Assessment of schistosomiasis transmission in the River Nile at Greater Cairo using malacological surveys and cercariometry

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Abstract Continuous field studies on the abundance and distribution of freshwater snails and cercarial populations are important for schistosomiasis control programs. In the present work, snail surveys and cercariometry were conducted for four successive seasons at 12 sites on the Nile River banks in the area of Greater Cairo to identify potential transmission foci for schistosomiasis. In addition, water physicochemical parameters were recorded. The results showed that the electrical conductivity, total dissolved solids, dissolved oxygen, and pH were within the permissible levels, except that the water temperature increased, especially in the spring season. Malacological surveys identified 10 native snail species at the studied sites of the Nile River, namely Bulinus truncatus, Biomphalaria alexandrina, Lymnaea natalensis, Lanistes carinatus, Cleopatra bulimoides, Melanoides tuberculata, Helisoma duryi, Bellamyia unicolor, Physa acuta, Thedoxus niloticus, and one invasive snail species, Thiara scabra. The calculated diversity index indicated that the structure of snails’ habitats was poor, while Evenness index indicated that the individuals were not distributed equally. Natural infection results identified no schistosome cercariae in B. truncatus and B. alexandrina. However, the cercariometry recovered Schistosoma cercariae in all the surveyed sites during all seasons with variable distribution. The preceding data suggest that there are still some active transmission foci for schistosomiasis infection in the Nile River. Moreover, the present finding highlights the importance of cercariometry as a complementary approach to snail samplings for identifying the transmission foci for schistosomiasis.

Keywords Snail surveys · Biomphalaria alexandrina · Bulinus truncatus · Cercariometry · Schistosomiasis

Introduction

Schistosomiasis is a widespread, neglected tropical disease that represents a public health problem in many tropical and subtropical countries. Schistosomiasis transmission has been reported in 78 countries, and recent estimates show that 236.6 million people required medication in 52 countries with moderate-to-high transmission (WHO 2022; https://www.who.int/news-room/fact-sheets/detail/schistosomiasis). Schistosomiasis is caused by blood flukes of the genus Schistosoma, of which three main species infect humans; Schistosoma mansoni, S. haematobium, and S. japonicum, which are transmitted by intermediate host snails Biomphalaria spp., Bulinus spp., and Oncomelania spp., respectively (Gryseels et al. 2006).

Egypt has long been recognised as an endemic site for intestinal schistosomiasis caused by S. mansoni infection and urogenital schistosomiasis caused by S. haematobium infection. These parasites are transmitted by Biomphalaria alexandrina and Bulinus truncatus snails, respectively (Othman and Soliman 2015). S. haematobium infection spreads south of Cairo through the Nile Valley, whereas S. mansoni infection is restricted to the Nile Delta. The National Schistosomiasis Control Programme (NSCP), started in 1977, has successfully reduced the prevalence of the two kinds of schistosomiasis (Barakat 2013). Despite the plan initiated by the Egyptian Ministry of Health and Population (MoHP) and supported by the World Health Organization to
Table 1 GPS coordinates for the surveyed sites on Nile River at Greater Cairo area

| Sites                          | Latitude  | Longitude |
|-------------------------------|-----------|-----------|
| AL-Qanater Al-Khairyah (*S1*)  | 30.174    | 31.142    |
| El-Kerateen (*S2*)             | 30.154    | 31.146    |
| West Cairo Electric Station (*S3*) | 30.130 | 31.192    |
| Ring Rd-Warrak (*S4*)          | 30.128    | 31.203    |
| El-Warrak (*S5*)               | 30.095    | 31.230    |
| Rod El-Farag (*S6*)            | 30.083    | 31.231    |
| El-Tahrir (*S7*)               | 30.046    | 31.228    |
| El-Manial (*S8*)               | 30.019    | 31.217    |
| El-Hwamdeyah (*S9*)            | 29.987    | 31.221    |
| Maadi (*S10*)                  | 29.962    | 31.243    |
| Helwan Water Station (*S11*)   | 29.925    | 31.283    |
| Marazik (*S12*)                | 29.793    | 31.296    |

Inject 10 million dollars for five successive years to eliminate schistosomiasis (WHO 2016), transmission is still being recorded from different parts of Egypt for *S. mansoni* (El Sharazly et al. 2016; Hagagg et al. 2017; Saad and Watany 2019) and *S. haematobium* (Bayoumi et al. 2016; El-Kady et al. 2020).

