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INTEGRATING AHP AND GIS FOR FIREFLY HABITAT CONSERVATION: A CASE STUDY ON MANGROVE ECOSYSTEM PRESERVATION

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ABSTRACT

Fireflies (*Pteroptyx tener*) are sensitive indicators of estuarine mangrove ecosystem health, yet their habitat requirements and spatial distribution are poorly understood. This study evaluated firefly abundance and habitat suitability along the Sepetang River in the Matang Mangrove Forest Reserve in Perak, Malaysia. Field surveys were conducted across 10 stations over six months (November 2021 to April 2022), recording adult firefly abundance, vegetation composition, and abiotic parameters, including air temperature, humidity, wind speed, rainfall, tidal level, and water quality. Environmental parameters were standardised and analysed using the Analytical Hierarchy Process (AHP) to derive their relative importance, which was integrated into a GIS-based zonation to produce spatially explicit suitability zones. A total of 111,615 fireflies were recorded, with Zone 2 identified as a hotspot due to dense *Sonneratia caseolaris* stands, favourable microclimatic conditions and proximity to the rivermouth. AHP indicated firefly abundance (22.2%), air humidity (11.8%), tidal level (11.5%) and air temperature (10.7%) as the most influential factors. Weighted Geographic Information System (GIS) layers classified the river into high, moderate, and low suitability zones, providing a systematic framework for conservation prioritisation. The integrated methodology combining field surveys, AHP and GIS modelling supports evidence-based, adaptive management and underscores the importance of microclimate, vegetation structure and hydrology in sustaining firefly populations in mangrove estuaries.

Introduction

Over the past 50 years, monitored wildlife populations have declined by 73%, with freshwater populations suffering the heaviest reductions. Habitat degradation and loss, driven primarily by the food system, is the most reported threat, followed by overexploitation, invasive species and disease (World Animal Foundation, 2024). While a study explored how natural hazards like earthquakes, hurricanes, tsunamis, and volcanoes impact species at risk of extinction. The study found that 3,722 species, primarily in the tropics and on islands are at risk, with hurricanes and earthquakes affecting the most species (Gonçalves *et al.*, 2024). While considerable attention has been devoted to the conservation of charismatic megafauna and economically valuable flora and fauna, many lesser-known invertebrate groups, particularly within the orders Coleoptera, Diptera, and Hymenoptera, remain underrepresented in both research and policy frameworks (Stork, 2018). Among these, fireflies (family *Lampyridae*) have garnered increasing interest due to their ecological importance, cultural value, and vulnerability to habitat degradation (Lewis *et al.*, 2024).

In Southeast Asia, and especially in Malaysia, mangrove forests are a critical ecosystem for many firefly species. These tidal forests play a crucial role in supporting the life cycle and food sources for fireflies. Firefly larvae prey on macro-snails that inhabit riverbeds and mudflats, highlighting the ecological significance of mangroves (Nada *et al.*, 2023). One of the most iconic firefly species in Malaysia is *Pteroptyx tener* (*P. tener*), a synchronous flashing species that congregates in large numbers along riverine mangrove belts. These luminous displays have not only ecological significance but also serve as a major ecotourism attraction, generating revenue for local communities (Bernard *et al.*, 2023; Poukin *et al.*, 2023; Zainaddin *et al.*, 2023).

However, the survival of *P. tener* is increasingly threatened by a variety of environmental stressors. These include mangrove deforestation for aquaculture and urban development, rising levels of water pollution from domestic and agricultural runoff, and the overarching threat of climate change, which alters the hydrology and salinity regimes of estuarine habitats (Lewis *et al.*, 2020; Lewis *et al.*, 2024). The Sepetang River in Perak has historically been one of the most important firefly observation sites in Peninsular Malaysia and is officially recognised as a Congregating Firefly Zone (CFZ). Yet, recent observations have reported a worrying decline in firefly abundance and behaviour. For instance, surveys have documented a significantly skewed male-to-female ratio (3:1), potentially indicating reproductive or environmental stress (Shahara *et al.*, 2017).

Despite the ecological and economic importance of fireflies in the Sepetang River, efforts to manage and conserve their habitats remain fragmented and largely reactive. A key gap lies in the lack of spatially explicit tools and decision-making frameworks that can guide conservation planning. Geographic Information Systems (GIS), when integrated with multi-criteria decision analysis tools such as the Analytic Hierarchy Process (AHP), offer a promising approach to spatially evaluate habitat suitability, prioritise conservation areas and mitigate future threats. However, such tools have rarely been applied to invertebrate species, particularly fireflies, in Malaysian estuarine landscapes (Idris *et al.*, 2025). Therefore, this study aims to fill the gap by creating a conservation-based spatial model using AHP and GIS to assess habitat suitability for *P. tener* along the Sepetang River. The specific objectives are: (i) To identify key environmental factors such as vegetation, microclimate and water parameters that affect firefly habitats; and (ii) to produce a conservation zoning map to support better management and long-term monitoring.

Materials and Methods

Study Area

The study was conducted in Kuala Sepetang, located in the Taiping district of Perak, Malaysia (04°51’ N, 100°38’ E), near the historical town of Taiping. The research focused on the Matang Mangrove Forest Reserve (MMFR), a globally recognised mangrove ecosystem known for its sustainable forest management and high biodiversity. Sampling was concentrated along the Sepetang River, which flows through the MMFR and supports a complex estuarine environment essential for local livelihoods, aquaculture and ecotourism.

The river is tidally influenced and bordered by mixed mangrove vegetation dominated by *Sonneratia caseolaris*, *Rhizophora mucronata* and *Rhizophora apiculata*. Ten sampling stations (SS1–SS10) were established along a longitudinal gradient from upstream to downstream to capture variation in vegetation structure, tidal exposure, and anthropogenic influence (Figure 1). Stations were selected based on the presence of active firefly colonies, defined as aggregation areas (swarms) comprising several adjacent display trees exhibiting synchronised flashing activity during peak observation periods. The distance between SS1 and SS10 was 5.63 km, and the site is approximately 8 km from the Kuala Sepetang jetty. Each station represented a firefly aggregation zone encompassing one or

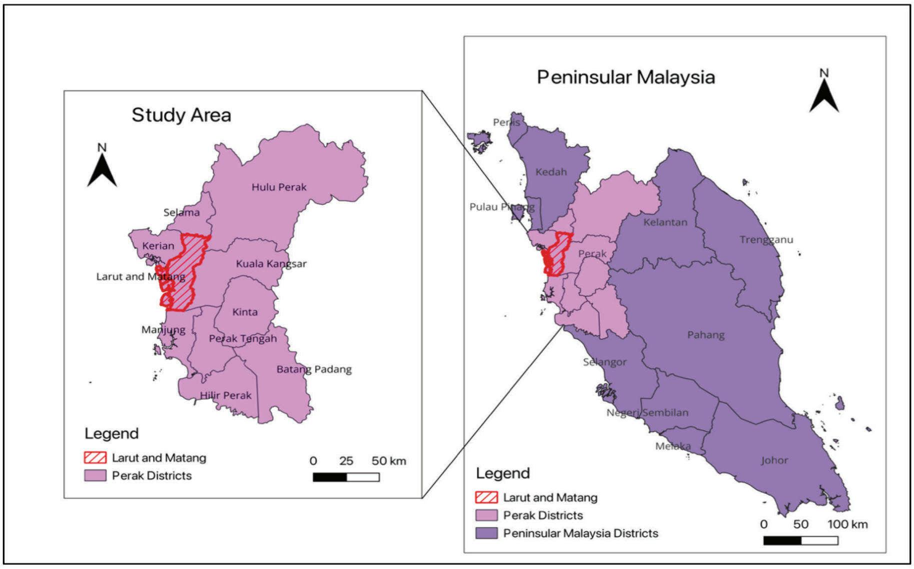

Figure 1: Study area along the Sepetang River, Malaysia

more display trees where synchronous flashing activity of *Pteroptyx tener* was consistently observed.

