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ARTICLE

The Interconnection of Reproductive Biology and Conservation Strategies for the Lesser Spiny Eel in the Progo River Ecosystem

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ABSTRACT

The lesser spiny eel (*Macrognathus aculeatus*) is a significant species in Southeast Asia's freshwater ecosystems, particularly in the Progo River, Indonesia. This study investigates the reproductive biology of the lesser spiny eel, focusing on size, weight, sex ratio, gonad maturity, fertility, and environmental influences on spawning. A total of 217 eels were sampled, and data on gonadal maturity index (GMI), fecundity, and oocyte size were collected and analyzed. The study found a balanced sex ratio of 0.95:1.0, with significant fluctuations during the spawning season. Female eels averaged 33.4 cm in length and 130.4 g in weight, while males averaged 31.6 cm and 107.7 g. Over 58% of females reached gonadal maturity level IV during peak spawning months, indicating synchronized reproductive cycles. The average fecundity at maturity level IV was 2062 ± 605 grains, with larger oocytes being released during spawning. The findings highlight the importance of hydrological conditions in the reproductive success of lesser spiny eels. The study confirms that environmental factors, such as rainfall and water temperature, significantly influence spawning behavior. The low relative fecundity suggests vulnerability to overfishing and habitat degradation, emphasizing the need for targeted conservation efforts. The lesser spiny eel's reproductive biology is intricately linked to environmental conditions, necessitating comprehensive conservation strategies that include habitat protection and community engagement. By fostering local involvement and awareness, conservation initiatives can enhance the sustainability of this species and its ecosystem, ensuring the long-term viability of the lesser spiny eel in the Progo River.

Keywords: Biodiversity; Community; Fecundity; Habitat; Maturity

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1. Introduction

The lesser spiny eel (*Macrognathus aculeatus*), a fascinating species inhabiting Southeast Asia's freshwater ecosystems, particularly the Progo River in Indonesia, has garnered significant attention from researchers and conservationists alike [1]. This enigmatic fish, known for its elongated body and distinctive spiny dorsal fin, plays a crucial role in the aquatic food web and indicates environmental health in its native habitat. As anthropogenic pressures continue to threaten freshwater ecosystems globally, understanding such species' reproductive biology and conservation needs becomes paramount for ensuring their survival and the integrity of the ecosystems they inhabit. Reproductive biology is critical to understanding any species, as it provides insights into their life history strategies, population dynamics, and resilience to environmental changes. The lesser spiny eel exhibits unique reproductive behaviors intricately tied to the seasonal hydrological patterns of the Progo River [2]. Factors such as water temperature, flow rate, and the availability of spawning substrates influence their breeding cycles. Recent studies suggest that these eels engage in complex mating rituals and exhibit parental care, which may enhance the survival of their offspring in a rapidly changing environment. Investigating these behaviors enriches our knowledge of the species and highlights the delicate interplay between aquatic organisms and their habitats.

The lesser spiny eel is a significant fish in the Special Region of Yogyakarta, providing both protein and revenue to the local people. They are in great demand and sell at higher market prices than walking catfish. They reside at the bottom of the water and are captured using fishing rods and cast nets. However, the native population of lesser spiny eel is rapidly declining due to habitat changes and increased exploitation. Unregulated harvesting may endanger lesser spiny eel populations in their native environment. Lesser spiny eels are classified as either Low Risk or Near Threatened; however, they are not yet on the Indonesian government's protected fish list. Capturing fire eels is challenging due to their small population, with captures accounting for less than 1% of the total individual output or weight. Efforts to produce fewer spiny eel have failed, suggesting that fishermen should continue to depend on river catch [3].

Conservation efforts for the lesser spiny eel are increasingly important as the Progo River faces pollution, habitat degradation, and overfishing threats. The river's biodiversity is under siege, and the lesser spiny eel and numerous other aquatic species are at risk of population decline. Conservation initiatives must be informed by a comprehensive understanding of the species' ecological requirements and reproductive strategies. By employing a multidisciplinary approach that includes habitat restoration, pollution control, and sustainable fishing practices, stakeholders can work collaboratively to safeguard the future of this unique eel and its ecosystem. Moreover, the cultural significance of the lesser spiny eel in local communities cannot be overlooked [4]. As a source of food and livelihood for many, the decline of lesser spiny eel would have far-reaching socio-economic implications. Engaging local communities in conservation efforts is essential, as they hold traditional knowledge and a vested interest in the river's health. Educational programs to raise awareness about the importance of biodiversity and sustainable practices can empower communities to become stewards of their natural resources, fostering a sense of ownership and responsibility toward conserving the lesser spiny eel and its habitat.

The lesser spiny eel is a vital component of the Progo River's ecosystem, and understanding its reproductive biology is crucial for effective conservation strategies [5]. As research continues to unveil the secrets of this remarkable species, it becomes increasingly clear that a holistic approach to conservation—one that integrates ecological, social, and economic factors is essential for ensuring the survival of the lesser spiny eel and the rich biodiversity of the Progo River. By prioritizing conservation efforts and fostering community engagement, we can work towards a sustainable future for this unique species and the intricate ecosystems they inhabit.

This study aims to investigate the reproductive biology of the lesser spiny eel in the Progo River, Yogyakarta, focusing on aspects such as size, weight, sex ratio, gonad maturity level, fertility, and environmental influences on spawning. The results of this study are very important as they can be used as references for managing the population dynamics and reproductive health of this species, as well as effective conservation. By analyzing the gonad maturity index and fertility of broodstock, this study attempts to understand the reproductive capacity of the lesser spiny eel and the implications of fishing pressure on the sustainability of its population. The findings of this study will be an essential database to ensure the long-term survival of the lesser spiny eel population in the Progo River ecosystem.

2. Materials and Methods

2.1. Study Area

The samples were collected downstream of the Progo River, the primary fishing location in Yogyakarta. An earthworm-baited bottom fishing rod was utilized to catch lesser spiny eel. The fishing line was positioned around 100 m downstream of the Kaminjoro weir (7°52′43.7″ S, 110°15′58.4″ E) at 1 to 4 m of water depth (**Figure 1**). Locations for fishing were in waterways with a sluggish current, sandy mud or gravel sand on the bottom, and flora as a shelter. The sampling was performed biweekly during the fishing season from November 2022 to February 2023.

