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Morphometric Traits and Growth Dynamics of Upstream-migrating *Anguilla bicolor bicolor* Elvers in North-Central Sri Lanka

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A B S T R A C T

The external morphology, morphometric characteristics, length-weight relationship (LWR), and Fulton's condition factor (K) of *Anguilla bicolor bicolor* elvers were examined. The LWR of the elvers, collected from the Mahavilachchiya reservoir of the Modaragam Aru River basin, Rajanganaya and Kalawewa reservoirs, and Kala Oya estuary of the Kala Oya River basin in Sri Lanka, was analyzed using the log-transformed power equation. A total of 83 elvers were collected from all locations, with the highest number (n=74) obtained from the Mahavilachchiya reservoir during the Northeast monsoon. The mean total length and body weight (± SD) of elvers in the Mahavilachchiya reservoir were 14.6 ± 0.5 cm and 4.48 ± 0.52 g. A strong positive correlation was observed between Log_{10} (L) and Log_{10} (W) of elvers (r = 0.98). LWR of the elvers was expressed as $W=0.001L^{3.03}$. K varied from 0.07 to 0.15, with a mean value of 0.11. Mean K values of elvers belonging to 0-10 cm, 10-20 cm, and 20-30 cm length groups were 0.11, 0.11, and 0.13, respectively, confirming that K increases significantly with elver growth, which may be attributed to differences in food and behaviour (feeding and migration), warranting further investigations. Although the condition factor increased with the elvers' size, the *b*-value of the length-weight relationship (3.03) did not significantly deviate ($p>0.05$) from 3, indicating that elvers exhibit isometric growth. The study provides baseline data for developing an elver fishery in dry-zone reservoirs after conducting a stock assessment of the elvers inhabiting the study river basins in Sri Lanka.

Keywords: *Catadromous fish, condition factor, eels, isometric growth, morphometric measurements*

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INTRODUCTION

Taxonomic context

Eels belong to the genus *Anguilla* (Schrank, 1798), which comprises sixteen species, three of which are further subdivided into two subspecies each (Ege, 1939; Watanabe, 2001, Arai, 2016). Freshwater eels, classified into thirteen tropical species and six temperate species (Arai and Kadir, 2017), utilise freshwater ecosystems for juvenile development before returning to marine environments for reproduction (Dorairaj, 1995; Chai and Arai, 2018; Arai, 2020).

Life history

The life cycle of freshwater eels, which begins and ends with the spawning of silver eels in the deep ocean, consists of six stages: preleptocephalus, leptocephalus, glass eel, elver, yellow eel, and silver eel (Dorairaj, 1995; Cresci, 2020). After hatching, the first larval stage is called preleptocephalus, followed by the planktonic leptocephalus stage. Leptocephalus larvae are carried by water currents towards coastal waters, during which they undergo metamorphosis. In coastal waters, leptocephalus metamorphose into transparent glass eels. Glass eels then recruit into coastal waters, such as estuaries and lagoons. After developing pigments, they are referred to as elvers. The total length of elvers can vary from 7 to 8 cm up to 30 cm, and the elvers migrate upstream along rivers connected to estuaries and lagoons. They then settle in reservoirs or lakes linked to these rivers and develop into yellow eels, which is the highest growth phase. Yellow eels eventually transform into silver eels and migrate back to the ocean (Tesch, 2003; Williamson et al., 2023).

Anguillid eels in Sri Lanka

Sri Lanka has 103 rivers that flow into the Indian Ocean, along with 64 associated catchments (De Silva, 1988; Fernando, 2002; Jayasinghe and Amarasinghe, 2018). The lagoons, estuaries, rivers, tributaries, and related reservoirs across the country provide excellent habitats for catadromous eels to complete their life cycles. Glass eel recruitment in estuaries and lagoons, combined with the upstream migration and survival of elvers, directly influences the adult eel population in inland waters (Cumaranatunga et al., 1997). Two eel species have been reported from Sri Lanka: *Anguilla bicolor bicolor* McClelland, 1844, and *Anguilla nebulosa nebulosa* Gray, 1831 (Deraniyagala, 1952; Wickstrom and Enderlein, 1988a, 1988b, 1991a, 1991b; Pethiyagoda, 1991; Cumaranatunga et al., 1992, 1994, 1995, 1997; Vithanage et al., 1994, 1998; Vithanage, 2000). Castle and Williamson (1974) described *A. bengalensis bengalensis* Gray, 1831, as a synonym for *A. nebulosa nebulosa*.