Schistosomiasis is mainly linked to the human socioeconomic situation. In poor communities, there is an inadequate water supply, and members of these communities can be infected if confronted with contaminated water (Bergquist and Whittaker 2012). Thus, ensuring access to clean water and a healthy sanitation system is important. It is also important to assess the quality of bodies of water from time to time. Most of the research on schistosomiasis focuses on disease prevalence among humans, and little is done to survey and identify the intermediate hosts of the disease. The pattern of snail intermediate hosts’ distribution and the prevalence of infection are among the measurable indicators that reflect the magnitude of transmission and offer precise maps for the potential distribution of the disease (Opisa et al. 2011). Integrating snail distribution with human parasitological data is a reliable approach for schistosomiasis mapping. However, human infection and snail sampling distortions complicate identifying the presence and distribution of intermediate host snails in the areas (Standley et al. 2010). Rather than being limited, chemotherapy is used on a wide scale, but the cost of repeated MDA is certainly a disadvantage. Snail control is recommended as a preventive measure side by side with chemotherapy, but this needs a detailed knowledge of snail distribution (Opisa et al. 2011). Understanding the ecological factors that control snail abundance is needed to predict their distribution (Habib et al. 2016). For example, temperature and water chemistry can impact snail ecology, physiology, and infection with schistosomes (Appleton and Madsen 2012; Habib et al. 2021). Besides snail surveillance, detecting schistosome cercariae in water is another important method for identifying active transmission sites. In this regard, numerous techniques have been proposed, such as the use of sentinel rodents (Chen et al. 2020), cercariometry (Prentice 1984; Ouma et al. 1989), and environmental DNA (eDNA) for the detection and surveillance of schistosomiasis (Sengupta et al. 2019; Alzaylaee et al. 2020).

Cercariometry is complementary to snail sampling because, in some cases, it provides information on the magnitude of the parasitic connection from vertebrates to snails (Theron 1986). In addition, the distribution of cercariae obtained from sampled snails depends on various environmental parameters such as water currents, periods of daylight, and the presence of snail predators. These parameters may differ on the same day and from season to season. Cercariometry can overcome these concerns and give a direct quantitative measure of the transmission potential of a specific water-contact site on a spatially and temporally basis (Prentice 1984; Aoki et al. 2003). Through cercariometry, researchers could rapidly and reliably assess infection risk from trematode parasites in natural water bodies (Worrell et al. 2011). However, because human and non-human schistosomes are frequently co-endemic, reliable xenomonitoring requires species identification. Identification by microscopy is difficult due to similarities in tail morphology within the *Schistosoma* genus, which can impair the accuracy of this technique (Frandsen and Christensen 1984; Agola et al. 2021). Thus, the technique depends greatly on researchers’ ability to differentiate human schistosome cercariae from non-human schistosomes.

The particular identification of *Schistosoma* cercariae is beneficial in assessing specific diagnoses in both natural and experimental settings (Cabaret et al. 1990). The morphology of the cercaria is critical in understanding the biological features and functions of that stage of *Schistosoma* development. Each species is bound to have its own set of features. Animal experiments must be used to diagnose the material on which such traits are based specifically. The procedure demands significant time, effort, and expertise in the taxonomic identification of schistosome cercariae employing microscopy (Kariuki et al. 2004). Numerous molecular techniques have been developed to overcome difficulties associated with microscopic identification. In this regard, testing eDNA is a reliable technique for identifying schistosome species in water filters recovered from cercariometry (Sengupta et al. 2019).

Greater Cairo is considered one of the world’s 15 largest cities by urban and population growth. Many industrial, commercial, tourist, and fishing activities extend along the Nile River banks as there are many water stations, rowing and social clubs, floating houses, restaurants, and water body police centers. Since the Nile River represents the...
main water resource for most Egyptians, it is mandatory to periodically evaluate the characteristics of its water to identify the major sources of pollution and their environmental and health consequences, as well as to identify the potential sources of parasitic infection, especially the occurrence of schistosomiasis intermediate hosts. Ibrahim et al. (2005) carried out the most recent comprehensive study on the status of schistosomiasis transmission in the Nile River at Greater Cairo, employing malacological and parasitological indicators, as well as cercariometry, to detect schistosome larvae in the Nile. The result of that study revealed the presence of *B. alexandrina* and *B. truncatus* in most of the studied sites. Moreover, the use of sentinel snails and mice and cercariometry identified active transmission of schistosomiasis at some sites along the Nile River. The present work was initiated to provide new insights on the risk of schistosomiasis transmission in the Nile River in the area of Greater Cairo using malacological surveys to investigate and identify the snails’ intermediate hosts and to examine the collected snails for natural infection as well as to use cercariometry to detect the presence of schistosome cercariae in the water. However, the shortage in funding hinders our ability to recruit more advanced techniques (i.e., eDNA) to monitor schistosomiasis transmission.

