A MALACOLOGY SURVEY TO MAP OUT SCHISTOSOMIASIS TRANSMISSION SITES ON MAGETA ISLAND, SIAYA COUNTY, WESTERN KENYA

BY

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DECLARATION

I declare that this thesis is my original work and it has not been submitted elsewhere for examination, award of a degree, or publication. Where other people's work has been used, this has properly been acknowledged and referenced per the University of Nairobi requirements.

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DEDICATION

I dedicate this thesis to my late mother Elizabeth Adongo Ogutu for instilling in me the values of discipline and patience and to my daughter Nelly Ayalo for inspiring me to work hard.

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LIST OF ABBREVIATIONS AND ACRONYMS

cm: Centimeter

GPS: Global positioning system

I.Hs: (Snail) Intermediate hosts

NTD: Neglected tropical disease

MDA: Mass drug administration

mm: millimeter

m: meter

m^2: Meter-square

^oC: Degrees Celsius

PZQ: Praziquantel

SCORE: Schistosomiasis Consortium for Operational Research and Evaluation

TAT: test-and-treat

WHO: World Health Organization

WHA: World Health Assembly

DEFINITIONS

Apex: top of an ovate shell

Malacology: The study of mollusks

Operculum: shell opening

Suture: The spiral lines on a snail shell

Umbilicus: A feature on the underside of *Biomphalaria* snail shell

Whorl: A complete coil in a snail's shell body

ABSTRACT

The persistence of human schistosomiasis in the Lake Victoria region is partly attributed to the presence of snail intermediate hosts in the genera of *Biomphalaria* and *Bulinus*. The areas around the Lake Victoria shores provide suitable habitats for the establishment of the snail intermediate hosts. A cross-sectional survey was carried out in August 2020 to map out schistosomiasis transmission sites on Mageta Island, western Kenya, to fill the gap in transmission risk to the Island's residents. A sampling of snails was done using a scoop made up of a stainless-steel sieve with a mesh size of 2 mm by 2 mm from 8 am to 11 am. A long pair of forceps was used to pick snails from sites where the scoop could not be used. The snails were identified to the species level and taken to the Mageta Health Centre for the cercarial shedding process. Cercariae shed by each snail were recorded as either bifurcate or non-bifurcate. Other parameters recorded from each habitat included the presence of human activities, presence, and identification of vegetation, and habitat bottom surfaces, among others (see Appendix 2). A total of 9,779 freshwater snails were collected from 116 habitats on Mageta Island. There were six snail species of medical importance (*Biomphalaria sudanica*, *Bulinus tropicus*, *Lymnaea natalensis*, *Biomphalaria pfeifferi*, *Bulinus nasutus*, and *Bulinus forskalii*) and four of non-medical importance (*Melanoides tuberculata*, *Bellamya* spp., *Physa acuta*, and *Pila ovata*). The most abundant snails were *Bi. sudanica* (86.94%; n= 8502) and *Bu. tropicus* (6.23%; n= 609) and the most abundant habitat types were natural habitats (94.82%; N = 110). Although most snails were found in natural habitats, the odds of finding snails in natural habitat were twice that of finding snails in a manmade habitat (OR = 2.052, 95% CI = 0.237 – 17.776), but without a significant difference (P = 0.514). Most snails were geographically distributed on the northern, eastern, and a few western parts of Mageta Island. Lake shoreline, swamps, and lagoons were classified as natural habitats, while banana plant holes, ditches, and boats were classified as manmade. Habitats classified as natural comprised 94.82% (N = 110) of the habitats and contained 96.32% (n = 9419) of the sampled snails. Manmade habitats comprised 5.17% (N = 6) of habitats and contained 3.68% (n = 360) of the sampled snails. *Biomphalaria sudanica* was the most abundant snail species (86.94%; n = 8502) followed by *Bulinus tropicus* (6.23%; n = 609). The mean number of *Bi. sudanica* (137.061 ± 1.49) was significantly higher (P < 0.05) in habitats with mud bottom surfaces. *Biomphalaria pfeifferi* and *Bu. nasutus* were only found in habitats with mud bottom surfaces. The mean number of *Bu. tropicus* and *Bu. forskalii* were significantly higher (P < 0.05) on rock and wood bottom surfaces,

respectively. Six snail species out of ten sheds come kind of cercariae with only five species shedding bifurcate cercariae. Snails collected from habitats with human activities had the highest prevalence of infection, but the shedding of cercariae was not associated with the presence or absence of human activities in habitats (P = 0.685). A total of only five sites harboring snails infected with bifurcate cercariae were found on Mageta Island. Vegetation played a major role in predicting the presence of snails in habitats on Mageta Island with *Eichhornia crassipes* (water hyacinth) harboring most snails. Even though there were few schistosomiasis transmission sites on Mageta Island, the mere presence of snail intermediate hosts in habitats around Lake Victoria and schistosomiasis infection being found among some of the residents, indicate that residents of Mageta Island are at an increased risk of schistosomiasis infection. Efforts to control the snail intermediate hosts should be carried out on Mageta Island in combination with studies on the prevalence of schistosomiasis among the residents.