Field Sampling and Data Collection

Firefly data were collected over six months, from November 2021 to April 2022, through field sampling conducted on five consecutive nights per month. Firefly abundance was estimated using a standardised nocturnal boat-based visual census along the riverbank during peak flashing hours (1900 to 2300 hours). Surveys were conducted from a slowly moving boat due to the limited accessibility of mangrove river margins. Observations were restricted to one riverbank at a time to avoid overlapping fields of view and to ensure consistency in sampling effort. Counts focused on adult *Pteroptyx tener* individuals displaying synchronous flashing behaviour on mangrove trees. To minimise double counting, abundance was estimated based on visually distinguishable individuals rather than flash frequency, using spatial position, flashing rhythm and short-range movement as identification criteria. Each individual was counted once using a manual hand counter. Two trained observers conducted simultaneous counts, and the mean value was used for subsequent analysis. The resulting data, therefore, represent relative adult abundance rather than absolute population size.

Specimens were collected using a standard sweep net (38 cm ring diameter, 91 cm handle, white muslin bag) and a hand net (13 × 13 cm). Collected specimens were identified in a laboratory setting using established taxonomic references, following Ballantyne and Lambkin (2013), while sex determination followed Jusoh *et al*. (2018). Environmental variables recorded at each station included air temperature, wind speed, relative humidity, rainfall distribution, tide level, and water quality parameters, namely pH, salinity, conductivity, clarity, and total dissolved solids. These variables were selected based on previous studies demonstrating their importance in influencing firefly activity, larval development, and habitat suitability (Kazama et *al*., 2007; Khoo et al., 2012; Abdullah *et al*., 2021; Bernard *et al*., 2023). Climatic data were supplemented with records from the Malaysian Meteorological Department, whereas water quality parameters were measured in situ using portable multiparameter instruments. Water samples were collected from the left bank, right bank, and midstream at each station to capture spatial variation within the river system.

Vegetation was also characterised at each station to assess habitat structure and composition. Dominant mangrove species, tree density and canopy cover were recorded following Lee *et al*. (2015), as vegetation structure influences firefly distribution by providing suitable perching, mating, and breeding habitats (Jusoh & Hashim, 2012). These environmental and biological data were measured during field sampling and used for preliminary ecological assessment. Following parameter screening, only seven criteria were retained for inclusion in the final AHP weighting and GIS-based habitat suitability analysis.

Analytical Hierarchy Process (AHP)

AHP is a structured decision-making method that prioritises and selects alternatives based on a hierarchy of criteria and their relative importance. By breaking down complex ecological problems into a hierarchical structure and using pairwise comparisons, AHP allows transparent, reproducible and ecologically meaningful weighting of environmental parameters. For instance, factors such as humidity, tidal regime, vegetation type, and water quality can be systematically assessed. Integrating AHP with GIS facilitates spatially explicit habitat zonation.

Step 1: Parameter Selection and Standardisation

Twelve environmental and biological parameters were initially compiled and standardised based on ecological relevance, direct field observations, and evidence from previous studies on firefly habitat requirements. These parameters comprised vegetation type, firefly abundance, air temperature, wind speed, air humidity, rainfall, tide level, water pH, salinity, conductivity, water clarity, and total dissolved solids. Following screening for ecological relevance, redundancy, and suitability for pairwise comparison, only seven criteria were retained for the final AHP weighting, namely air humidity, type of vegetation, rainfall distribution, wind speed, tide level, water pH, and air temperature. The remaining parameters, including firefly abundance and additional water-quality indicators were used only as supporting variables for ecological interpretation and were not included in the final pairwise comparison matrix.

Table 1: Initially measured environmental and biological parameters and suitability classes used for preliminary screening

Environmental Criterion	Unit	Value Class
Type of vegetation	Level	*S. caseolaris* (Very high) to *R. apiculata* (Low)
Number of fireflies	Individuals	< 1000 (Very low) to 20,001–60,000 (Very high)
Air temperature	°C	< 20 (Very low) to > 28 (Very high)
Wind speed	m/s	< 0.2 (Very low) to 0.9–1.0 (Very high)
Air humidity	%	< 60 (Very low) to 90–100 (Very high)
Rainfall	mm	< 0.5 (Very low) to > 30 (Very high)
Tide level	m	< 0.5 (Very low) to > 3.0 (Very high)
Water pH	Value	< 6 (Low) to > 8 (Very high)
Salinity	%	< 10 (Very low) to > 80 (Very high)
Conductivity	µS/cm	< 20 (Very low) to > 120 (Very high)
Water clarity	%	< 10 (Very low) to > 80 (Very high)
Total dissolved solids	ppm	< 0.1 (Low) to > 1.0 (Very high)

Note: The 12 parameters shown in Table 1 were used for preliminary ecological screening. Only seven criteria were retained and entered into the final AHP pairwise comparison matrix and weighting process

Table 2: Pairwise Comparison Matrix (PCM) for seven key criteria

	Air Humidity (%)	Type of Vegetation	Rainfall Distribution (mm)	Wind Speed (knots)	Tide Level (m)	pH Water	Air Temperature (°C)
Air humidity (%)	1	5	3	2	3	2	9
Type of vegetation	1/5	1	2	2	2	2	9
Rainfall distribution (mm)	1/3	1/2	1	2	3	3	7
Wind speed (knots)	1/2	1/2	1/2	1	2	3	7
Tide level (m)	1/3	1/2	1/3	1/2	1	2	5
pH water	1/2	1/2	1/3	1/3	1/2	1	3
Air temperature (°C)	1/9	1/9	1/7	1/7	1/5	1/3	1
Sum column	**2.98**	**8.11**	**7.31**	**7.98**	**11.70**	**13.33**	**41.00**

Note: The pairwise comparison matrix was developed based on expert judgments and structured according to the reciprocal requirement of the AHP method. The matrix yielded an acceptable consistency ratio (CR = 0.08), indicating that the comparisons were sufficiently consistent for deriving reliable criterion weights

Step 2: Pairwise Comparison and Weight Derivation Using AHP

The relative importance of the seven retained criteria was evaluated using a Pairwise Comparison Matrix (PCM), in which only air humidity, type of vegetation, rainfall distribution, wind speed, tide level, water pH, and air temperature were compared according to Saaty's 1 to 9 scale. The pairwise judgments were provided by three experts in mangrove ecology, firefly ecology and GIS-based habitat suitability modelling.

