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FRESHWATER GASTROPOD COMPOSITION AND THE KEY ENVIRONMENTAL DETERMINANTS IN HULU GANGA AND MA OYA RIVER BASINS OF SRI LANKA

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Abstract
The present study determined the distribution of freshwater gastropods in relation to several environmental variables, in two tributaries of the Mahaweli River, Hulu Ganga and Ma Oya in the Central Province of Sri Lanka. Pearson's Correlation and a multivariate statistical technique, Canonical Correspondence Analyses (CCA) were used to explore the environmental variables responsible for the species composition. In total eight species of gastropods were recorded. The most influential factors for the four species recorded in Hulu Ganga were dissolved oxygen (DO), total dissolved solids, conductivity and elevation, whereas in Ma Oya they were pH, conductivity, DO and temperature. The results of CCA show that measured environmental variables explained 95.76% of the variation in gastropod abundance in Hulu Ganga, but only 60.63% was explained in Ma Oya. Hence, there may be other unmeasured environmental factor(s) that influence the diversity and distribution of gastropods in Ma Oya.

Keywords: Abundance, aquatic habitat, distribution, environmental factors, freshwater snails

Introduction

Gastropods are among the most diverse groups of animals occupying various marine, freshwater and terrestrial habitats. However, of these, freshwater gastropods make up only about 5% of the total global gastropods (Bae & Park 2020). Furthermore, out of 409 families of known gastropods in the world, only 26 taxa are restricted to freshwater (Bouchet *et al*. 2005). On the other hand, freshwater gastropods are a highly threatened group of animals and account for about 20% of global gastropod extinctions (Strong *et al*. 2008).

Although they are all aquatic, freshwater gastropods occupy diverse aquatic microhabitats. Most live submerged, while many are attached to surfaces such as aquatic vegetation, stones, rocks, wood, and other solid surfaces, or soft sediment. Some are amphibious whereas a few can tolerate periods of time out of water. There are some gastropods that can aestivate for a long time in the soil during dry periods. Although most of the freshwater gastropods are herbivorous or omnivorous grazers, there are some predaceous species such as members of Family Glacidorbidae (Strong *et al*. 2008).

Gastropods are important members of freshwater ecosystems. They are important in maintaining aquatic food chains as well as ecological balance in their environment (Strong *et al*. 2008). They play a vital part in the ecosystem as grazers and detritivores. Many animals rely on them as a source of food. On the other hand, they are one of the main vectors or intermediate hosts of trematode parasites and diseases such as Schistosomiasis (Rao 1989). Some species of freshwater gastropods are also used as study organisms in various fields including evolutionary biology, ecology, physiology, behavioral studies and paleobiology (Strong *et al*. 2008). In addition, freshwater gastropods can be used as biomonitoring agents due to their wide ecological tolerance, slow vagility, adequate size and large population sizes (Hubendick 1958, Lau *et al*. 1998, Lee *et al*. 2002, Strong *et al*. 2008).

However, these animals are highly sensitive to environmental pollutants. Since they are slow movers, they have a limited ability to avoid unfavorable environments. Hence many of the species, especially those that show limited distribution are highly threatened. Therefore, understanding of the factors influencing the freshwater gastropod diversity and distribution as well as implementing strategies for the successful conservation of these animals are essential.

Even though freshwater gastropods are widely distributed throughout Sri Lanka, this inconspicuous group of invertebrates has received little or no attention and the factors affecting their distribution and composition are poorly studied. There are 39 known freshwater gastropod species in Sri Lanka, of which a large percentage is endemic (Starmuhlner 1974, Peries *et al*. 2015). However, their conservation status has not been thus far evaluated. In the present study, two tributaries of the Mahaweli River, Hulu Ganga and Ma Oya, which flow into the Victoria reservoir, were selected to determine freshwater gastropod distribution and abundance in relation to water quality parameters and elevation. Hulu Ganga originates in the Knuckles Mountain range and enters the Victoria reservoir from the North while Ma Oya originates from the Piduruthalagala conservation forest and enters the Victoria reservoir from the South West (Fig. 1).

Material and methods

***Study site*.** Sampling for freshwater gastropods was conducted in Hulu Ganga and Ma Oya, from September 2020 to May 2021 to determine the species richness and abundance of gastropods in relation to water quality parameters. Sampling was carried out in 30 sampling locations along each stream (Fig. 1). Initially, sampling was carried out from October 2020 to January 2021. These sites were re-sampled from April to May 2021. The total sampled distance in Hulu Ganga was 19.80 km, while it was 16.02 km in Ma Oya. The average distance between any two sites in Hulu Ganga was approximately 600 m, while in Ma Oya it was approximately 500 m.

***Gastropod identification and abundance*.** A systematic random sampling of freshwater snails was conducted at each location by establishing a 20 m transect line along shallow margins of the stream. A random starting point was selected from the transect line by using a random number table and starting from this point, a total of ten 1 m × 1 m quadrats was sampled for live gastropods. Freshwater snails were identified using Peiris *et al*. (2015). Identified individuals of each species were photographed using a digital single lens reflex camera (Canon EOS 750 D) equipped with a macro lens (Canon 100 mm f2.8 macro IS USM). Relative abundance of each species at each location was calculated.

***Measurement of environmental parameters*.** The elevation, pH, conductivity, total dissolved solids (TDS), dissolved oxygen (DO), water temperature and flow rate were measured at each location. Garmin Map GPS and CTDroidSriLanka were used to obtain the GPS locations of each site. A portable pH meter (Orion Model 230A) was used to measure pH in freshwater. A Thermo conductivity-TDS meter (Orion Model 105) was used to measure conductivity, TDS and temperature in freshwater. A portable dissolved oxygen meter (Hanna HI 9146) was used to measure DO. Each of the measured variables was taken in triplicate and averaged.