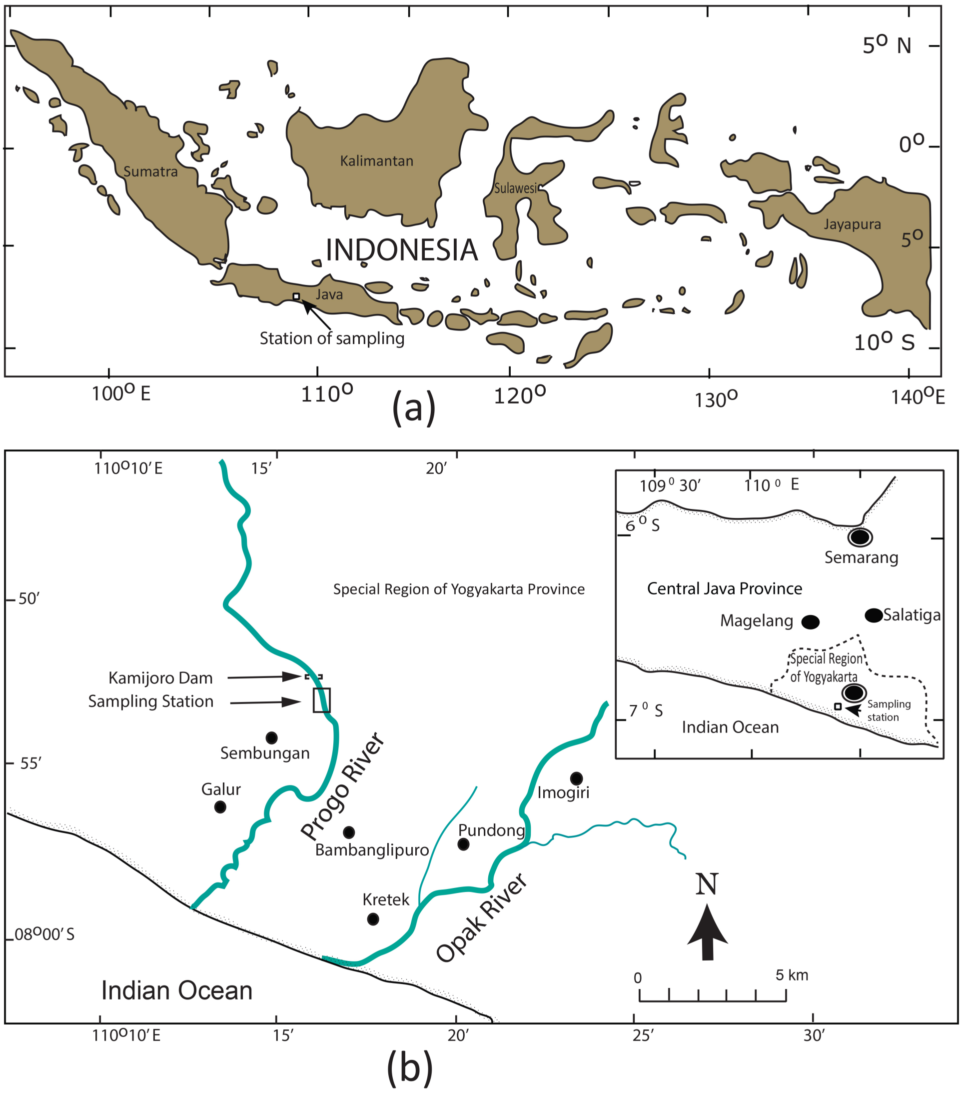


Figure 1. Map of the island of Java, located in the middle of the Republic of Indonesia **(a)** Kamijoro Dam, a sampling station for the fishing of lesser spiny eel, is located in the Special Region of Yogyakarta Province (**b**) Lesser spiny eel fishing was carried out when the water was clear, and the current was moderate during the rainy season using a fishing rod with earthworm bait.

2.2. Procedures

Lesser spiny eel[3] collected in the Progo River with fishing rods was kept fresh in boxes with ice cubes before being transported to the lab for species identification. Length and weight for each were measured using a stainless-steel ruler with an accuracy of 0.1 mm and an electric scale of 0.1 g. The abdomen was sliced from the anal part dorsally to the end of the abdominal cavity using surgical scissors. Subsequently, it was cut anteriorly to the base of the operculum and moved ventrally to the base of the pectoral fins. The gonads were exposed after the abdominal wall was opened, then the presence of testes identified males, while the presence of ovaries characterized females. Gonadal maturity level (GML) was determined by observing the gonads' features, including color, size, texture, and shape. The maturity phases were grouped differently, and **Table 1** was used to guide the process. The five stages of the gonad maturity level were identified: level I. immature, II. developing, III. mature, IV. spawning, and V. spent[6].

Table 1. The morphology of the gonad developmental phase of the lesser spiny eel, whose habitat is in the lower reaches of the Progo River.

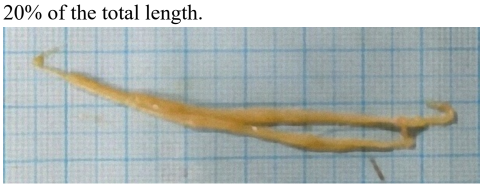
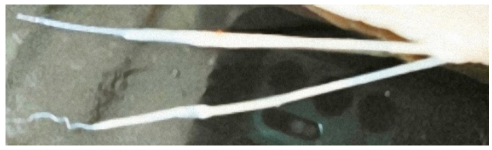
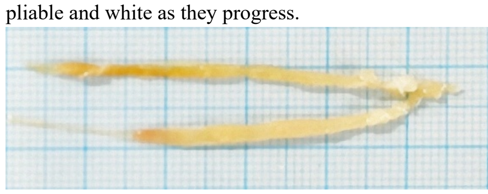
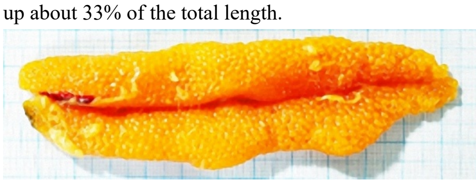
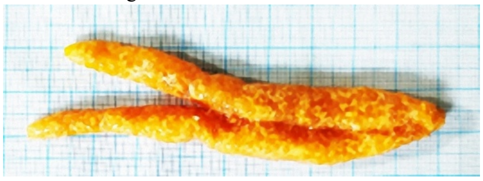
Maturity Level	Female	Male
Level 1 (Immature)	The ovaries are paired and attached to the abdominal cavity, thin elongated, transparent, and soft, with few or no obvious blood vessels. Through the wall of the ovary, the oocyte is not visible. The color of the ovary is light yellow, and it is about 20% of the total length. 	The testes grow longitudinally and adhere to the dorsal abdominal cavity as a pair. The testicular wall is milky white in appearance and seems to have capillaries. 
Level 2 (Developing)	On macroscopic examination, the ovaries were enlarged, with only a few oocytes visible. There are no visible blood vessels. Oocytes range in size from 0.65 to 1.20 mm. The ovary is yellow in color and occupies about a quarter of the total length. 	The testes are enlarging and turning white. There is an increased quantity of spermatocytes and spermatids in the testes. The testicular wall has visible capillaries. The testicles become more pliable and white as they progress. 
Level 3 (Mature)	The ovary is becoming increasingly larger. The development of yellowish oocytes and blood vessels is still going well. There is no ovulation, and the oocytes are spherical with a little rough surface. Blood vessels merge to form bigger capillaries on the ovarian wall's exterior surface. Oocytes can be seen plainly through the ovary's yellow wall. Oocytes range in size from 1.20 to 1.80 mm in diameter. The ovary makes up around 27% of the total length. 	The testes are enlarged and pale white posteriorly. The anterior is reddish because the blood supply and testicular volume increase markedly. Milt comes out with slight gentle pressure on the stomach. Spermatozoa grow in size. 
Level 4 (Spawning)	The ovaries are macroscopically large and have a thin and transparent membrane. The ovaries grow larger, dark yellow or reddish; the oocyte grains can separate, and the peripheral and central blood vessels are clear. Microscopically, there was an increase in yolk vesicles that filled the entire ooplasm. The oocytes were mature. Most oocytes were in the tertiary vitellogenin stage, and the oocyte diameter was 1.75–2.20 mm. The elongated ovary fills the entire abdominal cavity, making up about 33% of the total length. 	The testes are small and appear flabby and dark pink due to increased blood flow. The testicles are dilated, and most appear squiggly. There are blood vessels and viscous fluid. On gentle pressure, the semen will gush out. The lumen contains spermatozoa. Most of the spermatozoa migrate toward the periphery of the lobules. 