Table 3: Saaty's fundamental scale for pairwise comparisons in the AHP

Fundamental Scale (Row vs. Column)	
Extremely less important	1/9
	1/8
Very strongly less important	1/7
	1/6
Strongly less important	1/5
	1/4
Moderately less important	1/3
	1/2
Equally important	1
	2
Moderately more important	3
	4
Strongly more important	5
	6
Very strongly more important	7
	8
Extremely more important	9

Table 4: Consistency evaluation of the AHP pairwise comparison matrix for seven criteria

Consistency Measure	**Value**
Principal eigenvalue (λmax)	7.68
Consistency Index (CI)	0.11
Random Index (RI)	1.32
Consistency Ratio (CR)	0.09 (9%)
Consistency assessment	Acceptable

Step 3: Saaty's Fundamental Scale

Expert judgments were quantified using Saaty's 1 to 9 scale, where values greater than 1 indicate increasing importance of the row criterion over the column criterion and values less than 1 indicate lower importance.

Table 5: Saaty 1 to 9 scale for pairwise comparison

Scale	Description
1	Equal importance
3	Slightly more important
5	More important
7	Much more important
9	Extremely more important
2, 4, 6, 8	Intermediate values

Step 4: Weight Derivation and Consistency Analysis

The PCM was normalised by dividing each element by its column sum, and the priority vector (AHP weights) was calculated by averaging the rows of the normalised matrix. Consistency of expert judgments was evaluated using Equations (1) and (2):

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

$$\mathrm{CR} = \frac{CI}{RI} \quad (2)$$

Where λ_{max} is the principal eigenvalue, n is the number of criteria, and RI is the Random Index (Table 6). For seven criteria, λ_{max} = 7.68, CI = 0.11, and CR = 0.09, indicating acceptable consistency (< 0.10).

Step 5: AHP-Derived Weights and Ranking

After constructing the pairwise comparison matrix for the seven retained criteria and performing the normalisation process, the priority vector was calculated to obtain the final AHP weights for each environmental parameter included in the model.

The results (Table 7) indicate that relative humidity (%) is the most influential environmental factor, accounting for 32.8% of

Table 6: Random Index (RI) values for different numbers of criteria

N	1	2	3	4	5	6	7	8	9	10	11	12
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51	1.52	1.54

Source: Saaty (1980)

Table 7: AHP weights and ranking of environmental parameters

Parameter	CW	CA	AHP Weight	Weight (%)	Rank
Relative humidity (%)	0.015	0.9568	0.321	32.8	1
Air temperature (°C)	0.0840	1.469	0.181	18.1	2
Tide level (m)	0.082	1.2772	0.175	17.5	3
Wind speed (knots)	0.066	1.0910	0.142	14.2	4
Water pH	0.040	1.0073	0.086	8.6	5
Type of vegetation	0.034	0.9705	0.073	7.3	6
Rainfall (mm)	0.022	0.9117	0.022	2.2	7

Note:
*CW = Consistency weight; CA = Consistency assessment;
*Interpretation:
High AHP weight means that the factor has greater influence on firefly distribution.
Parameters with lower weights are still important but contribute less to habitat suitability in comparison to higher-ranked variables.
These weights are crucial for GIS-based multi-criteria analysis, ensuring that the most ecologically significant variables have appropriate influence on spatial predictions.

the overall weight, followed by air temperature (18.1%) and tide level (17.5%). Wind speed, water pH, type of vegetation and rainfall had comparatively lower weights, indicating a smaller relative influence on habitat suitability.

These weights provide a quantitative basis for integrating environmental parameters into GIS-based habitat modelling. By multiplying each standardised parameter layer by its corresponding AHP weight, the model reflects both suitability and importance, ensuring that critical factors have proportionally greater influence on the final habitat suitability index.

Step 6: Ecological Importance of Environmental Parameters

While AHP weights provide a quantitative measure of importance, ecological interpretation contextualises these results based on firefly biology and habitat requirements. The ecological interpretation presented here focuses only on the seven parameters retained in the final AHP weighting. The observed influence of each parameter on firefly abundance is summarised in Table 8.

Step 7: GIS-based Habitat Suitability and Zonation

AHP-derived weights for the seven retained criteria were integrated into GIS using Weighted Linear Combination (WLC). Each of the seven standardised parameter layers was multiplied by its respective weight and summed to generate a continuous habitat suitability index, which was then classified into high, moderate, and low suitability zones using the natural breaks method.

High-priority conservation areas were identified by combining the seven weighted criteria, with particular emphasis on vegetation structure, hydroclimatic conditions and water pH as the sole water-quality variable included in the final AHP model. Buffer and spatial analyses supported conservation planning according to local strategies (Jusoh & Hashim, 2012; Idris *et al.*, 2021). Sensitivity analysis confirmed the reliability of the zonation patterns (Chen & Wang, 2025).

High-priority areas for firefly conservation were identified by integrating vegetation structure, hydroclimatic conditions and water

Table 8: Observed influence of environmental parameters on firefly abundance

Rank	Parameter	Influence Level (According to Observation during Sampling)	Why it Matters for Fireflies
1	Type of vegetation	Very high	Provides habitat, moisture retention, shelter and prey (snails, worms); essential for larvae survival
2	Air humidity (%)	Very high	Prevents larval and adult dehydration; supports mating activity
3	Rainfall distribution (mm)	High	Maintains moist soil; poor distribution causes larval mortality
4	Air temperature (°C)	High	Controls metabolism, flashing behaviour and breeding season length
5	Wind speed (knots)	Moderate	Affects adult flight and light signalling during mating
6	Tide level (m)	Low–moderate	Important mainly in coastal/ mangrove habitats; flooding can kill larvae
7	Water pH	Low	Indirect effect via prey availability; important mainly if polluted or extreme