***Data analysis*.** A Pearson correlation analysis was carried out between freshwater snail abundance and each of the environmental parameters to determine the association between

Plate 7

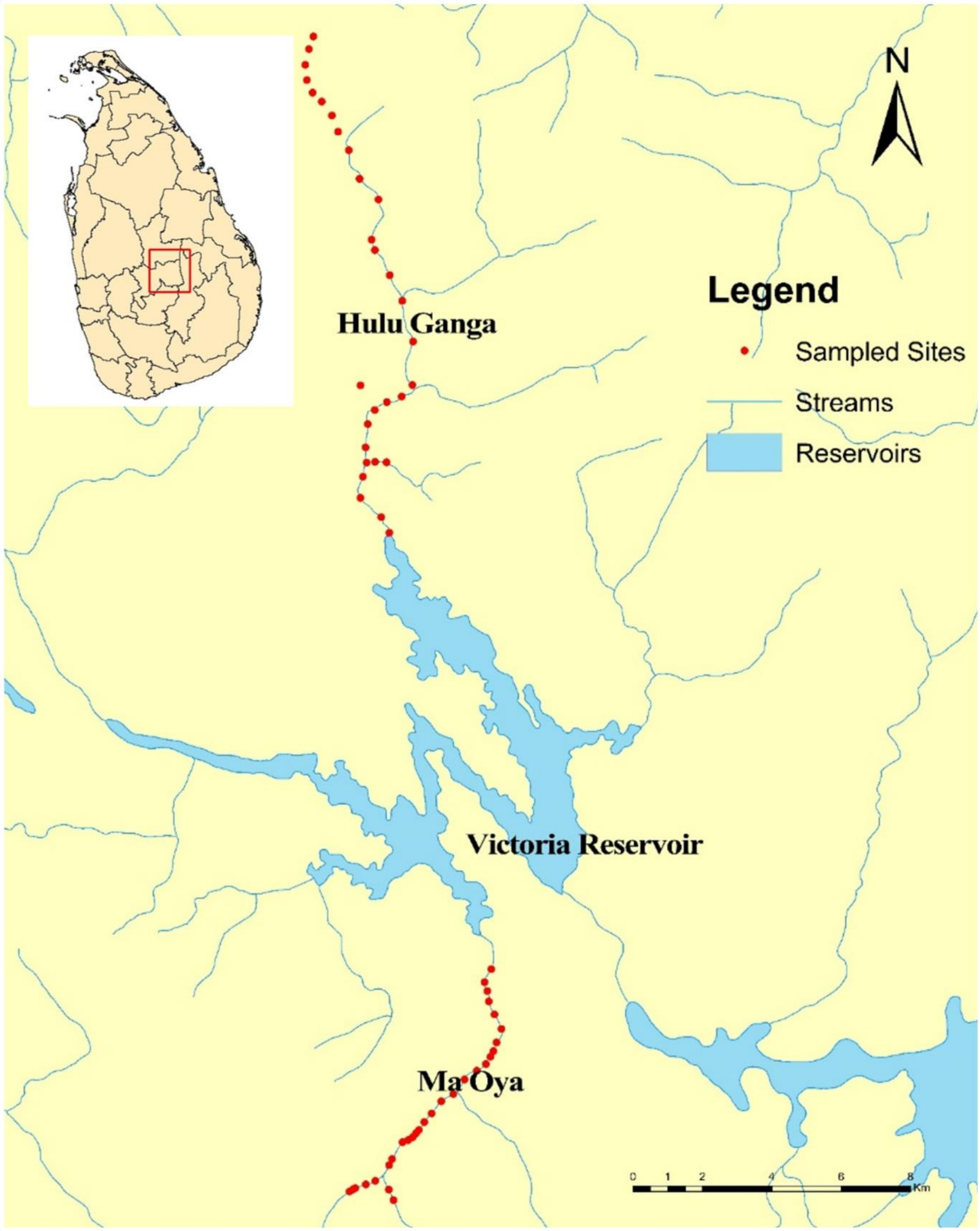

Figure 1. Sampling locations of freshwater gastropodes in Hulu Ganga and Ma Oya river basins within the Central Province of Sri Lanka

the variable and snail abundance and the direction of the correlation. Furthermore, a Canonical Correspondence Analysis (CCA) was carried out for both streams separately, using Canoco 5 software (ter Braak & Smilauer 2012) to determine the correlation between total measured environmental variables and gastropod species richness.

Results

Gastropod species richness. A total of eight species of freshwater snails belonging to five genera were found in Hulu Ganga and Ma Oya (Figs. 2, 3; Table 1). *Paludomus* (hereafter, *Pa*.) *bicinctus* and *Pa*. *chilinoides* were common to both streams. However, *Pa*. *decussatus* and *Pa*. *neritoides* were found only in Hulu Ganga, and the latter was found only in one location. *Pseudoplotia* (hereafter *Ps*.) *scabra*, *Melanoides tuberculata*, *Indoplanorbis exustus* and *Radix luteola* were recorded only from Ma Oya.

Of the eight species of gastropods recorded, *Pa*. *chilinoides* was the most abundant species in Hulu Ganga while *Pa*. *bicinctus* and *Pa*. *decussatus* were the second and third most abundant species respectively (Table 1). However, in Ma Oya, *I*. *exustus* showed the highest relative abundance while *Pa*. *chilinoides* showed the second highest abundance in this stream. In addition, *Pa*. *bicinctus*, *Ps*. *scabra* and *M*. *tuberculata* were the third, fourth and fifth abundant species respectively (Table 1). Although *R*. *luteola* was found in Ma Oya, its relative abundance was not calculated as it was found outside the sampled quadrats*.

Table 1. Freshwater gastropod abundance in Hulu Ganga and Ma Oya (relative abundance in brackets)

Species	Abundance	
	Hulu Ganga	Ma Oya
Paludomus bicinctus	353 (40.0%)	154 (15.5%)
Paludomus chilinoides	447 (50.7%)	288 (28.9%)
Paludomus decussatus	76 (8.6%)	—
Paludomus neritoides	6 (0.7%)	—
Pseudoplotia scabra	—	104 (10.5%)
Melanoides tuberculata	—	28 (2.8%)
Radix luteola	—	*
Indoplanorbis exustus	—	420 (42.2%)

Most of the time, *Pa*. *chilinoides* was found attached to rocks near the surface. Very few individuals of *Pa*. *chilinoides* were found completely submerged. In contrast, most of the individuals of *Pa*. *bicinctus* were found submerged while few were found attached near the surface. All *Pa*. *decussatus* individuals were found completely submerged, while all individuals of *Pa*. *neritoides* were found attached to the underside of rocks. Typically, *Ps*. *scabra* and *M*. *tuberculata* were found in sediment. *Radix luteola* was found only in polluted water pools in Ma Oya.

