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Research Article

Revisiting the Freshwater Ichthyofauna in Sayap Substation, Kinabalu Park: A Thirty-One-Year Update

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ABSTRACT

The Sayap Substation in Kinabalu Park, located at 1000 meters above sea level (m asl) lies within a transition zone of sub-montane and lowland forests. Given the dearth of long-term monitoring data to study the possible effects of environmental changes on fish populations, this study provides a 31-year update on ichthyofauna since the first survey conducted in 1992. Five stations were selected near the previous study locations where fish samples were caught via electrofishing and selected environmental parameters were collected concurrently. A total of 258 individuals from two families, four genera, and seven species of fish were recorded in the present survey. Gastromyzontidae (six species, 96.7% of total abundance) was the most dominant family, followed by Cyprinidae (one species, 3.3% of total abundance) in this transition zone. Notably, community composition has shifted over 31 years; genus *Parhomaloptera* that was dominant in 1992 has disappeared, replaced by *Glaniopsis* and *Protomyzon*. *Glaniopsis* composition decreased from 58.9% in 2007 to 30.6% in 2023, with *Protomyzon* becoming more prevalent. The shifts in community structure coupled with significantly higher water temperature and total suspended solids values serve as early warning signs that the ecological integrity of freshwater systems in Sayap Substation may be under stress. It is imperative to conduct regular monitoring of the freshwater habitat in Kinabalu Park, to identify emerging threats and develop appropriate strategies for conserving the freshwater fish population.

Keywords Biodiversity shifts; conservation; protected area; Sabah; UNESCO World Heritage Site.

INTRODUCTION

Sabah, which only comprises one-tenth of Borneo's land area, is home to over a third of Borneo's known freshwater fish species (Nyanti, 1995). However, scientific knowledge on the distribution, ecology and population trends of freshwater fish in Sabah remains limited particularly in high-elevation streams. Freshwater fish are facing enormous threats as a result of overfishing, habitat loss, water pollution, and climate change (Reid et al., 2019; Barbarossa et al., 2021). In addition to being a vital source of protein, freshwater fish sustain local economies through ecotourism and fisheries, which makes their conservation crucial for sustaining community livelihoods (Er et al., 2012; Amirullah et al., 2024). Protected areas have been advocated as a conservation strategy for freshwater fish biodiversity (Acreman et al., 2020). Kinabalu Park, a UNESCO World Heritage Site (Sheena et al., 2015), plays an important role for biodiversity conservation in Sabah. However, information on fish ecology and conservation status in the forest streams of the park are still scarce, probably due to challenging geographical features of the freshwater habitat in the park, hindering the study (Soo et al., 2024).

Kinabalu Park has six substations to serve as access points, administrative centres, and research sites to support the management and study of the park's natural resources and environment. Sayap Substation is one of the substations on the western side of Mount Kinabalu, situated at an elevation of around 1000 m asl. The Sayap Substation features a fascinating freshwater habitat located within the transition zone of sub-montane and lowland forests. This substation has recorded the highest elevation for an economically important cyprinid, *Tor tambra* (formerly known as *Tor douronensis*) (Jaafar et al., 2021; Soo et al., 2022) and it is almost exclusively inhabited by loaches from the Gastromyzontidae family, previously referred to as Balitoridae (Nyanti, 1995; Ishak et al., 2007). The first documented fish and water quality surveys in the Sayap Substation date to 1992 during the Sayap-Kinabalu Scientific Expedition (Heng et al., 1995; Nyanti, 1995), followed by an update conducted by Ishak et al. (2007). The changes in freshwater fish community structure and biodiversity in the area have remained unknown despite development having happened in the area and the inevitable impacts of climate change (Latip et al., 2020; Barbarossa et al., 2021).

The lack of systematic monitoring of ecology and assessment of human impact on the park has been raised as a concern regarding Kinabalu Park's status as a World Heritage site (IUCN World Heritage Outlook 2020). Regular survey on fish and water quality is critical in understanding the implications of environmental changes on freshwater communities over time (Demeke & Tassew, 2016). Despite being a protected area, Kinabalu Park has grown to be one of the most popular tourist destinations in the world and is therefore vulnerable to any form of environmental changes resulting from human activities (Latip et al., 2020). It has been shown that such activities alter the freshwater environment and greatly affect the populations of fish therein (Patil et al., 2015; Soo et al., 2022). Thus, expanding on the earlier research done in 1992 and 2007, this study aims to give an updated assessment of the fish populations in the Sayap Substation. As climate change continues to impact ecosystems globally, freshwater fish species in Kinabalu Park are also increasingly vulnerable to alterations in their habitats. Hamed et al. (2024) demonstrated a substantial intensification of warming and extreme rainfall over Borneo Island, with absolute temperatures rising by 0.5–2.5°C since 1991–2020, highlighting growing climate pressures on freshwater ecosystems. Thus, this research findings will provide useful insights into the fish and environmental changes that may have occurred within the region over the last 31 years.