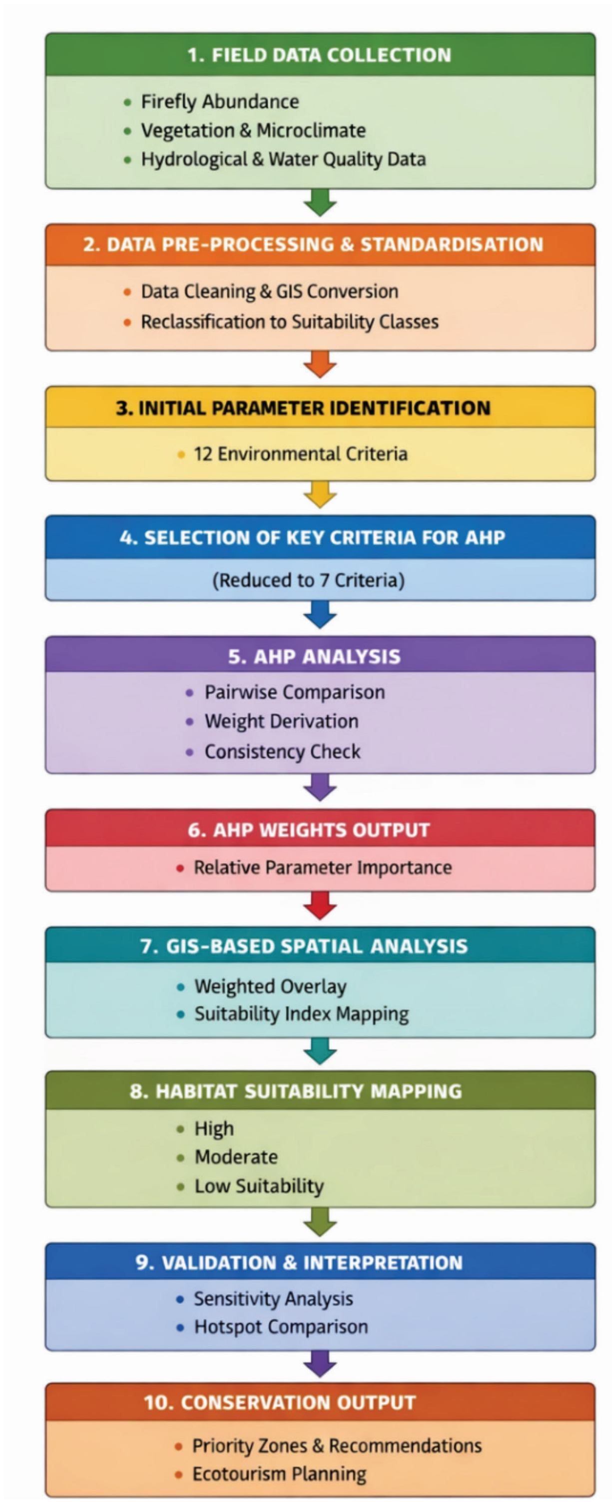

Figure 2: Complete AHP-GIS workflow for firefly habitat suitability mapping

quality variables. Buffer and spatial analyses supported conservation planning in line with local management strategies (Jusoh & Hashim, 2012; Idris *et al.*, 2021). Sensitivity analysis confirmed that the zonation patterns reliably reflected key environmental drivers (Chen & Wang, 2025).

Results and Discussion

Spatiotemporal Variation and Firefly Zonation

The AHP analysis showed that the final habitat suitability model was driven by seven retained criteria only. Among these, relative humidity emerged as the most influential factor, followed by air temperature and tide level, indicating that microclimatic and hydro-environmental stability plays a central role in shaping suitable habitats for *P. tener*. Wind speed, water pH, type of vegetation, and rainfall contributed additional explanatory value, although with lower relative weights. These findings indicate that the final zonation pattern was determined by the combined influence of the seven weighted criteria included in the AHP-GIS model.

Firefly Abundance in Relation to Abiotic Parameters

Firefly population monitoring conducted along the Sepetang River from November 2021 to April 2022 revealed notable spatiotemporal variations in abundance. The lowest population count was recorded in November 2021 with 13,194 individuals (11.84%), while the highest was observed in January 2022, reaching 26,761 individuals (24.02%). A gradual increase in abundance was observed from November 2021 to January 2022, followed by month-to-month fluctuations during the remainder of the study period (Figure 3). Only Station 6 surpasses this threshold, recording over 55,000 fireflies and is thus identified as a statistically and ecologically significant hotspot.

Meanwhile, Stations 1 to 5 and 7 and 8 demonstrate moderate abundance levels, generally ranging between 5,000 and 10,000 fireflies, remaining below the hotspot criterion. Stations 9 and 10 report the lowest abundance values, which may be indicative of deteriorated or unsuitable habitat conditions. The pronounced spatial variation in firefly populations underscores their sensitivity to localised environmental factors such as vegetation structure, water parameter, ambient light pollution, and anthropogenic disturbances. These findings point to the ecological importance of Station 6 and highlight the need for targeted conservation measures and further investigation into the environmental parameters that support or constrain firefly distribution across the landscape.

Figures 4 to 6 illustrate the monthly firefly population abundance in the Sepetang River, Perak, in relation to key abiotic factors,

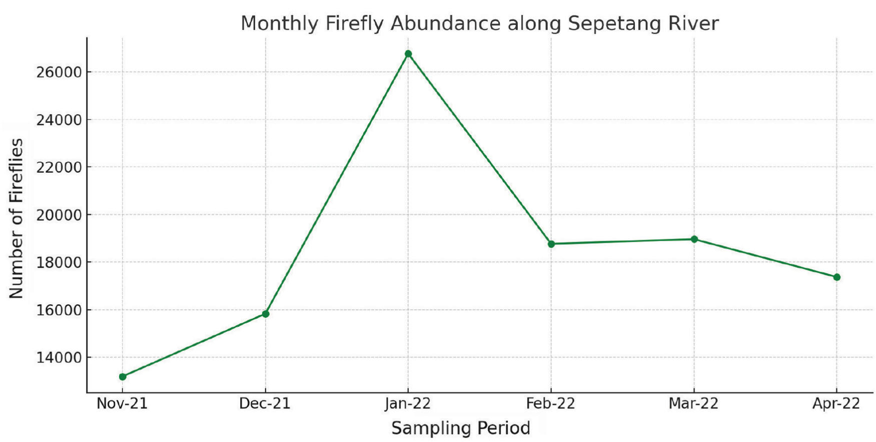

Figure 3: Firefly abundance by station

including weather conditions (air temperature, relative humidity, and wind speed) and river water parameters (tide level, pH, salinity, electrical conductivity, total dissolved solids, and turbidity).

Firefly abundance peaked during the first and second quarters of 2022, specifically from January to April. In contrast, the lowest populations were observed in November and December 2021. During the monitoring period, average monthly air temperatures [Figure 4 (b)] ranged from 25.2°C to 31.8°C, with no distinct trend correlating temperature to firefly abundance. Relative humidity [Figure 4 (c)] showed considerable variation, fluctuating between 67.56% and 97.12%. Wind speed [Figure 4 (d)] was generally calm (0 to 1.02