Table 1. *Cont.*

Maturity Level	Female	Male
Level 5 (Spent)	Macroscopically, the ovary is shrunken, with a thin and transparent membrane. The ovaries are smaller, pale yellow, and some oocytes are still visible. Peripheral and central blood vessels are fading. Most of the oocytes have been released during spawning. The ovaries are shriveled and are about 29% of the total length. 	This level was not found

2.3. Gonad Development Phases in the Female

2.3.1. Level 1 (Immature)

In the immature phase, the ovaries exhibit a simple structure characterized by a thin, elongated appearance. The ovarian tissue is transparent and soft, with minimal vascularization. Histologically, the oocytes are not visible through the ovarian wall, indicating an early stage of development. The cellular architecture is primarily composed of ovarian stroma with few germ cells present. The predominant color is light yellow, reflecting the immature state. The ovaries occupy about 20% of the total body length. A histo-micrograph at this stage would show a thin ovarian wall, sparse vascularization, and a lack of visible oocytes.

2.3.2. Level 2 (Developing)

At the developing stage, the ovaries enlarge significantly, and a few oocytes begin to appear. The histological examination reveals a more complex structure, with visible oocytes ranging in size from 0.65 to 1.20 mm. The ovarian stroma becomes more organized, and while blood vessels are not yet prominent, the overall tissue integrity is improving. The yellow color deepens as the ovaries occupy about 25% of the total length, indicating a transition towards maturation. A histo-micrograph would illustrate the presence of developing oocytes, a more robust ovarian stroma, and the early formation of blood vessels within the ovarian tissue.

2.3.3. Level 3 (Mature)

During the mature phase, the ovaries continue to grow, with a significant increase in the number of visible oocytes. Histologically, the oocytes are spherical, with a rough surface texture, indicating readiness for ovulation. The presence of blood vessels becomes more pronounced, merging to form larger capillaries on the ovarian wall. Oocytes range in diameter from 1.20 to 1.80 mm, and the ovaries now comprise approximately 27% of the total length. The yellow color deepens, reflecting the accumulation of yolk within the oocytes. A histo-micrograph would display numerous oocytes with distinct boundaries, visible blood vessels, and a thickened ovarian wall, showcasing the advanced stage of maturity.

2.3.4. Level 4 (Spawning)

In the spawning phase, the ovaries are macroscopically large with a thin, transparent membrane. Histologically, the oocytes are mature, with a significant increase in yolk vesicles filling the ooplasm. The oocytes, primarily in the tertiary vitellogenin stage, range from 1.75 to 2.20 mm in diameter. The ovarian tissue shows clear peripheral and central blood vessels, indicating high vascularization. The ovaries occupy about 33% of the total length, with a dark yellow or reddish appearance, signifying readiness for spawning. A histo-micrograph at this stage illustrates the mature oocytes with abundant yolk vesicles, clear blood vessels, and a well-defined ovarian structure, indicating readiness for ovulation.

2.3.5. Level 5 (Spent)

During the phase spent, the ovaries exhibit a shrunken appearance, characterized by a thin and transparent membrane. Histologically, the ovaries show a significant decrease in size, becoming pale yellow, and some oocytes may still be visible. The peripheral and central blood vessels are fading, indicating a post-spawning state. Most oocytes have been released, leading to a shriveled appearance of the ovaries, which now constitute about 29% of the total length. A histo-micrograph would reveal a reduced number of oocytes, a thin ovarian wall, and diminished vascularization, reflecting the spent condition of the ovaries.

2.4. Gonad Development Phases in Male

2.4.1. Level 1 (Immature)

In the immature phase, the testes exhibit a simple structure characterized by a milky white appearance. The testicular tissue is soft and elongated, adhering closely to the dorsal abdominal cavity. Histologically, the testicular wall shows minimal vascularization, and the presence of germ cells is limited. The tissue architecture primarily consists of the testicular stroma, with few spermatocytes and spermatids present. The testes occupy about 20% of the total body length, reflecting their immature state. A histo-micrograph at this stage would display a thin testicular wall with sparse vascularization and a lack of visible germ cells, indicating the early developmental stage of the testes.

2.4.2. Level 2 (Developing)

At the developing stage, the testes begin to enlarge and assume a more distinct structure. Histologically, there is an increase in the number of spermatocytes and spermatids, with some visible differentiation occurring. The testicular tissue shows a more organized architecture, and while blood vessels are not yet prominent, the overall integrity of the tissue is improving. The testes now appear more robust and occupy about 25% of the total length. A histo-micrograph would illustrate the presence of developing spermatocytes and spermatids, a more structured testicular stroma, and the early formation of blood vessels within the testicular tissue.

2.4.3. Level 3 (Mature)

During the mature phase, the testes continue to grow significantly. Histologically, there is a marked increase in the number of spermatocytes, and the presence of spermatozoa becomes evident. The testicular wall appears thicker, and blood vessels become more pronounced, merging to form larger capillaries. The testes now exhibit a pale white appearance at the posterior end and a reddish hue at the anterior, indicating increased blood supply. The testes occupy approximately 27% of the total length. A histo-micrograph would showcase numerous spermatocytes and spermatozoa, visible blood vessels, and a thickened testicular wall, indicating an advanced stage of maturity.