**Materials and methods**

**Study area**

The research included 12 sites along the Nile, from Al-Qanater Al-Khairiyah to Marazik (Fig. 1 and Table 1). These are located in Greater Cairo in the south of the Nile Delta in the Nile basin (30°03′45.47″ N, 31°14′58.81″ E), the largest metropolitan area in Egypt and the largest urban area in Africa and the Middle East. The population density in this area is very high compared to other parts of Egypt, with a total population estimated at 20,901,000; area: 1,709 km²; density: 10,400/km². Many human activities extend along the Nile River banks. The climate in Greater Cairo is a hot desert climate that characterizes subtropical regions. The annual average temperature is 21.3°C. Winter season is from December to February and it tends to be cold, moist, and rainy, while summer (June to August) is hot, dry, and rainless (Robaa 2003). The warmest month is July, with a maximum temperature of 34°C, and the coldest month is January, with a maximum average temperature of 18°C. Precipitation is about 18 mm per year.

**Sites selection**

The sites were selected based on their proximity to human activities and the availability of aquatic vegetation that supports snail abundance. Sampling was done along the shoreline of the Nile using a motorized boat. The GPS coordinates for each site were recorded using the Google Map application (Google, LLC, California, USA) on an android smartphone (Table 1). Samples were collected during winter (December to February), spring (March through May), summer (June to August), and autumn (September to December) of 2019–2020. Samplings were done by two experienced technicians inspecting vegetation using a hand-held dip net (30 min/site) according to WHO (1965).

**Water physicochemical characteristics**

Water characteristics that might affect snail abundance were recorded. Dissolved oxygen (mg/L) was recorded by a dissolved oximeter electrode (HANNA HI 9146; Hanna Instruments, Nasr City, Egypt). Water temperature (°C), conductivity (measured in μmohs/cm), total dissolved solids (TDS; measured in mg/L) and pH were measured using a PH-200 handheld portable pH and temperature meter and an AP-2 aquapro conductivity meter (HM Digital, Inc., Culver City, USA).

**Snail sampling**

Collected snails were transferred to plastic aquaria containing water from the same site until they were transferred to the laboratory for identification and detection of trematode infections. Snails were identified based on shell morphology according to published keys (Mandahl-Barth 1962; Brown 2002). For trematode infection, snails from the same species were placed individually in multi-well plates (2 ml of dechlorinated tap water/well) and exposed to artificial light for 2 h (Frandsen and Christensen, 1984). The plates were then examined under a stereomicroscope. Non-infected snails were monitored for 4 weeks and examined for cercarial shedding on a weekly basis as described beforehand.
Cercariae were identified based on gross morphological characteristics, swimming behaviour, and resting position as described by Frandsen and Christensen (1984). Cercariae belonging to the genus *Schistosoma* (human and avian schistosomes) were identified by their morphological features. The key features of human *Schistosoma* cercariae include the presence of a brevifurcate forked tail with each furcal arm less than half the length of the main tail stem, the absence of eyespots, and, unlike other brevifurcate-apharyngeate distome cercariae, the tail furcae bent backwardly in the resting position when observed in open water.

**Cercariometry**

Cercariometry was performed at each site preceding snail collection based on the method of Prentice and Ouma (1984) with some modification (Yousif et al. 1996). Briefly, a 20-L sample was collected from a wide area using a suction bump attached to a 5 L conical cylinder. From the cylinder extends a long hose, tightly sealed at the opening by a rubber band that reaches the water surface. Following the collection of water, the sample was directly centrifuged using a tube centrifuge with an opening at the bottom for runoff (Fig. 2). The precipitates from the tubes were then collected in a 200-ml plastic bucket. The process was repeated four times, and at the end, formalin was added to the sample to kill any cercariae present before sealing and transferring it to the laboratory. In the laboratory, iodine solution was added to the samples before checking under dissecting microscope for cercariae presence. The number of schistosome cercariae was recorded (Ouma et al. 1989).

**Statistical analysis**

Data of snail species abundance were statistically analyzed for the significance of differences between different seasons by one-way ANOVA test at \( p < 0.05 \), using the statistical program SPSS version 17 (SPSS, Inc., Chicago, IL) for windows. Diversity indices for species richness were calculated using Margalef’s diversity index (Margalef 1948), and Evenness index (Hill 1973).

**Results**

Water physicochemical parameters (i.e., water temperature, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and pH) were recorded in situ during sample collection (Table 2). Summer and spring had the highest average temperature degrees among all sites investigated, with 29.2 and 28.02°C, respectively. The lowest temperature was recorded during the winter (17.6°C). The pH was within the neutral range of 7.3 to 7.43 during all seasons. Dissolved oxygen values in autumn, winter, and spring were significantly higher compared to its value in summer. The concentration of dissolved oxygen ranged from 4.86 mg/L in summer to 9.4 mg/L in winter. Total dissolved solids fluctuated from 237.4 mg/L in spring to 273 mg/L in autumn. The electrical conductivity ranged from 340.5 μmohs/cm in summer to 435.4 μmohs/cm in winter.