CHAPTER 1: INTRODUCTION

1.1. Background Information

Human schistosomiasis (Bilharzia) is one of the most prevalent and persistent neglected tropical diseases (Colley *et al.,* 2014). Approximately 250 million people in the world living in 78 low- and middle-income tropical and sub-tropical countries are affected by the disease (Hotez *et al.,* 2014; Lai *et al.,* 2015). By 2019, an estimated 236.6 million people required preventive treatment and more than 105.4 million people had received treatment (WHO 2021). In Kenya, about 17.4 million people are at risk of schistosomiasis infection (Global Atlas for Helminth Infection 2021), with 6 million people infected with the disease (Chitsulo *et al*. 2002). The persistent success of human schistosomiasis is owed to snail hosts that produce human-infective cercariae in freshwater habitats.

In Sub-Saharan Africa, intestinal and urogenital schistosomiasis is transmitted by freshwater species of snails belonging to the genera *Biomphalaria* and *Bulinus*, respectively. In Kenya, intestinal schistosomiasis is transmitted by three taxa of *Biomphalaria* snails: *Bi. choanomphala, Bi. pfeifferi*, and *Bi. sudanica*. Urogenital schistosomiasis is transmitted by the *Bulinus africanus* group of snails, represented by *Bu. globosus*, *Bu. africanus,* and *Bu. nasutus*, and *Bulinus truncatus/tropicus* group represented by *Bu. tropicus* (potential intermediate host) and *Bu. truncatus.* The geographical distribution of the intermediate snail hosts corresponds to the areas where schistosomiasis is endemic in Kenya. *Biomphalaria pfeifferi* is found in the Lake Victoria area (Opisa *et al*., 2011), Mwea irrigation scheme canals, except in the tropical lowland belt along the coast (Brown, 2002; Morgan *et al.* 2001). *Biomphalaria sudanica* is mainly distributed along the shores of Lake Victoria (Opisa *et al*., 2011; Ofulla *et al.,* 2013). *Biomphalaria choanomphala* is found in the deep waters of Lake Victoria (Brown 2002; Mutuku *et al.,* 2019). The *Bulinus africanus* group is distributed in Coastal Kenya (Kariuki *et al*., 2004; *Dida et al*., 2014), Central Kenya (Brown 2002), and the Lake Victoria area (Opisa *et al*., 2011; Ofulla *et al.,* 2013; Chibwana *et al*., 2020).

The treatment of schistosomiasis is done successfully using praziquantel in areas where the disease is endemic (Doenhoff *et al*. 2009; Wiegand *et al.,* 2017). However, various studies have pointed out that mass drug administration (MDA) is not effective in controlling or eliminating schistosomiasis (Kihara *et al.,* 2012; Lelo *et al*. 2014; Masaku *et al.* 2017; Mutuku *et al.,* 2019). The persistent presence of the intermediate snail hosts where human beings come into contact with water puts at risk the success of the treatment efforts using MDA. Therefore, it is important

to identify the schistosomiasis transmission sites that are facilitated by the snail intermediate hosts to counteract the re-infection of the disease (Mutuku *et al.,* 2016). As a result, this study aimed to identify the schistosomiasis transmission sites in Mageta Island in Siaya County, western Kenya.

1.2. Research Problem

Human schistosomiasis is a parasitic disease transmitted through exposure to freshwater snail intermediate hosts infected with *Schistosoma* cercariae. The disease is persistent in endemic regions of sub-Saharan Africa despite efforts of morbidity control with praziquantel. In Kenya, human schistosomiasis re-infection occurs as soon as mass drug administration (MDA) is stopped (Lelo *et al*., 2014) because locals are always in frequent contact with water where schistosomiasis snail intermediate hosts inhabit. The Lake Victoria region in Kenya is a well-known hotspot for human schistosomiasis transmission (Odiere *et al.,* 2011, 2012; Olsen *et al.,* 2015; Wiegand *et al.,* 2017; Chadeka *et al*., 2019). Here, frequent water contact among locals is enhanced by dependance on the lake water for domestic, occupational and also recreational purposes. Water contact in habitats where schistosomiasis snail intermediate hosts exist is one of the factors contributing to transmission of human schistosomiasis in the Lake Victoria region (Figure 1).

In Mageta Island (the study area for this study), an island in the Lake Victoria region, artisanal capture fishing forms the primary income source for the locals (Omwega *et al*., 2006; Nunan, 2010; Abila *et al*., 2014), and promotes frequent contact with lake water. Men are mainly involved in fish capture from Lake Victoria while women participate in fish processing and trade (Lwenya and Abila, 2004). Women and children also come into contact with Lake Victoria water when conducting daily household chores such as fetching water, laundry, bathing, and washing utensils since the lake is the main source of water for the locals (Awange and Ong'ang'a, 2006). Moreover, the high level of poverty among the Lake Victoria fishers of Kenya due to a lack of alternative income sources except fishing (Abila *et* al., 2014; van den Broek 2019), impedes their capability to build safe water supply systems (Awange and Ong'ang'a, 2006). The water supply system is important in reducing contact with cercariae-infested water (Takeuchi *et al*., 2019). Unfortunately, people living around Lake Victoria region such as Mageta Island, are forced to rely on lake water because of lack or inadequate water supply systems. Therefore, the locals are always coming into contact with water where schistosomiasis snail intermediate hosts inhabit, increasing their exposure to the disease.