Gastropod correlation to environmental parameters. Elevation (Fig. 4A): Based on our observations, *Pa*. *chilinoides* was recorded between 457–595 m, *Pa*. *bicinctus* between 505–1,019 m, *Pa*. *decussatus*, which was found only in Hulu Ganga between 465–724 m, *Pa*. *neritoides* recorded from only one location in Hulu Ganga at an elevation of 568 m. *Melanoides tuberculata*, *Ps*. *scabra* and *R*. *luteola* were found in the same locations of Ma Oya where elevation ranged 591–595 m. *Indoplanorbis exustus* was also found only in Ma Oya at an elevation of 700 m. Overall, according to the present study, *Pa*. *bicinctus* which was the only species to be found above 1,000 m elevation showed the widest range in distribution according to elevation.

Water pH (Fig. 4B): In this study, each species of freshwater gastropod indicated a preference for specific pH ranges. *Paludomus chilinoides* was found in locations where pH ranged between 7.91–9.67. However, *Pa*. *bicinctus* was found in a narrower pH range of 8.13–8.40. *Paludomus decussatus* was found where pH ranged between 7.35–9.50. The pH value of the location where *Pa*. *neritoides* was found was 7.35. *Melanoides tuberculata*, *Ps*. *scabra* and *R*. *luteola* were distributed in water which had a pH range of 7.91–8.48. *Indoplanorbis exustus* was found in locations where pH ranged between 8.80–8.84.

Conductivity (Fig. 4C): Generally, *Pa*. *chilinoides* was recorded in water with conductivity of 86.50–130.50 µS while *Pa*. *bicinctus* was recorded from 64.67–118.0 µS. *Paludomus decussatus* showed the widest tolerance to conductivity and was found in waters where conductivity ranged from 44.12–105.67 µS. The conductivity where *Pa*. *neritoides* was found was 87.67 µS. *Melanoides tuberculata*, *Ps*. *scabra* and *R*. *luteola* were found where conductivity ranged from 113.17–130.50 µS. *Indoplanorbis exutus* was found where conductivity ranged between 58.83–74.16 µS.

TDS (Fig. 4D): According to the data gathered, *Pa*. *chilinoides* was found between 51.0–92.33 ppm TDS. The minimum and maximum TDS values in Hulu Ganga where *Pa*.

Plate 8

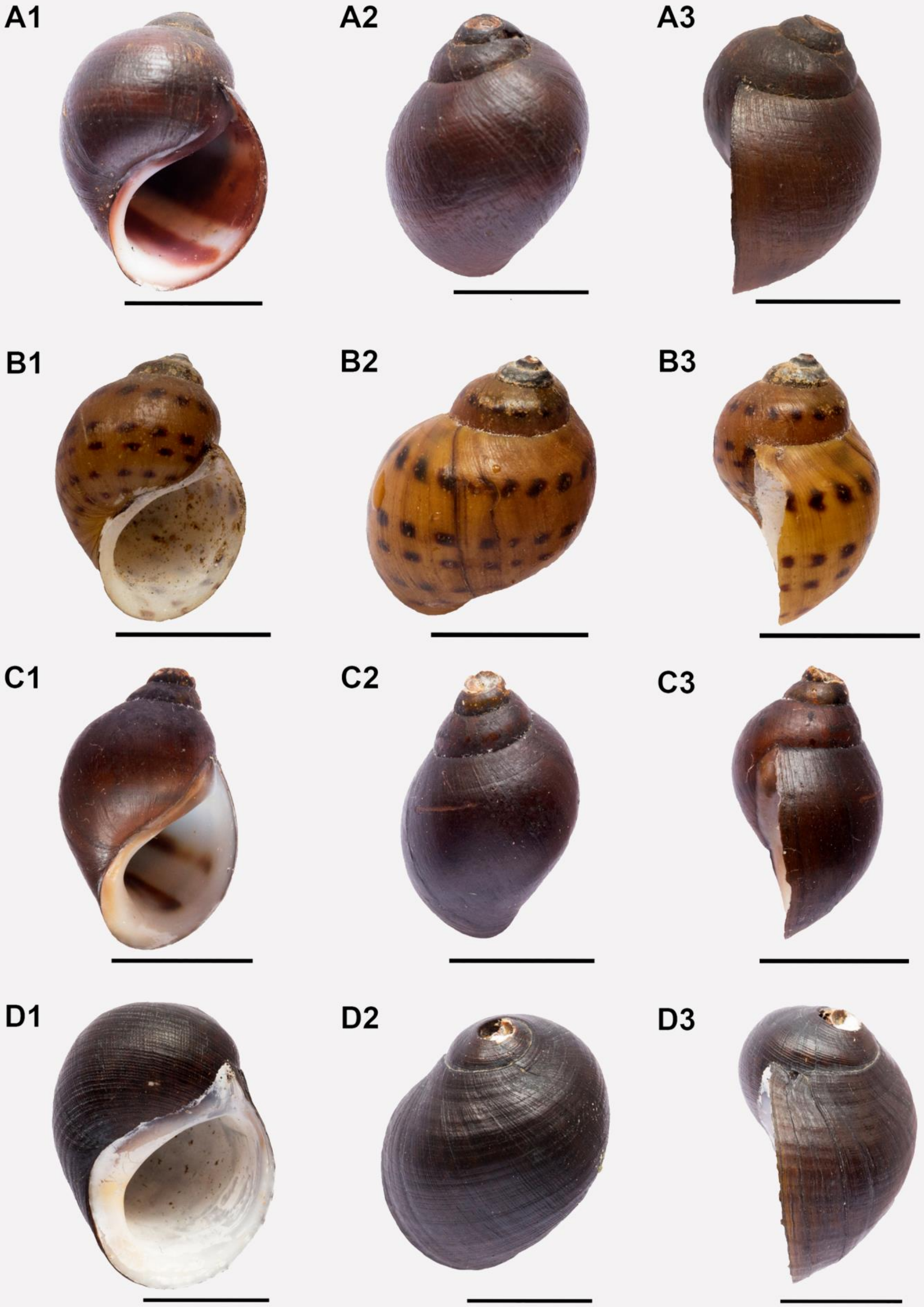

Figure 2. Apertural, abapertural and lateral views of the *Paludomus* shells **(A)** *P. bicinctus*, **(B)** *P. chilinoides*, **(C)** *P. decussatus*, and **(D)** *P. neritoides* sampled from the study locations in Hulu Ganga and Ma oya rivers in Sri Lanka; scale: 10 mm