Only a limited number of studies have been conducted on the biology, ecology, population structure, and fisheries of Anguillid eels in the Southern reservoirs of Sri Lanka. Ege (1939) has made the first record of Anguillid eels in Sri Lanka and utilised specimens of *Anguilla nebulosa nebulosa* McClelland, 1844, collected from the Keppu ela River in Diggela, Panadura, and *A. bicolor bicolor* McClelland, 1844, gathered from the Keppu ela River in Matale and Nuwara Wewa in Sri Lanka. For this study, the author has used both adults and elvers, with most of the preserved specimens sourced from the Colombo Museum. Also, Deraniyagala (1952) has reported evidence of eels from prehistoric sites in Wilpattu, Sri Lanka, and the author has noted the elvers of *A. bicolor bicolor* (length 4.7 - 5.8 cm) from the marine waters around Mannar and the elvers ranging from 5.4 to 5.7 cm from the Mannar estuary. Munro (1955) has reported the external morphology, habitat characteristics, and local names of *A. bicolor bicolor and A. nebulosa nebulosa,* the two freshwater eel species recorded in Sri Lanka. Of them, *A. bicolor bicolor* is common in coastal pla ins, whereas *A. nebulosa nebulosa* is typically found in mountain pools. In addition, several authors have conducted studies on the ecology and fisheries status of freshwater eels in the reservoirs of the southern coast of Sri Lanka. For instance, Wickstrom and Enderlein (1988a) have conducted a study in the Badagiriya, Muruthawela, Yodawewa, Ridiyagama, and Tissawewa reservoirs, which reports the two eel species, *A. bicolor bicolor* and *A. nebulosa nebulosa.* Total catch, Catch Per Unit Effort (CPUE), length-weight relationships, length distribution, and age determination using otoliths have also been reported. Wickstrom and Enderlein (1988b) have documented the abundance and occurrence of eels in the five lowland reservoirs, with the highest abundance found in the Badagiriya reservoir. Additionally, Wickstrom and Enderlein (1991a) have reported that the bycatch in fyke nets and longlines used to capture Anguillid eels was dominated by goby fish (*Glossogobius giurus*). Cumaranatunga et al. (1994) have highlighted the biological and ecological factors related to *A. bicolor and A. nebulosa* in the reservoirs of southern Sri Lanka, noting that *A. bicolor* has a greater tolerance for low oxygen compared to *A. nebulosa*, making *A. bicolor* the dominant species in reservoirs and lagoons of Sri Lanka. Vithanage et al. (1994) identified a linear relationship between otolith length and the total length of *A. bicolor* and *A. nebulosa* yellow eels. Ranawickrama et al. (1994) have studied the changes in body constituents of *A. bicolor* and *A. nebulosa* during their development, emphasising the importance of eels as a protein source.

Cumaranatunga et al. (1995) have reported the occurrence of glass eels, elvers, yellow eels, and silver eels of *A. bicolor bicolor* and *A. nebulosa nebulosa* from the Garanduwa and Malala River system, along with observations on morphometric characters, Gonadosomatic Index (GSI), Hepatosomatic Index (HSI), histological analysis of gonads and liver, and moisture and protein content of the liver and muscles of both species. The study has further divulged a significantly higher protein content in the muscles of *A. nebulosa nebulosa* compared to *A. bicolor bicolor*, and a considerably higher fat content in the muscles of *A. bicolor bicolor* than in *A. nebulosa nebulosa.* Ranawickrama and Cumaranatunga (1996) have studied the use of tags for estimating the growth of *A. bicolor bicolor* in the Garanduwa Lagoon, southern Sri Lanka. This study demonstrated a slow growth rate of *A. bicolor bicolor* in the Garanduwa Lagoon. Cumaranatunga and Vithanage (1996) have reported a histological examination of gonad, liver, skin, and thyroid tissues to identify the changes throughout the life stages of *A. bicolor bicolor*, mainly concerning sexual maturity and migration.

Also, Cumaranatunga et al. (1997) have studied the factors affecting the distribution and population size of *A. bicolor bicolor* and *A. nebulosa nebulosa* in the five reservoirs of the Malala River system. The results indicate that turbidity and conductivity primarily affect the distribution of these two species within the reservoirs of southern Sri Lanka. Vithanage et al. (1998) have determined the age of glass eels of *A. bicolor bicolor* entering the coastal waters of southern Sri Lanka using otolith growth increments, and a subsequent study has focused on the gonadal development and growth-related factors of *A. bicolor bicolor* and *A. nebulosa nebulosa* in the Garanduwa and Malala River systems of southern Sri Lanka. Vithanage (2000) has reported the morphological and anatomical characters related to the reproductive biology of eels, including histological analysis of gonadal development and the histological structure of the skin, liver, and thyroid gland at different life stages. Additionally, it determines the age using otoliths. Furthermore, Pethiyagoda (1991) explained the habitat characteristics of freshwater eels in Sri Lanka. *A. bicolor bicolor* is widely distributed in the lowlands, primarily in coastal areas, and is mainly found in marshy habitats and occasionally in rivers. *A. nebulosa nebulosa* is present in rivers and tanks but is rare in coastal swamps. It inhabits muddy substrates 5-10 m deep in the dry zone, while in the wet zone, it is found in rock pools of rivers that are greater than 3 m deep. Similar species, such as *A. bengalensis bengalensis* and *A. bicolor*, have been reported in later studies (De Bruin et al., 1995).

Morphometric measurements and length-weight relationship

Morphometric measurements of fish are primarily used to identify unknown species, sex, or hybrids, to recognise mutated forms of groups or species, and to classify biotypic relationships. Length-weight relationships determine the weight of a fish at a specific length and assess changes across different stocks of the same species. The condition factor of a fish explains its physical and biological status, which is influenced by factors such as physiology, pathogens, and feeding conditions. Thus, the condition factor is employed to assess fatness, gonad development, and the overall well-being of fish (Le Cren, 1951). Information on these aspects is crucial for stock assessments, population dynamics, and conservation and aquaculture efforts.