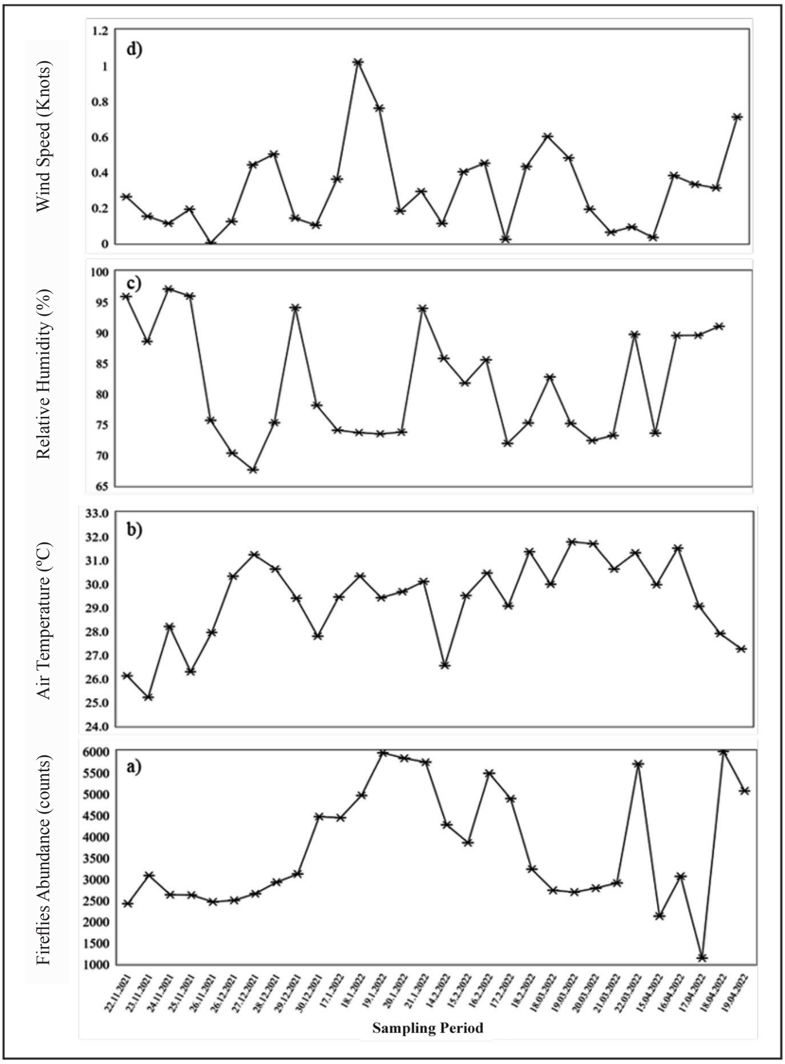

Figure 4: Comparing monthly abiotic parameters (weather) and firefly abundance along the Sepetang River in Perak. (a) Total monthly firefly population abundance (SS1–SS10 on selected display trees) for six months, from November 2021 to April 2022, (b) average daily air temperature for each month, (c) average monthly relative humidity, and (d) average monthly wind speed. Each month included five consecutive days of monitoring

knots), though slightly higher in January and April 2022. Notably, periods with fluctuating or lower humidity and temperature were observed in November 2021, February, and April 2022. The driest and warmest conditions occurred between December 2021 and March 2022.

Tidal levels [Figure 5 (b)] were mostly high during sampling times, ranging between 2.00 and 2.24 m, with occasional low tide days (1.00 to 1.66 m). Water pH levels [Figure 5 (c)] remained consistently acidic, ranging from 5.61 to 5.95, placing the water body within Class III

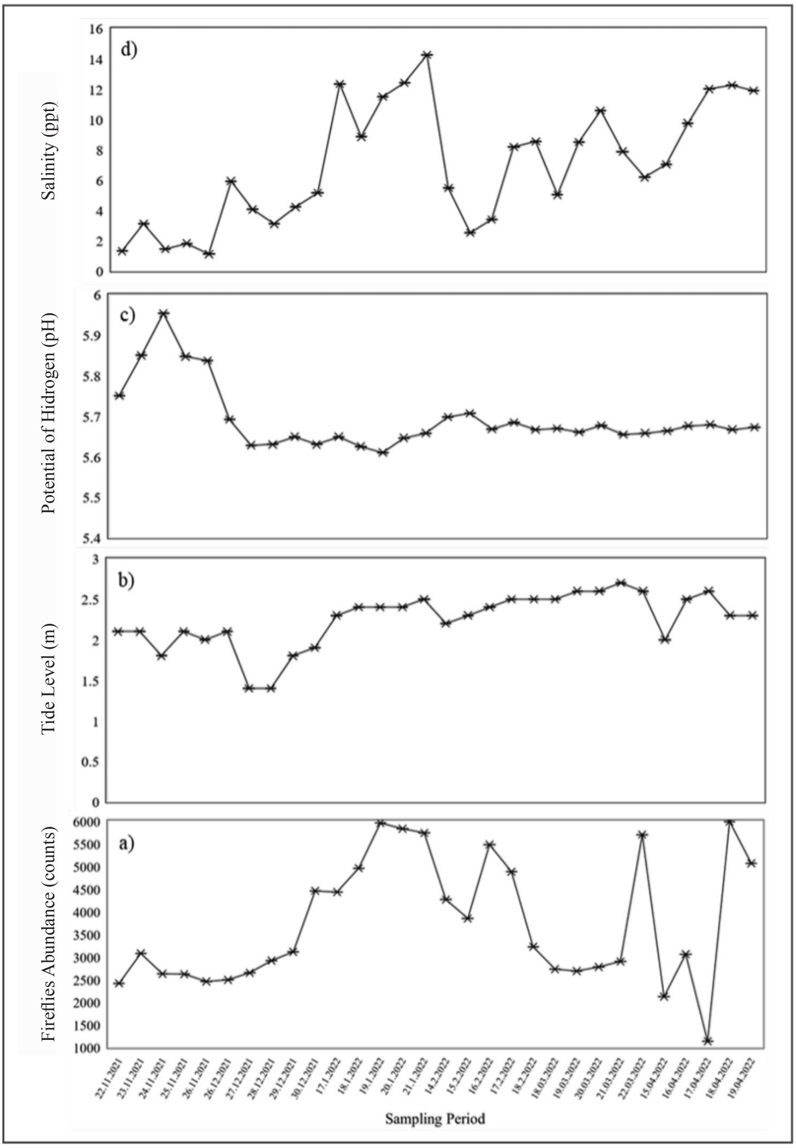

Figure 5: Monthly abiotic parameters compared to firefly abundance in the Sepetang River, Perak (river water measurements). (a) The monthly firefly population abundance (total for SS1–SS10) between November 2021 and April 2022, (b) the average daily tide level for each month, (c) the average monthly potential of hydrogen (pH), and (d) the average monthly salinity

of the Interim National Water Quality Standards for Malaysia (INWQS) suitable for fisheries, recreation, and aquatic life sustainability. Salinity levels [Figure 5 (d)] were mesohaline, averaging 6.99 ppt, consistent with the range reported by Chong (2006) for the Sepetang River (7 to 22 ppt).

Further water parameters are shown in Figure 6. The electrical conductivity [Figure 6 (b)] averaged 28.63 µS/cm, while total dissolved