Lake Victoria sustains habitats that befit the human schistosomiasis snail intermediate hosts (Brown, 2002; Standley *et al*., 2011). Given the importance of the intermediate snail hosts in determining the distribution and exposure risk of human schistosomiasis, it is crucial to have information on transmission points to plan effective control strategies (Opisa *et al*., 2011). Despite the role of the intermediate snail hosts in the transmission of schistosomiasis in the Lake Victoria region, very few studies have focused on identifying points of transmission, especially on the lake's islands. The knowledge gap on the distribution of intermediate snail hosts on the Mageta Island of Lake Victoria in terms of the transmission points presents an infection risk to its people. Therefore, this study aimed to carry out a malacology survey to map out schistosomiasis transmission sites on Mageta Island situated in Siaya County, western Kenya.

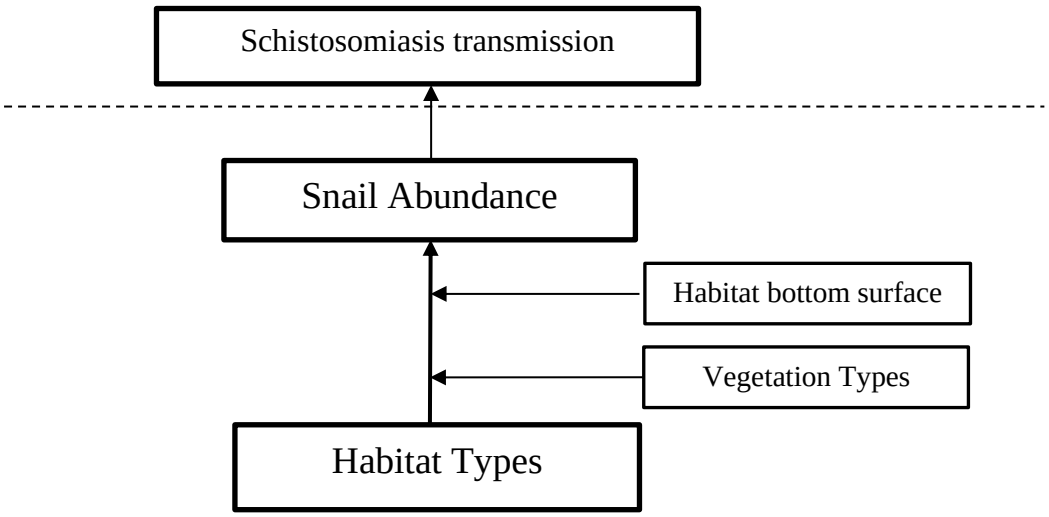

Figure 1: Conceptual framework illustrating the relationship between habitat types (independent variable) and snail abundance (dependent variable) on Mageta Island. The effect of habitat bottom surface and vegetation types as moderators of this relationship were also investigated. The arrows point to a cause-effect relationship while the boxes show variables of interest.

1.3. Justification and Significance of the Research

Mageta Island has never been targeted with any preventive chemotherapy interventions against schistosomiasis. However, geospatial modeling has predicted that the prevalence of *S. mansoni* infection along the shoreline of the Island is more than 50% (Woodhall *et al.,* 2013). Most studies on schistosomiasis in western Kenya have been done among communities living in mainland areas surrounding the Lake Victoria water mass (Handzel *et al.,* 2003; Mwinzi *et al.,* 2012), but few have been done on its Islands (Odiere *et al.,* 2012). Additionally, very few studies on the distribution of the snail intermediate hosts that transmit the disease have been done around the Lake Victoria region (Opisa *et al.,* 2012; Ofulla *et al.,* 2013; Mutuku *et al*., 2019) and its Islands (Standley *et al.,* 2010). Moreover, the spatial distribution of schistosome infections among the human population (Brooker *et al*. 2001; Standley *et al*. 2010; Scholte *et al*. 2014) and of intermediate snail hosts (Scholte *et al*. 2012) have been done using predictive maps to improve the allocation of available transmission control interventions. It is important to map the distribution of schistosomiasis snail intermediate hosts for proper planning and implementation of effective control interventions (Opisa *et al.,* 2011; Ofulla *et al.,* 2013).

The presence of uninfected and infected schistosomiasis snail intermediate hosts is often used to confirm that a water body is a potential transmission site or a transmission site, respectively (Zhang *et al*., 2009; Appleton & Miranda, 2015). Areas that have been found not to respond to praziquantel treatment are often those with a presence of schistosomiasis snail intermediate hosts, which continue to sustain infection among the human population (Lelo *et al*., 2014; Mutuku *et al*., 2019). The control of schistosomiasis cannot be achieved without integrating snail control among other methods of controlling the disease. The World Health Assembly (WHA) resolution 65.21 of 2012, called for the research and application of complementary and non-pharmaceutical control strategies for eliminating schistosomiasis. Snail control is currently not the main focus of the current global schistosomiasis control strategies (WHO 2006), but growing evidence suggests that it is the best strategy for disease control (McCullough, 1992; Sokolow *et al.* 2016, 2018; WHO, 2017), especially when combined with school-based and community-wide MDA interventions (Lo *et al.* 2018). Countries that have been successful in achieving long-term schistosomiasis control have incorporated snail control in their control strategies. For instance, the regional elimination of schistosomiasis in Japan by 1996 was achieved through the test-and-treat program with the main focus being on snail control (Tanaka and Tsuji, 1997).