Research gap

Available literature affirms that there are no recent studies on any aspects of eels. Also, there is limited information about elvers in Sri Lankan waters (Ege, 1939; Deraniyagala, 1952; Vithanage, 2000). No studies have been conducted on elver morphology, morphometric measurements, length-weight relationships, or condition factor analysis in Sri Lanka. The present study investigates the upstream migration of *A. bicolor*

bicolor elvers in the Kala Oya and Modaragam Aru river basins, and examines the external morphology, morphometric characteristics, length-weight relationship, and condition factor of *A. bicolor bicolor* elvers in the Mahavilachchiya reservoir, Anuradhapura District, Sri Lanka.

MATERIALS AND METHODS

Description of the study area

The present study, conducted from 2019 to 2024, focused on three perennial reservoirs located in two river basins in the North-central Province of Sri Lanka. The reservoirs examined were the Mahavilachchiya reservoir (8°28′57.1″N, 80°12′02.9″E) of the Modaragamaru river basin and the Rajanganaya (8°08′57.9″ N, 80°13′36.6″ E) and Kalawewa reservoirs (7°59′38.5″ N, 80°32′21.8″E) of the Kala Oya River basin, from which elvers were sampled. Elver sampling locations within the river basins included in the study are illustrated in Figure 1.

Elver sampling

As elver migration is directly linked to reservoir overflowing, sampling efforts were strategically conducted during these events rather than on a fixed calendar timeline. Sampling was conducted at night (8.00 pm to 12.00 am) in the Mahavilachchiya reservoir using scoop nets. In the Kalawewa and Rajanganaya reservoirs, elvers were collected from the base of the spillway and associated canals with scoop nets. In the Kala Oya estuary, elvers were collected from shallow marginal areas among mangroves using scoop nets and mosquito nets (length 3 m; width 1 m; mesh size 3 mm) between 9.00 am and 12.00 pm. All collected elvers were promptly preserved in 4% formalin. Species were identified based on the fin difference index (FDI), where $FDI=100Z.TL^{-1}$, with Z representing the ano-dorsal length and TL the total length of the elver (Ege, 1939; Arai et al., 2020).