Plate 9

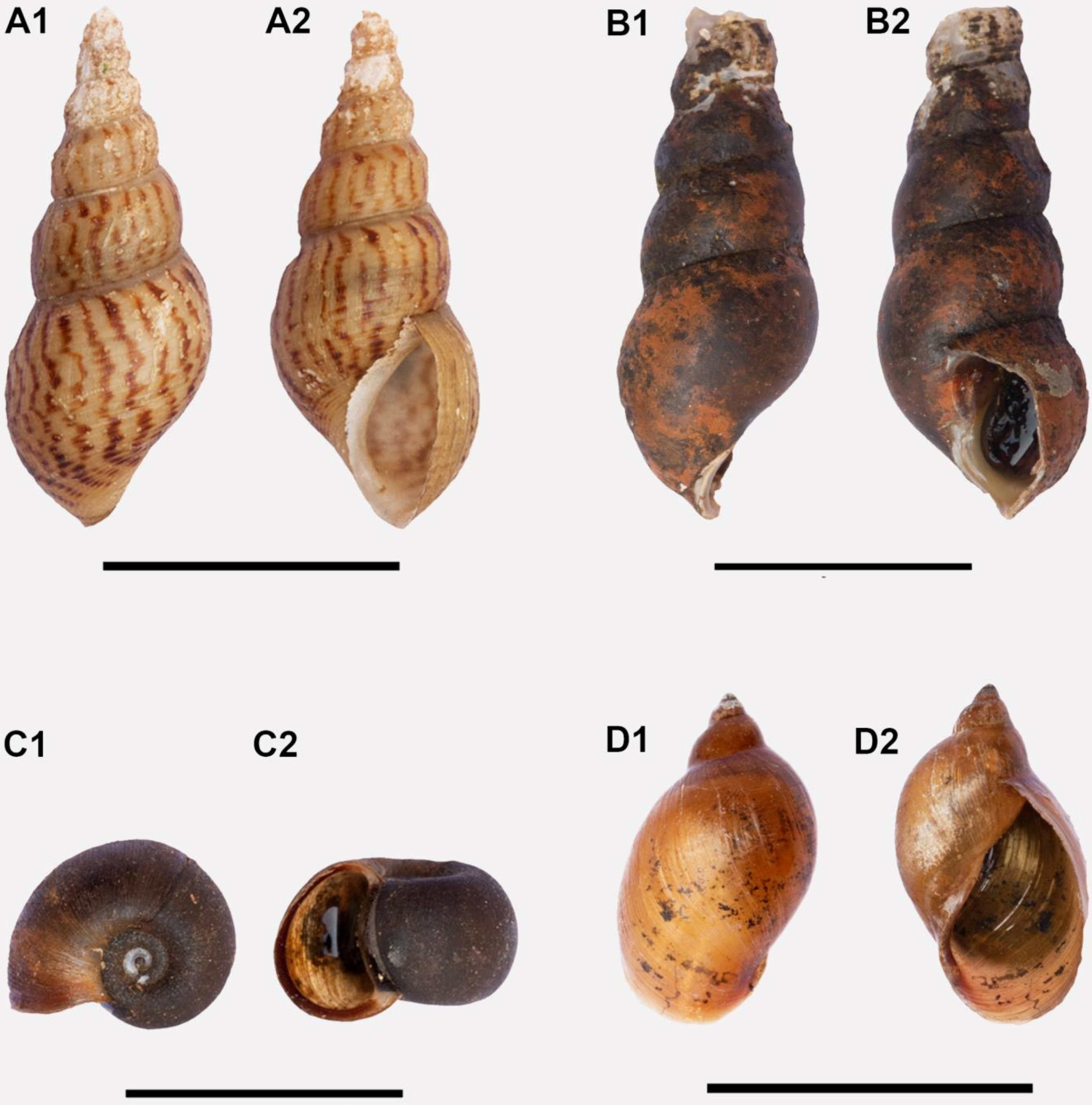

Figure 3. Apertural and abapertural views of the other freshwater gastropod shells: **(A)** *Pseudoplotia scabra*, **(B)** *Melanoides tuberculata*, **(C)** *Indoplanorbis exustus*, and **(D)** *Radix luteola* sampled from the study locations in Hulu Ganga and Ma oya rivers in Sri Lanka; scale: 10 mm

bicinctus was recorded were 21.83 ppm and 92.33 ppm. *Paludomus decussatus* was found in a TDS range of 25–61.83 ppm. Overall, among the *Paludomus* species, *Pa*. *decussatus* appears to be capable of inhabiting waters having a wider range in TDS. The TDS value of the location where *Pa*. *neritoides* was found was 24.17 ppm. *Melanoides tuberculata*, *Ps*. *scabra* and *R*. *luteola* were found in locations where TDS ranged from 70.33–86.33 ppm. *Indoplanorbis exutus* was found between 38.83–53.33 ppm TDS.

Water temperature (Fig. 4E): In the sampled sites, the water temperature ranged between 17.50–24.10°C. *Paludomus chilinoides* was found in locations where water temperature ranged between 21.02–24.18°C. *Paludomus bicinctus* was found at temperatures between 17.50–24.10°C. *Paludomus decussatus* was found in water at temperatures between 19.98–22.95°C. The water temperature at the location where *Pa*. *neritoides* was found was 19.98°C. *Melanoides tuberculata*, *Ps*. *scabra* and *R*. *luteola* were found in water with a temperature range between 21.02–24.0°C. *Indoplanorbis exustus* was found in locations where temperature ranged from 22.33–22.55°C.