Mageta Island is one of the Islands of Lake Victoria where the prevalence of schistosomiasis is unknown. Despite the exposure risk that the people on the Island are in due to frequent contact with lake water, which intermediate host snails might inhabit, no schistosomiasis studies among the human population have been done. This study aimed to map out schistosomiasis transmission sites on Mageta Island with implications for disease studies among the human population.

1.4. Research Objectives

1.4.1. General Objective

To identify schistosomiasis transmission sites on Mageta Island which is located within Lake Victoria in Siaya County in western Kenya.

1.4.2. Specific Objectives

1. To document the diversity of freshwater snail species on Mageta Island in western Kenya.
2. To assess the prevalence of trematode infections in freshwater snails on Mageta Island.
3. To develop a schistosomiasis risk map for Mageta Island.
4. To investigate the association between plant species and the occurrence of snails in freshwater habitats on Mageta Island.

1.5. Research Hypotheses

1.5.1. Null Hypothesis

1. The diversity of schistosomiasis snail intermediate hosts is not related to habitat type.
2. There is no relationship between schistosomiasis transmission sites on Mageta Island and human activities.

1.5.2. Alternative Hypothesis

1. The diversity of schistosomiasis snail intermediate hosts is related to habitat type.
2. There is a relationship between schistosomiasis transmission sites on Mageta Island and human activities.

CHAPTER 2: LITERATURE REVIEW

Schistosomiasis is classified as one of the neglected tropical diseases (NTDs) (WHO 2012). The disease is neglected because of the absence of well-established global funding, poverty, lack of political voice among the affected people, and underappreciated global burden (Payne and Fitchett 2010; Karunamoorthi *et al*. 2018). Despite the global effort to control schistosomiasis through preventive chemotherapy, many people still suffer from the disease as they did 50 years ago. The main obstacle in reducing or eliminating schistosomiasis in most countries has been reliance on a single control strategy for treating infected people with PZQ (Sokolow *et al*. 2018). Various studies have recommended an integrated approach to schistosomiasis control (Engels *et* al. 2002; Gray *et al*. 2010; Sokolow *et al*. 2018). One of the approaches is snail control which some argue is the best at eliminating schistosomiasis (Gray *et al.* 2010; King and Bertsch 2015). Snail control used to be the main focus of schistosomiasis control before the discovery of preventive chemotherapy (Sokolow *et al*. 2016). But the persistent burden of schistosomiasis is an indication that preventive chemotherapy alone cannot lead to elimination by the year 2025 as called on by WHO (WHO 2012).

2.1. Distribution and Burden of Schistosomiasis

2.1.1. Global Distribution of Schistosomiasis

Worldwide, human schistosomiasis is caused by 5 species of blood fluke parasites. Intestinal schistosomiasis is caused by *Schistosoma mansoni* in Africa, the Middle East, Brazil, the Caribbean, Venezuela, and Suriname (WHO, 2019). *Schistosoma japonicum* and *S. mekongi* cause intestinal schistosomiasis in China, Indonesia, and the Philippines, and several districts of Cambodia and the Lao People's Democratic Republic respectively. *Schistosoma intercalatum* specifically causes intestinal schistosomiasis in central African countries. However, urogenital schistosomiasis is specifically caused by *S. haematobium* in Africa, the Middle East, and Corsica in France (WHO, 2019). In Kenya, schistosomiasis is caused by *S. mansoni* and *S. haematobium* (GAHI, 2021), and the most prevalent form in the Lake Victoria region is caused by the former (Handzel *et al.*, 2003; Mwinzi *et al.*, 2012).

2.1.2. Global Burden and Control Strategies of Schistosomiasis

More than 250 million people are infected with schistosomiasis globally and an estimated 800 million people are at risk of infection (Lai *et al.* 2015), resulting in a total of 3.3 million disability-adjusted life years (DALYs) (Hotez *et al.* 2014). An estimated 90% of all cases of

schistosomiasis are in sub-Saharan Africa where more than 20 million suffer from the chronic form of the disease (Table 1). The chronic form of schistosomiasis decreases the capacity of those infected to continue with their everyday work and in some cases, it results in death. In children, the disease causes anemia, stunted growth, and reduces the ability to learn (Colley *et al*., 2014).

The current recommended control strategy for schistosomiasis aims at preventing morbidity through regular treatment with PZQ to reduce infection intensity. Praziquantel is the only recommended drug for treating those infected with human schistosomes (WHA 2012). The drug has proved effective in treating schistosomiasis for the past three decades in many countries (Olveda *et al.* 2016). But experience from countries that have eliminated or reduced its prevalence (Figure 2) has shown that morbidity control alone is not entirely effective in controlling or eliminating the disease (Sokolow *et al*. 2016, 2018). Through a combination of preventive chemotherapy, snail control, health education, and hygiene improvement, China has managed to successfully control *Schistosoma japonicum* which has been eliminated in several provinces (Utzinger *et al*. 2005). In Japan, schistosomiasis was eliminated by 1996 through a test-and-treat (TAT) campaign together with snail control (Tanaka and Tsuji 1997). In Africa, schistosomiasis has been eliminated in Tunisia and is close to elimination in Morocco (Sokolow *et al.* 2016). The prevalence of the disease is below 10% in Egypt and less than 1% in Brazil. However, in other sub-Saharan countries, schistosomiasis prevalence above 50% has been reported (Figure 3).