A total of 11 snail species were identified at the studied sites of the Nile River, including ten native species; *B. truncatus*, *B. alexandrina*, *Helisoma duryi* (Family: Planorbidae), *Lymnaea natalensis* (Family: Lymnaeidae), *Lanistes carinatus* (Family: Ampullariidae), *Cleopatra bulimoides* (Family: Paludomidae), *Melanoides tuberculata* (Family: Eunikidae).
Thiaridae), *Bellamya unicolor* (Family: Viviparidae), *Physa acuta* (Family: Physidae), and *Theodoxus niloticus* (Family: Neritidae) in addition to one invasive snail species, *Thiara scabra* (Family: Thiaridae).

The total number of collected snails was 1339 specimens during the four seasons, and the highest number of snails (669) was recorded during the summer season. *M. tuberculata* and *B. unicolor* were the most abundant snail species, recording 217 and 228, respectively. The most common medically important snail species was *B. truncatus*, with 74 individuals. The invasive snail, *T. scabra*, was found during all seasons with 91 individuals (Table 3). Snail distribution data for the summer, autumn, winter and spring seasons of 2019–2020 are summarised in Fig. 3. *M. tuberculata* and *B. unicolor* showed 24% and 22% of the total number of collected snails during summer, respectively, while *C. bulimoides* was 39% during autumn. On the other hand, *T. niloticus* showed the highest percentage of 20% during winter, while both *L. carinatus* and *B. unicolor* had the highest percentage during spring (33%).

The diversity index was below (1), which indicates that the structure of snails’ habitats was poor. Meanwhile, Evenness index ranged between 0.037 to 0.048, which indicated that the individuals were not distributed equally (Fig. 4).

Screening of the collected snails for natural infection did not identify any trematode cercariae. However, the results of cercariometry revealed the presence of cercariae belonging to the genus *Schistosoma* in all investigated sites. However, it was not possible to identify the exact species (*mansoni* or *haematobium*) under the microscope. The highest percentage was during the spring season (100% cercarial distribution; cercariae were present in all investigated sites), followed by autumn (42%), summer (25%), and winter (8%). Out of the 12 investigated sites, El-Sasff and Helwan sites, showed the highest percentages of cercariae with 14 and 22%, respectively, during the summer season (Fig. 5).

![Summer snail samples](image_url)
![Autumn snail samples](image_url)
![Winter snail samples](image_url)
![Spring snail samples](image_url)

**Fig. 3** Distribution of snail samples collected from the Nile River in the area of Greater Cairo during summer, autumn, winter and spring seasons 2019–2020

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### Table 2 Water physicochemical parameters during different seasons