MATERIALS & METHOD

Study area and sampling stations

The present study area was located at the Sayap Substation in Kinabalu Park, Sabah. The substation is powered by a mini-hydropower plant that generates electricity by harnessing the flowing river water. It is well-known as a hiking attraction that leads to the Kemantis Waterfall. Samplings were conducted in September 2023 at five stations which covered the main river of Sungai (Sg.) Wariu and its tributaries covering an altitude range from 870 to 1071 meters above sea level (m asl). The weather was good with no heavy rainfall throughout the sampling period. Station 1 and Station 3 were located at the lower and upper parts of the main river, Sg. Wariu. Station 2 was located at the lower part of Sg. Kemantis near the junction of Sg. Kemantis and Sg. Wariu. Station 4 was located at the upper part of Sg. Kemantis, nearby the Kemantis Waterfall and a mini-hydropower plant. Lastly, Station 5 was located at Sg. Lumatok near the suspension bridge (Fig. 1).

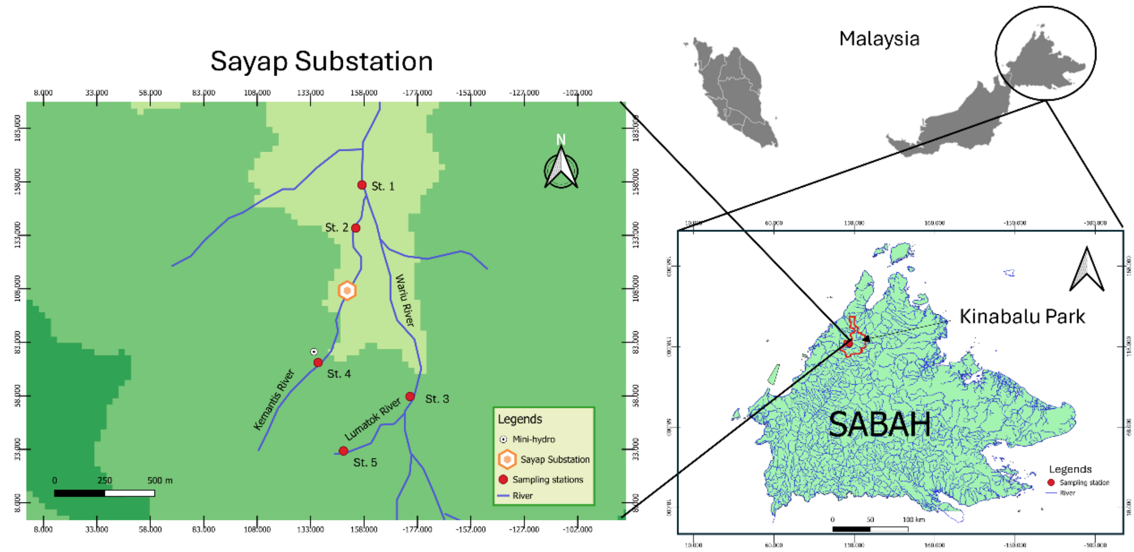

Figure 1: Map of study area indicating sampling stations in Sayap Substation which is located in the Kinabalu Park, Sabah, Malaysia.

Field sampling and laboratory analysis

GPS coordinates and elevations were recorded at each station using a Portable Global Positioning System (Garmin GPSMAP® 64S). The river width at each station was recorded using measuring tape. Fish sampling was conducted by using an electrofishing device powered by an adjustable 600-watt power inverter (SUSAN-735MP) with a 12V battery (NIKO YTZ5S-BS). The watt current was adjusted to approximately 300 watts current, a level whereby fish were affected mildly with a lower mortality rate. Sampling was carried out along a 25-to-30-meter stretch at each station in a downstream-upstream direction. Stunned fish were then collected using a scoop net with a mesh size of 0.2 cm. The electrofishing exercise was carried out for approximately 20 to 30 minutes at every station. Fish collected were then sorted, enumerated, and identified morphologically by referring to the available taxonomic key (Inger & Chin, 2002; Tan, 2006; Kottelat, 2012). Unidentified individuals of fish were euthanised with an overdose of NIKA transmore solution, fixed in 10% formaldehyde, and then preserved in 70% ethanol for further identification in the laboratory. Lastly, online global databases of fish species including FishBase (Froese & Pauly, 2025) and Eschmeyer's Catalog of Fishes (Fricke et al., 2025) were used to confirm the taxonomic status of fish sampled.

Water quality parameters were measured concurrently with the fish samplings in this study. The water pH and temperature were measured using a multi-parameter pen-type water quality tester (Gain Express M0199720). Dissolved oxygen (DO) was measured using a DO meter (SMART SENSOR AR8406). All water quality meter was calibrated before being used in the field. Triplicate water samples were collected from each station for total suspended solids (TSS) analysis that was determined via the Gravimetric method (Rice et al., 2012) at the Institute for Tropical Biology and Conservation, Universiti Malaysia Sabah.