DO (Fig. 4F): The DO range for *Pa*. *chilinoides* was 4.04–8.13 ppm. The DO range for *Pa*. *bicinctus* was 3.52–8.13 ppm. *Pa*. *decussatus* had a DO range of 3.89–5.71 ppm. The DO level in the location where *Pa*. *neritoides* was found was 5.56 ppm. *Melanoides tuberculata*, *Ps*. *scabra* and *R*. *luteola* were found in a DO range between 5.21–6.24 ppm. *Indoplanorbis exutus* was found in a DO range between 5.13–5.23 ppm.

Flow rate (Fig. 4G): *Paludomus chilinoides* was found in 0.13–0.32 m/s flow rate. The maximum and minimum flow rate values in Hulu Ganga where *Pa*. *bicinctus* was found were 0.32 and 0.19 m/s. *Paludomus decussatus* was found in a flow rate ranging between 0.22–0.28 m/s. The flow rate of the location where *Pa*. *neritoides* was found was 0.28 m/s. *Melanoides tuberculata*, *Ps*. *scabra* and *R*. *luteola* were found in locations where flow rate ranged from 0.20–0.26 m/s. *Indoplanorbis exutus* was found where flow rate ranged from 0.11–0.12.

According to the Pearson's correlation analysis (Table 2), elevation and flow rate had a significant negative correlation with the abundance of *Pa. chilinoides* in Hulu Ganga while conductivity, TDS and temperature had a significant positive correlation. On the other hand, only elevation had a significant negative correlation with the abundance of this species in Ma Oya, while conductivity and TDS had significant positive correlations with its abundance. In contrast to the above species, the abundance of *Pa. bicinctus* had significant positive correlations with both the elevation and the flow rate in both streams, while conductivity and temperature had negative correlations with the abundance of *Pa. bicinctus* only in Hulu Ganga.

Table 2. Pearson's correlation analysis of the freshwater snail abundance and measured environmental factors for Hulu Ganga and Ma Oya; *p*-values indicate within brackets, * indicates significant correlations.

Species	*r*-values						
	Elevation	pH	Cond	TDS	DO	Temp	FR
Hulu Ganga							
Paludomus chilinoides	-0.730* (0.001)	0.367 (0.135)	0.825* (≤ 0.01)	0.824* (≤ 0.01)	0.103 (0.685)	0.763* (≤ 0.01)	-0.624* (0.006)
Paludomus bicinctus	0.719* (0.001)	-0.376 (0.124)	-0.531* (0.023)	-0.307 (0.215)	-0.417 (0.085)	-0.669* (0.002)	0.752* (0.000)
Paludomus decussatus	0.068 (0.789)	0.039 (0.878)	-0.393 (0.106)	-0.603* (0.008)	0.302 (0.223)	-0.138 (0.586)	-0.115 (0.648)
Ma Oya							
Paludomus chilinoides	-0.709* (≤ 0.01)	-0.231 (0.288)	0.567* (0.005)	0.587* (0.003)	-0.268 (0.217)	-0.130 (0.554)	-0.111 (0.613)
Paludomus bicinctus	0.492* (0.017)	-0.004 (0.987)	-0.145 (0.508)	-0.279 (0.197)	0.124 (0.573)	0.180 (0.411)	0.542* (0.008)
Melanoides tuberculata	-0.033 (0.881)	0.076 (0.732)	0.169 (0.440)	0.082 (0.712)	0.094 (0.669)	-0.223 (0.307)	-0.204 (0.351)
Pseudoplotia scabra	-0.035 (0.872)	0.009 (0.966)	0.085 (0.701)	0.236 (0.278)	0.286 (0.186)	0.214 (0.327)	0.284 (0.189)
Indoplanorbis exustus	0.413* (0.050)	0.309 (0.151)	-0.668* (≤ 0.01)	-0.619* (0.002)	0.021 (0.924)	-0.105 (0.634)	-0.665* (0.001)