| Sites         | Parameters | Al-Qanater | Al-Khair-yah | West Cairo Electric Station | Ring Rd-Warrak | El-Warrak | Rod El-Farag | El-Tahir | El-Manial | El-Hawa-mdeya | Maadi | Helwan Water Station | Manazik | Mean ± SD |
|---------------|------------|------------|--------------|-----------------------------|----------------|-----------|-------------|----------|-----------|----------------|-------|---------------------|---------|------------|
|               | Temp (°C)  | Summer     | 25           | 29.5                        | 29.5           | 31.5      | 29.8        | 29.5     | 29.9      | 30             | 25    | 25                  | 29.2 ± 0.6 |
|               |            | Autumn     | 20.9         | 20.1                        | 20.1           | 19.7      | 19.9        | 20.3     | 20.4      | 20.3           | 20.3  | 22.3                | 20.5 ± 0.89 |
|               |            | Winter     | 17.3         | 17.2                        | 17.4           | –         | 16.8        | 18.3     | 18.3      | 18.6           | 18.9  | 15.9                | 17.6 ± 1.02 |
|               |            | Spring     | 28.6         | 28.2                        | 28.6           | 28.2      | 28.5        | 27.9     | 27.8      | 27.7           | 29.4  | 28.5                | 26.4 ± 28.02 ± 0.86 |
|               | pH         | Summer     | 7.2          | 7.1                         | 7.21           | 7.3       | 7.35        | 7.63     | 7.6       | 7.79           | 7.75  | 7.6                 | 7.42 ± 0.1 |
|               |            | Autumn     | 7.6          | 7.7                         | 7.6            | 7.9       | 7.4         | 7.4      | 7.1       | 6.9            | 7     | 6.9                 | 7.3 ± 0.33 |
|               |            | Winter     | 7.05         | 7.21                        | 7.7            | –         | 8.2         | 7.3      | 7.2       | 7.46           | 7.7   | 7.43                | 7.37 ± 0.4 |
|               |            | Spring     | 7.6          | 7.33                        | 7.21           | 7.53      | 7.6         | 7.21     | 7.4       | 7.28           | 7.8   | 7.5                 | 7.43 ± 0.17 |
|               | DO (mg/L)  | Summer     | 4.67         | 4.9                         | 4.87           | 5.03      | 4.73        | 4.25     | 5.2       | 5.1            | 4.6   | 4.52                | 4.86 ± 0.12 |
|               |            | Autumn     | 7.8          | 7.4                         | 8.9            | 7.9       | 8.4         | 7.6      | 8         | 8.9            | 9.4   | 8                   | 8.3 ± 0.65 |
|               |            | Winter     | 8.9          | 10.7                        | 8.8            | –         | 8.9         | 8.83     | 9.2       | 10.2           | 8.5   | 10.1                | 9.25 ± 0.83 |
|               |            | Spring     | 8.66         | 9.38                        | 8.4            | 9.77      | 10.2        | 7.8      | 9.2       | 9              | 9.8   | 9.07                | 11.7 ± 9.43 |
|               | TDS (mg/L) | Summer     | 132          | 266                         | 274            | 243       | 283         | 281      | 367       | 242            | 256   | 248                 | 257.3 ± 15.0 |
|               |            | Autumn     | 269          | 273                         | 200            | 294       | 281         | 222      | 308       | 313            | 306   | 315                 | 273 ± 57.3 |
|               |            | Winter     | 244          | 226                         | 240            | –         | 244         | 235      | 320       | 338            | 328   | 240                 | 267 ± 41.2 |
|               |            | Spring     | 260          | 255                         | 261            | 245       | 226         | 233      | 223       | 228            | 230   | 229                 | 237.4 ± 14.1 |
|               | EC μmohs/cm| Summer     | 206          | 318                         | 397            | 287       | 406         | 405      | 367       | 347            | 373   | 380                 | 340.5 ± 18 |
|               |            | Autumn     | 386          | 393                         | 401            | 425       | 402         | 447      | 446       | 453            | 450   | 432                 | 423 ± 23.7 |
|               |            | Winter     | 353          | 326                         | 348            | –         | 350         | 450      | 475       | 480            | 795   | 465                 | 435.4 ± 132.4 |
|               |            | Spring     | 370          | 365                         | 375            | 350       | 322         | 336      | 321       | 330            | 325   | 326                 | 341.25 ± 19.3 |

(–) dash refers to undetermined data during winter season
Discussion

The Nile River is a vital source of life in Egypt, particularly in the Greater Cairo area, where many human activities occur along the river’s banks. While these activities have a detrimental impact on the water quality and biodiversity of the Nile, they also represent a potential source of parasitic infections, especially schistosomiasis, a disease that has a long history among Egyptian people. Therefore, it is crucial to investigate any risks of schistosomiasis transmission represented by the presence and distribution of snails, the intermediate hosts or cercariae, and the human infective stages. The distribution of the snails that transmit schistosomiasis is controlled by various biotic and abiotic factors (Gilioli et al. 2017; Habib et al. 2021), delineating the epidemiology of the disease (Habib et al. 2016, 2021). Moreover, the abundance and distribution of snails are unpredictable, making it challenging to understand their impacts on indigenous freshwater populations (Larson et al. 2020).

The chemical parameters of water for the surveyed sites along the Nile River in Greater Cairo revealed that water temperature tends to increase during the spring season (26.4–29.4°C), nearly equal to that recorded during the summer season (25–31.5°C) in the current study. These results exceeded the concern level determined by the National Recommended Water Quality Criteria for temperature (25°C) (EPA 2009). Although summer was the highest season in terms of snail numbers collected (669 snails), there was no association between temperature and the number of snails

Table 3 The abundance of snails’ species during different seasons

| Snail species               | Summer | Autumn | Winter | Spring | Total | % of abundance |
|----------------------------|--------|--------|--------|--------|-------|----------------|
| Bulinus truncatus          | 29     | 21     | 15     | 9      | 74    | 5.50           |
| Biomphalaria alexandrina  | 24     | –      | –      | –      | 24    | 1.80           |
| Lymnaea natalensis         | 20     | –      | –      | 1      | 21    | 1.60           |
| Lanistes carinatus         | 86     | 32     | 1      | 59     | 178   | 13.30          |
| Cleopatra bulimoides       | 44     | 37     | 36     | 5      | 122   | 9.10           |
| Melanoides taberculata     | 163    | 35     | 17     | 2      | 217   | 16.20          |
| Helisoma duryi             | 76     | 31     | 19     | 10     | 136   | 10.20          |
| Thiara scabra*             | 41     | 28     | 8      | 14     | 91    | 6.80           |
| Bellamytaunicolor          | 150    | –      | 20     | 58     | 228   | 17.00          |
| Physa acuta                | 18     | 1      | 36     | 6      | 61    | 4.60           |
| Theodoxus niloticus        | 18     | 117    | 38     | 14     | 187   | 14.00          |
| Total                      | 669    | 302    | 190    | 179    | 1339  |                |