Secondary data extraction

Fish and environmental parameters were extracted from the studies by Heng et al. (1995), Nyanti (1995), and Ishak et al. (2007) for comparison with the present study. All surveys were conducted within the same river systems and altitudinal zones with a similar sampling approach. All fish species reported in the previous studies were reviewed and cross checked with FishBase (Froese & Pauly, 2025) and Eschmeyer's Catalog of Fishes (Fricke et al., 2025) to ensure that species found from literature are standardized to avoid spelling errors and synonyms. However, it is important to acknowledge the limitation while using secondary data for data analysis as possible errors in fish species identification and different sampling seasons could have an impact on the quality of the secondary data and introduce potential biases.

Data analysis

Individuals-based rarefaction curve analyses were applied in determining the fish biodiversity including species richness, Shannon diversity index, and Simpson diversity index for the current survey in 2023. Kruskal Wallis test with a Dunn’s post hoc test was conducted to compare environmental parameters including water temperature (°C), pH, DO (mg/L), TSS (mg/L), river width (m), and elevation (m asl) measured in 1992 (Heng et al., 1995), 2007 (Ishak et al., 2007), and 2023 (present study). Fish community composition among sites and survey years together with the environmental parameter was analysed using non-metric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarities of species abundance data, using the function *metaMDS* in the R package *vegan*. Environmental variables (water temperature, pH, dissolved oxygen, total suspended solids, stream width, and elevation) were fitted onto the NMDS ordination using the function *envfit*, with the strength and significance of associations assessed using squared correlation coefficients (R^2) and permutation tests (999 permutations). Variations in fish community composition among survey years were statistically tested using permutational multivariate analysis of variance (PERMANOVA) with the function *adonis2*, based on Bray-Curtis distances and 999 permutations, including pairwise comparisons among years. Analysis in this study was performed by using RStudio software version 4.3.3 (R Core Team, 2024) and Paleontological Statistics software package version 4.16c (Hammer et al., 2001).

RESULT

Fish community structure and biodiversity in the Sayap Substation, Kinabalu Park

A total of 258 individuals of freshwater fish representing two families, four genera and seven species were recorded from five stations in the mountainous forest stream of Sayap Substation, Kinabalu Park (Table 1). The two families are Gastromyzontidae and Cyprinidae, where

Gastromyzontidae dominated with 250 individuals representing six out of seven species, accounted for 96.9% of the total fish caught. The genus *Protomyzon* is the most abundant, contributing 60.9% of the composition, followed by *Glaniopsis* (30.6%). The most abundant fish species inhibited in the area is *Protomyzon whiteheadi* (60 individuals), followed by *Protomyzon griswoldi* (50 individuals), *Glaniopsis hanitschi* (49 individuals), *Protomyzon borneensis* (47 individuals), *Glaniopsis denudata* (30 individuals), and *Gastromyzon monticola* (14 individuals), all from the Gastromyzontidae family. *Tor tambra* from Cyprinidae family contributed to the remaining 3.15% with only eight individuals collected. *Protomyzon borneensis* was the most prevalent fish species where it occurs at every station in this study. Conversely, *T. tambra* and *G. monticola* were only found in Sg. Kemantis where *T. tambra* was restricted to the downstream station with low elevation. Individuals-based rarefaction curve shows that both species richness and diversity was estimated to be highest at mid-elevation of station 2 (Lower Sg. Kemantis) followed by the lowest elevation station in this study (station 1- Lower Sg. Wariu). The highest elevation station, station 5 (Sg. Lumatok) was estimated to be the least in both abundance and diversity, with just two species recorded (Fig. 2).

Table 1: Freshwater fish composition in forest streams of Sayap Substation, Kinabalu Park, collected in year 2023.

Family	Species	IUCN Red List Category and Criteria (IUCN 2024)	S1: Lower Sungai Wariu	S2: Lower Sungai Kemantis	S3: Upper Sungai Wariu	S4: Upper Sungai Kemantis	S5: Sungai Lumatok	Sayap Substation
Cyprinidae	*Tor tambra*	Data deficient	0	8	0	0	0	8
Gastromyzontidae	*Gastromyzon monticola*	Least concern	0	9	0	5	0	14
Gastromyzontidae	*Glaniopsis denudata*	Least concern	16	1	13	0	0	30
Gastromyzontidae	*Glaniopsis hanitchi*	Least concern	9	9	5	0	26	49
Gastromyzontidae	*Protomyzon borneensis*	Near threatened	4	13	9	21	4	47
Gastromyzontidae	*Protomyzon griswoldi*	Least concern	0	10	6	34	0	50
Gastromyzontidae	*Protomyzon whiteheadi*	Least concern	1	13	20	22	0	60
	Total		30	63	53	82	30	258

Comparison of fish assemblages and water quality between previous and current study

Three fish species including *Glaniopsis hanitschi, Protomyzon borneensis,* and *P. whiteheadi* were consistently recorded from all surveys (Fig. 3). The genus *Parhomaloptera* which was the most dominant genus in 1992 (60.0%) disappeared in the surveys conducted in 2007 and 2023 (Table 2). Several other species such as *Protomyzon aphelocheilus*, *Neohomaloptera johorensis*, and *Glaniopsis gossei* were only recorded in 1992. Conversely, *Gastromyzon lepidogaster* and *G. monticola* were respectively recorded only in 2007 and 2023. The genus *Glaniopsis* composition in Sayap Substation increased from 22.7% in 1992 to 58.9% in 2007 but decreased to 30.6% in 2023 where it was replaced by the genus *Protomyzon* that increased steadily from 15.3% in 1992 to 60.9% in 2023.