Plate 10

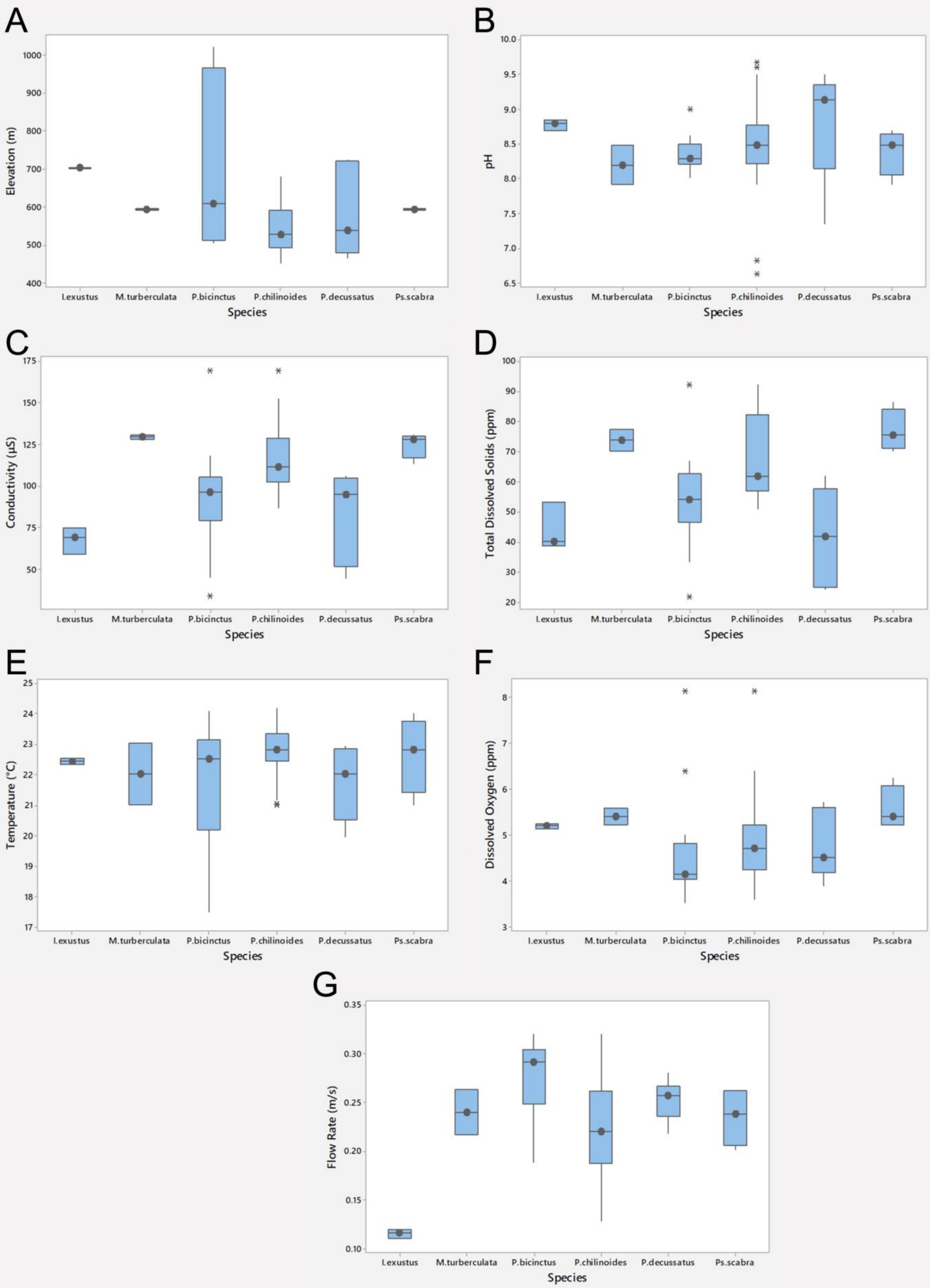

Figure 4. Aquatic environmental factor ranges **(A)** elevation, **(B)** water pH, **(C)** conductivity, **(D)** TDS, **(E)** temperature, **(F)** DO, **(G)** flow rate for each gastropod species in Hulu Ganga and Ma Oya rivers in Sri Lanka

Table 3. Summary of Canonical Correspondence Analyses (CCA) for Hulu Ganga and Ma Oya

Statistics	Axis 1	Axis 2	Axis 3	Axis 4
Hulu Ganga				
Eigenvalues	0.7739	0.6655	0.1016	0.0876
Explained variation (cumulative)	45.51	84.64	90.61	95.76
Pseudo-canonical correlation	0.9491	0.9560	0.9468	0.0000
Explained fitted variation (cumulative)	50.22	93.41	100.00	
Permutation test results: on all axes pseudo-F = 13.8, *p*=0.002				
Ma Oya				
Eigenvalues	0.9218	0.5179	0.1620	0.0285
Explained variation (cumulative)	34.28	53.55	59.57	60.63
Pseudo-canonical correlation	0.9618	0.7996	0.5537	0.2836
Explained fitted variation (cumulative)	56.54	98.25	98.25	100.00
Permutation test results: on all axes pseudo-F = 3.3, *p*=0.004				

Paludomus decussatus, which was found only in Hulu Ganga, showed a significant negative correlation with TDS. Since *Pa*. *neritoides* was recorded only from one site in Hulu Ganga, its association with the measured environmental parameters could not be determined. *Melanoides tuberculata* and *Ps*. *scabra* did not show significant correlations with any of the measured water quality parameters.

Canonical Correspondence Analysis (CCA). (see Fig. 5, Table 3). The first four axes of the CCA for Hulu Ganga explained 95.76% of the cumulative variation, while in Ma Oya the first four axes explained only 60.63% of the cumulative variation. In Hulu Ganga, DO had the closest and strongest association with the first axis followed by flow rate so these two were the strongest variables that accounted for the gastropod species assemblage in this river. In addition, TDS and conductivity that were closely associated with the second axis also helped explain the gastropod variation. However, in Ma Oya, pH had the strongest relationship with the first axis. Thus, it is a significant factor affecting the gastropod variation in this stream. In addition, DO and temperature had the strongest relationships with the second axis.

Discussion

Gastropod species richness. According to Amarasinghe & Krishnarajah (2009), in addition to *Pa*. *chilinoides* and *Pa*. *bicinctus*, *Pa*. *tanschaurica* and *P*. *nigricans* have been recorded in the Mahawali basin. However, these two species were not recorded in the study area. According to early records by Layard (1854), *Pa*. *chilinoides* is the most common *Paludomus* species in Sri Lanka and Starmuhlner (1974) recorded this species from Attanagalla, Kegalla, Kandy, Peradeniya, Udawela, Badulla, Monaragala, Kokagala, Habarana, Ritigala, Kurunegala and Narammala. In more recent times *Pa*. *chilinoides* has been recorded in both the wet and the dry zones (de Silva 1994). In previous studies, *Pa*. *bicinctus* was found in the mountains in the eastern Central Province and Uva Province (Starmuehlner 1984). *Paludomus decussatus* has been recorded from the Uva Province (Starmuhlner 1974) and in Gal Oya (de Silva 1994). According to Starmuhlner (1974), *Pa*. *neritoides* is present in the Central, Southern, Western, Sabaragamuwa and Uva provinces.

According to previous studies, the other four species recorded during the present study show a wide distribution on the island as well. *Pseudoplotia scabra* and *M*. *tuberculata* are distributed in the Southern, Western, Sabaragamuwa, Central, Uva, North-Central, and North-Western provinces (Starmuhlner 1974). *Radix luteola* is distributed in the Southern, Western, Central, Uva, and North-Western provinces (Starmuhlner 1974). *Indoplanorbis exustus* is distributed in the Southern, Western, Sabaragamuwa, Central, Uva, North-Western, and Northern provinces (Starmuhlner 1974). According to de Silva (1994), *M*. *tuberculata*, *R. luteola* and *I*. *exustus* are widespread in both the Wet and the Dry Zones.