Mean ± SE 60.82 ± 15.9B 27.45 ± 10.1A 17.27 ± 4.4A 16.18 ± 6.5A

F-value 4.214
p value 0.011

*An invasive snail species.
*A insignificant difference at $p > 0.05$;
*B significant difference between different seasons at $p < 0.05$
collected. This was obvious in spring, for example, where the mean temperature from all sites was 28.02°C, and the number of snails collected was the lowest (179 snails) of all seasons. Temperature is a major contributor to climate change (Stocker 2014). The temperature change has an evident effect on schistosomiasis as it controls the distribution and reproduction of the snail intermediate hosts (Campbell-Lendrum et al. 2015). Opisa et al. (2011) found a positive correlation between temperature and the abundance of B. pfeifferi, B. sudanica, and Bulinus globosus. Mathematical modeling indicates that the effect of small temperature rises in areas where schistosomiasis is prevalent will be determined by the species of snail acting as an intermediate host. For example, the temperature range for the survival of simulated B. alexandrina populations was 12.5–29.5°C compared to 14.0–31.5°C for B. pfeifferi populations. In areas where B. alexandrina is the host, a 2°C increase in temperature can more than double the risk of S. mansoni infection (McCreesh and Booth 2014).

Under laboratory conditions, both B. alexandrina and B. truncatus have the same optimum temperature for growth and reproduction (26–28°C) (El-Emam and Madsen 1982). However, El-Khayat et al. (2009) declared that B. alexandrina and B. truncatus could tolerate a wide range of temperatures reaching 34°C. Furthermore, Joof et al. (2021) observed that water temperatures ranging from 22.1 to 38.3°C did not show any statistically significant association with the seasonal abundance of Bulinus spp. Bulinus snails can tolerate higher temperatures due to their ability to aestivate and adapt, which explains the occurrence of S. haematobium in warmer areas than S. mansoni (Rubaba et al. 2016). Schistosomiasis transmission can occur at lower or higher threshold temperatures. For instance, S. mansoni can maintain its life cycle at temperatures as low as 11.5°C and high temperatures up to 40°C (Pflüger 1982). Studies on the effect of temperature on S. japonicum and its snail host, Oncomelania hupensis, revealed that the temperature rise could expand the potential transmission areas of schistosomiasis japonica (Yang et al. 2005; Zhou et al. 2008). However, Stensgaard et al. (2013) expected climate change and global warming to reduce the habitats suitable for schistosomiasis vectors in Africa.

The pH of the water was found to be neutral at all the investigated sites during different seasons. Spring and summer showed the highest and lowest snail abundance, respectively, yet both were identical in their pH values. The impact of pH on snails’ abundance remains a controversial issue. Marie et al. (2015) found that the highest percentage of snails was recorded in the neutral pH range, while it decreased when pH was below 7 and higher than 9. Also, Makela and Oikari (1992) reported that an acidic pH level was unfavorable to mollusks’ occurrence. Similarly, Joof et al. (2021) found the abundance of Bulinus snails to increase with a decrease in water pH. Furthermore, Logronio (2020) observed that pH was negatively correlated to the number of infected snails and declared that the highest water pH level might lead to a decrease in infection. However, Opisa et al. (2011) did not find any correlation between pH (6.7–11.2) and the abundance of B. pfeifferi, B. sudanica, and Bulinus globosus.

The present work showed that dissolved oxygen was recorded at the lowest level during the summer range of 4.25–5.92 mg/L. Previous research has found that snail intermediate hosts’ optimal dissolved oxygen concentration is between 0.4 and 16.0 mg/L (Harman and Berg 1971; Yirenya-Tawiah et al. 2011). These findings are in accordance with the present results of snail surveying, where the highest snail abundance (669) was recorded during the summer season. B. pfeifferi, B. sudanica, and L. natalensis snails prefer sites with low dissolved oxygen (Olkeba et al. 2020). The negative correlation between snail abundance and the high level of dissolved oxygen may be attributed to the snails’ ability to occupy sites rich in organic matter (Galardo-Mayenco and Toia 2002). Regarding total dissolved solids (TDS), the highest mean value was recorded in the autumn season, with a concentration of 273 mg/L. Biomphalaria snails can be found in habitats with extremely variable TDS concentrations. For example, Barbosa et al. (2017) found B. straminea and B. glabrata in breeding sites with TDS ranging from 148 to 661 ppm. Moreover, Allan et al. (2020) found a positive correlation between the presence of intermediate host snails and total dissolved solids. The present study indicated that the summer season had the lowest conductivity with 340.5 μmohs/cm. This correlates with the observed highest abundance of snails during the summer. A positive correlation was also observed between the abundance of different Biomphalaria species and low conductivity (Kazibwe et al. 2006; Rowel et al. 2015; Trienekens et al. 2022).