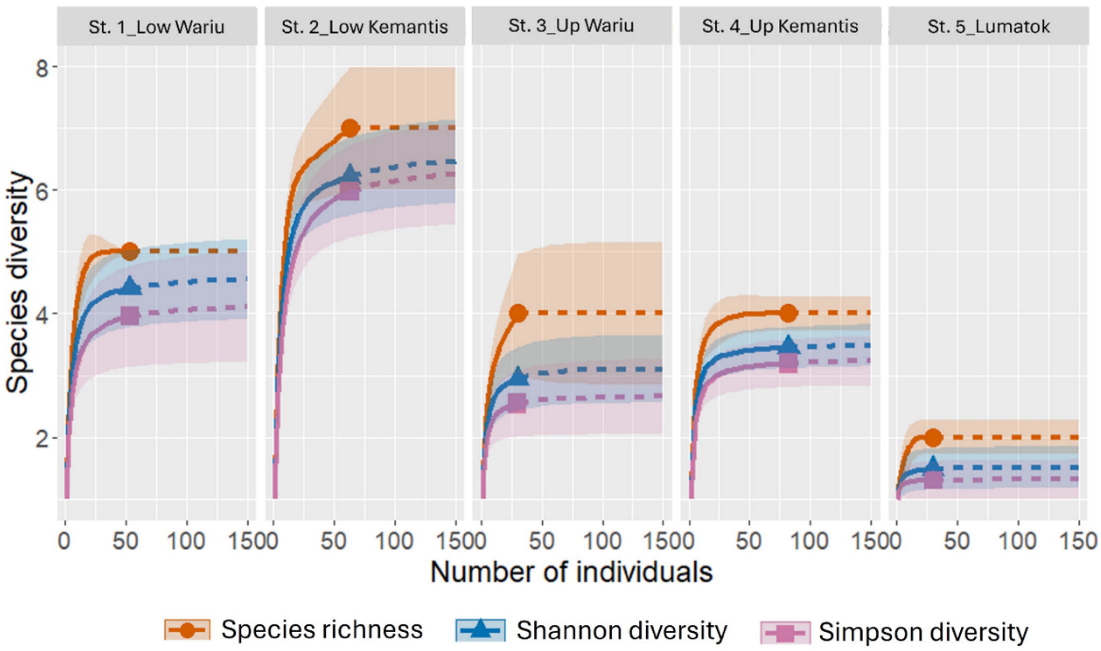

Figure 2: Comparisons of individuals-based rarefaction and extrapolation of species richness and diversity in each station in the 2023 survey. Solid lines represent mean diversity estimates, while shaded bands indicate 95% confidence intervals.

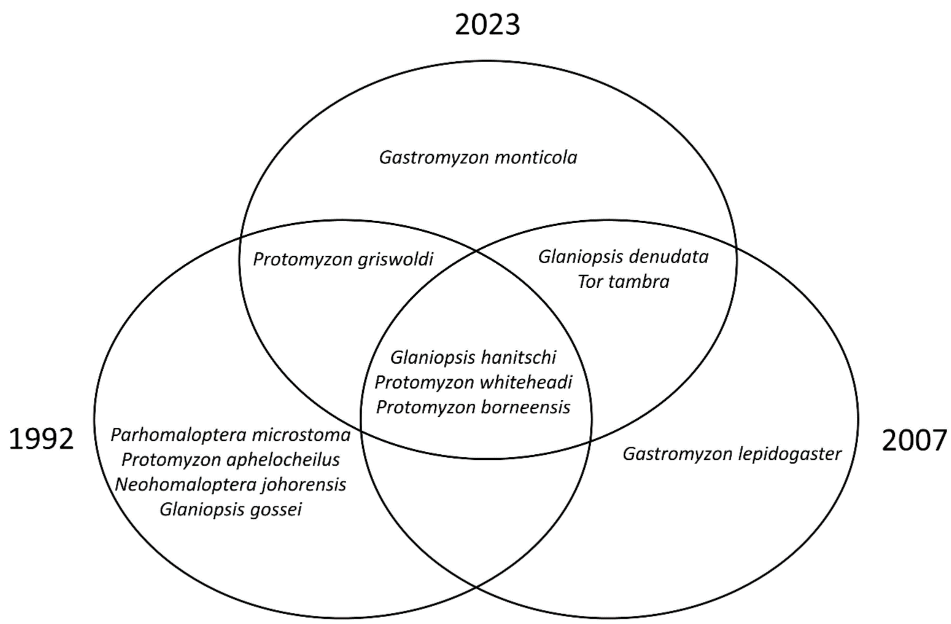

Figure 3: Venn Diagram showing the fish population recorded in 1992 (Nyanti, 1995), 2007 (Ishak et al., 2007) and 2023 (current study).

