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Application of GIS for Monitoring Firefly Population Abundance (*Pteroptyx tener*) and the Influence of Abiotic Factors

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ABSTRACT

This study focuses on the *Pteroptyx tener* species in the Sepetang River, Malaysia, aiming to evaluate the firefly's abundance and explore its correlation with various biotic and abiotic parameters. The study was conducted over six months, from November 2021 to April 2022, utilizing Geographic Information System (GIS) software to apply hotspot mapping and Inverse Distance Weighting (IDW) analysis to elucidate the spatial distribution of firefly populations. A total of 111,615 individuals were recorded, with a particular focus on this firefly species' presence on their display trees. Hotspot analysis showed that Station 6, located at the mouth of a river with dense mangroves, hosted 55,723 fireflies (50.01%). In contrast, Stations 9 and 10, near ponds and shrimp settlements, recorded 517–723 fireflies (0.65% and 0.46%). Pearson's correlation coefficient (r) unveiled a statistically significant positive correlation ($r = 0.88$, $p < 0.05$) between wind speed and the abundance of firefly populations within the Sepetang River. However, no statistically significant correlation ($p > 0.05$) was found between firefly abundance and various other abiotic parameters, including relative humidity (RH), air temperature, tide level, pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and water clarity. Thus, the results revealed the preference for fireflies due to the availability of vegetation, wind speed and minimal disturbance in this area. In conclusion, this study's information significantly adds to our understanding of these interesting insects and their complicated relationships in nature. It underscores the importance of preserving their habitats and ecosystems.

Keywords: Abiotic parameters, Geographic Information System (GIS), insect population, Inverse Distance Weighting (IDW), Pearson's correlation coefficient (r), *Pteroptyx tener* species

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INTRODUCTION

Geographic Information System (GIS) is a computer-based platform facilitating the collection, storage, analysis, and visualization of spatial data, integrating diverse sources like satellite imagery, maps, surveys, and non-spatial data. Through this integration, GIS offers a comprehensive perspective of specific geographic areas, serving as a powerful tool for comprehending and managing intricate spatial relationships within the environment (Tu & Hoang, 2023). Recently, the advancement of information availability and tools for information management has facilitated the development of geographically based databases essential for protecting biodiversity, and the operation of many conservation programs is inherently spatial (Malavasi, 2020). GIS plays a pivotal role in biodiversity monitoring, allowing targeted surveys and tracking species and habitat distribution changes over time (Rocchini et al., 2016).

In contrast, international research has shown a more widespread use of GIS to examine the relationships between insect species and their environments. Studies on various insect populations, such as the spotted borer, African oil palm weevil, anuran species, insect pests, termites, aphids, and others (Kokila et al., 2021; Lubis et al., 2023; Keinath et al., 2023; Roy et al., 2020; Ozsahin et al., 2022; Du et al., 2020) have extensively employed GIS to investigate the influence of biotic (living) and abiotic (non-living) parameters on their distribution, behavior, and abundance. These international studies have showcased the diverse applications of GIS in entomological research, highlighting its effectiveness in analyzing complex ecological patterns, understanding habitat preferences, and predicting species responses to environmental changes. Through the comprehensive integration of GIS, researchers have uncovered valuable insights into the intricate relationships between insects and their surrounding ecosystems, contributing to the advancement of ecological knowledge and conservation strategies on a global scale.

GIS and its related technologies are indispensable for informed decision-making, particularly in addressing the spatial aspects relevant to biodiversity (Mileti et al., 2024). Balaman (2019) explained that GIS is useful for gathering, documenting, storing, analyzing, presenting, and managing spatial and geographic data utilizing interactive maps. Also, creating web GIS tools to map and describe habitats and biodiversity, particularly the future distribution of species, can play an important role in conservation planning (Obeidavi et al., 2019). Additionally, regarding commercialization, GIS output maps that include clear captions and grouping of various colors and patterns make it simpler to visualize the geographic information. It makes inexperienced GIS users comfortable using the application (Paramasivam, 2019). A wide spectrum of specialized fields, such as geology, geomorphology, geography, geophysics, hydrology, hydrogeology, environmental science, oceanography, meteorology, and atmospheric science, heavily rely on geospatial data to grapple with complex Earth-related dilemmas.

Some of these predicaments would be exceptionally arduous to tackle without integrating GIS (Zhou, 2021).

In Malaysia, despite its potential, the utilization of GIS applications has been relatively limited. For example, a study by Idris et al. (2021) focused on assessing firefly habitats. This study integrated GIS with remote sensing techniques, allowing researchers to comprehensively analyze various landscape factors that affect firefly populations. Using GIS tools, the researchers could map the distribution of firefly habitats, discern the influence of different landscape elements on their populations, and propose effective conservation strategies to protect these vulnerable species. This study provided valuable information on the ecological requirements of fireflies and highlighted the importance of preserving their habitats. The study conducted by Poukin et al. (2023) only used ArcGIS 9.3 to delineate and map sampling stations within their designated study area.

The documentation of Congregating Firefly Zones (CFZs) in Malaysia, as outlined in the study by Wong (2022), demonstrates the importance of GIS in understanding the spatial distribution of firefly populations. GIS was utilized to accurately map the locations of these CFZs along rivers, providing valuable spatial data for conservation planning and management. Moreover, the study's emphasis on conducting in-depth research on firefly species diversity aligns with GIS's role in facilitating data collection, analysis, and visualization. GIS can help researchers identify areas with high biodiversity and prioritize conservation efforts accordingly. Additionally, the Selangor Declaration on the Conservation of Fireflies highlights the critical role of protecting firefly habitats, a task that GIS can support through spatial analysis of habitat threats and identifying priority conservation areas.

The lack of a GIS approach to collect biodiversity data poses a significant challenge to efficient conservation efforts, particularly in monitoring firefly populations in Malaysia. This limitation hampers the ability to collect accurate and comprehensive data, essential to understanding firefly populations and implementing effective conservation strategies. Therefore, this research aims (1) to assess the spatial distribution of firefly population abundance, (2) to map the Inverse Distance Weighting (IDW) and firefly population abundance correlation using GIS tools, and (3) to analyze the influence of abiotic factors on the firefly population abundance.

MATERIALS AND METHODS

Study Area

Figure 1 shows the location of Kuala Sepetang (Sepetang Estuary) in the Larut, Matang, and Selama districts of Perak, Malaysia. Sepetang Estuary is located at coordinates 4°50'26"N 100°37'42"E and is a rapidly developing fishing village. The length of the Sepetang River is approximately 32 km, while the catchment area is about 189 km^2. It was also one of

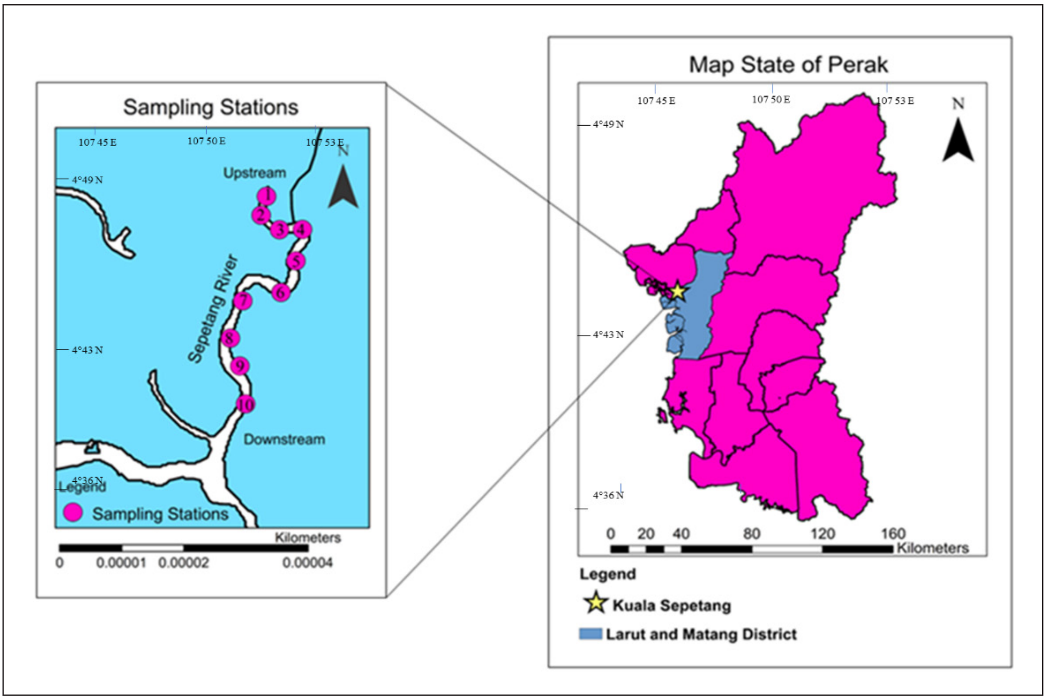

Figure 1. The sampling stations (SS1–SS10) along the Sepetang River

Malaysia's Congregating Firefly Zones (CFZs), which aims to protect the firefly colonies of the river, especially *Pteroptyx tener* (Wong & Yeap, 2012).