2.4.4. Level 4 (Spawning)

During the spawning phase, the testes are macroscopically smaller and flaccid, exhibiting a dark pink appearance due to increased blood flow. Histologically, the presence of spermatozoa is abundant, and the testicular tissue exhibits high vascularization with clear peripheral and central blood vessels. The lumen of the seminiferous tubules is filled with viscous fluid containing spermatozoa. The testes occupy about 30% of the total length, reflecting their readiness for spawning. A histo-micrograph at this stage would illustrate the abundant spermatozoa in the lumen, well-defined blood vessels, and a dilated testicular structure, indicating readiness for spawning.

2.4.5. Level 5 (Spent)

In the spent phase, the testes exhibit a shrunken appearance and a pale pink color. Histologically, there is a significant decrease in the number of spermatozoa, and the testicular tissue shows signs of post-spawning recovery. The peripheral and central blood vessels are returning to normal, indicating a return to a resting state. The testes now appear shriveled and occupy about 29% of the total length. A histo-micrograph would reveal a reduced number of spermatozoa, a thin testicular wall, and diminished vascularization, reflecting the spent condition of the testes.

2.5. Data Analysis

Data were analyzed descriptively by presenting tables, pictures, and graphs, specifically on sex ratio, length, and weight distribution. The distribution of gonadal maturity level (GML), gonadal maturity index (GMI), fecundity, oocyte diameter, and length of the first sample to mature were determined. The sex ratio was assessed by comparing the number of males with females monthly and tested with the chi-squared (χ^2) test. The study's hypothesis (H0) is that the sex ratio of female and male lesser spiny eel is balanced (1:1) at the 95 % confidence level ($\alpha = 0.05$; df = 1; χ^2 table = 3.84).

The following formula was used to determine the gonadal maturity index (GMI):

$$\text{GMI} = \frac{Wg}{W} x\ 100,$$

Wg = gonad weight; W = body weight

Fish fecundity refers to the number of eggs ready to be released before spawning. Therefore, small or undeveloped oocytes were excluded from determining fecundity. It was calculated using the formula below, fecundity (F):

$$\mathrm{F} = \frac{Wg}{gs} x\ nt, \text{ gs = weight of gonad samples;}$$
nt = number of oocytes of gonad samples

The number of eggs that have reached final maturity in the ovary in each female brood before spawning is known as relative fecundity (Fr). It can be determined using the formula below:

$$\mathrm{Fr} = \frac{F}{W}, \mathrm{F = Fecundity, W\ =\ body\ weight}$$

The proportion of broodstock that has reached gonadal maturity (Lm50 %) indicates the estimated length of the fish. To determine the length of the first gonad mature, the following formula is used:

$$\mathrm{Lm50\%} = \frac{1}{(1\ *\ e^{(a-b*L)})}$$

Using the following formula, the equation can be changed into a linear regression equation:

$$ln\left(\frac{1}{lm50\%} - 1\right) = a - bl$$

Notation: Lm50% = Length when the gonads mature for the first time, L = total length (cm), a = intercept, b = slope.

3. Results

The length and weight of lesser spiny eels sampled in this study are shown in **Figures 2** and **3**. Among the 217 overall lesser spiny eels examined, 105 were females, while 112 were males. Female lesser spiny eels ranged in size from 20.5 to 44.4 cm (average ± s.d., 33.4 ± 3.3), weighing between 22 and 239 g (130.4 ± 35.8). Meanwhile, the males were found in lengths ranging from 21.8 to 51.0 cm (31.6 ± 6.3) and weighed between 33 and 381 g (107.7 ± 72.1). The female length distribution exhibited two distinct modes, indicating a more varied population structure with multiple size classes. In contrast, the male length distribution was characterized by a single mode, suggesting a more uniform size range among male lesser spiny eels.

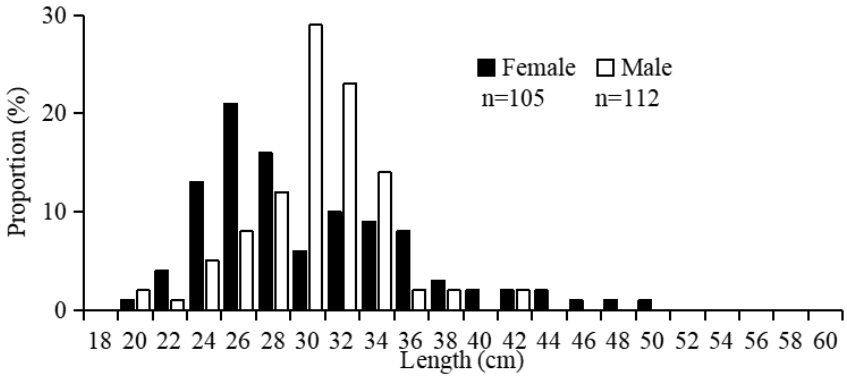


Figure 2. The length distribution of lesser spiny eel captured in the lower reaches of the Progo River, Yogyakarta Special Region Province.

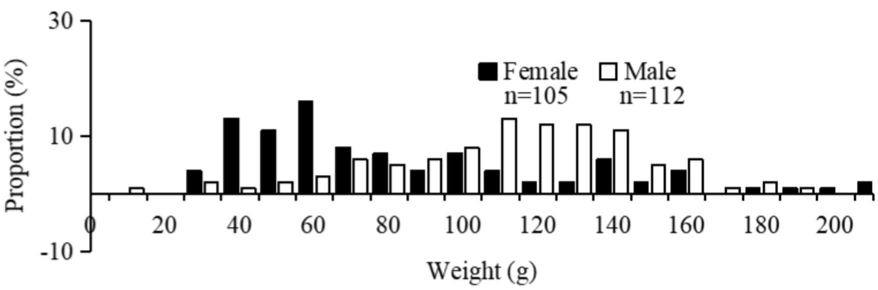


Figure 3. The weight distribution of lesser spiny eel collected in lower portions of the Progo River of the Yogyakarta Special Region Province.

The Progo River's lesser spiny eels show significant differences in length distribution between sexes. Females have a size range of 20.5 to 44.4 cm, with an average length of 33.4 cm, while males have a size range of 21.8 to 51.0 cm, with an average length of 31.6 cm. Males have a broader size range but a smaller average length. This skewed distribution may impact population dynamics and reproductive strategies, as smaller males may have different mating success compared to larger males.

The data show that female lesser spiny eels generally weigh more than males, with females averaging 130.4 g and males at 107.7 g. The females' weight range is between 22 and 239 g, while males range from 33 to 381 g. The dominance of females in the 110–160 g weight range suggests that they play a more significant role in reproductive output, potentially enhancing fecundity and reproductive success, which are crucial for the species' sustainability.