Gastropod correlation to environmental parameters. Elevation: Generally, freshwater macro-invertebrate richness decreases with increasing elevation (Cárcamo *et al*. 2019, Maltchik *et al*. 2010). According to Amarasinghe & Krishnarajah (2009), *Paludomus* species recorded from Sri Lanka are stratified according to elevation: *Pa*. *chilinoides* (100–1,000 m), *Pa*. *sulcatus* (100–500 m), *Pa*. *nigricans* (1,000–2,000 m), *Pa*. *bicinctus* (500–

Plate 11

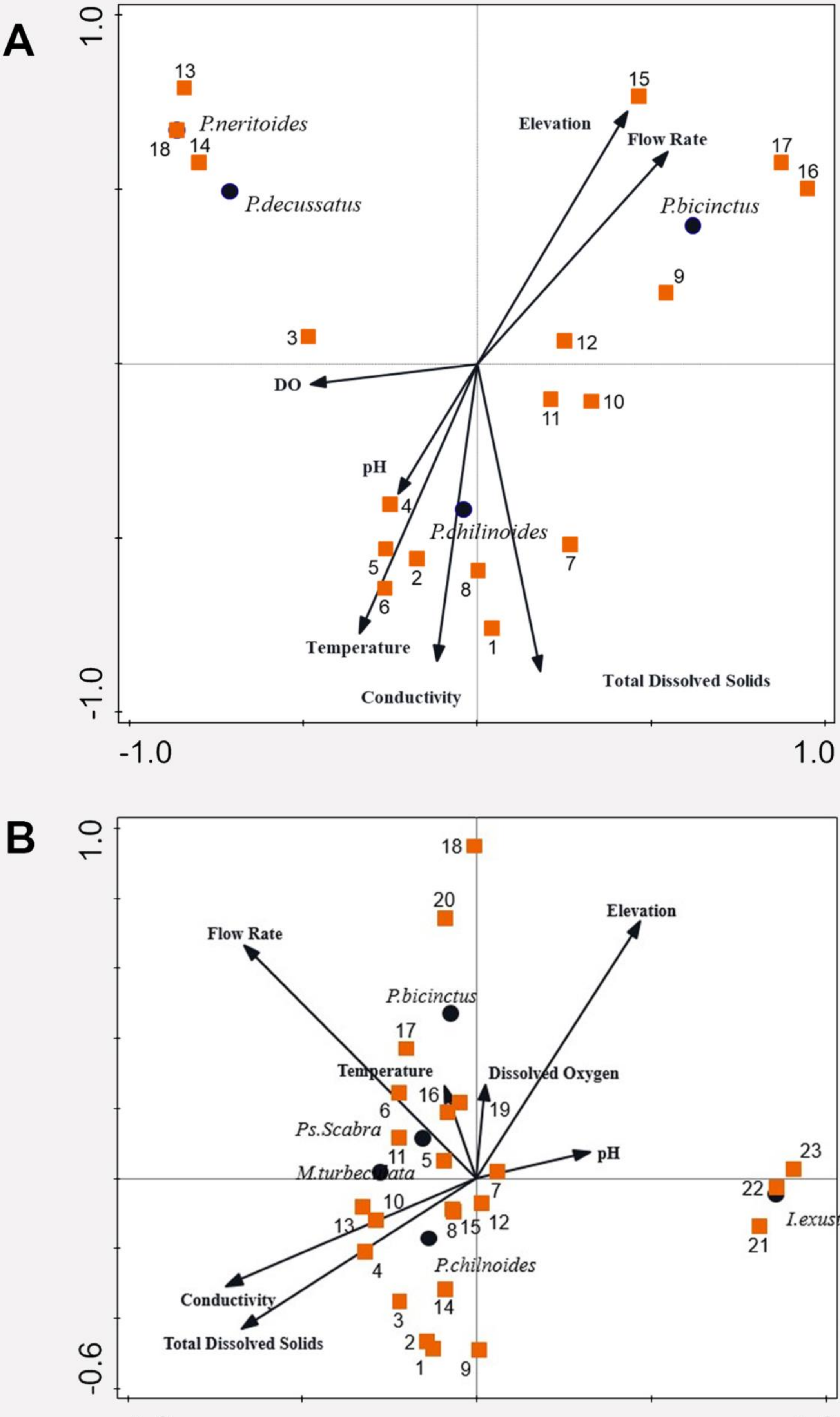

Figure 5. Canonical Correspondence Analyses (CCA) ordination diagram showing relationships between the environmental parameters and gastropods' relative abundance in **(A)** Hulu Ganga and **(B)** Ma Oya rivers

1,500 m), *Pa*. *tanschaurica* (100–1,000 m), and *Pa*. *neritoides* (100–500 m). Since the present study was done in a narrow elevational range, where all the sampled locations were within the Central Province, more studies in other areas are required to determine the distribution and the association between elevation and abundance of freshwater gastropod species.

Water pH: None of the species from this study, showed significant correlations with pH. However, freshwater gastropods are considered to be highly sensitive to pH, since acid deposition can have various direct and indirect effects on gastropods (Økland 1992). The freshwater gastropod diversity is most diverse when the pH is neutral, while it becomes least diverse when pH is low (Spyra 2010, Marie *et al*. 2015, Spyra 2017). Many snails can tolerate low pH values when calcium ion concentration in water is high (Økland 1992). Freshwater gastropod shells appear to erode after exposure to low pH (Glass & Darby 2009). However, snails can regrow shells easily where high concentrations of Ca^{2+} ions are found in the water. Furthermore, low pH can affect the regulation of important ions such as Na^{+} ions in aquatic invertebrates (Havas & Advokaat 1995). Nevertheless, several other studies indicate that pH is rarely a factor limiting the distribution and abundance of freshwater snails (Ofoezie 1999, Cañete *et al*. 2004, Zalizniak *et al*. 2009, Oloyede *et al*. 2017).

Conductivity: For some species there was no association between conductivity and abundance. According to Starmuhlner (1984), the type of rocks in the streambed can influence the chemical composition of freshwater in mountainous areas. Sri Lanka, which is an old continental island, the central mountains consist of old Precambrian granitic rocks (Starmuhlner 1984). Starmuhlner (1984), further states that the surface waters in mountainous areas of Sri Lanka are deprived of electrolytes: electrolytic conductivity of 8.8–89 μS (mean values: 10–30 μS), very soft; total hardness of 0.08–2.35 °dH (mean values: <1° dH) and slightly acidic (pH: 5.5–6.8).