The Methodology

During a six-month continuous monitoring period at the Sepetang River, the most active activity of fireflies was observed flashing their lights between 19:35 and 22:00 MST, persisting even during heavy rain. The study area experiences a tropical climate characterized by abundant rainfall from October to January, which constitutes the rainy season. In contrast, the period between February and September represents the hottest months in this region. Consequently, the sampling activities were conducted during two distinct seasons: the rainy season (November 2021 to December 2021) and the dry season (January to April 2022), starting from 5:30 p.m. to 9:00 p.m.

The selection of sampling stations was based on the presence of firefly colonies observed on the display trees, which were marked using a handheld Altimeter GPS+ attached to an iPhone X, version 4.7.3. Table 1 lists abiotic parameters and the units and instruments used during field studies. Rapid on-site day and night sampling assessment also ensured systematic data collection of fireflies, vegetation, and insect mimics. The use of rapid assessments is also crucial to avoiding loss of data and misinformation. The applied rapid assessment was adapted from the work of Jusoh et al. (2011).

Table 1
Abiotic parameters, units, instruments, and notable features

Abiotic Parameter	Measurement	Unit	Instruments
Electrical Conductivity	MicroSiemens per centimeter	µS/cm	Hach SensION 5 waterproof conductivity meter and conductivity probe
Total Dissolved Solids	MicroSiemens per centimeter	ppm	Hach SensION 5 waterproof conductivity meter and conductivity probe
Water Salinity	MicroSiemens per thousand	ppt	Hach SensION 5 waterproof conductivity meter and conductivity probe
Potential of Hydrogen	MicroSiemens per centimeter	pH	Hach SENSION1 Waterproof Ph/mV meter electrode
Clarity/Turbidity	Nephelometric Turbidity Units	NTU	Hach 2100P portable turbidimeter
Wind Speed	Meters per second	knots	Smart Sensor Mini Anemometer with an LCD digital display
Air Temperature	Celcius	ºC	Benetech GM1361+ humidity temperature meter
Relative Humidity	Percentage	%	Benetech GM1361+ humidity temperature meter
Tide Level	Meters	m	Tideschart application (Developer: 7th Gear)

Visual Counting

The visual counting method was chosen over alternative techniques since it is fast and low-cost (Jusoh et al., 2010a), particularly in field studies where real-time observations are crucial. Two trained observers were tasked with implementing this method, as Jusoh et al. (2010a) suggested, to mitigate potential visual biases stemming from variations in visual acuity or observer habits. Furthermore, the reliability of visual counting can be enhanced through validation by different observers conducting repeated observations, ensuring the accuracy of data collection.

The study implemented several measures to minimize the likelihood of overestimation. First and foremost, extensive training was provided to the observers involved in the counting process. This training focused on developing a standardized approach to identify and distinguish individual fireflies, considering their unique flashing patterns and behaviors. Additionally, rigorous training sessions were conducted to enhance the observers' visual acuity and consistency in counting. Moreover, the study established specific observation periods during the counting. This temporal restriction was intended to ensure the counts were made within a defined time frame, reducing the chances of overcounting due to repetitive observations of the same fireflies.

Regular assessments were also conducted to monitor observer performance and minimize potential biases that might lead to inaccurate counting. These assessments aimed to identify any variations or discrepancies in the counting process, allowing immediate corrective actions to be taken. While manual counting presents certain limitations and potential concerns, the study took proactive measures to justify its use as a reliable estimation method. The rigorous training, standardized counting protocols, and careful monitoring of the counting process were all critical components in ensuring the accuracy and validity of the population estimations for *Pteroptyx tener*.

Sweep-netting

The sweep net technique used in this study complies with ethical guidelines for firefly conservation in many ways. First, it is non-invasive, allowing researchers to capture adult fireflies for species identification and taxonomic studies without harming them or their habitat and does not require continuous daily monitoring. This approach is important to minimize any adverse effects on the fireflies and their environment during data collection. Sweep net sampling is efficient for estimating the presence and abundance of species in the field and remains the best approach (Edde, 2022). Second, sweep nets have proven efficient in species identification, allowing researchers to accurately study the physical characteristics of various firefly species and their flicker patterns. This method also minimizes errors by accurately identifying captured specimens, such as *Pteroptyx tener*, in this study, thus maintaining the specificity of the data collected. Furthermore, sweep-netting also assisted in estimating the abundance and population density of adult fireflies in our research area. This data was valuable for understanding population abundance and monitoring changes over time.

Spatial and Non-spatial Data Analysis Techniques

Spatial and non-spatial data analysis techniques played a crucial role in the study. The hotspot analysis required prior geocoding, involving deriving firefly distribution coordinates using sampling stations and vegetation coordinates in the study area. Utilizing Google Earth and the Earth Point tool for geocoding, which is essential for changing location descriptors into specific Earth positions, facilitated the application of hotspot analysis, resulting in a comprehensive hotspot map.

Additionally, the study employed Inverse Distance Weighted Interpolation (IDW) within ArcGIS version 10.3 for mapping abiotic parameters from sampling stations. IDW operates on the principle that proximate items share more similarities than distant ones, considering the localized impact of each measured location. This technique assigns higher weights to points nearest the forecast location, gradually decreases as distance increases and provides a detailed spatial representation of abiotic parameters in the study area.

Pearson Correlation Coefficient (r)

Pearson's correlation coefficient measures the strength and direction of a linear relationship between two variables (Obilor & Amadi, 2018). Ranging from -1 to +1 for continuous data, a value approaching +1 signifies a perfect positive relationship, while a value nearing -1 indicates a perfect negative correlation. A value of 0 implies no correlation between the two variables. The technique is more precise and accessible for interpretation than just looking at the R-value. Table 2 interprets Pearson's correlation coefficient (r), and Table 3 indicates its strength and direction for the variables.

Table 2
Correlation type between two variables with interpretation of the Pearson's correlation coefficient (r) (Turney, 2022)

Pearson correlation coefficient (r)	Correlation type	Interpretation
Between 0 and 1	Positive correlation	All the variables change in the same direction when one variable changes
0	No correlation	The variables have no relationship
Between 0 and -1	Negative correlation	All the variables change in the opposite direction when one variable changes.

Table 3
Pearson's correlation coefficient (r) strength and direction (Turney, 2022)

Pearson correlation coefficient (r) value	Strength	Direction
> .5	Strong	Positive
Between .3 and .5	Moderate	Positive
Between 0 and .3	Weak	Positive
0	None	None
Between 0 and -.3	Weak	Negative
Between -.3 and -.5	Moderate	Negative
< -.5	Strong	Negative

RESULTS AND DISCUSSION

Total Population Abundance of *Pteroptyx tener* Along the Sepetang River

Table 4 presents the findings from a six-month monitoring period (November 2021 to April 2022) at ten sampling stations along the Sepetang River, focusing on the population abundance of *Pteroptyx tener*. A total of 111,615 individuals were collected, revealing significant variations in abundance levels across the sampling stations and months. SS6 showed the highest SE ± Mean (16417.11 ± 496.25), while SS10 had the lowest (155.17 ± 3.73). Notably, January 2022 exhibited the highest SE ± Mean (4265.17 ± 2692.30), indicating greater variability, while November 2021 had the lowest (2082.07 ± 1319.40). The mean firefly count on November 21 was 13,194, with a moderate SE, suggesting reasonable precision. December 2021 maintained a mean count of 15,631, with an increased SE, indicating greater variability. January 2022 had the highest SE ± Mean (26923 fireflies, 4265.17 ± 2692.30), signifying a larger range of variance. February and March 2022 had intermediate SE ± Mean values (21,701 and 16,793 fireflies, respectively), and April 2022 showed a mean count of 17,373 with an SE of 2616.29 ± 1737.30 (Table 4).

Figure 2 shows a hotspot map that displays the total firefly abundance over a six-month monitoring period at ten Sepetang River sampling stations. Consistent with prior research by Jusoh et al. (2010a), this study supports the observation that the Sepetang River is a major hotspot for *Pteroptyx* fireflies. Station 6, strategically located in the river's mouth bar with clustered mangrove trees, exhibited exceptionally bright flashing patterns, hosting 55,723 fireflies, representing 50.01% of the total (Table 4). This unique setup suggests the fireflies' preference for this area. Mouth bars, formed by sediment accumulation at river mouths, can serve as suitable firefly habitats depending on vegetation availability, water quality, and minimal disturbances. The presence of mangrove trees and other aquatic plants in mouth bars creates favorable conditions for fireflies, as their larvae thrive in moist, semi-aquatic environments. Studies by Fu et al. (2005; 2006) indicate that semi-aquatic larvae inhabit soil and leaf litter along riverbanks, occasionally transitioning to water environments for foraging.