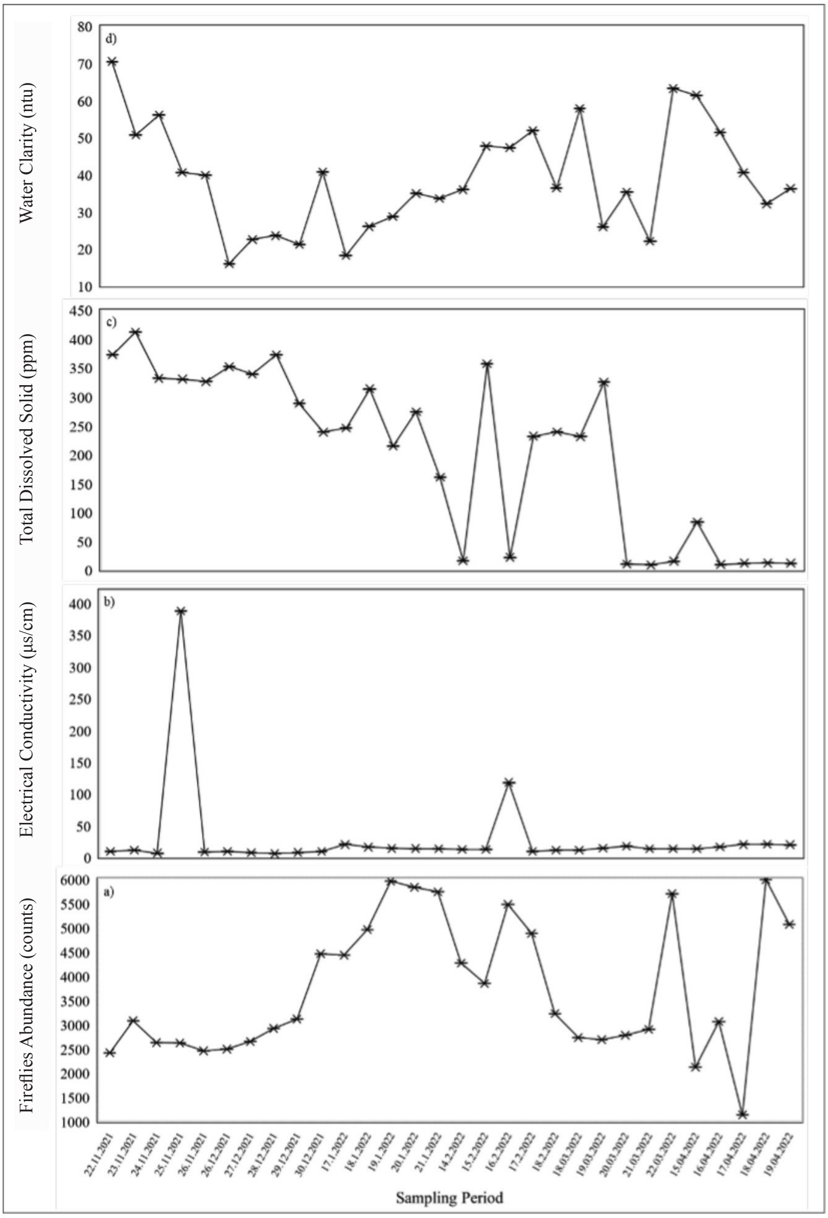

Figure 6: Comparing monthly abiotic parameters and firefly abundance along the Sepetang River, Perak (river water measurements). (a) Average monthly firefly population abundance (total for SS1–SS10) between November 2021 and April 2022, (b) average daily electrical conductivity for each month, (c) average monthly total dissolved solids, and (d) average monthly water clarity (turbidity)

solids [Figure 6 (c)] measured at 205.15 ppm. Water clarity or turbidity [Figure 6 (d)] was relatively high, with a mean value of 38.93 NTU. These measurements suggest moderate levels of ion content and suspended particles, with potential implications for ecological stability and light penetration in aquatic habitats.

Although salinity, conductivity, total dissolved solids, and water clarity were measured to characterise general river conditions, these variables were not included in the final AHP weighting and were used only as supporting descriptors of the habitat environment.

Firefly Zonation

Among the 10 sampling stations, Station 6 recorded the highest number of fireflies, accounting for 50.01% of the total population. Located in Zone 2, Station 6 is dominated by dense stands of *S. caseolaris*, a tree species known to be the preferred display site for *P. tener*. This ecological association identifies Station 6 as the primary hotspot for fireflies in the study area. Conversely, the lowest abundances were recorded at Stations 9 and 10, with only 723 (0.65%) and 517 (0.46%) individuals, respectively (Table 9). These sites represent population coldspots, potentially influenced by factors such as sparse vegetation cover, elevated salinity levels, or other environmental stressors.

The firefly zonation map (Figure 7) represents the final output derived from AHP, highlighting zones along the Sepetang River based on habitat suitability and ecological characteristics relevant to *P. tener*. Zonal analysis provides critical insights into firefly distribution patterns, ecological preferences and behavioural tendencies across distinct riverine segments, ultimately aiding in the identification of critical habitats for conservation prioritisation (Jusoh *et al.*, 2010; Khoo *et al.*, 2016; Wong, 2022).

Zone 2 encompasses Station 6, which is located near the rivermouth. According to Table 9, Zone 2 is densely vegetated with *S. caseolaris*, a species strongly associated with *P. tener* aggregation and mating displays (Abdullah *et al.*, 2021; Cheng *et al.*, 2021). This vegetation type provides ample perching structures, moderate canopy cover, and favourable microclimatic conditions. Dense vegetation dominated by *S. caseolaris* and *Nypa Fruticans* have been reported as key attributes for synchronous flashing and reproductive success in fireflies (Foo & Dawood, 2017; Jaikla *et al.*, 2020; Idris *et al.*, 2025). Zone 2 recorded the highest abundance of fireflies, with 92,096 individuals, thus emerging as the most favourable habitat among the three delineated zones.

In contrast, Zone 1 (Stations 1 to 4), located upstream and adjacent to shrimp ponds, is also dominated by *S. caseolaris*. Although this zone supports a relatively high number of fireflies (17,007 individuals), the abundance is still markedly lower than in Zone 2. Anthropogenic disturbances, such as aquaculture activities and artificial lighting, in this region may negatively impact firefly behaviour, as supported by previous studies linking light pollution to reduced mating synchronisation and population decline (Firebaugh & Haynes, 2016; Hazmi & Sagaff, 2017; Owens & Lewis, 2018; Mbugua *et*

Table 9: Firefly zonation summary

Zone	Station(s)	Type of Vegetation	Total Fireflies per Zone	Distribution Level	Key Features
Zone 1	1, 2, 3, and 4	*S. caseolaris*	17,007	High	Upstream; adjacent to shrimp ponds
Zone 2	5, 6, and 7	*S. caseolaris*	92,096	Very high	Rivermouth; dense shady vegetation
Zone 3	8, 9, and 10	*Rhizophora* spp.	2,507	Low	Downstream; near freshwater fishponds

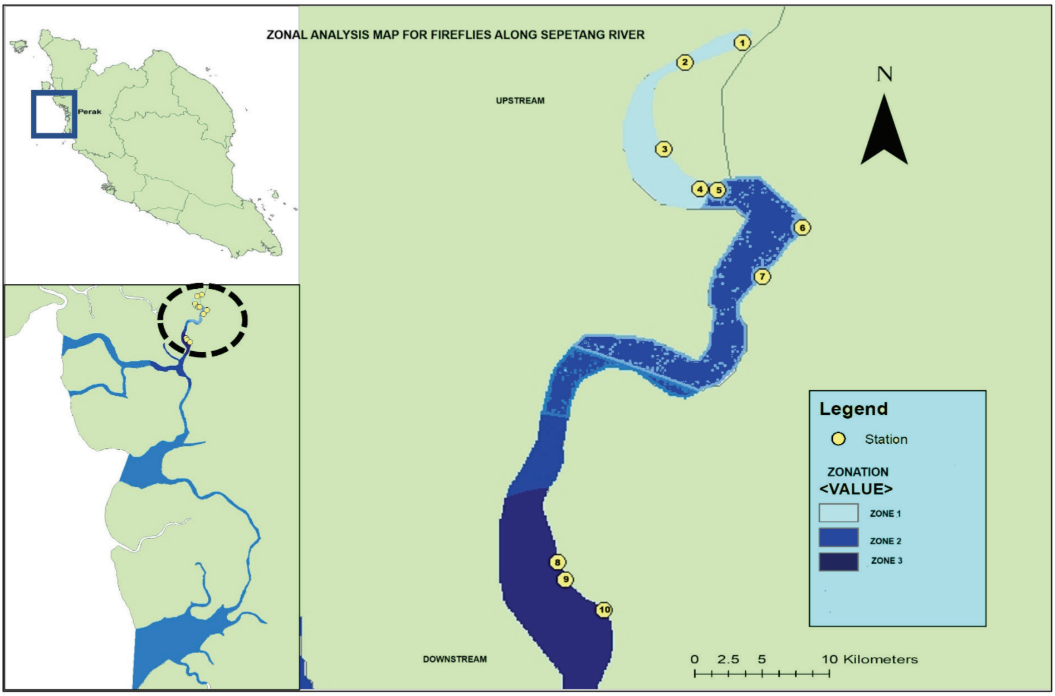

Figure 7: Firefly zoning map

al., 2020; Owens *et al.*, 2021). Such associations have also been reported in Eastern India, where Luciolinae species abundance and conservation potential were highest in riverine, precipitation-rich habitats dominated by dense vegetation (Kruskal-Wallis, p = 0.02), highlighting the sensitivity of fireflies to both structural and environmental habitat features (Gosh *et al.*, 2025).