Table 2 shows a balanced sex ratio of females to males at 0.95:1.0, indicating a stable population. However, monthly variations show fluctuations, especially during the spawning season in November[6], where the ratio was skewed to 0.37:1.0. This imbalance may be due to ecological or behavioral factors. The subsequent months, from December to February, show a return to balance, suggesting stabilization due to environmental conditions or spawning behaviors.

Table 2. Sex ratio of lesser spiny eel in the lower Progo River.

Category	Nov	Dec	Jan	Feb	Sum
Female	10	45	35	15	105
Male	27	37	35	13	112
Total	37	82	70	29	217
Ratio F:M	0.37:1.0*	1.22:1.0	1.0:1.0	1.15:1.0	0.95:1.0
$\chi 2$ count	7.811	0.780	0	0.310	0.165

Note: The overall female-to-male ratio is balanced; The sign * shows significantly different ($p > 0.05$), X table > 3.84.

The gonadal maturity level (GML) distribution, as shown in **Figure 4**, reveals a significant difference in reproductive readiness between the sexes. Female gonads dominate at GML IV (over 58.1%), indicating a substantial portion of the female population is ready for spawning. Males show a higher prevalence at GML I (>56.5%), suggesting that lesser spiny eels are more likely to be prepared for reproduction. The synchronized reproductive cycle from November to February may be advantageous for successful spawning events.

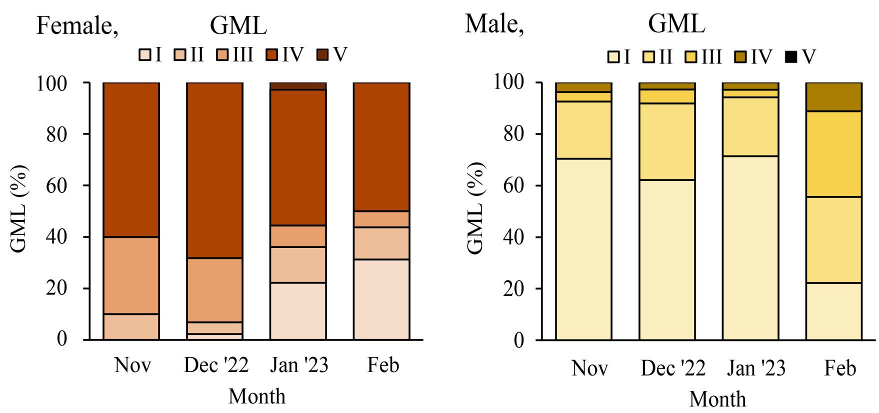


Figure 4. The gonadal maturity level distribution of female and male lesser spiny eel in The Progo River Downstream.

Figure 5 shows that female lesser spiny eels have a significantly higher GMI (7.93 ± 4.43) compared to males (0.17 ± 0.12), indicating greater reproductive capacity. It suggests that females reach maturity at a higher rate and maintain consistent reproductive output. The variability in male GMI suggests potential challenges in achieving reproductive readiness[7], which may impact population dynamics and success during critical spawning periods.

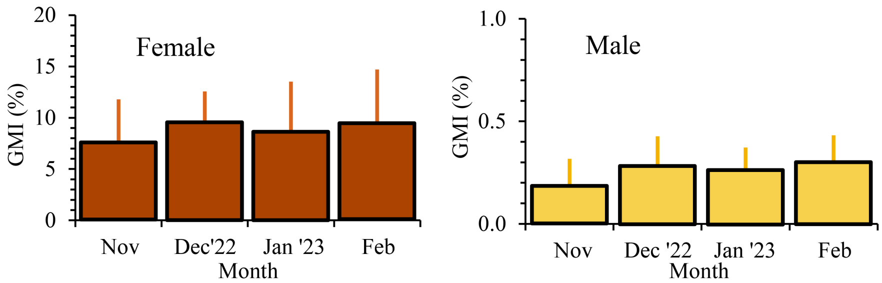


Figure 5. The average gonadal maturity index of female lesser spiny eel in the Progo River downstream. The bar line is the standard deviation.

Figure 6 shows the distribution of oocyte diameters at GML III and IV stages, and the proportion of oocytes ovulated at spawning. In GML III, oocyte diameters ranged from 0.8 to 2.4 mm, with a peak of 1.9 mm. Oocytes with a diameter of 1.2–1.8 mm were the most dominant, comprising 7–10% of the proportion. In GML IV, oocyte diameters ranged from 1.0 to 2.6 mm, with a significantly higher proportion of large oocyte groups.

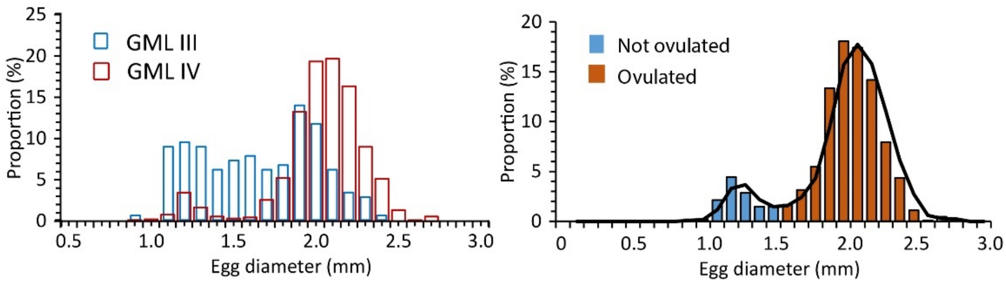


Figure 6. Distribution of lesser spiny eel oocytes in GML III and IV stages (left panel).

Note: The right panel shows the estimated proportion of not ovulated oocytes and ovulated at spawning. The oocytes had diameters ranging from 0.8 to 2.7 mm and were divided into two groups: small and large. The small group comprised 12.78%, while the large group accounted for 87.22%. During spawning, only large oocytes were released for fertilization, while the small group remained in the gonad. After spawning, the small group would grow larger for further spawning.

Fish gonad samples from GML III and IV were used to estimate fecundity. The average and range of oocyte numbers per individual, fecundity, relative fecundity (grain/g body weight), and oocyte diameter were presented in **Table 3**. Parental eggs in GML III had oocyte counts between 1229 and 3799 grains, while fecundity ranged from 157 to 485 grains. The relative fecundity ranged from 1.5 to 8.1 grain/g body weight, and the oocyte diameter ranged from 1.13 to 2.03 mm. In GML IV, the number of oocyte grains was slightly higher but six times greater, indicating an increase in reproductive capacity as females mature. The relative fecundity in GML IV was significantly greater, ranging from 7.1 to 45.8 grains per gram of body weight, indicating the potential for populations to sustain themselves through effective spawning strategies.