Table 4
Cumulative number, mean value, and standard error of Pteroptyx tener *along the Sepetang River*

Sampling Station	Nov-21	Dec-21	Jan-22	Feb-22	Mar-22	Apr-22	Total Per Station	SE ± Mean
SS1	72	87	118	65	70	190	602	180.17 ± 8.17
SS2	115	88	327	425	336	458	1749	526.74 ± 13.03
SS3	799	1101	1095	1244	901	1239	6379	1866.37 ± 43.80
SS4	831	1099	1642	1829	1303	1574	8278	2434.37 ± 34.12
SS5	2233	4952	6120	6207	2573	3038	25123	7481.78 ± 151.78
SS6	7250	6238	14242	9845	9023	9125	55723	16417.11 ± 496.25
SS7	1292	1510	3175	1666	2260	1351	11254	3338.48 ± 123.05
SS8	418	319	100	200	109	121	1267	385.63 ± 11.63
SS9	116	182	73	121	105	126	723	212.96 ± 3.70
SS10	68	55	31	99	113	151	517	155.17 ± 3.73
Total Per Month	13194	15631	26923	21701	16793	17373	111615	-
SE ± Mean	2082.07 ± 1319.40	2094.17 ± 1563.10	4265.17 ± 2692.30	3102.82 ± 2170.10	2600.10 ± 1679.30	2616.29 ± 1737.30	-	-

Lewis et al. (2020) assumed that because the larval stage of fireflies spends months to years either underwater or in soil, excessive pesticide concentrations in water and soil may be particularly damaging to aquatic fireflies (such as *Aquatica* and *Sclerotia*). It might also damage *Pteroptyx* firefly larvae, known to lodge among the roots of riparian mangrove trees and in the vegetation behind adult display trees or soil (such as terrestrial fireflies *Lampyris*, *Photinus*, and *Photuris*). Firefly eggs are deposited in soil, moss, or decaying wood; pupae develop underground or on tree trunks and may be exposed. Meanwhile, aquatic larvae in various settings exhibit diverse behaviors, including bottom-dwelling and back-swimming (Ho et al., 2010; Vaz, Guerrazzi et al., 2021).

SS5, with the highest firefly count ranging from 11,254 to 25,123 individuals, represents a notable hotspot, constituting 22.55% of the total population (Table 4). This increase in activity is attributed to the concealed and darker environments of SS5 and SS6, strategically positioned away from human activity and light sources. Vaz, Manes et al. (2021) support this, stating that fireflies prefer darker areas, highlighting light pollution as a potential threat. In contrast, SS9 and SS10, close to potential disturbances like shrimp ponds and human settlements, recorded only 517–723 individuals, constituting 0.65% and 0.46%, respectively. Hazmi and Sagaff (2017) noted the detrimental effects of pollutants from shrimp ponds on fireflies, indicating a connection between habitat disruption and firefly abundance.

In the Rembau-Linggi estuary, Peninsular Malaysia, the growing number of oil palm plantations has encroached on the riverbank area, affecting the breeding of fireflies *Pteroptyx tener*. It is challenging because riverbank mangrove forests have transformed into agricultural, aquaculture, and urbanization zones (Jusoh & Hashim, 2012). This transformation is exacerbated by the economic benefits associated with firefly ecotourism, which encourages human activities that endanger firefly habitats in Malaysia, such as in Sepetang Estuary and Rembau-Linggi (Jusoh et al., 2010a; Jusoh et al., 2010b). As a result, many riverine firefly species will face extinction because of this practice. Broad areas of mangrove banks along riverbanks have been cleared in

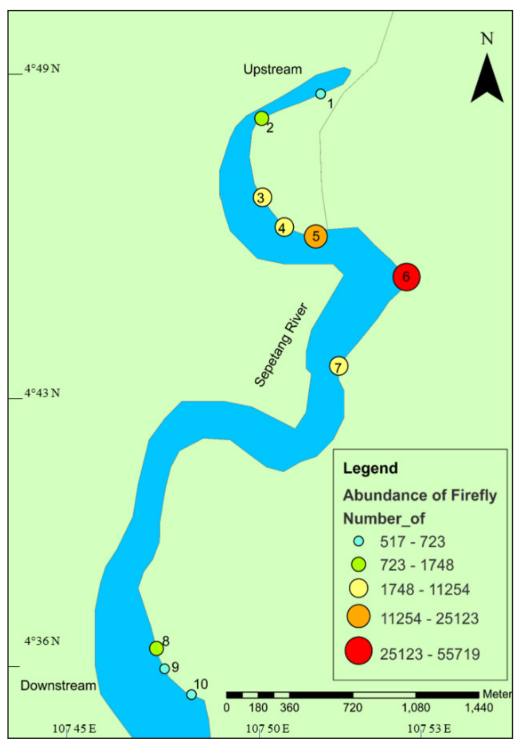

Figure 2. Firefly hotspot map along the Sepetang River

Southeast Asia for oil palm plantations, shrimp farms, or flood mitigation. This region was rendered unsuitable for the growth and reproduction of *Pteroptyx* firefly larvae and their snail prey larvae (Jusoh et al., 2010b; Jusoh & Hashim, 2012; Khoo et al., 2012; Thancharoen, 2012; Wong & Yeap, 2012). It has been reported that influences from anthropogenic, rapid, and extensive urbanization, industrialization, and ecotourism have jeopardized the mangrove habitat that *Pteroptyx* fireflies live on (Prasertkul, 2018; Sartsanga et al., 2018; Wong & Yeap, 2012).

The study emphasizes that stations with high firefly abundance, like SS5 and SS6, are likely to maintain their populations due to factors such as habitat quality, protection from disturbances, habitat continuity, pollution levels, and past habitat degradation. Human settlements and land use changes, including mangrove conversion to shrimp ponds, negatively impact stations like SS1, SS2, SS3, SS8, SS9, and SS10. Converting mangrove forests for economic gains, driven by firefly ecotourism, threatens firefly habitats, leading to potential extinction. SS5 and SS6, located away from anthropogenic activities, exemplify the negative impacts of rapid urbanization, industrialization, and ecotourism on mangrove habitats.

Observing the highest total population in January 2022 (26,923 individuals) aligns with seasonal patterns and favorable climate conditions. January likely represents a peak mating season for *Pteroptyx tener*, as reported by Ho et al. (2010). The study also considers the impact of weather conditions, with wet and dark nights favoring firefly activity, while dry seasons may decrease their activity. The temporal variations in precipitation levels, alternating between rainy and dry periods, influence firefly behavior. The lowest abundance in November 2021 (13,194 individuals) corresponds to the end of the breeding period, in line with Koken et al.'s (2022) findings on the breeding period of *Photinus immigrans*. This pattern suggests that the breeding period for *Pteroptyx tener* in the Sepetang River spans from mid-June to early November (Figure 3).

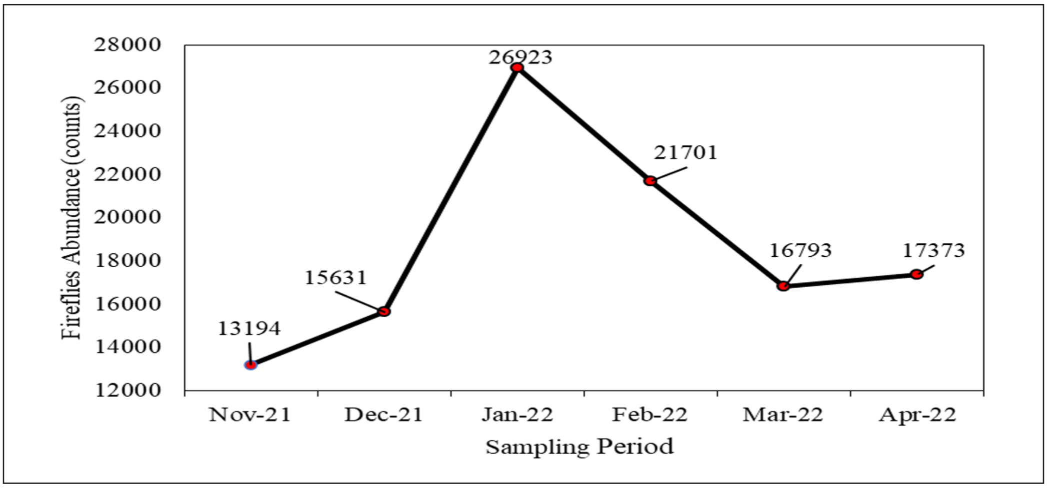

Figure 3. The abundance of fireflies recorded monthly at 10 sampling stations along the Sepetang River

Firefly Population Abundance and Abiotic Influences

Human activities along the Sepetang River, including physical changes, settlements, and commercial areas, have led to water deterioration, with the Water Quality Index indicating 59% pollution and classifying the river in the class III category (Hazmi & Sagaff, 2017). Long-term surveys reveal declines in glowworm and mangrove firefly populations due to water quality deterioration (Atkins et al., 2017; Jusoh & Hashim, 2012; Khoo et al., 2014). Hazmi and Sagaff (2017) also stated that the deterioration of water quality would cause the number of fireflies to decrease and the population's extinction. The population of fireflies is closely linked to water quality in their habitats, as they deposit their eggs in crevices or loose soil on the ground in tidal floodplains of rivers (Faudzi et al., 2021). For example, Abdullah et al. (2020) found that the lowest abundance of fireflies in Sungai Raan, Miri, Sarawak, was related to the river's location in the center of a fishing village, where domestic activities and fishing vessels create anthropogenic pressure on the river. In contrast, a healthy mangrove environment, like Sungai Niah, supported the largest firefly populations.