The relationship between conductivity and freshwater snail abundance can be species-specific. For example, the New Zealand mud snail, *Potamopyrgus antipodarum* cannot grow rapidly in water where conductivity is in the range of 25–200 μS (Herbst *et al*. 2008). Other studies show that abundance of some species, such as *Lanistes lybicus* has a negative relationship with conductivity while some species such as *Bulinus senegalensis* has a positive relationship with conductivity (Salawu & Odaibo 2014).

According to Marie *et al*. (2015), conductivity affects the abundance and distribution of *M*. *tuberculata*. This disparity with the present study may be because the effects of conductivity are not felt alone, but in combination with other factors.

TDS: Several authors have indicated that TDS has a significant effect on the abundance and distribution of freshwater snails (Heeg 1975, Rekha *et al*. 2020). According to Heeg (1975), mortality of *Bulinus africanus* increased 46% when the snails were transferred from 490 ppm TDS natural water to 126 ppm laboratory water. Therefore, TDS can also affect the abundance of freshwater gastropods.

In contrast, the abundance of *I*. *exustus* had a significant negative correlation with elevation, conductivity, TDS and flow rate in Ma Oya (Table 2). The relationship between *I*. *exustus* and TDS in the present study is similar to what was observed in Tamil Nadu by Rekha *et al*. (2020). This is not surprising as they are known as stagnant water species (Starmuhlner 1974).

Water temperature: Water temperatures in Sri Lankan mountain streams varies between 15°–30°C (Starmuhlner 1984). Previous studies show that depending on the species, water temperature can affect freshwater gastropod abundance positively or negatively (Lodge *et al*. 1987, Bae & Park 2020, Olkeba *et al*. 2020). One reason for the positive association is because higher temperature can increase the metabolic rate of gastropods, and this increases the size of the snail population reducing the time required for development periods (Yigezu *et al*. 2018). The other possible reason is the higher food availability at higher temperatures (Olkeba *et al*. 2020). Snails have a wide range of temperature tolerance from 19–34°C. Nevertheless, they can tolerate lower temperatures than higher temperatures (Marie *et al*. 2015). In the present study, no extreme temperature fluctuations were observed. An expansion of the study into the dry zone and at higher altitudes would enable the determination of the actual temperature ranges that each species is able to tolerate.

DO: Several studies indicate that there is a significant association between freshwater snail abundance and DO (Salawu & Odaibo 2014, Marie *et al*. 2015, Olkeba *et al*. 2020). Usually, snails prefer low DO levels which indicate their ability to live in water where higher concentrations of organic matter are present (Olkeba *et al*. 2020). Pulmonate snails including *Bulinus* sp. and *Lymnaea natalensis* prefer water with high dissolved oxygen levels (Marie *et al*. 2015). However, according to some studies there is no significant association between freshwater snail abundance and DO (Oloyede *et al*. 2017).

Other important factors for gastropods. In addition to the above-mentioned factors, the distribution of freshwater gastropods may be influenced by other physiological, physicochemical, hydrological and biological factors. The type of substrate, from sandy, silt or muddy bottoms to pebble or boulders may greatly influence the gastropod assemblage (Hawkins & Murphy 2016). Scrapers prefer to attach to rocks and logs whereas others prefer a sandy substrate (Hawkins & Murphy 2016). On the other hand, some gastropods like *Planorbis vortex*, *I. exustus*, *Lymnaea peregra* and *R. luteola* prefer substrates with macrophytes possibly due to the higher food availability and as suitable surfaces on which egg masses can be deposited (Lodge 1985, Lodge 1986, Marie *et al*. 2015, Oloyede *et al*. 2017). In addition, macrophytes can provide protection to snails from predators (Olkeba *et al*. 2020). Canopy cover can also have either a positive or negative affect depending on the species. Canopy type is one factor that can determine the type of sediment (Hawkins and Murphy 1982). Freshwater invertebrates, which can feed on algae prefer habitats with little or no canopy and hence streams without shade have higher abundance of freshwater invertebrates when compared to streams with shade (Hawkins & Murphy 1982). Rainfall can also affect the abundance and distribution of freshwater gastropods. It has been reported that rainfall has a negative effect on the abundance of gastropods in Brazil (Buss *et al*. 2004). Water depth affects different species differently. For some species water depth and abundance are positively correlated, while for some snails the correlation is negative (Oloyede *et al*. 2017, Olkeba *et al*. 2020).

Biotic factors such as the presence of predators, inter and intra-species competition and food (macrophytes and periphyton) are important factors which contribute to the abundance and distribution of freshwater gastropods (Brown 1982, Lodge 1985, Lodge 1986, Vaughn 1986, Crowl & Schnell 1990, Marie *et al*. 2015, Oloyede *et al*. 2017). When competition is high, the snail densities decrease (Brown 1982). Most of the time generalist species are successful when competition occurs (Brown 1982). Sometimes, when two species co-occur, population sizes of both species can be reduced allowing them to coexist (Giovanelli *et al*. 2005). When two species co-occurred in the present study, such as *Pa. chilinoides* + *Pa. bicinctus*, *Pa. chilinoides* + *Pa. decussatus*, and *Pa. decussatus* + *Pa. neritoides*, the two co-occurring species occupied different microhabitats, indicating possible niche partitioning.

It is evident that a combination of multiple factors influences the diversity and abundance of freshwater gastropods. Therefore, in addition to the environmental parameters which were measured in this study, other biotic and abiotic parameters may affect the freshwater snail diversity and abundance. More studies therefore are needed to understand how diverse environmental dynamics affect gastropod species distribution and composition.

Conclusion

According to the present study, elevation and the measured water quality parameters have species-specific effects on gastropod abundance and distribution. Since only about 60% of the variation in abundance was explained by measured factors in Ma Oya, other unmeasured environmental and habitat quality parameters in Ma Oya may contribute to the variation in gastropod abundance in this stream.

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