The reproductive biology of lesser spiny eels is analyzed through oocyte diameters. Larger oocytes (2.0 mm) are more prevalent during spawning, suggesting they are primary fertilizers. Smaller oocytes may remain in the gonad for future cycles. Fecundity data show a significant increase in reproductive output from GML III to GML IV, emphasizing the importance of oocyte size in determining reproductive success. Females in GML IV have a larger oocyte diameter than those in GML III. The reproductive capacity of lesser spiny eels is relatively low based on the average number of eggs produced.

Figure 7 reveals that lesser spiny eels in the lower Progo River reach their first spawning maturity at lengths of 27.15 cm and 44.5 cm, respectively, indicating a significant increase in reproductive potential with size. This 1.6 times size ratio highlights the potential for larger females to contribute more significantly to the population's gene pool by producing more eggs. Male lesser spiny eels reach their first spawning maturity at 32.72 cm and 51.0 cm, with a similar proportional relationship between their maximum size and the size at which they first reach gonadal maturity. It suggests a possible evolutionary strategy in which males may need to attain a specific size to compete for mating opportunities. At the same time, females may benefit from being larger to produce more eggs, thereby enhancing their reproductive fitness.

Table 3. Mean and range of total egg (grain), fecundity (grain), relative fecundity (grain/g bw), and size of oocyte diameter (mm) of broodstock in GML III and GML IV.

Parameter	GML III				GML IV			
	Total Egg (grain)	Fecundity (grain)	Relatif Fecundity (grain/g bw)	Oocyte Diameter (mm)	Total Egg (grain)	Fecundity (grain)	Relatif Fecundity (grain/g bw)	Oocyte Diameter (mm)
Average	2426	310	3.7	1.60	2364	2062	15.2	1.97
Maximum	3799	485	8.1	2.03	4730	4126	45.8	2.32
Minimum	1229	157	1.5	1.13	1246	1086	7.1	1.18
Deviation	974	124	2.7	0.35	693	605	6.8	0.25

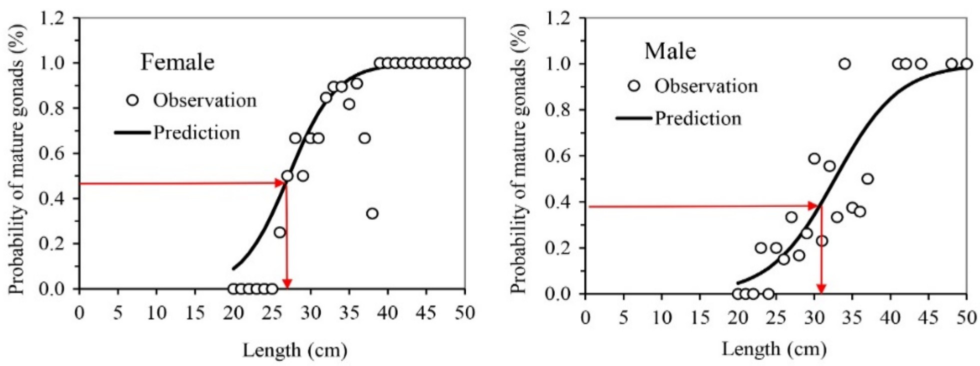


Figure 7. The estimated length at first maturity of female and male lesser spiny eel in the Progo River downstream.

The rainfall data from 2020 to 2023 (**Figure 8**) indicates significant monthly variations, with an average annual rainfall of approximately 375.3 mm/month [8,9]. The rainfall data for Kulon Progo district reveals significant seasonal variations that can play a crucial role in the spawning behavior of lesser spiny eels. Lesser spiny eels typically spawn during the rainy season when water levels rise, and floodplain areas are inundated. The data indicates peak rainfall during October to December, which aligns with the spawning period for these lesser spiny eels. Increased precipitation during these months creates suitable habitats for the lesser spiny eels to lay their eggs, as the flooded areas provide ample food resources and protection for the developing larvae. The average monthly rainfall during this period suggests a conducive environment for the spawning process, as the lesser spiny eel are known to prefer shallow, warm waters for reproduction. The elevated water levels create favorable conditions for spawning, offering ample habitat and food sources for the larvae. The data shows that months with higher rainfall, such as October to December, can be critical for successful reproduction.

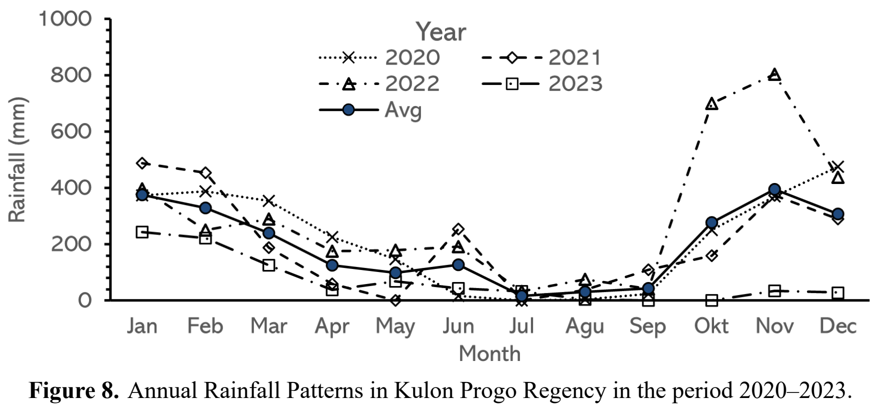


Figure 8. Annual Rainfall Patterns in Kulon Progo Regency in the period 2020–2023.

The rainfall data from 2020 to 2023 show significant monthly variations, with an average annual rainfall of 375.3 mm per month. The Kulon Progo regency experiences substantial seasonal variations, which can impact the spawning behavior of lesser spiny eels. Lesser spiny eels typically spawn during the rainy season when water levels rise, and floodplain areas are inundated. Peak rainfall occurs between October and December, which aligns with the spawning period for these lesser spiny eels. Increased precipitation creates suitable habitats for laying eggs, as flooded areas provide food resources and protection for larvae. The average monthly rainfall during this period is conducive to spawning, as lesser spiny eels prefer shallow, warm waters for reproduction.