Table 1: Current estimated total number of individuals with morbidity and mortality due to *Schistosoma mansoni* and *S. haematobium* infection in Sub-Saharan Africa

Schistosome species	Estimated morbidity and mortality (millions)
S. haematobium	
At risk of infection	436
Infected	112
Hematuria during previous 2 weeks	71 (52-89)
Dysuria during previous 2 weeks	32 (17-55)
Minor bladder morbidity (detected by ultrasound)	76 (67-92)
Major bladder morbidity (detected by ultrasound)	24 (15-31)
Moderate hydronephrosis	9.6
Major hydronephrosis	9.6
Non-functioning kidney	[1.7]
Non-functioning kidney (deaths/year)	[0.15]
Bladder cancer (deaths/year)	
Males	[0.011]
Females	[0.0023]
S. mansoni	
At risk of infection	393
Infected	54
Diarrhoea during previous 2 weeks	0.78 (0.0-7.8)
Blood in stool during previous 2 weeks	4.4 (3.0-8.3)
Hepatomegaly (mid-sternal line)	8.5
Splenomegaly	[6.3]
Ascites	[0.29]
Haematemesis (ever)	[0.93]
Haematemesis (deaths/year)	[0.13]

Source: WHO 2021

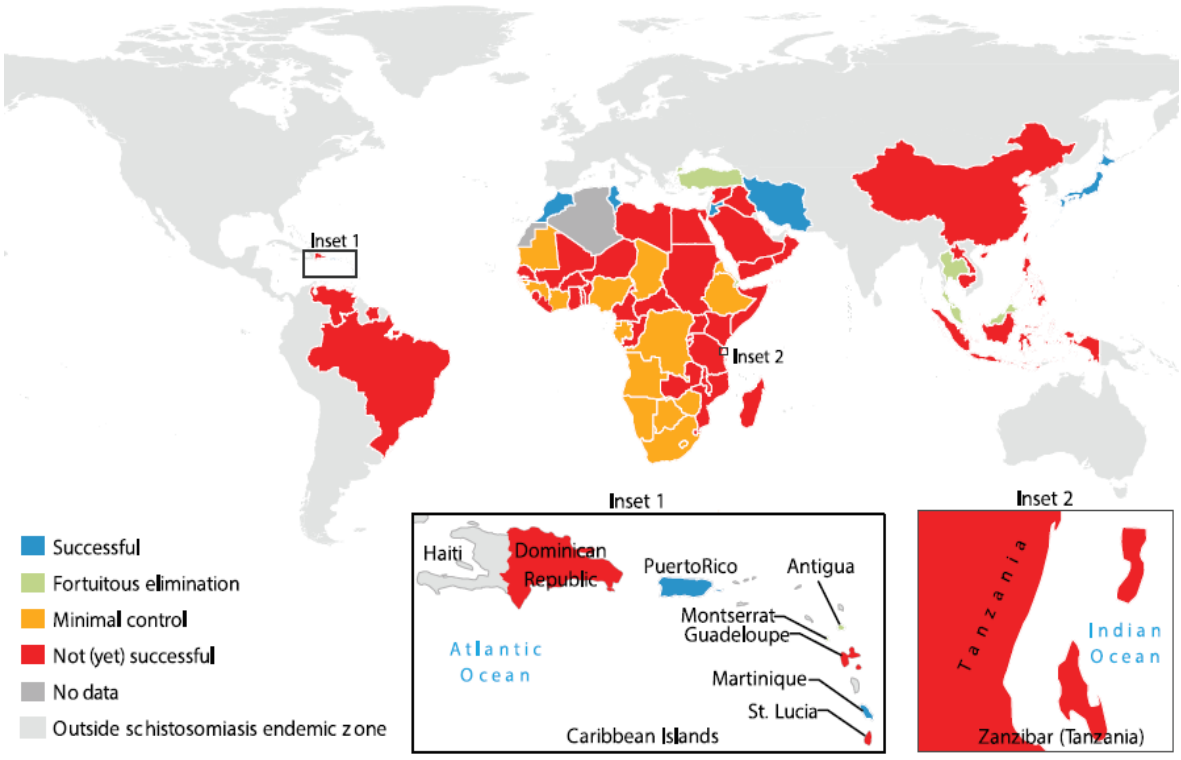

Figure 2: Global schistosomiasis control or elimination efforts (Sokolow *et al*. 2016).