Hazmi and Sagaff (2017) emphasize the vulnerability of fireflies to environmental changes and their dependence on factors like water quality. The decline, though not as extreme as in other regions, raises concerns about potential extinction. Global instances of insect population decline, such as a 76% decrease in flying insect biomass in German protected areas (Hallmann et al., 2017) and a 50% reduction in European grassland butterfly populations (Van Swaay et al., 2013), underscore the severity of the issue. River water pollution in Japan has similarly led to a decline in firefly populations (Ohba & Wong, 2004).

Moreover, firefly numbers decrease due to changes in river water quality caused by pollution, diesel consumption, and development around firefly habitats (Jusoh et al., 2010b). Mangrove areas, like Kuala Sepetang, suffer from poor waste disposal, further impacting water quality. Herbicides and pesticides from nearby agricultural areas contribute to river pollution (Asyraf et al., 2013). The correlation analysis indicates a significant positive relationship between wind speed and firefly abundance, highlighting the impact of abiotic factors on firefly populations, while other parameters show less statistically significant correlations (Table 5). Figure 4 visually represents the correlation between various abiotic parameters and fireflies' abundance.

The study reveals a non-significant relationship between RH and the firefly population at Sepetang River sampling stations ($r = -0.53$, $p = 0.28$) (Table 5). It contradicts Norela et al.'s (2017) findings yet aligns with Abdullah et al. (2020), who reported a weak, non-significant correlation in other rivers. The highest RH at SS1, SS2, and SS3 did not correspond to high firefly abundance, supporting the conclusion that RH does not influence Sepetang River firefly abundance (Figure 5).

While RH is vital in firefly ecology, influencing breeding and mating, its role is complex. Studies by Axmacher et al. (2009), Fazal et al. (2012), Kaiser et al. (2017), and

Table 5
Values of the Pearson correlation coefficient (r) analysis of abiotic parameters

Parameters	Correlation	*r* value	*p* Value
Relative Humidity	None	-0.53	0.28
Air Temperature	None	0.38	0.46
Wind Speed	Positive	0.88	0.02
Tide Level	None	0.48	0.34
pH	None	-0.57	0.24
Electrical Conductivity	None	-0.42	0.40
Salinity	None	0.71	0.12
TDS	None	-0.18	0.73
Water Clarity	None	-0.43	0.39

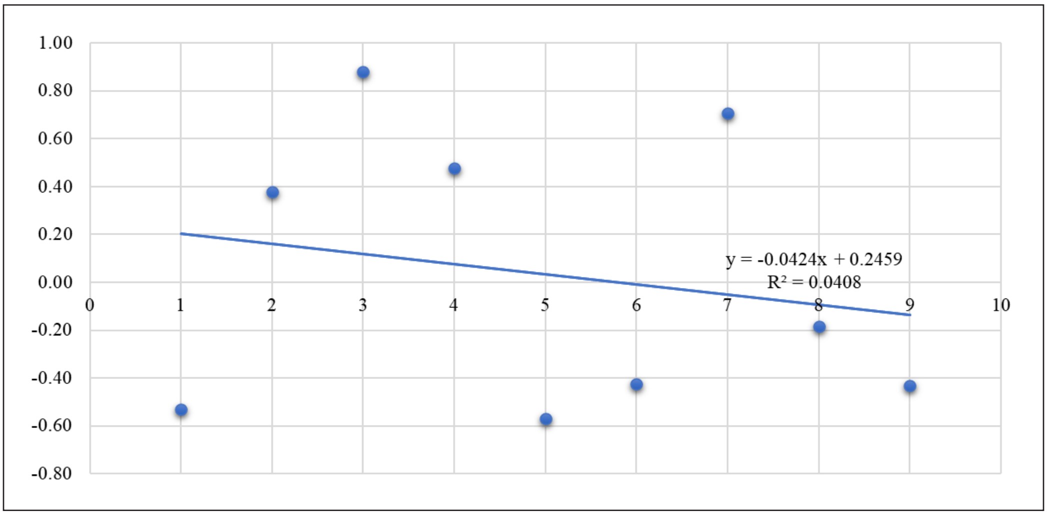

Figure 4. The correlation between various abiotic parameters (relative humidity, air temperature, wind speed, tide level, pH, EC, salinity, TDS, and water clarity) and fireflies' abundance

Cheng et al. (2020) highlight its relevance. However, the connection between RH and firefly numbers is intricate and context-dependent, varying across environments. Considering various determinants like habitat quality, light pollution, predation dynamics, and pesticide use, caution is warranted in interpreting correlations between RH and firefly abundance. Globally, RH alone is unlikely to be the primary factor affecting firefly populations; instead, a complex interplay of ecological factors shapes their abundance.

The correlation between fireflies and water pH was strongly negative and statistically significant ($r = -0.57$, $p = 0.24$) (Table 5). This finding aligns with Faudzi et al.'s (2021) discovery in Sungai Cherating, Malaysia, indicating that pH is not correlated with firefly populations. Shahara et al. (2017) also found no significant relationships between TDS, temperature, RH, wind speed, water salinity, conductivity, and firefly populations at Bernam

River, Selangor. Abdullah et al. (2021) supported the lack of significant differences in pH between sampling stations in the Rembau River. The study, spanning rainy and dry seasons, noted lower pH during the rainy season due to increased H_2CO_3 formation. Referring to Figure 6, sampling stations SS5 and SS6, with suitable water pH, had the highest firefly abundance. The river water pH across all stations was around 5.70, with temperatures ranging from 28°C to 31°C, suitable for tropical mangrove forests. Robertson-Bryan (2004) highlighted the preference of estuarine-dwelling species for pH levels between 6.5 and 8.5. Marine organisms will struggle to survive if the pH rises or falls below 5.0 or above 9.0. The pH value of water is one of the main predictors for determining the level of water pollution, such as eutrophication and water degradation (Feng et al., 2017). Along the Sepetang River, the pH was acidic, approaching neutral, ranging between 5.61 and 5.95. pH impacts various chemical processes in aquatic environments, including acid-base reactions, solubility reactions, oxidation-reduction reactions, and complexation (Saalidong et al., 2022).

The firefly population in Sungai Sepetang shows a positive correlation with salinity ($r = -0.71$), although this correlation is not statistically significant ($p = 0.12$). The average salinity of freshwater from the river is 0.5 ppt or less, falling within the mesohaline range (6.99 ppt) considered normal for organism survival. Elevated salinity beyond tolerance ranges can impact stress, reproduction, and survival rates (Palmer et al., 2008). Salinity influences