4. Discussion

The reproductive biology of the lesser spiny eel (*Macrognathus aculeatus*) has been the subject of much investigation, notably in terms of gonadal maturity, fecundity, and environmental impacts. The results of this study are consistent with earlier studies emphasizing the importance of hydrological conditions on the reproductive success of freshwater fish species [10]. The water temperature and flow rates are important predictors of spawning behavior in freshwater fish, including lesser spiny eel [11]. This research confirms that the Progo River's seasonal hydrological patterns [12] have an important role in the lesser spiny eel's reproductive cycles, emphasizing the need to consider environmental variables when developing conservation measures [13]. The hydrological patterns, including variations in water temperature and flow, significantly influence the reproductive cycle of lesser spiny eels by triggering their migration to spawning grounds and affecting the timing of spawning events [14]. Understanding how hydrological conditions affect the reproductive success of freshwater fish allows conservation efforts to be better targeted to conserve fragile species such as the lesser spiny eel [15]. Implementing actions to protect rivers' natural flow and temperature, such as lowering pollution and restoring riparian vegetation, might assist in securing the survival of communities that rely on these environments. Overall, this study emphasizes the significance of comprehensive conservation methods, including the intricate relationships between aquatic ecosystems and environmental variables [16].

This research discovered five unique phases of gonadal development congruent with categories. The prevalence of gonads at maturity level IV during the spawning season indicates a well-defined sexual cycle. Many lesser spiny eels perform coordinated breeding activities [17]. This synchronization is critical for increasing reproductive success because it raises the chance of fertilization within the brief spawning window [18]. The finding that more than 58% of female spiny eels were at GML IV during peak spawning months emphasizes the significance of timing in reproductive strategy [19]. These results indicate that female spiny eels may have evolved to coordinate their reproductive activities to increase their odds of successful reproduction [20]. The large proportion of females reaching maturity level IV during the spawning season suggests that environmental signals may drive this coordinated breeding behavior. Understanding the elements that determine spiny eel reproductive cycles might significantly impact spiny eel conservation and management. Further investigation into the processes behind this synchronization might provide important information about these intriguing fish's reproductive strategies [21].

The fecundity results from this research are consistent with prior studies in the area. GML IV's average fecundity (2062 ± 605 grains) is consistent with studies by LaBrie [22], who found fecundity ranges for several freshwater spiny eel species [23]. However, the relative fecundity of 15.2 ± 6.8 grains/g of body weight indicates a limited reproductive potential. It has consequences for population sustainability, especially under human stress. This study is crucial because it demonstrates the lesser spiny eel's sensitivity to overfishing and habitat deterioration [24]. Understanding the lesser spiny eel's reproductive potential is critical for conservation efforts and management methods to guarantee the species' long-term viability [25]. The low relative fecundity suggests that even little disruptions to their environment or population might have a substantial detrimental effect [26]. By integrating these results into conservation programs, we may help to safeguard endangered lesser spiny eel populations and promote their long-term viability in the face of growing human pressures [27].

The sex ratio observed in this research, which stands at 0.95:1.0, is consistent with previous studies that have reported similarly balanced ratios in other spiny eel communities [28]. However, the significant imbalance recorded at the beginning of the spawning season, with a ratio of 0.37:1.0, raises concerns about the potential impacts of fishing pressures on population dynamics. This fluctuation in sex ratios over time suggests that environmental stresses may adversely affect reproductive success, a trend also documented in other studies of lesser spiny eel populations [29]. These findings underscore the intricate relationships between human activities and the natural reproductive processes of lesser spiny eel. The pronounced imbalance at the onset of the spawning season highlights the species' vulnerability to overfishing and other anthropogenic pressures [30]. Additionally, the fluctuating sex ratios over time suggest that environmental pressures can disrupt the delicate balance of reproduction in these lesser spiny eel populations, underscoring the importance of ongoing monitoring and conservation efforts to ensure their long-term sustainability [31]. Environmental pressures, such as changes in water temperature, pollution, habitat destruction, and alterations in food availability, can disrupt lesser spiny eel reproduction, thereby disrupting the delicate balance necessary for successful spawning and development.

Furthermore, the estimated size at initial maturity in this research (27.15 cm for females and 32.72 cm for males) is comparable with results from previous studies on freshwater spiny eels, which often show that size at maturity varies greatly depending on ecological conditions [32]. Consider exploring studies that focus on specific environmental factors such as water quality, pollution, and habitat complexity, as these conditions can significantly influence the maturity of the lesser spiny eel. Additionally, examining research on localized ecosystems may provide valuable insights into how varying environmental conditions affect reproduction and population dynamics in this species. This association underscores the need to do localized research to understand better how unique environmental factors impact development and maturation rates in the lesser spiny eel [33]. Understanding the elements that govern the lesser spiny eel's development and maturity is critical for developing successful conservation measures. Localized studies give researchers useful insights into how environmental variables affect species reproductive success and population dynamics. This knowledge will be critical for designing tailored conservation initiatives that meet the lesser spiny eel's specific requirements and ensure long-term survival in the wild [34].

The oocyte diameter distribution reported in this research, with two separate peaks in GML IV, is consistent with the results of Wright [35], who discovered comparable patterns in other fish species. The prevalence of bigger oocytes during spawning implies a selective ovulation technique that may improve offspring survival under variable environmental settings [36]. This adaptation technique is important because it may help the lesser spiny eel maximize reproductive success in shifting environments [37]. Overall, our results emphasize the need to know the lesser spiny eel's reproductive behaviors to put effective conservation measures in place. By adjusting to environmental changes by selective ovulation, this species may boost its odds of generating healthy offspring and keep its population constant in the face of habitat change [7]. Further study of the lesser spiny eel's reproductive biology will be required to design focused conservation measures to ensure its long-term survival in the wild [38].

Furthermore, gonadal maturity index (GMI) values suggesting greater reproductive investment in females than males are consistent with prior research results, which imply that female lesser spiny eels normally devote more resources to reproduction [39]. This distribution might represent evolutionary strategies aimed at maximizing reproductive output, especially in unpredictable juvenile survival rates. The variation in GMI values emphasizes the need to consider sex-specific reproduction mechanisms when planning conservation efforts. Understanding how female lesser spiny eels spend resources for reproduction relative to males is critical for conservation efforts, particularly in low juvenile survival rates [40]. Recognizing the female discrepancy in GMI values allows conservationists to modify measures to maintain and sustain lesser spiny eel populations successfully.

The rainfall patterns in Kulonprogo district significantly impact the gonad development and spawning season of *Macrognathus aculeatus*, also known as the lesser spiny eel. From 2020 to 2023, the average monthly rainfall was 375.3 mm, with peaks from October to December. It aligns with the eel's spawning season, as increased precipitation leads to rising water levels and floodplain inundation. These conditions are crucial for the eel's reproductive success, as they provide suitable habitats for egg-laying and food resources.