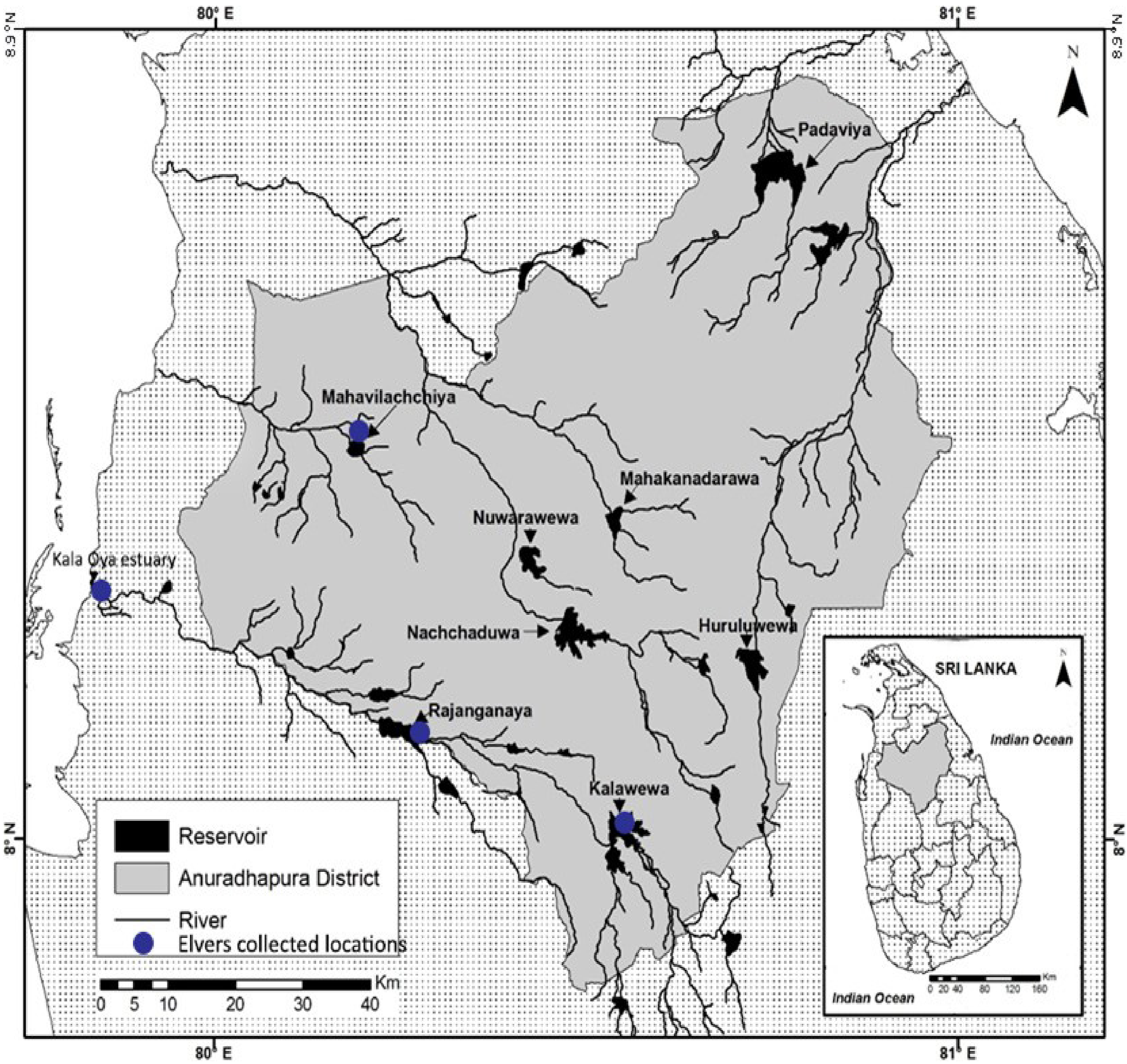

Figure 1. Map of the Anuradapura district, showing sampling locations of elvers in the study river basins (Inset: Map of Sri Lanka showing the Anuradapura district).

Morphometric measurements

Lengths were measured using a measuring board and a digital calliper, achieving accuracies of 1 mm and 0.1 mm, respectively. Weight was measured to 0.0001 g using an analytical balance (KERN-ABJ 220-4NM). A total of 24 morphometric measurements used by Ege (1939) were reported for *A. bicolor bicolor* elvers. All morphometric measurements were reported as range and mean ± SD (mm). Chromatophore patterns on the head, lateral sides, and caudal peduncle were photographed with a trinocular microscope (Euromex; OX 3035). Elver samples collected from the Mahavilachchiya reservoir were used for measurements, because other samples were damaged during collection.

Statistical analysis

Seventy-four *A. bicolor bicolor* elvers were utilised for the length-weight relationship and condition factor analysis. Descriptive statistics for morphometric characters were performed using Microsoft Excel 2016. The length-weight relationship was calculated using the power equation, $W = aL^b$, where W is the total wet weight of the fish (g), L is the total length of the fish (cm), *a* is the coefficient associated with body form, and *b* is an exponent representing isometric growth when equals to 3.0 (Le Cren, 1951; Jisr et al., 2018). The base 10 logarithmic transformed form of the power equation was used to determine *a* and *b* as $Log_{10}(W)=Log_{10}(a)+bLog_{10}(L)$. The correlation between Log_{10} (W) and Log_{10} (L) was established. A simple linear regression was conducted between Log_{10} (W) and Log_{10} (L), and the regression line was drawn. The coefficient of determination (R^2) was then calculated (Azrita et al., 2024). Correlation and regression analyses were performed using SPSS 16.0, and a graph was created using Microsoft Excel 2016. The significant difference between the computed *b* value and the isometric growth value (3.0) was determined using the Student's *t*-test, following the equation $t_s= (b-3)/SE_b$, where t_s is *t*-test value, *b* is the growth exponent, and SE_b is the standard error of b (Sokal and Rohlf, 1987). When *b* = 3, *b* ≠ 3, *b* > 3, and *b* < 3 indicate isometric, allometric, positive allometric and negative allometric growth, respectively (Sanuja et al., 2024). The Fulton's condition factor of the elvers was determined, following the equation $K=100. \ W/L^3$, where K is Fulton's condition factor, W is the total wet weight, and L is the total length (Ricker, 1975; Dalpathadu et al., 2023). K was calculated for elvers of 0-10 cm, 10-20 cm and 20-30 cm length groups, and statistical significance was compared using one-way analysis of variance (ANOVA) in SPSS 16.0.

RESULTS

Elver sampling

A total of 83 *A. bicolor bicolor* elvers were collected throughout the study. The highest number of elvers (n = 74) was encountered in the Mahavilachchiya reservoir, with a mean fin difference index (FDI) reported as 0.53% (<5%). FDI values confirmed that the collected elvers belong to the shortfin eel category. The locations, number of elvers, mean total lengths, and weights of the elvers are summarised in Table 1.

Although this study began in 2019, sampling efforts were significantly impacted by the COVID-19 pandemic, which substantially stopped gathering samples during 2020 and 2021. Additionally, sample collection primarily depended on reservoirs overflowing during the Northeastern monsoon. Limited elver samples were obtained from the estuaries because elver availability varied with changes in water levels. During the rainy season, elvers were not encountered in the estuary due to low salinity, high flow rates, and increased turbidity.

Table 1. Locations, number of elvers, and mean total length and weight (± SD) of the collected elvers.