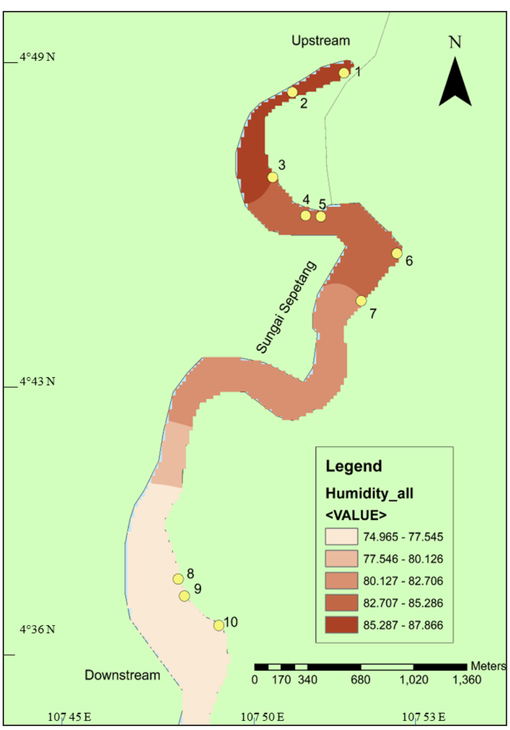

Figure 5. Average of relative humidity

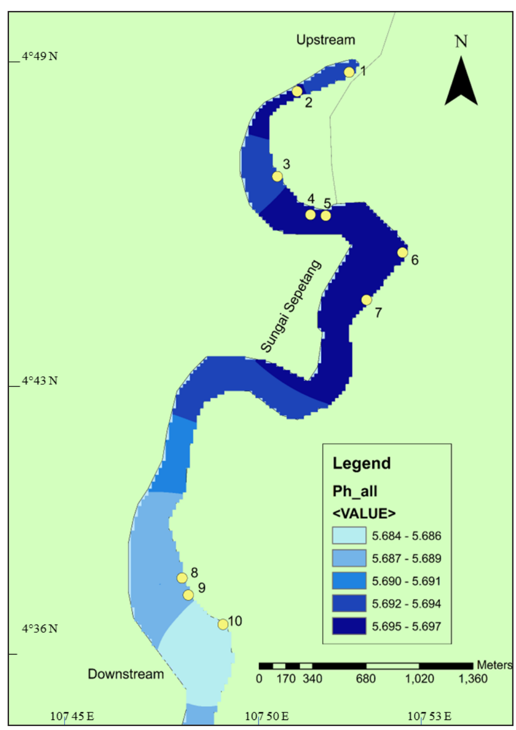

Figure 6. Average pH level

water density, increasing dissolved salt concentration and higher density (Corbett, 2007). The conductivity of the Sepetang River (28.63 s/cm) falls within the normal freshwater range, influenced by its clay-type soil. Mangroves in the area with high salinity tolerance remain unaffected by moderate temperature (31.8°C) and salinity conditions (6.99 ppt) (Figure 7).

Mangroves are plants with a high tolerance to salinity, tidal variations, temperature, and moisture growing in the intertidal zone (Tokan et al., 2018; Yahya et al., 2020). Therefore, the conditions of temperature (31.8°C) and salinity (6.99 ppt), which are not extreme in Sungai Sepetang, do not affect the condition of mangrove trees in the area. The humidity there is also very high, 97.12% and is very suitable for mangrove plants that display trees by fireflies. Changes in the salinity reading of the river water may be due to the difference in the measurement time concerning the tide. The populations of fireflies in the Selangor and Rembau rivers are unaffected by water salinity, according to Khoo et al. (2012) and Asri et al. (2021). Salinity levels are relatively lower in freshwater systems like rivers compared to marine or ocean environments.

Adult fireflies, with a terrestrial life stage, spend most of their lives in terrestrial habitats, exhibiting ecological behaviors primarily terrestrial in nature. Their reproductive behaviors near riverine locales emphasize the importance of water quality for firefly populations. The study underscores the ecological nuances of terrestrial habitats, diurnal navigation toward arboreal sustenance, and orchestration of nocturnal mating behaviors near riverine locales as key determinants of firefly population abundance. Monitoring the salinity levels of the Sungai Sepetang River is crucial due to its role as a water source for the mangrove forest ecosystem, impacting ecotourism and local economic growth in the future. Salinity levels across sampling stations, divided into oligohaline and mesohaline, are suitable for fireflies, as observed in mesohaline stations (SS5 and SS6) with high abundance, contrasting with mesohaline stations (SS4, SS7, SS8, SS9, and SS10) exhibiting lower firefly abundance.

In Malaysian rivers like Sepetang, Rembau, and Chukai, an increase in insect abundance is linked to decreased salinity levels, which are crucial for larval growth and firefly survival. Maintaining optimal salinity is essential, as it affects the soil where fireflies lay eggs and larvae develop (Abdullah et al., 2019). Asri et al. (2021) found peak firefly populations in downstream river zones with ideal salinity. Conversely, in the Selangor River, an increase in salinity negatively impacted firefly populations in *Sonneratia caseolaris* along the riverbanks (Khoo et al., 2012).

Pteroptyx tener larvae inhabit the upper soil horizon/organic layer, which is washed regularly by the tidal river. They spend most of their time hunting their host (*Cyclotropis carinata*; Assimineidae) in this zone. Importantly, their eggs and pupae, which reside in the upper soil layers, might be used as effective environmental health indicators. Living at a higher soil horizon makes them highly susceptible to water and soil quality changes

(Cheng et al., 2020). Non-synchronous fireflies, such as *Pteroptyx bearni*, *Pteroptyx valida*, and *Pteroptyx gelasina*, are typically encountered in waters with higher salinity and species such as *Rhizophora*, *Aviccenia, Sonneratia alba*, and *Excoecaria.* In contrast, *Pteroptyx tener* and *Pteroptyx malaccae* are synchronous fireflies that inhabit brackish waters where *Sonneratia caseolaris*, *Gluta renghas*, *Talipariti*, and *Barringtonia* were found (Wong, 2022).

The wind speed showed a highly strong positive correlation (r = 0.88) with the population of fireflies and a significant positive relationship at (p = 0.02) (Table 5). The observed correlation with wind speed implies that it plays a significant role in shaping the abundance of fireflies. Fireflies are small, delicate insects, and wind conditions can influence their ability to fly. High wind speeds can make it difficult for fireflies to engage in mating displays and aerial activities. Therefore, they may be more active and abundant on nights with calmer winds. It is the same as the results obtained by Asri et al. (2021), where, temporally, the wind speed showed a significant negative relationship with the abundance of fireflies (F = 6.72, p < 0.05).

Fireflies rely on their bioluminescent flashes for communication and mating. Wind can disrupt these signals, making it difficult for fireflies to locate and communicate with potential mates. Calm nights with lower wind speeds are likely more conducive to successful firefly mating displays, which can lead to higher population abundances. For insects to engage in flight activity (in the case of *Pityophthorus juglandis*), moderately high temperature and moderate wind speed conditions are required. When the temperature was about 30°C, and the wind speed was approximately 2 km/h, male and female *Pityophthorus juglandis* flew the most due to the following second-order interactions between the factors (Chen & Seybold, 2014).

When the wind speed can affect a firefly species (*Pteroptyx valida*) larger than *Pteroptyx tener*, which is approximately 11.0 ± 0.02 mm in length (Jaikla et al., 2020), it is expected that this study discovered wind speed to affect *Pteroptyx tener*. Adult males of *Pteroptyx valida* were smaller than females, averaging 10.1 ± 0.04 mm and

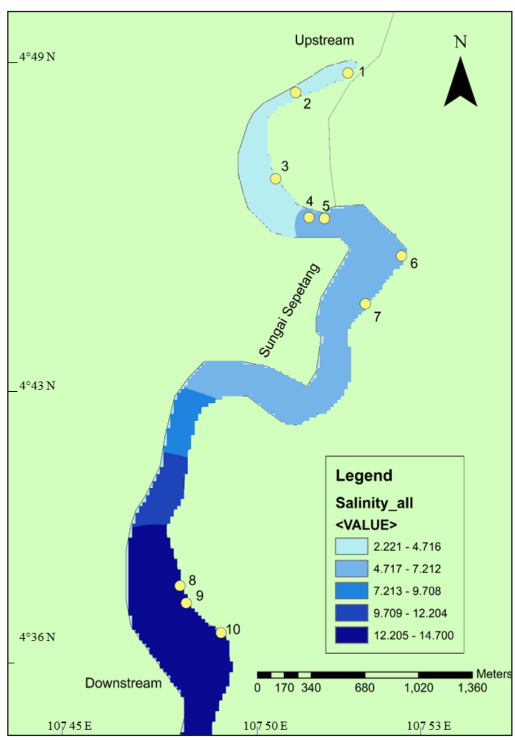

Figure 7. Average salinity level

11.4 ± 0.10 mm, respectively (Jaikla et al., 2020). On the other hand, the *Pteroptyx tener* is comparatively smaller, with males measuring between 5391.411 µm or 5.39 mm and 5391.130 µm or 5.39 mm in length. In contrast, females are larger, ranging from 6861.083 µm or 6.86 mm to 6858.535 µm or 6.86 mm, surpassing the length of adult males.

Wind speed impacts *Pteroptyx tener* fireflies in the Sepetang River as they fly in search of mates. Small (5–7 mm), the *Pteroptyx tener* is easily carried by moving air (Gatehouse, 1997). Wang et al. (2007) stated that wind, rain, and colder weather cause a drop in firefly luminous activity. According to Abdullah et al. (2019), the population number of fireflies in the Rembau River has been affected by wind speed. In addition, there is a strong negative correlation between wind speed and the diversity and number of insects in the Sepetang and Chukai rivers.