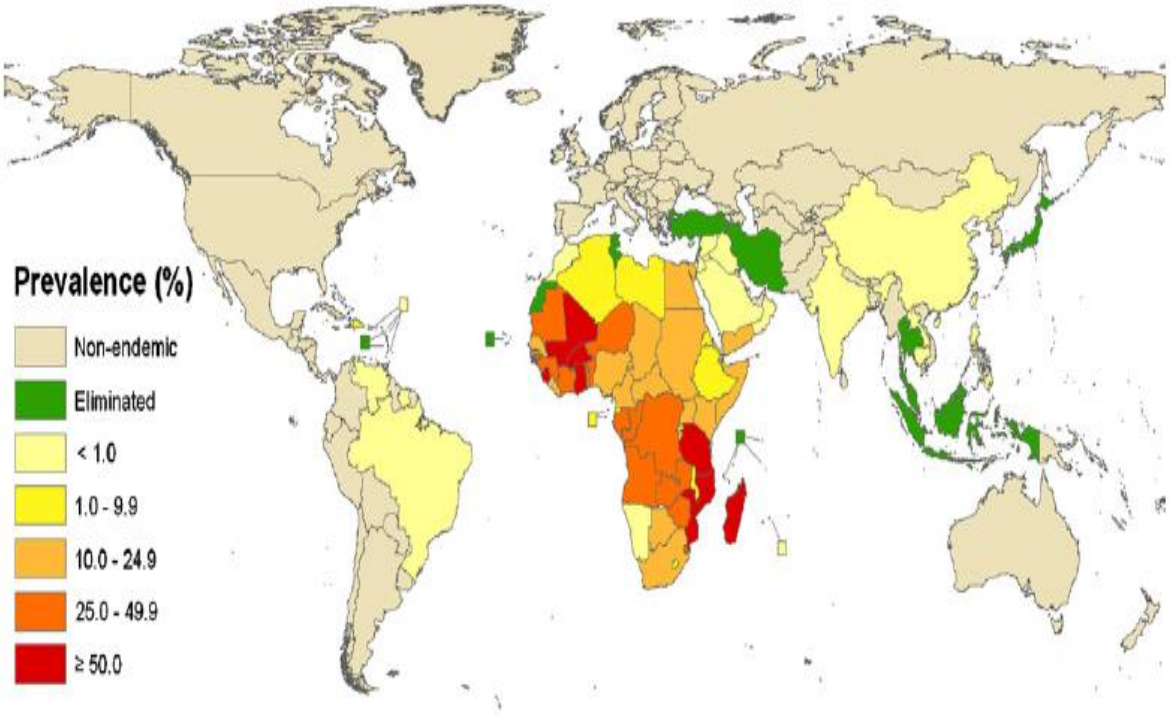

Figure 3: Global distribution of schistosomiasis with prevalence estimates (Utzinger *et al*. 2011)

2.1.3. Schistosomiasis Distribution in Kenya

Intestinal and urogenital schistosomiasis is endemic in Kenya (Figure 4). Human schistosomiasis is endemic in 32 counties made up of 158 endemic sub-counties (National NTD Strategic Plan 2016-2020). The risk factors for schistosomiasis in Kenya include fishing and rice farming in irrigation schemes mostly in rural communities, including limited access to potable water, poor sanitation, and hygiene, as well as limited knowledge of the cause and transmission of schistosomiasis. High prevalence of the disease is present in three regions of Kenya: Nyanza, Central, and Coast. In Nyanza, the two forms of schistosomiasis are common in urban and suburban areas around Lake Victoria, and adjacent islands with the most prevalent form being *S. mansoni* in the following sub-counties; Siaya, Bondo, Rarieda, Kisumu East, Kisumu West, Nyando, Homa Bay, Suba, Rachuonyo, Migori, Rongo, Kuria West, Kuria East, Kisii Central, Kisii South, Nyamira, Masaba, Gucha South, Borabu, and Manga. In Central Kenya, the most prevalent schistosomiasis is *S. mansoni* present in irrigated agricultural areas of Kirinyaga, Murang'a North, and Kiambu West. In the Coastal region, urogenital schistosomiasis is the only form of the disease in the following sub-counties; Kwale, Kinango, Msambweni, Kaloleni, Kilifi, Malindi, Lamu, Tana Delta, Tana River, and Taveta (National NTD Strategic Plan 2016-2020).

Schistosomiasis is also present in Lower Eastern Kenya in the following sub-counties; Kitui, Mbeere, Mwingi, Machakos (both forms), Mwala, Mbooni, Kibwezi, Nzaiu, Makueni, Kangundo, and Yatta (National NTD Strategic Plan 2016-2020). The risk of intestinal schistosomiasis is also present in the west and east of Nairobi and urogenital schistosomiasis in the Northeastern part of Kenya extending from Garissa Town to Wajir, and Mandera. In Rift Valley only intestinal schistosomiasis is present in the following sub-counties; Baringo Central, Baringo North, West Pokot, Eldoret East, Naivasha, Trans Mara, and Kajiado North. In Western Kenya, intestinal schistosomiasis is present in Lugari, Busia, Teso North, Teso South, Samia, and Bunyala.

