, Malaysia. *IOP Conference Series: Earth and Environmental Science*, 736, 012021.
- Herschy, R. W. (1993). The velocity-area method. *Journal of Hydrology*, 8(3), 7–10.
- Hirji, R., & Davis, R. (2009). *Environmental Flows in Water Resources Policies, Plans, and Projects: Case Studies*. The World Bank.
- Huang, J., Huang, Y., & Zhang, Z. (2014). Coupled effects of natural and anthropogenic controls on seasonal and spatial variations of river water quality during baseflow in a coastal watershed of Southeast China. *PLOS One*, 9(3), e91528.
- Inglis, G. J., Hurren, H., Oldman, J., & Haskew, R. (2006). Using habitat suitability index and particle dispersion models for early detection of marine invaders. *Ecological Applications*, 16(4), 1377–1390.
- Johnson, J. A., Sivakumar, K., & Rosenfeld, J. (2017). Ecological flow requirement for fishes of Godavari River: Flow estimation using the PHABSIM method. *Current Science*, 113(11), 2187–2193.
- Li, F., Cai, Q., Fu, X., & Liu, J. (2009). Construction of habitat suitability models (HSMs) for benthic macroinvertebrates and their applications to instream environmental flows: A case study in Xiangxi River of Three Gorges Reservoir region, China. *Progress in Natural Science*, 19(3), 359–367.
- Liu, J., Liu, Q., & Yang, H. (2016). Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality. *Ecological Indicators*, 60, 434–441.

- Liu, S., Mo, X., Xia, J., Liu, C., Lin, Z., Men, B., & Lina, J. (2006). Estimating the minimum in-stream flow requirements via the wetted perimeter method based on curvature and slope techniques. *Journal of Geographical Sciences*, 16(2), 242–250.
- Maharjan, B., Pachel, K., & Loigu, E. (2016). Trends in urban storm water quality in Tallinn and influences from stormflow and baseflow. *Journal of Water Security*, 2(1).
- Merritt, R. W., & Cummins, K. W. (1996). *An Introduction to the Aquatic Insects of North America* (3rd ed.). Kendall/Hunt Publishing Company.
- Mohan, C., Gleeson, T., Famiglietti, J. S., Virkki, V., Kumm, M., Porkka, M., Wang-Erlandsson, L., Huggins, X., Gerten, D., & Jahnig, S. C. (2022). Poor correlation between large-scale environmental flow violations and freshwater biodiversity: Implications for water resource management and the freshwater planetary boundary. *Hydrology and Earth System Sciences*, 26, 6247–6262.
- Nelson, F.A. (1989). *Guidelines for Using Wetted Perimeter (WETP) Computer Program of The Montana Department Of Fish, Wildlife and Parks*. Montana Department of Fish, Wildlife and Parks.
- Norris, R. H., & Thoms, M. C. (1999). What is river health? *Freshwater Biology*, 41(2), 197–209.
- O’Keeffe, J., & Le Quesne, T. (2009). *Keeping Rivers Alive: A Primer on Environmental Flows and Their Assessment*. WWF Water Security Series.
- Orth, D. J. (1987). Ecological considerations in the development and application of instream flow-habitat models. *Regulated Rivers: Research & Management*, 1(2), 171–181.
- Payne, T. R. (2003, June 1-5). The concept of weighted usable area as a probable suitability index within the instream flow incremental methodology. IFIM Users Workshop, Fort Collins, CO.
- Piniewski, M., Laizé, C. L. R., Acreman, M. C., Okruszko, T., & Schneider, C. (2011). Effect of climate change on environmental flow indicators in the Narew Basin, Poland. Proceedings of the 2011 International SWAT Conference & Workshops, Toledo, Spain.
- Poff, N. L., & Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshwater Biology*, 55(1), 194–205.
- Power, M. E., Sun, A., Parker, G., Dietrich, W. E., & Wootton, J. T. (1995). Hydraulic food-chain models. *BioScience*, 45(3), 159–167.
- Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill.
- Schneider, M., Noack, M., Gebler, T., & Kopecki, I. (2010). *Handbook for Habitat Simulation Model CASiMiR, Module-Casimir-Fish Base Version*. Ecological Engineering GmbH.
- Shang, S. (2008). A multiple criteria decision-making approach to estimate minimum environmental flows based on wetted perimeter. *River Research and Applications*, 24(1), 54–67.
- Stein, E. D., Zimmerman, J., Yarnell, S. M., Stanford, B., Lane, B., Taniguchi-Quan, K. T., Obester, A., Grantham, T. E., Lusardi, R. A., & Sandoval-Solis, S. (2021). The California Environmental Flows Framework: Meeting the challenges of developing a large-scale environmental flows program. *Frontiers in Environmental Science*, 9.
- Suhaila, A. H., Hanapi, N., Mohd Afendi, M. F. S., & Mohd Sah, A. S. R. B. (2016). Ephemeroptera, Plecoptera, Trichoptera and Odonata (Insecta) diversity and distribution at Bukit Merah Reservoir river feeders. *Wetland Science*, 14(3), 328–336.
- Szałkiewicz, E., Kałuża, T., & Grygoruk, M. (2022). Detailed analysis of habitat suitability curves for macroinvertebrates and functional feeding groups. *Scientific Reports*, 12.
- Tegos, A., Schlüter, W., Gibbons, N., Katselis, Y., & Efstratiadis, A. (2018). Assessment of environmental flows from complexity to parsimony-Lessons from Lesotho. *Water*, 10(10), 1293.

- Tennant, D. L. (1976). Instream flow regimens for fish, wildlife, recreation, and related environmental resources. *Fisheries*, 1(4), 6–10.
- United States Environmental Protection Agency (USEPA) (1982). Handbook for sampling and sample preservation of water and wastewater.
- United States Environmental Protection Agency (USEPA). EPA Method 160.2.
- Walling, B., Chaudhary, S., Dhanya, C. T., & Kumar, A. (2017). Estimation of environmental flow incorporating water quality and hypothetical climate change scenarios. *Environmental Monitoring and Assessment*, 189, 225.
- Walsh, C. J., Fletcher, T. D., & Burns, M. J. (2012). Urban stormwater runoff: A new class of environmental flow problem. *PLoS ONE*, 7(9), e45814.
- Wentworth, C. K. (1922). A scale of grade and class terms for clastic sediments. *The Journal of Geology*, 30(5), 377–392.
- Yang, Y., Yin, X. A., & Yang, Z. F. (2016). Environmental flow management strategies based on the integration of water quantity and quality: A case study of the Baiyangdian Wetland, China. *Ecological Engineering*, 96, 150-161.
- Yule, C. M., & Sen, Y. H., (2004). *Freshwater Invertebrates of The Malaysian Region* (pp. 394-511). Academy of Sciences Malaysia.
- Zhu, Z., Huai, W., Yang, Z., Li, D., & Wang, Y. (2021). Assessing habitat suitability and habitat fragmentation for endangered Siberian cranes in Poyang Lake region, China. *Ecological Indicators*, 125, 107594.
- Zorkeflee, A. H., Hamidon, N., Zakaria, N., Ghani, A. A., & Siang, L. C. (2005). Incorporating GIS in water resources modelling: Application of SWAT 2005 model in Sungai Kurau, Perak and CCHE2D model in Tasik Harapan, USM, Penang.