Jaikla et al. (2020) conducted a study on the impact of wind speed and direction on the horizontal distribution of *Pteroptyx* species in Thailand. According to the findings, the firefly species prefer to be perched on tree branches facing away from the direction of the strongest winds in Surat Thani, Phetchaburi, Krabi and Nakhon Si Thammarat. More than 45° on either side of the wind direction is where 85% of these firefly species are perched. 13.1% of the fireflies fell within 45° of the current wind direction on either side, while 1.9% fell upwind. Wind speed has a large impact on the temporal variation of the firefly. Additionally, variations in wind speed were found to cause variations in the size of the firefly population in Rembau River, Negeri Sembilan (Abdullah et al., 2019; Asri et al., 2021). This finding may be related to exposure to the Southwest monsoon, which winds up to 15 knots stronger than those in the Sepetang and Chukai rivers (Asri et al., 2021).

Sampling stations with high wind speeds are at SS7, SS8, SS9, and SS10, which are directly proportional to the relatively low firefly population recorded in this area. SS1-SS6 are among the stations that consistently record a higher population abundance of fireflies compared to other stations (Figure 8). Additionally, a bubble graph was included to support the IDW map results of the relationship between the abundance of fireflies and abiotic parameters (Figure 9).

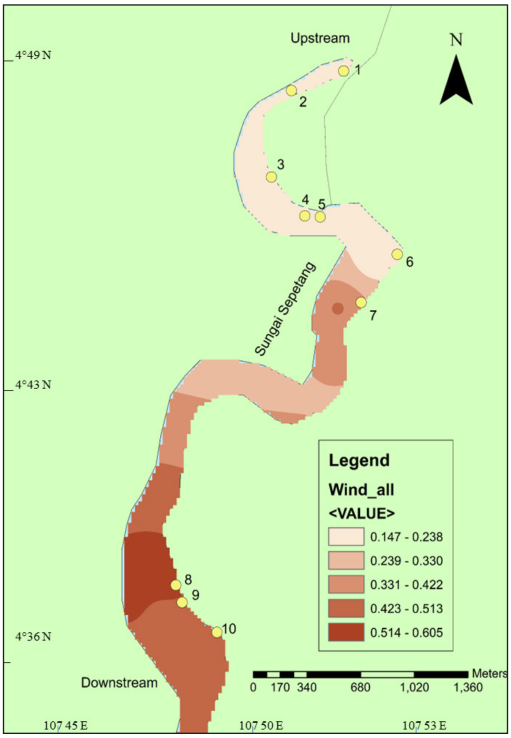

Figure 8. Average wind speed

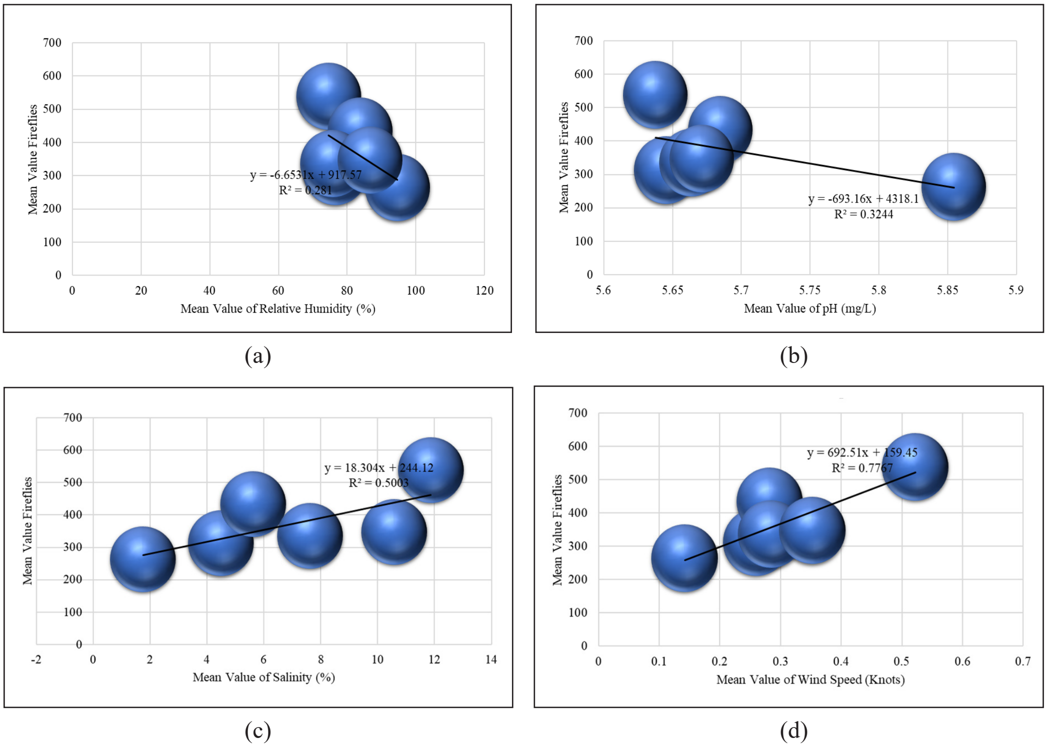

Figure 9.The connection between the mean abundance of fireflies and (a) relative humidity, (b) pH, (c) salinity and (d) wind speed

The results of the TDS and fireflies' population reveal a weak negative correlation (r = -0.18), lacking statistical significance (p = 0.73) (Table 5). Existing scientific research minimally connects TDS to firefly populations, with studies emphasizing more prominent threats like habitat destruction, light pollution, pesticide use, and climate change. In freshwater, TDS is generally low (<500 ppm), with seawater and brackish water concentrations ranging between 500 to 30,000 and 30 to 40,000, respectively (Moran, 2018). Sepetang River's low TDS concentration, below 500 ppm, fosters an ideal environment for aquatic life, particularly firefly larvae reliant on tiny snails as a food source (Peng et al., 2020).

TDS primarily denotes the concentration of dissolved ions, with firefly larvae being aquatic and exposed to TDS levels in their habitats. While firefly larvae adapt to various freshwater environments, they are less tolerant of highly saline waters. Excess TDS, often due to human activities, threatens aquatic organisms (Caedo-Argüelles et al., 2013). Abdullah et al. (2020) found no statistically significant correlation between TDS and fireflies in the Niah and Raan Rivers. Similarly, Shahara et al. (2017) observed a weak and non-significant correlation between fireflies and abiotic factors, including TDS, in the Bernam River, Selangor.

TDS concentrations in the study consistently remained below 500 ppm (Figure 10), with no significant differences among stations. This observation explains the absence of an effect of TDS on firefly population abundance. The indirect and less significant relationship between TDS and firefly abundance in adult fireflies is influenced by courtship, mating, and reproduction factors. Adult fireflies, primarily terrestrial during their short-lived stage, allocate energy to these activities, making them less directly impacted by TDS levels in water (Angelini et al., 2010).

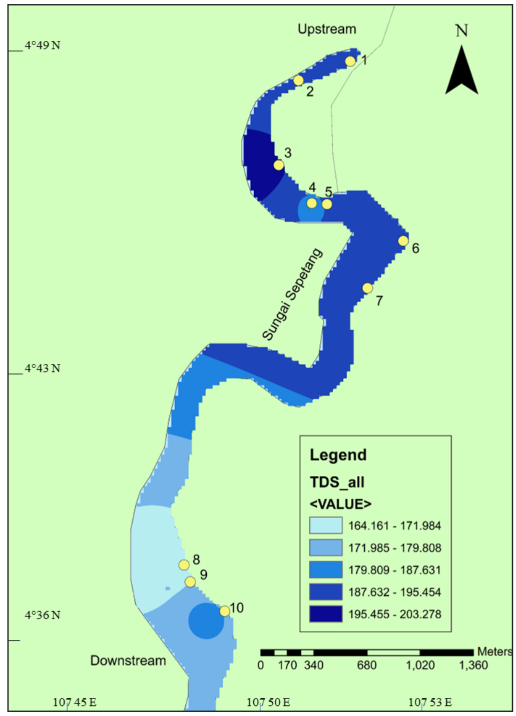

Figure 10. Average of TDS

The firefly population in the Sepetang River shows a moderately negative correlation with water clarity ($r = -0.43$), but this relationship is not statistically significant ($p = 0.39$) (Table 5). Water clarity, measured at 38.93 NTU, is suitable for living organisms, although it may conceal parasites like Cryptosporidium. Changes in water clarity, induced by factors like suspended solids, wind-induced sediment re-dispersion, and rainfall, can indirectly impact firefly populations (Stevenson & Bravo, 2019; Booth et al., 2000). The survival rate of flying insects (Caddisflies) is not significantly different when their larvae are exposed to varied levels of water clarity at either water temperature. That is, the water clarity level does not affect the life of flying insects (Suzuki et al., 2018).