M. tuberculata and B. unicolor were the most abundant snails recorded 16.2 and 17.1%, respectively in the current study. These findings are partially consistent with El-Khayat et al. (2017), who found M. tuberculata and B. unicolor abundances in the Nile River to be 13.9 and 16.7%, respectively. Meanwhile, the most common medically important snail species was B. truncatus, which agrees with the findings of Ibrahim et al. (2005). They revealed that B. alexandrina was less abundant than B. truncatus in the Nile River at Greater Cairo. On the other hand, other species of competitor snails such as Pomacea glauca, Marisa cornuarietis, M.s tuberculata, and H. duryi may also have a role in the control of medically important snail populations (Pointier and Jourdane 2000; Frandsen and Madsen, 1979). Also, Pointier et al. (1994) attributed the absence of B. glabrata, the snail host of S. mansoni, to the invasion
of Thiaras granifera and M. tuberculata in the rivers of the littoral central region of Venezuela.

Several factors have been reported to introduce invasive freshwater snails into new water bodies (Yirenya-Tawiah et al. 2011; Oladejo et al. 2021). In the present work, the invasive snails, T. scabra, were found during all seasons, with 91 individuals and an abundance percentage of 6.8%. Previous surveys have shown that the genus Thiaras was not considered to be represented in the molluskian fauna of Egypt (Ibrahim et al. 2006; Hussein et al. 2011; Abd Elwakeil et al. 2013; Abdel-Gawad and Mola 2014; Lotfy and Lotfy 2015). However, T. scabra as an invasive snail has been recorded for the first time in the Nile stream, Upper Egypt by Mostafa and Hussien (2018). These findings may interpret the current abundance of T. scabra snails at investigated sites in the Nile River. T. scabra is native to Asia with a distribution range from South and Southeast Asia, South China, and the western Pacific Islands (Brondt, 1974). Its introduction to the Nile River is still unknown until now. However, it might be introduced by some migratory birds. Recently, parasitologists have been increasingly interested in the Thiaridae family for harbouring numerous species that serve as intermediate hosts of human and animal diseases. T. scabra acts as an intermediate host for different trematode species. The most dangerous ones are the lung flukes of the genus Paragonemus and the intestinal flukes (Jayawardena et al. 2010; Krailas et al. 2011; Chontananarth et al. 2017). The present study revealed that the invasive snails were less abundant than the indigenous species. On the contrary, Oladejo et al. (2021) found that the invasive freshwater snails were more abundant (82.15%) than indigenous species (17.85%). Also, Oloyede et al. (2017) recorded 77.17% of invasive freshwater snails at Eleyele dam, southwest Nigeria.

According to the calculated diversity index, the present results indicated that the structure of snails’ habitats was poor, while the Evenness index indicated that the individuals were not distributed equally. These results are in parallel with Mahmoud and Sayed (2018), who found 13 species of snails at 5 sites in the Damietta Governorate with a diversity index ranging from poor to bad. Also, El-Zeiny et al. (2021) studied the five stations in Damietta Governorate, Egypt, and discovered that the diversity index ranged from poor to bad. Many agricultural chemicals, the degree of aquatic pollution (Ojija 2015), and the speed of the water may lead to changes in the status of snail habitats and cause adverse effects on their distribution and population (Mahmoud et al. 2018).

No schistosome cercariae were recovered from B. alexandrina and B. truncatus snails collected during the present snail survey. However, cercariometry identified Schistosoma cercariae in the investigated sites during the spring season (100% cercarial distribution), followed by autumn (42%), then summer (25%), and winter (8%). Cercariometry determines cercariae’s daily, seasonal, and spatial distribution in natural water bodies. Cercariometry has some flaws in its practices and data analysis, but it does provide valuable information on active schistosomiasis transmission sites (Aoki et al. 2003). The results of cercariometry and snail sampling were significantly different. The distribution of cercariae was not positively correlated with B. alexandrina or B. truncatus numbers or the occurrence of natural infection. We couldn’t confirm whether the recovered cercariae belong to S. mansoni or S. haematobium. Still, we suggest that these cercariae belong to S. haematobium because B. truncatus was found during all seasons while B. alexandrina was only found in the summer season. These findings show that cercariometry is more sensitive than other methods for detecting potential schistosomiasis transmission sites. This finding agrees with Yousif et al. (1996), who found that snail sampling revealed only 7 positive sites in the governorates of Kafr El-Sheikh, Ismaillia, and El-Minia, whereas cercariometry revealed 45 positive sites. In Kwaile, Kenya, Muhoho et al. (1997) observed an apparent discrepancy between cercariometry and snail sampling results. However, Ouma et al. (1989) discovered a moderately positive relationship between S. mansoni cercariae recoveries and the number of infected B. pfeifferi detected by sampling.