Table 2: Summary of fish genus composition (%) recorded in 1992, 2007, and 2023 in Sayap Substation, Kinabalu Park, Sabah.

Fish genus composition (%)	Year		
	2023	**2007**	**1992**
Glaniopsis	30.6	58.9	22.7
Parhomaloptera	0.0	0.0	60.0
Protomyzon	60.9	38.3	15.3
Gastromyzon	5.4	1.7	0.0
Neohomaloptera	0.0	0.0	2.0
Tor	3.1	1.1	0.0
Remark	Present study	Ishak et al. (2007)	Nyanti (1995)

Table 3 summarizes environmental parameters in Sayap Substation, Kinabalu Park, Sabah across 31 years. The average water temperature in Sayap Substation steadily increased from 18.2 ºC recorded in 1992, 18.8 ºC recorded in 2007, to 19.8 ºC recorded in 2023. The average water temperature recorded in 1992 was significantly lower ($p < 0.05$) than the average water temperature recorded in 2023, indicating a notable increase of 1.6 ºC after 31 years. Similar pattern was observed for TSS which increased across the years from 0.7 mg/l in 1992, 1.2 mg/1 in 2007 to a staggering value of 24.7 mg/l recorded in 2023, approximately 35 times higher after 31 years. The average dissolved oxygen (DO) value was found significantly lower ($p < 0.05$) in 2007 compared to those in 1992 and 2023. In contrast, the average pH value of 7.0 in 1992 was significantly lower ($p < 0.05$) than the average pH value of 7.7 recorded in 2007.

Table 3: Mean and standard deviation of environmental parameters recorded in 1992, 2007, and 2023 in Sayap Substation, Kinabalu Park, Sabah.

Year	Environmental Parameters						Remark
	Temperature (ºC)	pH	DO (mg/L)	TSS (mg/L)	Width (m)	Elevation (m asl)	
2023	19.8 ^{a} ± 0.5	7.5 ^{a,b} ± 0.1	7.7 ^{a} ± 0.3	24.7 ^{a} ± 5.8	4.7 ^{a} ± 2.4	984 ^{a} ± 86	Present study
2007	18.8 ^{a,b} ± 0.2	7.7 ^{a} ± 0.1	6.6 ^{b} ± 0.1	1.2 ^{a,b} ± 0.5	4.8 ^{a} ± 1.9	1005 ^{a} ± 81	Ishak et al. (2007)
1992	18.2 ^{b} ± 0.4	7.0 ^{b} ± 0.4	7.2 ^{a,b} ± 0.1	0.7 ^{b} ± 0.1	3.3 ^{a} ± 1.5	895 ^{a} ± 87	Heng et al. (1995)

Same letters indicate no significant difference at p-value > 0.05.

The Non-metric Multidimensional Scaling (NMDS) ordination plot (Fig. 4) illustrates that fish assemblages are associated negatively with water temperature and TSS in NMDS 1. The *envfit* analysis showed that water temperature had a statistically significant relationship ($R^2 = 0.443$, $p = 0.035$) with fish assemblages whereas TSS showed a marginal association ($R^2 = 0.344$, $p = 0.078$) with fish assemblages. These two parameters emerged as the key factors in differentiating fish communities between stations by years. The positioning of all stations in 1992 in the right side of the plot compared to those in 2007 and 2023 that are mostly in the left side of the plot, further illustrates shift in fish composition, which is associated with higher water temperature and TSS. Stations located at Sg. Lumatok are positioned close to each other over 31 years. However, stations at Sg. Wariu and Sg. Kemantis from different years are located farther apart, especially in the year 1992. Permutational analysis of variance also revealed that fish community composition was significantly different among the survey years (Pseudo-F = 3.956, P = 0.003), and post hoc tests indicated significant differences between surveys in 1992 and 2007 (p = 0.010) and between surveys in 1992 and 2023 (p = 0.007).