Sampling location	Year	Elvers collected	Mean fin difference index ± SD	Mean length ± SD (mm)	Mean weight ± SD (g)
Mahavilachchiya reservoir	2019	74	0.53±0.66	146.3 ± 39.5	4.48 ± 4.51
Rajanganaya reservoir	2022	02	0	172.0 ± 33.9	6.60 ± 5.66
Kalawewa reservoir	2019	03	0	219.0 ± 30.1	15.56 ± 5.86
Kala Oya estuary	2024	04	1.41±1.41	86.8 ± 6.7	1.05 ± 0.22

External morphology

The dorsolateral sides of the *A. bicolor bicolor* elvers were observed to be dark brown/red (Figure 2). Well-developed pigments were noted on the lateral head both above and below the eye, as well as on the dorsal and ventral sides of the abdomen and caudal peduncle, indicating that the elvers had reached the VIB stage of pigment development (Figure 3) (Tesch, 2003). Elver migration in the Mahavilachchiya reservoir was observed during the Northeast monsoon period (November to January). A study conducted during the overflowing of the Mahavilachchiya reservoir confirmed the occurrence of elvers at the base of the spillway, with groups of elvers climbing along the angled spillway wall (Figure 4). In other reservoirs, elvers were seen hiding under rocks in the outlet canals and small pools at the base of the main spillway (after the rainy season and after the spillage of water from the reservoir). At the Kala Oya estuary, elvers were spotted among decaying leaves, mangrove roots, and shallow marginal areas of the estuary.

Figure 2. External morphology of the *A. bicolor bicolour* preserved in 4% formalin, collected from the Mahavilachchiya reservoir. Arrowheads indicate the origins of the dorsal and anal fins.

Figure 3. Pigment development on the lateral side of the head (A), trunk region (B), and caudal peduncle (C) of *A. bicolor bicolor* elver.

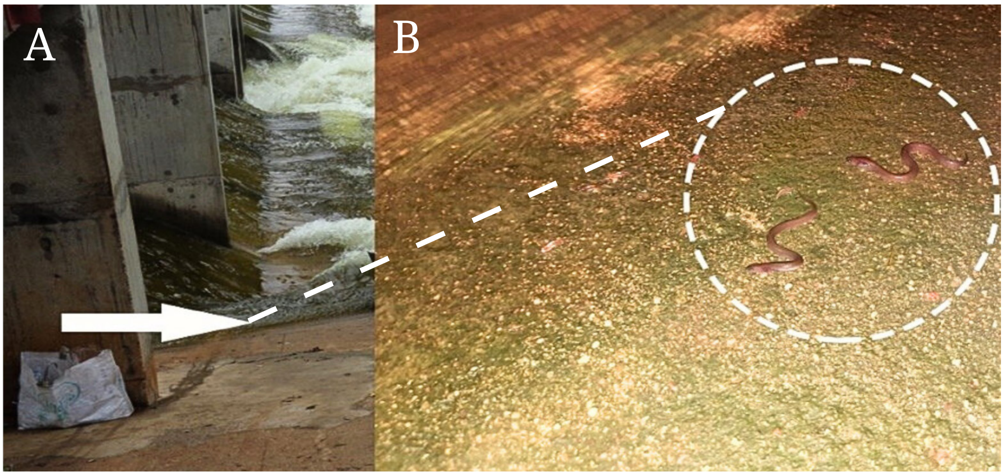

Figure 4. Elver migration in the Mahavilachchiya reservoir. The arrow indicates the location of the spill where the elvers were observed (A), and the elvers' movement along the spill (B).

Morphometric measurements

The morphometric measurements of the elvers collected from the Mahavilachchiya reservoir are summarised in Table 2.

Table 2. The morphometric measurements of *A. bicolor bicolor* elvers collected from the Mahavilachchiya reservoir, Sri Lanka.

Morphometric character	***A. bicolor bicolor* (n = 74)** Range (mm)	Mean ± SD (mm)
Total length	77-256	146.3 ± 39.5
Pre-anal length	29-103	57.1 ± 16.2
Pre-dorsal length	29-102	56.4 ± 16.3
Head length	8-20	17.4 ± 4.7
Pre-anal length without head length	19-73	39.7 ± 11.8
Pre-dorsal length without head length	19-72	38.9 ± 12.0
Distance between the verticals through the anus and origin of the dorsal fin	0-4	0.7 ± 1.2
Length of the tail	47-150	87.1 ± 23.0
Body depth at the gill opening	3.4-11.6	6.2 ± 1.7
Body depth at anus	4.0-13.6	6.7 ± 1.9
Width at anus	2.9-11.2	5.6 ± 1.8
Tip of snout to anterior margin of eye	1.8-5.3	3.3 ± 0.9
Horizontal diameter of the eye	1.3-3.4	1.9 ± 0.5
Tip of upper jaw to angle of mouth	2.1-8.9	4.8 ± 1.4
Tip of lower jaw to angle of mouth	2.5-9.6	5.2 ± 1.6
Distance from the perpendicular through the eye-centre on the margin of the upper jaw to the angle of gape	0.24-31	1.0 ± 3.6
Distance from the eye-centre to the margin of the upper jaw	0.8-3.0	1.50 ± 0.5
Distance between the upper and lower ends of the gill opening	1.0-3.7	1.9 ± 0.6
Length of the base of the pectoral fin	1.0-3.5	2.1 ± 0.6
Length of pectoral fin	1.6-8.1	4.1 ± 1.4
Distance between the bases of the anterior and posterior nostrils	0.9-3.6	2.0 ± 0.6
Dorsal distance between the base of the anterior nostrils	0.9-3.5	1.8 ± 0.5
Dorsal distance between the clear margins of the posterior nostrils	1.7-6.9	3.4 ± 1.0
Dorsal distance between the clear margins of the eyes	1.8-6.5	3.3 ± 0.9
Width at gill opening	2.9-11.9	5.5 ± 1.8