While water clarity and turbidity may not directly affect adult fireflies, variations in these parameters can indirectly influence firefly populations by altering the abundance and distribution of prey species. Fireflies in the Sepetang River may have adapted to the specific water quality conditions, with some species being more tolerant to changes in clarity and turbidity. Excessive turbidity in watersheds can indicate the presence of organic and inorganic materials, posing concerns such as increased algal growth or sediment suspension. Continuous monitoring of turbidity is crucial due to its potential detrimental effects on ecosystems. However, in the Sepetang River, the absence of abnormally strong wind conditions mitigated noticeable cloudiness in the water, reducing any potential effect on firefly abundance (Gillett & Marchiori, 2019; Smith & Davis-Colley, 2001).

The study suggests that firefly larvae may thrive in suitable habitats despite variations in water clarity, such as submerged vegetation or debris, offering protection and food sources. Short-term variations in water quality, including turbidity, may be tolerated by firefly populations, but prolonged periods of poor water quality can have a more pronounced negative impact. The lack of a consistent correlation between water clarity and firefly abundance, as shown in the IDW map (Figure 11), indicates that changes in water clarity do not consistently predict variations in firefly populations.

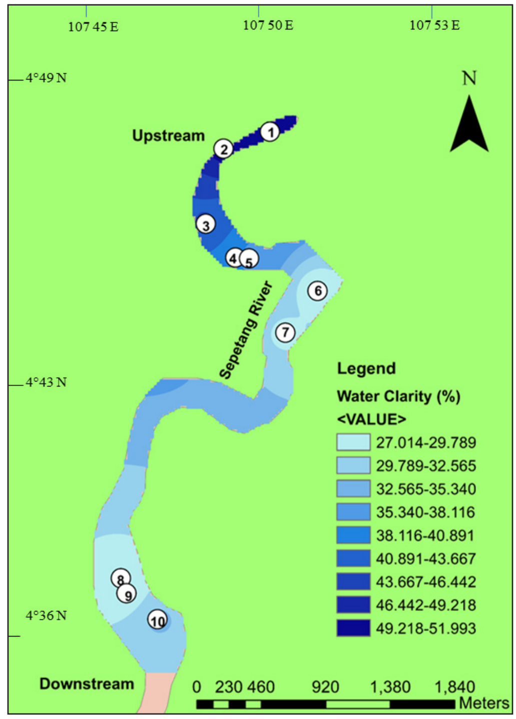

Figure 11. Average of water clarity

Firefly population and air temperature are also moderately but positively correlated (r = 0.38) without a statistically significant relationship (p = 0.46) (Table 5). Abdullah et al. (2021) also stated that there was no statistical significance between the sampling station and the temperature (F = 0.814, p > 0.05). Fireflies and air temperature were also correlated moderately but positively correlated (r = 0.38) without a statistically significant relationship (p = 0.46). According to (Khoo et al., 2012), for three years (2006 to 2008), the average monthly temperature and RH, which are constant and only slightly fluctuate, do not appear to alter the trend of an increasing adult firefly population. Findings by Rabha et al. (2021) suggest that the species is active on hot days due to a "hot effect" and may disappear during winter due to a "cold effect." The average temperature of 29.33°C obtained from this study indicates that it does not exceed 34°C. According to Rabha et al. (2021), temperatures above this threshold, with even slight increases, likely signify the denaturation of the enzyme luciferase, which catalyzes the light-producing reaction in fireflies.

The report given by Abdullah et al. (2019) also showed that temperature and RH were not significantly correlated with the insect community. Like what Mahadimenakbar et al. (2018) discovered, parameters such as air temperature, RH, wind speed, and light intensity did not exhibit unusual patterns. The highest and medium air temperature was recorded at SS4-SS10, while SS5 and SS6 also included these two stations as hotspot areas and recorded the highest overall population abundance of fireflies. It shows that there is no difference and that the effect of air temperature on the firefly population is not significant (Figure 12). Furthermore, it was shown that the density of firefly larvae was higher in sago plantations than in palm oil plantations, which may be related to the cooler, more humid, and shaded environment near the sago patch. The soil temperature in the orchard is also substantially higher at a depth of 5 cm than in the sago patch and oil palm plantation (Kirton et al., 2006).

The Sepetang River's electrical conductivity (EC) of 28.63 s/cm falls within the normal freshwater range (0-1,500 µs/cm), serving as a reliable baseline for salinity and TDS estimates (Fondriest Environmental, 2014). Firefly species, known for their adaptability to various climates, can thrive in diverse geographic regions with varying temperature regimes (Faust, 2004; Usener & Cognato, 2005; Lloyd, 2008; Nada & Ballantyne, 2018). The study's average temperature of 29.33°C is below the critical threshold of 34°C for enzyme luciferase denaturation in fireflies, as Rabha et al. (2021) suggested. A moderate negative correlation ($r = -0.42$) and non-significant relationship ($p = 0.40$) between EC and firefly population indicate a healthy river environment. The EC value (47.72 µS/cm) is relatively low, typical for freshwater habitats, contrasting with saline or brackish environments—mangrove ecosystems, usually saline, host firefly species adapted to slightly higher EC levels.

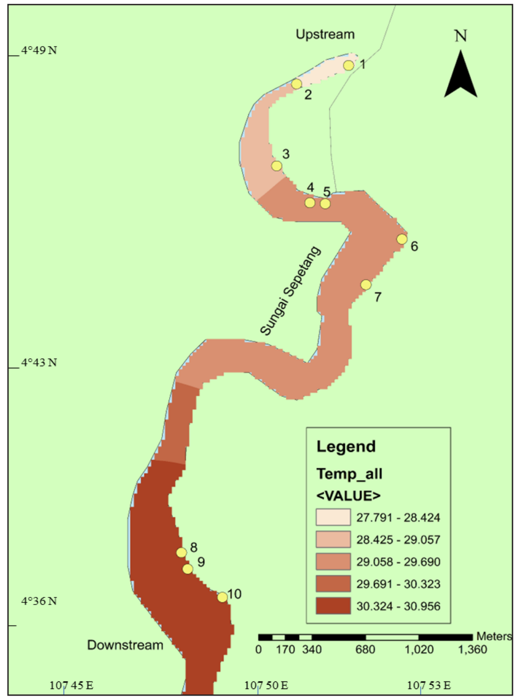

Figure 12. Average of air temperature in the river water sample

Water temperature significantly influences conductivity, causing daily fluctuations, with warmer water exhibiting higher conductivity (Fondriest Environmental, 2014). Though water flow changes can affect conductivity and potentially impact firefly habitats, the study suggests that daily temperature-related changes might not immediately and profoundly affect adult fireflies. Research findings indicate stable conductivity levels during the monitored period, with no extreme temperature, salinity, or TDS changes. The absence of a correlation between EC and firefly population abundance, emphasized by the IDW map analysis, underscores their relationship's non-linear and complex nature (Figure 13).

The firefly population in the Sepetang River shows a moderately positive but statistically insignificant correlation with tidal levels ($r = 0.48$, $p = 0.34$) (Table 5) (Angelini et al., 2010). It implies that changes in tidal levels do not significantly impact the abundance of fireflies in the river. The study emphasizes the importance of further research into the relationship between firefly abundance and tidal levels, cautioning against taking the current findings for granted. While firefly larvae adapt to varying water levels, adults primarily rely on terrestrial habitats for their activities (McHugh & Liebherr, 2009; Reed et al., 2020; Riley et al., 2021). Tidal levels, which primarily affect aquatic environments, may have a limited direct impact on adult fireflies. Firefly larvae are known to be resilient to tidal fluctuations if suitable aquatic habitats are available (Angelini et al., 2010).

The consistent and predictable tide levels observed in the Sepetang River, influenced by gravitational forces from the moon and sun, suggest that fireflies have adapted to these environmental conditions. This adaptation is likely due to certain environmental factors supporting the reproduction and survival of firefly larvae, as they deposit their eggs in damp habitats (Angelini et al., 2010). Fireflies may adapt their breeding behavior based on tide levels to meet specific environmental requirements, such as moisture levels and food availability. It further emphasizes the ecological nuances influencing firefly populations in the Sepetang River area.