Zone 3, covering Stations 8 to 10 and located downstream near coastal areas and freshwater fish ponds, is primarily vegetated by *R. mucronata* and *R. apiculata*. These species, although dominant in mangrove ecosystems, appear to be less suitable for *P. tener* display activities. This zone recorded the lowest firefly abundance (2,507 individuals), consistent with findings that *P. tener* shows a strong preference for *Sonneratia*-dominated habitats due to their open and low-branching structure, with horizontally spreading limbs, providing high canopy accessibility (Khoo & Phon, 2019; Husin *et al.*, 2024).

Overall, the zonation reveals a spatial gradient in habitat suitability, with Zone 2 emerging as a potential firefly hotspot. This can be attributed to an optimal combination of riparian vegetation, proximity to the rivermouth, and microclimatic factors such as humidity, precipitation, shade, and reduced artificial lighting conditions known to enhance firefly congregation and reproductive success (Jusoh *et al.*, 2010; Gosh *et al.*, 2023; McNeil *et al.*, 2024; Gosh *et al.*, 2025). These findings reinforce the need for targeted conservation efforts in Zone 2 and indicate the value of multi-criteria spatial analysis in firefly habitat assessment and management.

The analysis of environmental parameters for *P. tener* habitat suitability along the Sepetang River revealed that the number of fireflies exerted the highest influence (22.2%) in determining zonal suitability. This was followed by relative humidity (11.8%), tide level (11.5%), and air temperature (10.7%), suggesting that microclimatic stability plays a central role in firefly ecology. Although water parameters did not rank among the top factors directly influencing firefly abundance, their ecological relevance remains significant. For instance, water pH (7.8%) emerged as the sixth most important parameter, and it plays a significant role in modulating dissolved carbon dynamics and can serve as an indicator of eutrophication and water quality degradation (Zhang *et al.*, 2025).

Likewise, electrical conductivity (7.5%), ranked seventh, reflects salinity, total dissolved solids, and overall hydrological stability, all of which are useful benchmarks for monitoring estuarine ecosystems (Fondriest Environmental, 2025). Although individually less influential, lower-ranked parameters such as salinity, water clarity, and total dissolved solids collectively shape the microhabitat conditions essential for firefly survival and reproduction. Variations in these parameters can affect soil moisture balance, vegetation health, and overall estuarine stability factors critical to sustaining suitable environments for larval development and adult congregation (Corwin & Yemoto, 2020). These parameters are especially relevant in mangrove systems where subtle shifts in water parameters can lead to broader ecological consequences. Hence, water-related variables, while indirectly linked to firefly numbers, should be integrated into a comprehensive conservation strategy.

The type of vegetation (3.1%) and rainfall (1.9%) were the least influential factors in this study. However, their ecological significance should not be dismissed. Vegetation, particularly *S. caseolaris*, offers important microhabitats and mating display platforms for *P. tener*, especially when arranged in dense, shaded formations (Idris *et al.*, 2021; Nur-Fatehah *et al.*, 2022). In contrast, areas dominated by *Rhizophora* spp., as observed in Zone 3, supported notably fewer fireflies. This is likely due to differences in canopy structure, leaf density, and branch architecture, which are crucial for firefly courtship and signalling behaviour. Rainfall, while ranked lowest, may still exert seasonal influence, particularly during periods of extreme drought or flooding (Hermann *et al.*, 2016; Evans *et al.*, 2019; Fallon *et al.*, 2019; Merten, 2024; Pérez, 2024). Although fireflies can tolerate typical seasonal variation, prolonged hydrological stress could affect reproductive cycles and larval survival rates.

The spatial analysis further reinforces these findings. Zone 2, which includes Stations 5, 6, and 7, was identified as a hotspot for firefly populations. This zone was characterised by extensive *S. Caseolaris* tree coverage, shaded canopy structure and proximity to river mouth conditions considered highly favourable for *P. tener*. Notably, Station 6, recorded the highest firefly count among all surveyed sites. These findings align with previous studies documenting the preference of fireflies for *Sonneratia*-dominated mangroves in Peninsular Malaysia (Jusoh *et al.*, 2010; Khoo *et al.*, 2012; Abdullah *et al.*, 2021). Spatial analysis identified Zone 2 as the most suitable habitat, suggesting that this area provides an optimal combination of biotic and abiotic conditions necessary for sustaining firefly populations. This finding has direct implications for conservation prioritisation, as targeted efforts in Zone 2 could yield higher conservation efficacy due to its established ecological suitability.

The findings of this study indicate that firefly abundance is strongly influenced by microclimatic conditions, with relative humidity and tidal levels emerging as the most significant environmental predictors. These variables not only affect firefly presence but also reflect the broader ecological conditions that support their life cycle, particularly mating behaviour and larval development. The high rank of air humidity and tidal influence underscores the importance of dynamic environmental factors in shaping firefly habitat suitability. The findings of this study indicate that firefly abundance is strongly influenced by microclimatic conditions, with relative humidity and tidal levels emerging as the most significant environmental predictors. This is consistent with the work of Bernard *et al.* (2023), who reported a strong positive correlation between firefly abundance and relative humidity ($r = 0.724$, $p = 0.008$) in Sulaman Lake, Sabah. Similarly, Poukin *et al.* (2023) found that firefly populations along the Klias River were significantly higher during the northeast monsoon, highlighting the influence of seasonal tidal regimes. These variables not only affect firefly presence but also reflect the broader ecological conditions that support their life cycle, particularly mating behaviour and larval development. Khoo *et al.* (2012) further emphasised that environmental factors, such as humidity, salinity, and water temperature, play a critical role in shaping adult firefly flashing behaviour, a key component of mating success. The high rank of air humidity and tidal influence, therefore, underscores the importance of dynamic environmental factors in determining firefly habitat suitability.

Although water parameters such as pH, salinity, conductivity, and total dissolved solids, were ranked lower in their direct association with firefly abundance, they should not be considered negligible. Long-term ecological integrity of estuarine mangrove systems depends on water chemistry, as subtle shifts in these parameters can influence microbial communities, prey availability, and larval habitats potentially resulting in delayed or indirect effects on firefly populations. For example, a study of *Pteroptyx* fireflies along the Rembau River found a moderately positive correlation between pH and adult abundance ($r = 0.408$, $p < 0.05$), while biochemical oxygen demand and ammonia were negatively correlated, suggesting sensitivity to water chemistry perturbations (Abdullah *et al.*, 2021). In a regional review of Southeast Asian populations, lower salinity was consistently linked to higher larval insect abundance, underscoring the importance of maintaining salinity within tolerable ranges for larval development (Abdullah *et al.*, 2019; Bernard *et al.*, 2023). Meanwhile, studies in the Cherating River found that total dissolved solids and conductivity exhibited weaker associations with firefly numbers compared with dissolved oxygen and temperature but emphasised their foundational role in shaping aquatic habitats (Faudzi *et al.*, 2021). These findings highlight that even when water chemistry variables rank lower in immediate statistical models, their cumulative influence on ecosystem processes is vital for sustaining healthy firefly populations.