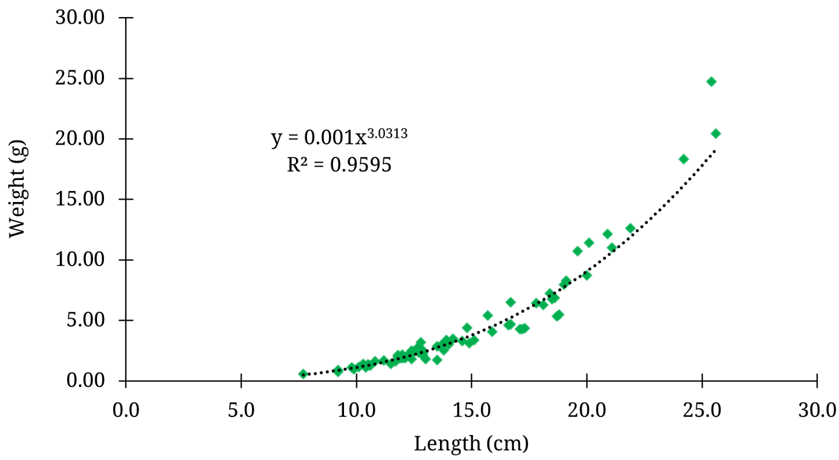

Figure 5. Length-weight relationship of *A. bicolor bicolor* elver collected from the Mahavilachchiya reservoir.

Length-weight relationship

There was a strong positive correlation between the Log_{10} (L) and Log_{10} (W) of *A. bicolor bicolor* elvers (Pearson correlation = 0.98). The regression line displayed a significant R^2 value of 0.96 (Figure 5). The length-weight relationship of the elvers studied was expressed in the regression equation: Log 10 W=-2.99 +3.03 Log 10 L and in the power equation as $W=0.001L^{3.03}$. The Fulton's condition factor ranged from 0.0706 to 0.1520, with a mean value of 0.11, indicating good growth conditions for the studied elvers. The calculated *b* value of 3.03 was not significantly different from 3 ($p > 0.05$), demonstrating isometric growth of *A. bicolor bicolor* elvers.

Table 3. Mean ± SD, minimum, and maximum Fulton's condition factors for the studied length groups of *A. bicolor bicolor* elvers. (Values with similar superscripts (a, b) raw-wise are not significantly different from one another ($p > 0.05$)).

Condition factor	Length group (cm)		
	0-10	10-20	20-30
Mean ± SD	$0.11^{ab} \pm 0.01$	$0.11^{a} \pm 0.02$	$0.13^{b} \pm 0.01$
Minimum	0.09	0.07	0.12
Maximum	0.12	0.15	0.15
Sample number	05	62	07

Condition factor

Fulton's condition factor, compared among length groups, is presented in Table 3. The mean Fulton's condition factor for the 0-10 cm length group was not significantly different from that of the 10-20 cm length group. However, the mean Fulton's condition factor for the 20-30 cm length group was significantly higher than that of the 10-20 cm length group, indicating that the condition factor of the elvers increases significantly with their growth.

Table 4. Comparison of elver lengths from various studies and locations, including the present study.

Study/reference	Sampling location	Total length of elvers
Ege (1939)	Keppu Ela River, Panadura	-
Deraniyagala (1952)	Sea off Mannar and estuaries	4.7 cm to 5.8 cm and 5.4 cm to 5.7 cm; shoal of elvers, total length 10 cm
Wickstrom and Enderlein (1988a)	No records of glass eels and elvers from the rivers of Sri Lanka	-
Vithanage (2000)	Malala River system, Southern, Sri Lanka	Elvers are closer in size to yellow eels
Present study	Mahavilachchiya, Rajanganaya, Kalawewa reservoirs, and Kala Oya estuary	Mean total length of *A. bicolor bicolor* elvers; 14.6 cm, 17.2 cm, 21.9 cm, and 8.7 cm, in each reservoir, respectively.

DISCUSSION

The first record of elvers in Sri Lankan waters was documented by Ege (1939), who used preserved elvers collected from the Keppu Ela River, Panadura. Later, several researchers (Deraniyagala, 1952; Wickstrom and Enderlein, 1988a; Vithanage, 2000) reported finding elvers in Sri Lankan reservoirs (Table 4).

The times of upstream migration for elvers differ between tropical and temperate eels. Elvers of *A. anguilla* in England are reported to migrate upstream along the River Thames from April to October (Naismith and Knights, 1988). In the Mahavilachchiya reservoir, elver recruitment was observed from November to January. These results indicate that elver recruitment into the reservoirs of the North Central Province of Sri Lanka occurs during the Northeast monsoon. The North Central Province receives rainfall from the Northeast monsoon, resulting in the spilling of reservoirs. This allows elvers to locate habitats within the reservoirs that were previously occupied by silver eels, which migrated to the ocean. During the present study, a few elvers were collected from the Kalawewa reservoir in August, September, and October, and from the Rajanganaya reservoir in November. Elvers were not observed during the spilling period in either the Kalawewa or Rajanganaya reservoirs. The elvers collected could be those which were left after the previous spilling period. Furthermore, elvers were reported from the Kala Oya estuary in July. The Rajanganaya and Kalawewa reservoirs are connected to the Kala Oya River basin, which flows into the ocean at the Kala Oya estuary.