Because of the complexities of transmission foci, water velocity, snail distribution, and cercarial shedding patterns from snails, establishing a precise relationship between cercarial densities and the number of infected snails is likely difficult. Although xenomonitoring, or the surveillance of infected intermediate host snails, is a very effective approach that offers information on the patterns of transmission between humans and snail vectors, it is limited by the necessity to test vast numbers of snails, as only a small proportion of a total snail population is infected (Weerakoon et al. 2018). Furthermore, most malacological surveys used to determine the natural infection of vector snails rely on a single annual sample of densely packed snail populations spread across a large area. In transmission foci where snail host species sampling is the only method used, this method may underestimate the true level of infectivity. Schistosomiasis transmission in large bodies of water such as the Nile is likely seasonal (Kloetzl and de Azavedo Vergetti, 1988). Thus, cercariometry and snail surveys are recommended for pinpointing schistosomiasis transmission sites (Aoki et al. 2003).

The major drawback of using cercariometry as a stand-alone approach in the surveillance of schistosomiasis is the inability to differentiate between species of schistosomes contaminating the body of water investigated. In Africa, numerous Schistosoma species exist, and non-specialists cannot designate a Schistosoma sp. cercaria to the species level based on morphological criteria because of morphological similarities between human and non-human species. The most dangerous ones are the lung flukes of the genus Paragonemus and the intestinal flukes (Jayawardena et al. 2010; Krailas et al. 2011; Chontananarth et al. 2017). The present study revealed that the invasive snails were less abundant than the indigenous species. On the contrary, Oladejo et al. (2021) found that the invasive freshwater snails were more abundant (82.15%) than indigenous species (17.85%). Also, Oloyede et al. (2017) recorded 77.17% of invasive freshwater snails at Eleyele dam, southwest Nigeria.

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schistosomes (Frandsen and Christensen 1984). For example, *Schistosoma bovis* (causing bovine schistosomiasis) and *S. haematobium* are transmitted by the same *Bulinus* species, may occur sympatrically in the same habitat, and their cercariae are very similar in morphology and hence difficult to distinguish (Agola et al. 2021). Therefore, mammalian schistosomes, such as the bovine schistosome, can make pinpointing locations implicated in *S. haematobium* transmission difficult. In Egypt, there are no records for *S. bovis* in the country. Therefore, we believe that the cercariae recovered belong to human schistosomes.

Multiple techniques have been developed to identify schistosomes in the water bodies, ranging from deploying sentinel mice to collect cercariae from the water to collecting environmental DNA samples comprising DNA from intact or disintegrating bodies of schistosomes or their snail hosts followed by sequencing to validate species identifications (Kamel et al. 2021). Monitoring events in snails or water also aids in determining whether specific schistosome species have been introduced into new areas or reintroduced into former endemic areas, defining transmission hot spots spatially and temporally, and assessing the success of intervention methods aimed at the human population (Amarir et al. 2014, Weerakoon et al. 2015). Using schistosome or snail eDNA collected from water samples is one of the most promising advancements in the environmental diagnosis of schistosomes (Sengupta et al. 2019). eDNA has been used successfully to detect *S. mansoni* (Sato et al. 2018), *S. haematobium* (Akande et al. 2012), and *S. japonicum* (Fornillos et al. 2019) in water samples. A surveillance strategy that combines eDNA-based monitoring with classic and molecular xenomonitoring approaches might be used to correctly assess *Schistosoma* species found in natural habitats (Alzaylaee et al. 2020). Molecular xenomonitoring detects the presence of *Schistosoma* DNA in snails using traditional PCR (Melo et al. 2006) or quantitative PCR (Kane et al. 2013), providing evidence of water contamination with schistosome miracidia penetrating snails as well as pre-patent infection with developing schistosome larvae (Pennance et al. 2018).

**Conclusion**

Schistosomiasis remains a public health problem in some parts of Egypt. The present study identified some transmission foci for *S. haematobium* along the Nile River in Greater Cairo. The present data indicate that periodic surveying of snail species, particularly those that serve as intermediate hosts of digenetic trematodes, is important for disease control. Combining snail sampling with cercariometry improves the identification of schistosomiasis transmission foci in large bodies of water like the Nile. Given the advent of molecular technologies, more comprehensive surveys should be undertaken to identify active transmission foci using molecular xenomonitoring and environmental DNA approaches. It is also important to identify the species of snails distributed in the Egyptian water courses to check for the presence of any invasive species that pose a threat to human health. Further studies are needed to investigate the origin of invasive snails, the relationship between the invasive and indigenous freshwater snails, and how they established themselves in the habitat and developed ecological links with the indigenous species.

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**Declarations**

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** All applicable institutional, national, and international guidelines for ethics were followed.

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