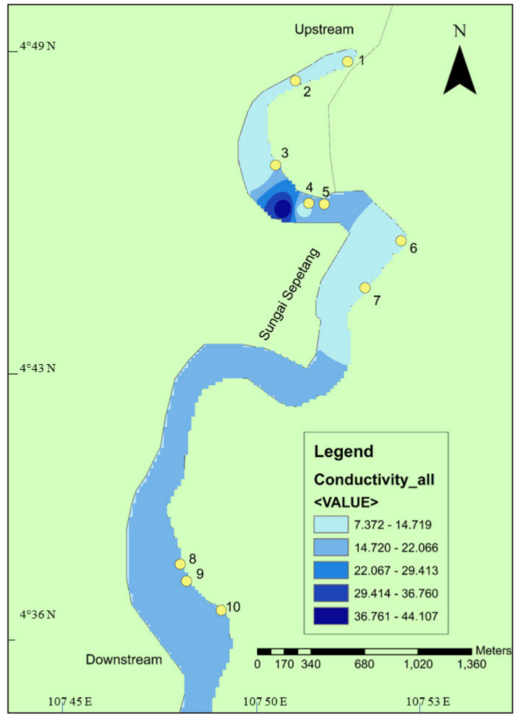

Figure 13. Average of electrical conductivity

Tide levels are primarily influenced by the gravitational forces exerted by the moon and sun, resulting in a tidal cycle. The tidal cycle exhibits variability and is not uniformly consistent monthly. Tides are influenced by multiple elements, such as the positioning of the moon and sun, and can lead to variations in water levels. The study's results indicate a consistent and predictable tide level in the Sepetang River area, and the fireflies have adapted; accordingly, certain environmental conditions in the area likely support the reproduction and survival of their larvae. Fireflies frequently deposit their eggs in damp habitats, and their larvae may require a specific environment for growth. Fireflies may adapt their breeding behavior to align with a specific tide level if it provides a favorable habitat. These modifications may arise due to the need for ideal moisture levels, the availability of food, or other ecological considerations. Fireflies are predominantly found in terrestrial ecosystems, such as grasslands and forests, rather than aquatic tidal environments. However, if fireflies were to adapt to a tidal-influenced environment, it would likely be due to biological factors that result in consistently higher tide levels than the average monthly tide level. A bubble graph was also included to support the IDW map results of the relationship between the abundance of fireflies and abiotic parameters (Figure 14).

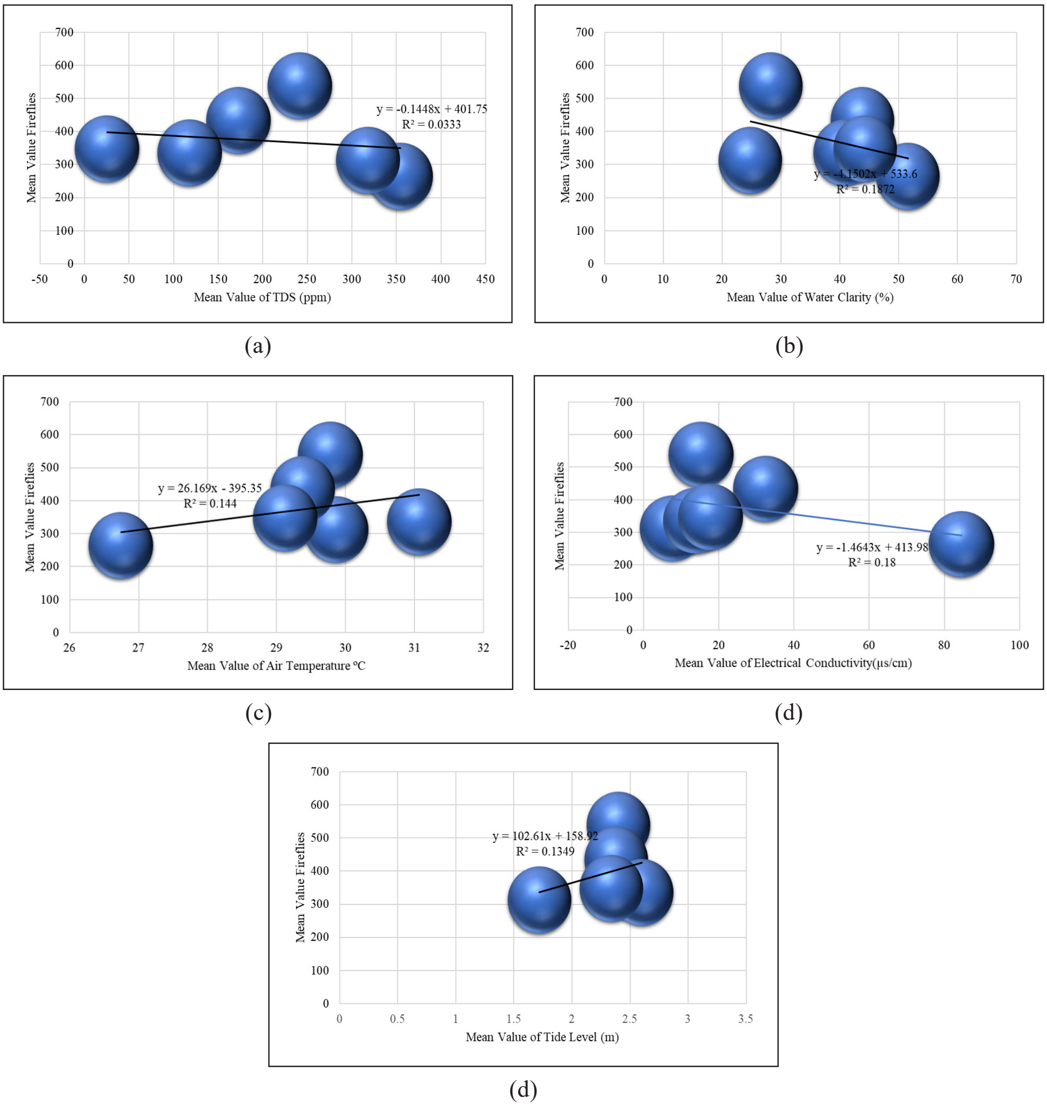

Figure 14. The connection between the mean abundance of fireflies and (a) TDS, (b) water clarity, (c) air temperature, (d) electrical conductivity and e) tide level

CONCLUSION

The statistically significant positive correlation between wind speed and firefly abundance highlights the importance of considering specific abiotic factors in understanding the dynamics of firefly populations. However, the lack of statistically significant correlations between firefly abundance and other abiotic parameters, such as RH, air temperature, tide level, pH, EC, salinity, TDS, and water clarity, suggests the need for further investigation into the complex relationships between these parameters and firefly population dynamics. These findings contribute significantly to understanding firefly ecology and emphasize the complex interplay between abiotic factors in their habitat selection and population dynamics. This study highlights the importance of preserving the Sepetang River mangrove ecosystem. It underscores the need for extended research efforts to uncover the intricacies of firefly behavior and their delicate ecological interactions. This study suggested that future studies should include a more extended sampling period (a year or more that consists of all seasonal factors) to monitor fireflies' abiotic parameters and optimize data collection. Focus should also be given to including other abiotic parameters such as vegetation suitability, vegetation health, insecticides contained in the vegetation, prey of firefly larvae (mangrove snail: *Cyclotropis carunculata*), artificial light pollution, light intensity, air quality, climatology, and soil quality (water level in soil) along the Sepetang River. However, for the long-term survival of the fireflies that live along the Sepetang River, they should be protected by focusing on ecological, physical, and biological aspects, including protecting all species of vegetation that occupy the area.

Our study differentiates our research methodology using GIS software, specifically ArcGIS version 10.3. These advanced tools facilitate detailed spatial analysis, particularly through hotspot mapping and IDW analysis, thereby improving our understanding of firefly population distribution. On the other hand, previous studies either rely solely on GPS data or do not incorporate direct mapping methodology (Shahara et al., 2017; Asri et al., 2021), potentially limiting the accuracy and comprehensiveness of their spatial analysis. Our study offers a comprehensive view of the spatial distribution of firefly populations, which is significant for conservation efforts and understanding habitat preferences. While certain previous studies investigated specific aspects such as habitat modification or the influence of abiotic factors on firefly populations (Abdullah et al., 2021; Faudzi et al., 2021; Jusoh & Hashim, 2012), our research introduces a new dimension through its emphasis on spatial analysis.

While previous studies covered various rivers and estuaries across various regions, providing a broader understanding of firefly ecology in Malaysia (Abdullah et al., 2019; Abdullah et al., 2020; Wong, 2022), our study focused on a specific geographic area. This concentration may limit the generalizability of our findings compared to studies covering different regions. However, the depth of spatial analysis facilitated by GIS techniques mitigates this limitation. Similar to several previous studies, our research explores the correlation between environmental factors and firefly abundance, yielding valuable insights into the ecological determinants of firefly populations. However, while previous studies examined a variety of environmental variables, our study focused primarily on spatial distribution and may not delve into specific ecological interactions that affect firefly populations.

Our study and previous research underscore the importance of certain vegetation types as habitats for fireflies, enriching our understanding of species preferences and ecosystem associations. However, while our study provides valuable insight into habitat preference through spatial analysis, it may not offer detailed information on species diversity and ecological interactions because it explicitly focuses on these aspects. Our research greatly contributes to the field by leveraging GIS techniques for spatial analysis, thereby providing detailed insights into firefly population distribution. However, to achieve a comprehensive understanding of firefly ecology, integrating findings from previous studies investigating diverse dimensions such as habitat modification, species diversity, and ecological interactions is desirable.

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