The presence of elvers in the estuary and the two main reservoirs of the river basin confirms long-distance upstream migration within the Kala Oya River basin. Similarly, the collected elvers and direct observations made at the Mahavilachchiya reservoir verify elver migration along the Modaragam Aru river basin. All elvers collected during the current study from the Mahavilachchiya reservoir were identified as *A. bicolor bicolor*, indicating a higher recruitment of *A. bicolor bicolor* into freshwater bodies of North-central province. In the Mahavilachchiya reservoir, more elvers were observed when the water flow rate decreased at the end of the spilling period. This suggests that elvers are unable to swim against a strong water flow. Knights and White (1998) stated that elvers have limited swimming ability against water flow rates exceeding 0.2 - 0.5 ms^{-1}. Moreover, elvers with a total length greater than 10 cm are reported to be able to swim against water flow rates of 1.5 - 2.0 ms^{-1} (Knights and White, 1998; Tesch, 2003).

The present study observes that elvers utilised the wet cement walls of the spill as supportive structures for their movements. Elvers measuring up to 12 cm in length can ascend vertical, rough surfaces by adhering to them using surface tension. Their climbing ability decreases as their body weight increases (Jellyman, 1977). No elvers were observed around the spillways of the Mahavilachchiya reservoir during the daytime of the spilling period. This could be to avoid predation and high temperatures. Similarly, Jellyman (1977) reported that elvers of *A. australis schmidtii* and *A. dieffenbachii* show active movements during the night. Beentjes et al. (1997) stated that elvers use cutaneous respiration while climbing. To prevent desiccation from high temperatures, they avoid movement during the daytime.

Results affirm that upstream migration of elvers occurs in the middle of the year. Typically, the reservoirs included in the present study overflow, and the river basins spill during the northeast monsoon, from December to March. Elvers expected to be recruited into the upstream reservoirs are expected to migrate to the base of the reservoirs before December. How exactly they determine the timing for upstream migration remains an unknown factor. Environmental influences, such as the downflow and flow rate of freshwater during rainy seasons, changes in salinity and conductivity, water temperature, and photoperiod, can stimulate this process (Arai, 2020).

Vithanage (2000) has conducted a histological study on *A. bicolor bicolor* elvers obtained by rearing glass eels in an aquarium. The gonads of elvers measuring 9.5 cm in length exhibited thread-like strands and large, oval-shaped primary oogonial cells. A translucent, slimy, brown skin has been reported in elvers. Histological studies have revealed that elvers possess a thicker skin, which contains more mucous cells, compared to glass eels. Furthermore, compactly arranged hepatic cells were noted in the liver of elvers. These findings demonstrate anatomical changes in the elvers. Studies based on otolith microchemistry have shown that upstream migrating elvers enter freshwater, remain in brackish water, or migrate between freshwater and brackish water during their yellow eel stage (Tsukamoto and Arai, 2001). Identifying developmental stages based on pigment development is essential for determining the precise life stage during recruitment. The identification of pigment patterns has depended on the pigment development guide for *A. anguilla* (Tesch, 2003). No guide has been found for identifying elvers of tropical species. Elvers of both species reported in this study were found to be at the VIB stage, approaching the yellow eel stage.

The present findings indicate isometric growth in *A. bicolor bicolor* elvers in the studied reservoir. Isometric growth in elvers indicates their body shape remains proportionally constant as they increase in size. This consistent morphology suggests that their swimming ability, prey capture, and habitat utilization do not change with growth, which is critical for their survival during upstream migration. Very few studies have examined the length-weight relationship and condition factor analysis of tropical Anguillid eels (Ismail et al., 2017). A recent survey conducted by Boulenger et al. (2015) has revealed isometric growth in adult European eels of both male and female sexes, as well as in combined sexes. Studies have reported that *A. bicolor* in tropical regions exhibits isometric growth (Kottelat, 2013; Samuel et al., 2025). Other factors such as water temperature, salinity, maturity stage, and sex also influence the differences in the length-weight relationship (Le Cren, 1951).

A significantly higher Fulton's condition factor in the 20-30 cm length group suggests that *A. bicolour bicolor* elvers in this group have proportionally greater weights relative to their lengths. This may be due to their larger energy reserves and favourable ecological factors, including sufficient food supply, suitable habitat, reduced predation, and acceptable water quality parameters compared to the smaller length groups. Additionally, they may remain in one location with less movement than the smaller elvers group. Future studies should aim to understand the impacts of habitat conditions, diets, predation, and environmental factors on the differences in condition among various length groups. Cumaranatunga et al. (1997) indicated that *A. bengalensis bengalensis* silver eels captured from the Malala lagoon have a higher Fulton's condition factor compared to *A. bengalensis bengalensis* yellow eels captured from the Kuda Badagiriya, Badagiriya, and Mahalaga wewa reservoirs in southern Sri Lanka. It was observed that silver eels migrating towards waters with high conductivity experience better conditions. Furthermore, turbidity and conductivity were identified as the primary physicochemical factors affecting the condition factor and distribution of *A. bengalensis bengalensis* and *A. bicolor bicolor* in southern reservoirs. This suggests that Anguillid eels can achieve better condition if they are subjected to ex-situ culture from juveniles to adults in aquaculture systems.