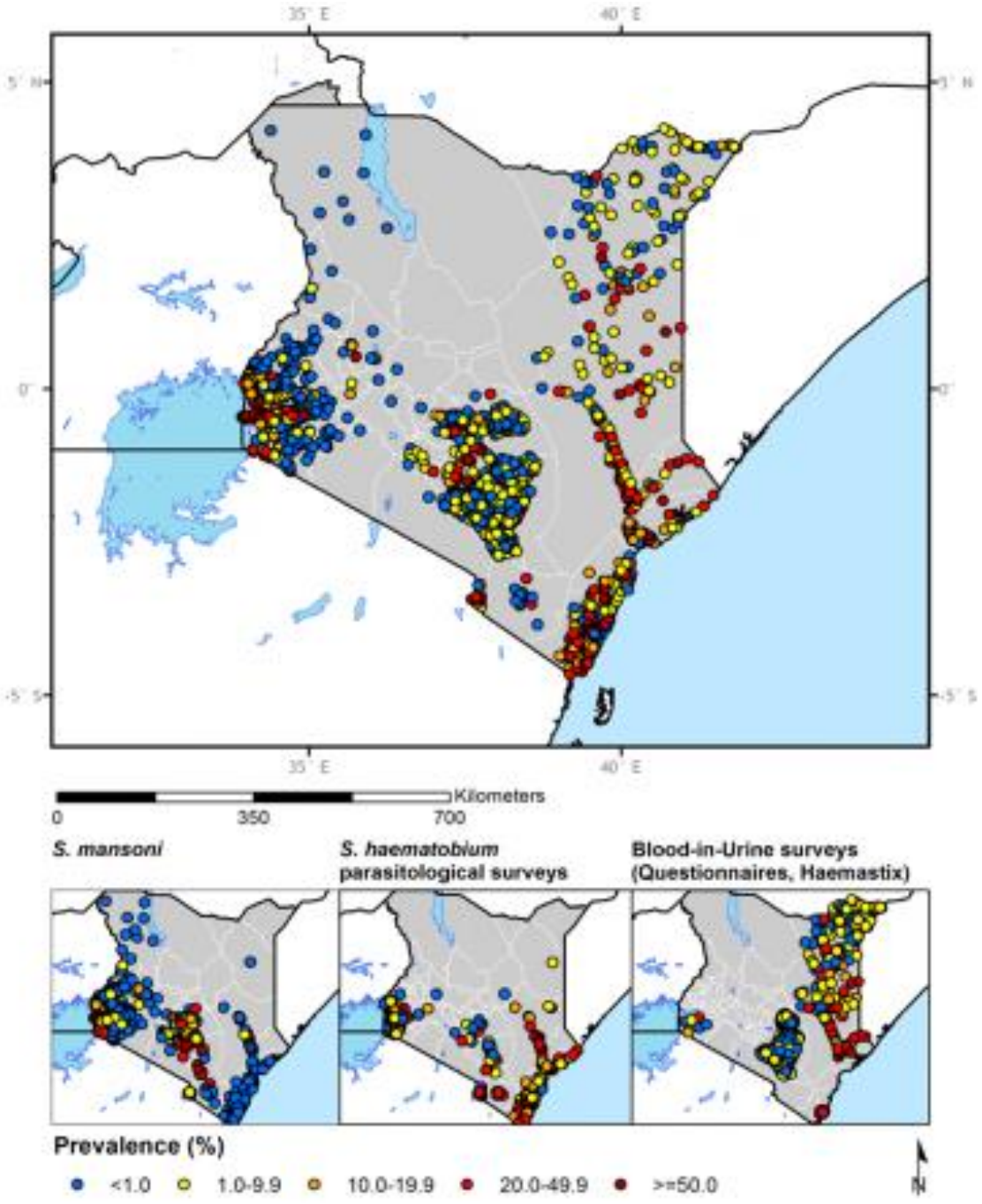

Figure 4: Distribution of human schistosomiasis showing point prevalence for *S. mansoni* and *S. haematobium* in Kenya (Global Atlas of Helminth Infections, 2021).

2.1.4. Schistosomiasis Control Efforts in Kenya

In Kenya, schistosomiasis is controlled through preventive chemotherapy to reduce morbidity among at-risk populations using PZQ. In 2008, the Schistosomiasis Consortium for Operational Research and Evaluation (SCORE) was established to evaluate the optimal practices related to the control and elimination of schistosomiasis through MDA in Western

Kenya (Colley, Jacobson, and Binder 2020). Under the SCORE project, various studies have been conducted to provide solutions to the best-integrated practices to stop transmission and eliminate schistosomiasis. One of the SCORE findings is that MDA alone is not enough to reach the goal of elimination of schistosomiasis, hence the need to use other alternative methods (Colley *et al*., 2020). In 2012, the Kenyan Ministries of Health and Education began a National School-Based Deworming Program (NSBDP) in schistosomiasis endemic regions (Nyanza, Western, Coast, and Rift Valley) of Kenya. The impact of the NSBDP was monitored and evaluated by the Kenya Medical and Research Institute (KEMRI) from 2012 to 2017. The monitoring and evaluation (M&E) programs were done before and after MDA intervention and repeated cross-sectional surveys. A study done by Mwandawiro *et al*., (2019) presents the results of the 5-year M&E program in 200 schools across Kenya surveyed for baseline, mid-term, and end-line assessments. The study revealed that MDA reduced the morbidity of schistosomiasis, but there was a need for complementing the MDA interventions.