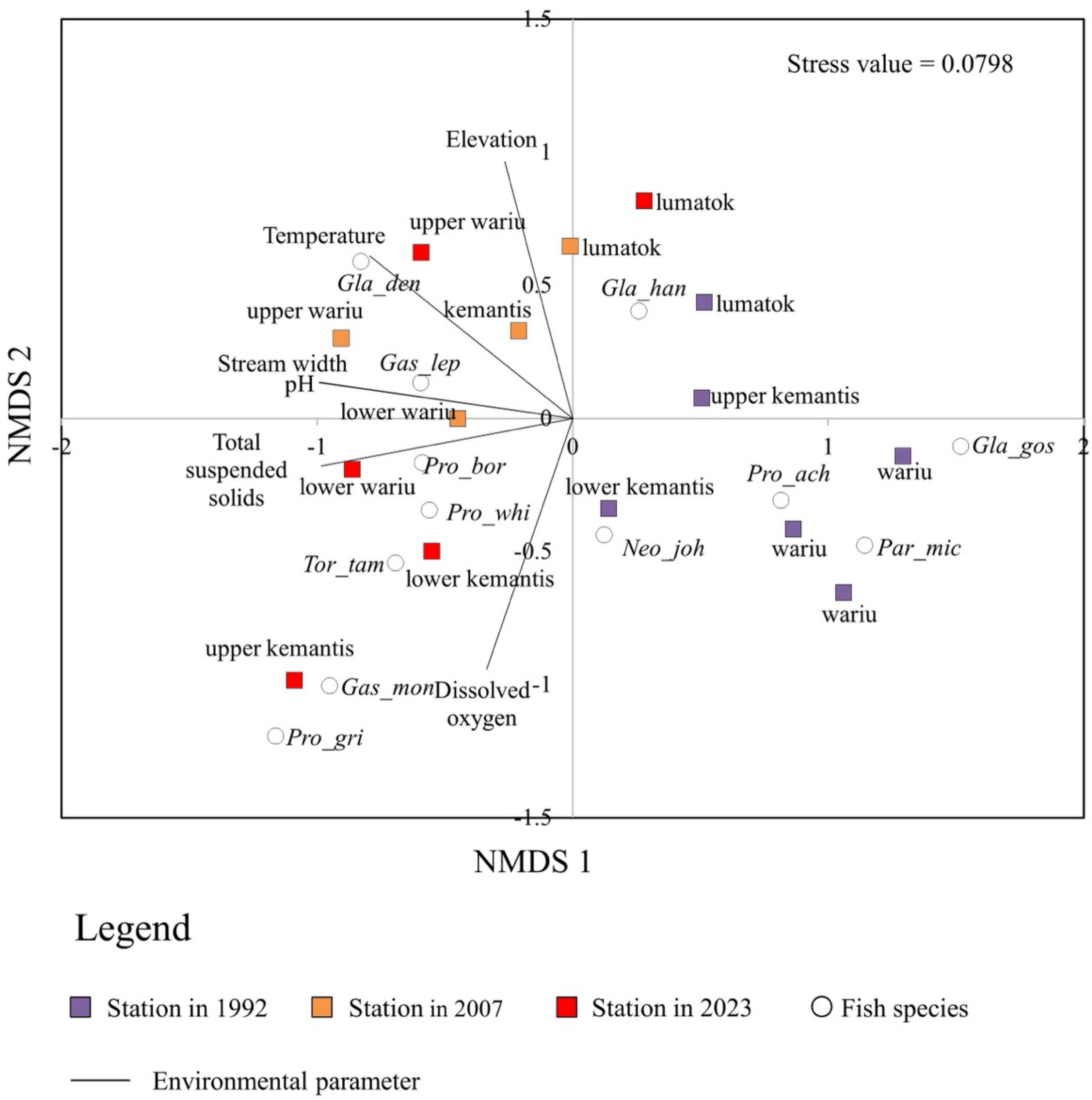

Figure 4: Ordinations of sampling stations by nonmetric multidimensional scaling (NMDS) based on the Bray-Curtis dissimilarity matrix using fish species abundance data. A second matrix of environmental variables was incorporated into the NMDS. The stress value (0.0798) is goodness-of-fit metrics.

DISCUSSION

Fish biodiversity shifts in Sayap Substation, Kinabalu Park over 31 years

The current study provides an update of freshwater fish biodiversity in the Sayap Substation, Kinabalu Park from the previous studies by Nyanti (1995) and Ishak et al. (2007). We recorded a total of 258 individuals representing two families, four genus and seven species in the recent survey. Two fish species namely *P. griswoldi,* and *G. monticola* that were not found in the previous studies were reported in the present study whereas *G. lepidogaster* that was recorded in the previous study, was not found. The discrepancy of fish composition could be caused by several factors such as natural fluctuations and seasonal variations, or habitat changes and climatic factors which could modify the availability of food and resources, subsequently leading to shifts in fish population and distribution over time (Radinger et al., 2017; Cutler et al., 2020; Tao et al., 2024). This study is an initial effort to delve into how fish biodiversity has changed over time in Sayap Substation, Kinabalu Park. The area is not routinely surveyed nor monitored systematically. Thus, the main limitation of the present study of one-time sampling approach, may not capture the full temporal dynamics and natural fluctuations of the fish community in the area. Sampling bias could lead to the absence and presence of some species, particularly rare species in the area like *G. lepidogaster* where only three individuals were caught in 2007 (Oliveira et al., 2016).