The synchronization of gonadal maturity, particularly the prevalence of Level IV during peak spawning periods, emphasizes the significance of environmental cues, such as rainfall, in determining reproductive timing. The histological features indicate that successful reproduction in lesser spiny eels is closely linked to optimal conditions, reinforcing the need for conservation strategies. Understanding these developmental phases is crucial for assessing the reproductive health of the species and informing management practices to ensure long-term viability amid ecological pressures. Rainfall plays a crucial role in the reproductive biology of *Macrognathus aculeatus*, a freshwater species. During the rainy season, nutrient availability and suitable spawning habitats promote gonadal maturation in male and female lesser spiny eels. The physiological changes during this time are closely linked to environmental cues provided by rainfall. Increased water levels enhance fertilization chances and support the growth of larger oocytes, which are predominantly released during the spawning process. Therefore, rainfall patterns in the Kulon Progo district synchronize the reproductive cycles of *Macrognathus aculeatus*.

This research on the *Macrognathus aculeatus* in the Progo River provides an in-depth examination of its reproductive biology, emphasizing gonadal maturity, fecundity, and oocyte size dispersion. It delineates five phases of gonadal development, so augmenting the comprehension of the reproductive cycle and spawning time for both genders. The study indicates comparatively poor reproductive capability, highlighting substantial fecundity disparities across maturity stages III and IV, underscoring the influence of environmental conditions on population sustainability. The research also analyzes oocyte size distribution, revealing that only bigger oocytes are released during spawning, whilst smaller ones are preserved for subsequent cycles. It also assesses the length at which lesser spiny eels attain gonadal maturation, offering essential data for conservation efforts and population management amid environmental constraints.

Researchers have identified environmental factors that impact fish distribution, including water quality, habitat structure, and human activities [41]. Urbanization has been shown to negatively impact native fish populations, resulting in habitat destruction and pollution. Conservation efforts should focus on addressing these factors to ensure the long-term survival of these critical species [42]. Pollution poses significant threats to endemic fish populations, leading to their decline [43]. Researchers recommend implementing sustainable practices and conservation strategies to protect these unique fish species and their habitats. The Department of Fisheries at UGM [44] and the marine and fisheries service of the Special Region of Yogyakarta have conducted the distribution of native fish species. However, spiny eels have not been distributed due to their scarce populations, unsuccessful spawning efforts, and unknown biological parameters [45].

The conservation needs of the lesser spiny eel (*Macrognathus aculeatus*) in the Progo River ecosystem are critical, given the species' vulnerability to environmental changes and human activities. Research has demonstrated that hydrological conditions, including water temperature and flow rates, are vital predictors of spawning behavior in freshwater fish, including the lesser spiny eel [46]. The seasonal patterns of the Progo River significantly influence the reproductive cycles of this species, highlighting the importance of maintaining natural hydrological regimes for successful spawning and overall population sustainability. The study indicates that over 58% of female spiny eels reach gonadal maturity during peak spawning months, which is indicative of their reliance on specific environmental cues for reproduction [47]. Conservation strategies must, therefore, prioritize the protection of the river's natural flow and temperature, alongside efforts to mitigate pollution and restore riparian vegetation, as these actions can enhance the reproductive success of the lesser spiny eel and contribute to the resilience of the ecosystem.

Moreover, the lesser spiny eel's relatively low fecundity, with an average of 2062 ± 605 grains at maturity level IV, raises concerns regarding its long-term viability under anthropogenic pressures [48]. The species exhibits a sensitive response to overfishing and habitat degradation, which underscores the necessity for targeted conservation efforts. Implementing community-based conservation initiatives that involve local stakeholders can enhance the effectiveness of preservation strategies, as the cultural significance of the lesser spiny eel as a food source necessitates public awareness and engagement [49]. Additionally, ongoing monitoring of population dynamics, including sex ratio fluctuations and environmental stressors, is essential to adapt conservation measures effectively. By integrating ecological research with community involvement, conservation programs can be tailored to address the specific needs of the lesser spiny eel and ensure its survival in the Progo River ecosystem amidst growing human impacts.

Reproductive strategies play a crucial role in shaping the population dynamics and ecological role of lesser spiny eels within their habitat[50]. Observed differences in size and reproductive capacity between the sexes, with females exhibiting greater fecundity and a more variable size distribution, suggest they are crucial in enhancing population sustainability through higher reproductive output. This reproductive strategy, particularly during the rainy season when environmental conditions are favorable, ensures that many offspring are produced, which can thrive in floodplain areas that provide ample food and shelter[51]. Furthermore, the synchronization of spawning events among females and the size-dependent reproductive maturity of males suggest strategic adaptations to maximize mating opportunities and genetic diversity within the population[52]. These reproductive behaviors not only influence population structure and stability but also contribute to ecological balance by supporting food web dynamics in their aquatic ecosystems. As lesser spiny eels function as both prey and predators, they maintain biodiversity and ecosystem health[53].

This study highlights the socioeconomic impact of the lesser spiny eel's decline, emphasizing the need for community involvement in conservation efforts[54]. The cultural significance of the species as a food source necessitates education and community involvement in conservation practices. This collaborative approach can improve the effectiveness of conservation initiatives, ensuring the survival of the species and its dependent livelihoods.

5. Conclusions

The reproductive biology of the lesser spiny eel (*Macrognathus aculeatus*) in the Progo River has provided critical insights into its gonadal maturity, fecundity, and the influence of environmental factors, such as rainfall, on spawning behavior. The study highlights the significant differences between sexes in terms of size, weight, and reproductive capacity, emphasizing the need for a nuanced understanding of the species' reproductive strategies. The findings indicate that the lesser spiny eel's reproductive success is closely tied to seasonal hydrological patterns, which are essential for the species' sustainability.

Given the lesser spiny eel's vulnerability to environmental changes and human activities, effective conservation strategies must prioritize the protection of its natural habitat, including maintaining the hydrological integrity of the Progo River. Efforts should focus on mitigating pollution, restoring riparian vegetation, and engaging local communities in conservation initiatives that recognize the species' cultural significance as a food source. By fostering community involvement and awareness, conservation programs can be tailored to address the specific needs of the lesser spiny eel, ensuring its long-term viability in the face of growing anthropogenic pressures.

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Institutional Review Board Statement

The lesser spiny eel, utilized in this study, is not classified as a protected or endangered species under the Law of the Republic of Indonesia Number 60 of 2007, which pertains to the conservation of fish resources. The lesser spiny eel was captured using fishing rods with earthworm bait, a method sanctioned by the Law of the Republic of Indonesia Number 45 of 2009 concerning Fisheries. The ethical approval was obtained from Gadjah Mada University, Indonesia. All methods involved in the study were performed in accordance with relevant guidelines and regulations.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data is available by request to the author. All data is original and confidential; participants are protected.

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Conflicts of Interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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