Collectively, these results reinforce the importance of adopting a multi-parameter conservation framework. Focusing solely on firefly counts or vegetation types would overlook critical ecological drivers. Instead, an integrated strategy that encompasses climatic, hydrological and vegetative dimensions is essential for sustaining viable firefly populations within estuarine mangrove ecosystems. This approach aligns with contemporary principles of ecosystem-based management and highlights the interconnectedness of habitat components in the conservation of bioluminescent species.

Conclusions

This study identified the number of fireflies (22.2%) as the most influential factor in determining habitat suitability along the Sepetang River. Among the vegetation types, *S. caseolaris*, despite contributing a lower overall weight (3.1%) was found to be the most significant tree species supporting firefly presence, particularly in Zone 2, which emerged as a clear habitat hotspot. Notably, Station 6, located within Zone 2 and characterised by dense, shaded *S. caseolaris*, recorded the highest firefly population. Other key environmental variables contributing to habitat suitability include air humidity (11.8%), tide level (11.5%), and air temperature (10.7%), highlighting the importance of microclimatic and hydrological stability. While factors such as wind speed, rainfall distribution, and water parameters (pH, conductivity, salinity) were ranked lower, they still play supporting roles in shaping the ecological conditions necessary for *P. tener* survival.

Figure 8 illustrates the integrated methodological framework linking field data collection, analytical processing, and conservation planning. Field surveys measuring temperature, humidity, wind, tide, water quality,

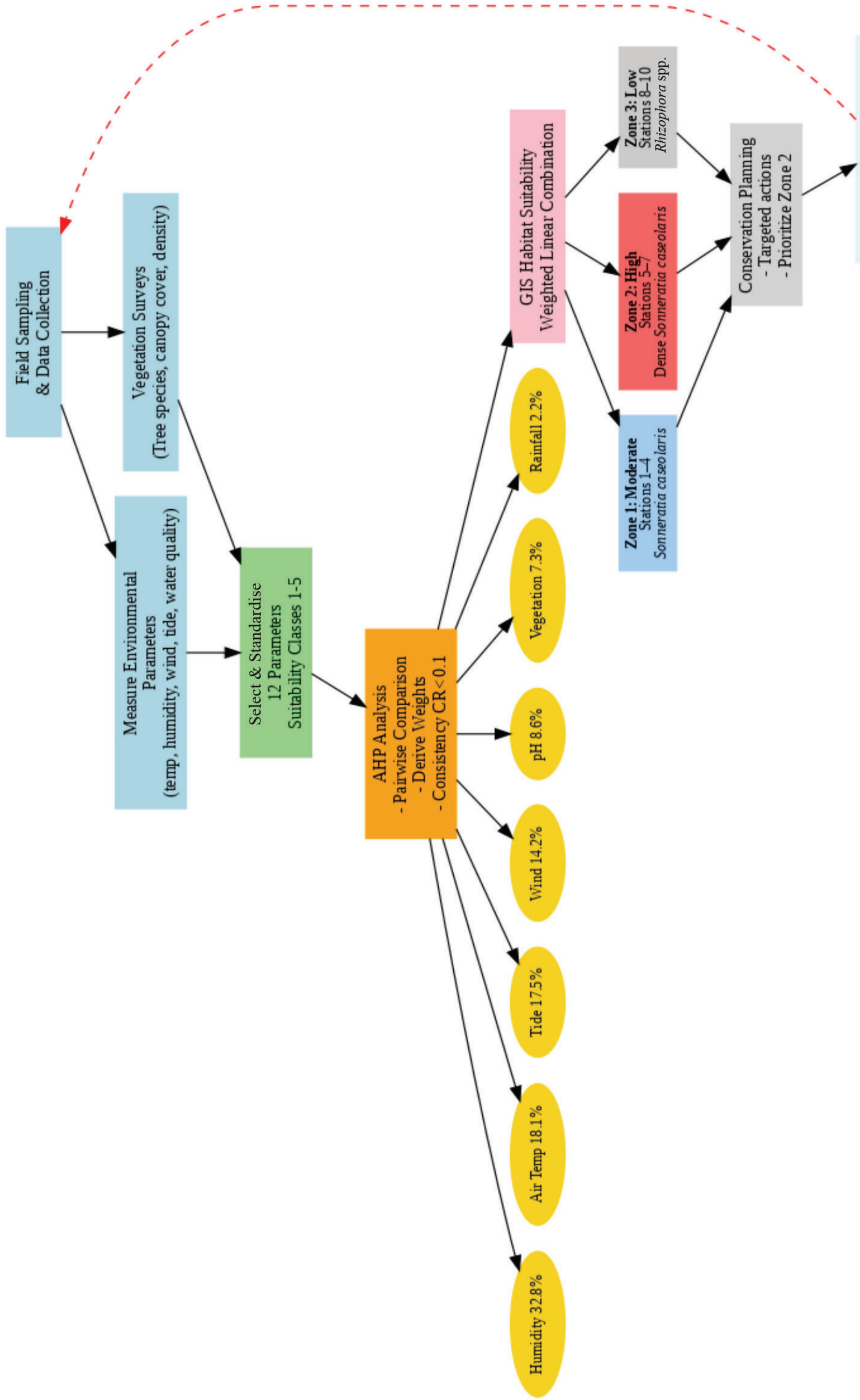

Figure 8: Structured methodological framework linking field sampling, AHP-based analysis, GIS habitat suitability modelling and conservation planning for *P. tener* along the Sepetang River

and vegetation provide the foundational dataset. Environmental parameters are standardised and analysed via AHP to derive weighted importance, with relative humidity, air temperature, and tide being most influential. Weighted layers are incorporated into a GIS-based habitat suitability model using a weighted linear combination, producing spatially explicit Zones 1 to 3 of high, moderate, and low suitability. Zone 2, with dense *Sonneratia* vegetation and favourable microclimatic conditions, is identified as the priority hotspot. A feedback loop allows adaptive management by refining AHP weights and GIS outputs with updated field observations, supporting dynamic, evidence-based conservation strategies. The zonal analysis adopted in this study provided a systematic approach to evaluating spatial habitat suitability, allowing for the identification of priority conservation areas. These findings contribute valuable insights for the development of targeted conservation and habitat management strategies for firefly populations in mangrove ecosystems, particularly in estuarine environments under increasing anthropogenic and climatic pressure.

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Author Contributions Statement

Nurhafizul Abu Seri conducted the field surveys, performed GIS-based spatial analysis and led the manuscript writing. Azimah Abd Rahman conceptualised the research design, supervised the analytical framework and guided the integration of the Analytical Hierarchy Process (AHP) with GIS. Both authors contributed to data interpretation, manuscript revisions, and approved the final version of the article for submission.

Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefits, commercial, or financial conflicts and declare absence of conflicting interests with the funders.

Ethics Statement

All information communicated in this article does not need ethical approval for research or informed consent because human or animal subjects were not involved.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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