Despite the one-time sampling approach and small sample size, the current study demonstrated noticeable fish biodiversity shifts over time in the area. The genus *Glaniopsis* was once the most dominant fish species in Sg. Kemantis that contributed more than 70% of the community structure in 2007 (Ishak et al., 2007) and 39.7% in 1992 (Nyanti, 1995), yet the dominance has reduced to 15.9% in station 2 (Lower Kemantis) and the fish genus was absent in station 4 (Upper Kemantis) in present day. A similar pattern was observed for the genus *Parhomaloptera* and other species that were only recorded in 1992. This phenomenon is probably due to frequent human presence and the increasing activities near the stations. Sayap Substation's mini-hydro facility which was established in 2019 is located near to station 4. Moreover, the station is situated near the well-known Kemantis Waterfall hiking trail, representing one of the main attractions to visitors in this substation. Regular human interventions such as clearing shrubs and recreation activities along the river over time, could have slowly altered the habitat, making it less suitable for these species to occur in this station (Moraga et al., 2022). The anthropogenic impacts on substantial shift in fish community structure particularly in Sg. Kemantis is corroborated by the NMDS analysis where the shifts are associated with TSS over years. Although water qualities of the forest streams in Sayap Substation are still classified as Class I according to the National Water Quality Standards for Malaysia, except for the TSS at station 1 which was classified as Class II (Department of Environment, 2024), the average TSS value in 2023 is approximately 35 times higher than the average TSS value in 1992. Increased TSS value is often linked to soil erosion due to anthropogenic activities resulting in sediment influx through surface runoff (Ling et al., 2018). The significant increments of TSS value may lead to species replacement, altering the composition and dynamics of the local ecosystem (Adewoyin & Okoh, 2020; Rohaningsih & Aisyah, 2023) as higher levels of TSS are indicative of higher nutrient levels that can be beneficial for fish that adapt to such conditions, but excessive amounts could be harmful (Kjelland et al., 2015). Comparatively, fish assemblage in Sg. Lumatok which is located much further from any human settlement and activities in the substation, is consistent over 31 years as illustrated by the close positioning in the ordination plot (Fig. 4).

The present study also revealed that water temperature is associated with fish community structure in the study area. The average water temperature in 2023 was 19.8 ºC; 1.0 ºC higher than the average of 18.8 ºC in 2007 and 1.6 ºC higher than the average of 18.2 ºC in the 1992 survey. Higher water temperature in forest streams could be subject to several factors such as canopy removal and the high levels of TSS due to direct solar radiation and heat absorption by suspended particles (Ling et al., 2016). The significant increment of water temperature over 31 years is also in line with broader global trends of rising temperatures due to climate change, contributed by increased greenhouse gas emissions, leading to higher average temperatures worldwide (Gagnon, 2022). Natural climate variability, including phenomena like El Niño and La Niña, can also influence temperature fluctuations and impact long-term trends (Goddard &

Gershunov, 2020). Climate change is disrupting ecosystems and species populations, with one of the main anticipated consequences being species range shift (Comte & Grenouillet, 2013). The impact of range shifts may pose a substantial challenge to highland fish, where suitable habitats are dwindling and species movement is hampered. *Protomyzon* is an example of a widely distributed genus, but its population size decreases with decreasing altitude whereas genus *Glaniopsis* on the other hand dominate higher elevation in Kinabalu Park (Samat, 1990; Soo et al., 2024). The lower water temperature at higher elevation may be the key adaptation for *Glaniopsis* which has probably experienced physiological adaptation to inhabit such environment since lower temperatures could reduce the metabolic rate (Liu et al., 2019; Lear et al., 2020). The dominancy by *Protomyzon* in the present day may also be the result of an upward shift of *Protomyzon* species with a wider temperature tolerance and reduction of stenothermal species of *Glaniopsis*. In addition, lowland fish may also shift upward in elevation as demonstrated by *Tor tambra* under the family Cyprinidae. Chin (1996) reported the occurrence of this species in Kinabalu Park up to 800 m asl. The fish was not found in the 1992 survey, but was found at 890 m asl in low density (1.1%) in 2007. The present finding demonstrated that *T. tambra* was found to occur at 914 m asl at Lower Sg. Kemantis, contributing to a higher fish composition of 3.1%. This showed that the fish may have somehow moved up the elevation gradient of about 100 m asl over the past few decades. This shift towards higher elevation over the past few decades could be due to climate change that cause the warming of the river water making the fish move upstream (Comte & Grenouillet, 2013). The impacts of climate change on freshwater fish in the mountain habitat has been supported by previous literature (Markovic et al., 2014; Knouft et al., 2017; Carosi, 2022; Larsen et al., 2022). Nonetheless, given the limitation of comparing just three time points over 31 years in the present study, climate change impacts on fish distribution in the forest streams of Sayap Substation is not conclusive and requires further study.