The global market exhibits a high demand for live glass eels, elvers, and adults (Kuroki et al., 2014). The European eel fishery industry relies on both adults and the glass eel stage.

European glass eels (*A. anguilla*) are exported globally for aquaculture. Additionally, there is a higher demand for Japanese glass eels (*A. japonica*) and American glass eels (*A. rostrata*) (Silfvergrip, 2009). No exceptional fishery for glass eels that has not been used for farming exists in Sri Lanka. However, during the current survey, fishers in the Ganagewadiya area reported that they collect glass eels and elvers for export to the Philippines, which is believed to occur without the necessary permission from the Sri Lankan government. In countries where large numbers of glass eels have been captured, a decline in eel populations has been observed (Knights, 2003). Scientifically designed stock assessments should be conducted for all stages of eels, including glass eels, elvers, yellow eels, and silver eels, before establishing an export market to ensure the sustainability of eel stocks in inland waters and the local eel fishery industry (International Union for the Conservation of Nature, 2024).

Glass eels can be cultivated within culture systems until they reach the elver stage, which would command a higher price in the export market (Rindom et al., 2014). Before developing such systems, it is essential to identify suitable feeding methods for glass eels and elvers. There is significant potential to develop a glass eel and elver fishery in Sri Lanka, especially in estuaries, lagoons, and reservoirs. Therefore, there is considerable potential for culturing Anguillid eels as a viable aquatic species in the country. Additionally, establishing a procedure for exporting live eels, including elvers, is advisable after conducting a comprehensive stock assessment.

Anthropogenic activities that can affect various stages of the life cycle of Anguillid eels have been identified through this study. The height and angle of the dams can have a negative impact. This may not affect silver eels, as they migrate downstream with heavy water flow during rainy seasons; however, there may be significant effects on elver recruitment. Difficulties faced by elvers attempting to ascend the vertical dams have been observed during this study. Furthermore, the use of artificial lighting around the dams can impact eel movement, as eels are nocturnal. Artificial lights have been noted at the Rajanganaya reservoir. Fishers have reported that the number of elvers entering the reservoir has decreased compared to previous years. They believe this decrease is due to the high-intensity lights installed on the dam. When reservoirs overflow, fish and villagers catch fish around the spill. The fishing gear and methods they use may injure or adversely affect the upstream migration of elvers. Fishers use plant extracts to capture fish trapped in the pools adjacent to the dams following the reservoir spill, which is commonly observed in the Kalawewa reservoir. Fishers target larger species, such as tilapia and carp. These toxic substances may be harmful to the elvers trapped in those pools after the reservoir spills.

It is recommended that fish ladders be built to support the upstream migration of elvers year-round, thereby promoting the stock enhancement of Anguillid eels in upstream reservoirs. This is a critical development needed if the government seeks to improve the local eel fishery industry, aiming to establish a better local market and to introduce a foreign market for the Anguillid eel species found in inland waters.

The findings of this study further recommend more precise research using DNA barcoding, environmental DNA (e-DNA), and satellite telemetry to accurately identify migratory circuits and patterns of elvers in estuaries, lagoons, river basins, and reservoirs. Additionally, long-term studies on elver recruitment into river basins and reservoirs are advised. These investigations should include monitoring survival in relation to environmental factors and human activities. It is also advised to study the feeding methods of elvers through DNA metabarcoding. Such research would help determine the dietary requirements of elvers, which is crucial for establishing captive breeding and ex-situ larval rearing in Sri Lanka, aiming to develop an elver export market.

CONCLUSION

The present study confirms the presence of upstream migrating *A. bicolor bicolor* elvers within the Modaragam Aru and Kala Oya River basins of the Anuradhapura District in Sri Lanka. These migrating elvers are mainly reported from the Mahavilachchiya reservoir within the Modaragam Aru river basin. The length-weight relationship indicates isometric growth, suggesting a stable and healthy growth pattern during their upstream migration. Significantly higher Fulton's condition factor in large elvers (20-30 cm length group) indicates a change in their physiology or better resource availability during their migration. The current study provides baseline data on the distribution and growth pattern of *A. bicolor bicolor* elvers in Sri Lanka for establishing an elver fishery in the country, targeting the export market. However, scientifically designed and comprehensive stock assessments should be carried out before establishing an export market to ensure the sustainability of eel stocks in inland waters and the local eel fishing industry.

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AUTHOR CONTRIBUTIONS

Conceptualisation: B. D. M. M., K. H. M. A. D., P. R. T. C.; methodology: B. D. M. M., K. H. M. A. D., P. R. T. C.; formal analysis: B. D. M. M.; data curation: B. D. M. M.; writing- original draft preparation: B. D. M. M., K. H. M. A. D.; writing- review and editing: B. D. M. M., K. H. M. A. D., P. R. T. C.

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DECLARATION

Informed consent statement

The work was done following all ethical and technical principles of the research guidelines for the care and use of animals, data collection, and preparation of the manuscripts.

Conflict of interests

The authors declare that no conflict of interest exists that could potentially affect the reported work in this paper.

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