Freshwater fish have been known to exhibit elevational changes in their diversity and abundance patterns (Soo et al., 2021). The present findings revealed that species diversity and abundance were the highest at the mid-elevation station (Station 2 - Lower Sg. Kemantis) and lowest at the highest elevation station (Station 5 - Sg. Lumatok). This finding contradicts the results of the preceding study, where the lowest elevation station exhibited the highest diversity. However, both studies agreed that fish diversity decrease as elevation increases. Higher elevation is usually associated with extreme environment such as lower water temperature, decreased oxygen availability and limited source of food, which can impose physiological limitations (Souchet et al., 2020, 2021). Many species might not have the adaption needed to live under these conditions, which lead to decrease in diversity (Vejříková et al., 2016). On the other hands, the mid-domain effect, which asserts that species diversity tends to be greater at intermediate elevation (Bhatt et al., 2012; Geange et al., 2012; Feng et al., 2017; Dani et al., 2023), is caused by the overlapping of species range and environmental condition from lower and higher elevation at intermediate elevations (Dey et al., 2015; Henriques et al., 2022; Soo et al., 2021). This offers a greater range of resources and habitat, supporting a more diverse fish community (Griffiths et al., 2021).

Conservation implications for freshwater fish in the Sayap Substation and Kinabalu Park

The present study demonstrated that despite being a protected area, the freshwater ecosystem in the Sayap Substation is experiencing ecological changes as reflected in its fish biodiversity and water quality. All loach species (except for *P. borneensis*) found in the present study are classified as Least Concern because majority of their distribution range falls within the protected area and therefore, regarded as relatively low risk from threats (IUCN, 2024). However, noticeable changes in fish community composition have clearly shown their vulnerability in the Sayap Substation. Particularly, *Glaniopsis* spp. have shown sensitivity to habitat disturbances, highlighting their vulnerability to environmental changes even though they are inhabiting a protected area, underscoring the need for conservation actions.

This present study also serves as an early warning that the ecological integrity of forest streams in Sayap Substation may be under stress and hence call for continued monitoring and further research to identify potential factors responsible for such changes. Freshwater fish are vulnerable to environmental changes and anthropogenic disturbances through habitat loss, pollution and climate change (Schmeller et al., 2018). Although it is hypothesized that recreational activity and climate change could be the main factors that contributed to changes in fish biodiversity and water quality in Sayap Substation, the present study could not reflect the overall picture across Kinabalu Park, a UNESCO World Heritage Site. The last comprehensive fish and water quality surveys in Kinabalu Park were conducted three decades ago by Samat (1990). Changes in the biodiversity hotspots and elevation ranges of fish in the park could have occurred through time due to the environmental changes. In addition, declines and losses of freshwater biodiversity within protected areas have been documented worldwide and the role of a protected area in conserving freshwater biodiversity has constantly been raised (Chessman, 2013; Bower et al., 2015; Frederico et al., 2018). It is vital to determine whether Kinabalu Park can adapt to the potential effects of anthropogenic and climate change and serve as refuges for freshwater fish (Parks et al., 2023).

Thus, intensive field surveys to identify hotspots of freshwater fish endemism and the elevational range of fish in Kinabalu Park forest streams, are of paramount importance to conserve native and endemic species of fish in Kinabalu Park. Regular monitoring is also crucial for understanding long-term trends and identifying emerging threats and conservation needs of fish. Integrating advanced techniques such as environmental DNA (eDNA) for fish surveys is recommended as it is considered more appropriate to be implemented in protected areas (Fernandez et al., 2018), especially apt for detecting rare fish species (Shaw et al., 2016). Ultimately, the information can inform updates to the park's management plans, guiding targeted conservation efforts such as the identification of priority areas for habitat restoration and species reintroduction to ensure the long-term viability of freshwater ecosystems in Kinabalu Park, a UNESCO World Heritage Site recognized for its exceptional natural value and biodiversity.

CONCLUSION

The present study provides an important update on the fish population in the Sayap Substation, Kinabalu Park, 31 years after the first research in the area. Although the study has several limitations, it provides important insights of the changes in this important protected area. These findings underpin changes in the dominant fish species and water quality values and thus providing an early warning sign that the forest streams in the park have undergone some degree of alteration over the 31 years. This study also underscores the associations of environmental factors particularly water temperature and TSS in biodiversity shifts of fish. These findings have broader implications for the management and conservation in the freshwater habitats of Kinabalu Park. Regular and long-term baseline data are crucial to analyse the health of freshwater ecosystems in Kinabalu Park and detect potential threats or changes in biodiversity over time to develop effective strategies to safeguard the unique biodiversity and ecosystem services provided by the forest streams in Kinabalu Park.

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DECLARATIONS

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Ethical approval/statement. This study involving animal was approved by Animal Ethics Committee UMS [Ref: AEC 0014/2023] and animal was handled with humane treatment.
Generative AI use. The authors declared that generative AI has been used in the completion of this manuscript in compliance with the JTBC policies for final proofreading to correct the language error.

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