Other post-MDA intervention studies have also shown that the program cannot be used alone to eliminate schistosomiasis. In 2005, the Kenyan Ministries of Health and Education collaborated with the Japan International Co-operation (JICA) and KEMRI and initiated a parasite control program for *S. mansoni* and soil-transmitted helminths (STHs) among school-age children. Before MDA intervention, a study was done in 5 primary schools in Mwea Division, Kirinyaga County. The prevalence of *S. mansoni* was 47.4% and reduced to 8.6% after MDA intervention (Kihara *et al*., 2007). However, a 4-year follow-up study revealed that there was re-infection at a rate of 16% for *S. mansoni* six months after treatment (Kihara *et al*., 2012). Additionally, after two years of withdrawal of the MDA intervention in the same area, there was an increased prevalence of *S. mansoni* to 53.7% among 387 school children (8-16 years) in 3 primary schools (Masaku *et al*., 2015). In the eastern part of the Lake Victoria area in Kenya, persistent hotspots have been found in a 5-year follow-up study. The MDA intervention was less effective at reducing *S. mansoni* prevalence and intensity in hotspot villages compared to other villages outside the hotspot area (Wiegand *et al*., 2017). The MDA programs effectively reduce schistosome morbidity, but the risk of re-infection after withdrawal of the program interferes with the control efforts. In schistosomiasis endemic areas of Kenya, the use of MDA alone cannot be used to reduce transmission (Lelo *et al*., 2014).

The risk of re-infection with schistosomiasis is aggravated by the selective treatment of at-risk populations with PZQ. The current schistosomiasis control programs in Kenya target school-age children. The exposure to schistosome infection is not restricted to school-going children

but the entire population. Various studies have shown that pre-school children (Sassa *et al*., 2020) and other population groups (Masaku *et al*., 2017) should be included in the MDA programs.

2.2. The Pathology of Schistosomiasis

2.2.1. *Schistosoma mansoni* and *S. haematobium*

Schistosomiasis is a unique helminthic infection because of two reasons: its pathogenesis is due to the human immunopathological reaction to *Schistosoma* eggs and not to the adult worms; most pathology is caused by host-immune responses (granulomatous reactions and delayed-type hypersensitivity) (Robert *et al.* 2009). The disease is divided into three phases: migratory, acute, and chronic. The migratory phase is marked by the penetration of cercariae, the infective larval form of the schistosome parasite on human skin, causing skin irritation or dermatitis if the patient's immune system has been sensitized to previous exposure to cercarial penetration (Robert *et al.* 2009). The acute phase (also called Katayama fever) results in a change in an antigen-antibody ratio when the female schistosome starts producing eggs two months after infection with cercariae. Symptoms associated with this phase include chills and fever, malaise, headache, fatigue, muscle aches, lymphadenopathy, and abdominal pain. The chronic phase occurs in response to the cumulative deposition of eggs in tissues and host immune reactions against the eggs. Not all eggs laid by female schistosomes penetrate the walls of the gut (*S. mansoni* eggs) or bladder (*S. haematobium* eggs), but most of them are swept into the circulation and become trapped in organs where they result in granulomatous responses. In the chronic phase, eggs are surrounded by inflammatory cells that form pseudotubercles, and the encapsulated eggs die and later calcify. The effects on host organs and tissue are numerous and include abdominal pain, bloody diarrhea, progressive enlargement of the liver and spleen, ascites, and lethargy (Gryseels *et al*. 2006; Robert *et al.* 2009).

Infection with *S. haematobium* is marked with blood in the urine (hematuria) and progressive damage of the bladder wall leading to carcinoma and also causes ureter fibrosis and kidney damage in some advanced cases. In the late stages of urogenital schistosomiasis, symptoms in females may include genital lesions, vaginal bleeding, painful intercourse (dyspareunia), and fallopian tube damage. In males, urogenital schistosomiasis may result in damage to the prostate and seminal vesicles, leading to irreversible infertility (Olveda *et al*., 2013). In both sexes, urogenital schistosomiasis is a risk factor for Human Immunodeficiency Virus (HIV) infection (Mbabazi *et al*., 2011).

2.2.2. The Life Cycle of Schistosomes

The life-cycle of schistosomes involves sexual reproduction in vertebrate definitive hosts (humans) and asexual reproduction in snail intermediate hosts (*Biomphalaria* and *Bulinus*). Adult schistosomes that cause intestinal schistosomiasis, prefer living within the superior mesenteric veins draining the large intestine of the human host. In urogenital schistosomiasis, adult schistosomes prefer living in vesicle venules of the urinary bladder. The adult male and female schistosomes mate and produce fertilized eggs. Some of the eggs are shed into the environment through feces (in *S. mansoni* infection) and urine (*S. haematobium* infection). The majority of the eggs are retained in human host tissues where they induce granulomatous inflammatory lesions (Colley *et al.* 2014).

The eggs that reach a freshwater body hatch into the free-living and ciliated larval form known as miracidia. The miracidia swim until they penetrate a suitable intermediate snail host where they transform into mother sporocysts which later produce daughter sporocysts. The daughter sporocysts produce cercariae that are shed from the snail into the surrounding water body. The cercariae infect humans who come into contact with the infested water. The cercariae can survive for up to three days in the water before they deplete their energy reserves and die. The asexual part of the lifecycle takes 4 to 6 weeks before cercariae are shed from the snail into the surrounding water body (Figure 5). After the cercariae penetrate the human skin, they transform into schistosomulae that move through the bloodstream to the liver where they take 5 to 7 weeks to mature into adults. *Schistosoma mansoni* adults pair up and move to the mesenteric veins, while *S. haematobium* move to the vesicle venules of the bladder, where they start to produce eggs (Colley *et al.* 2014).

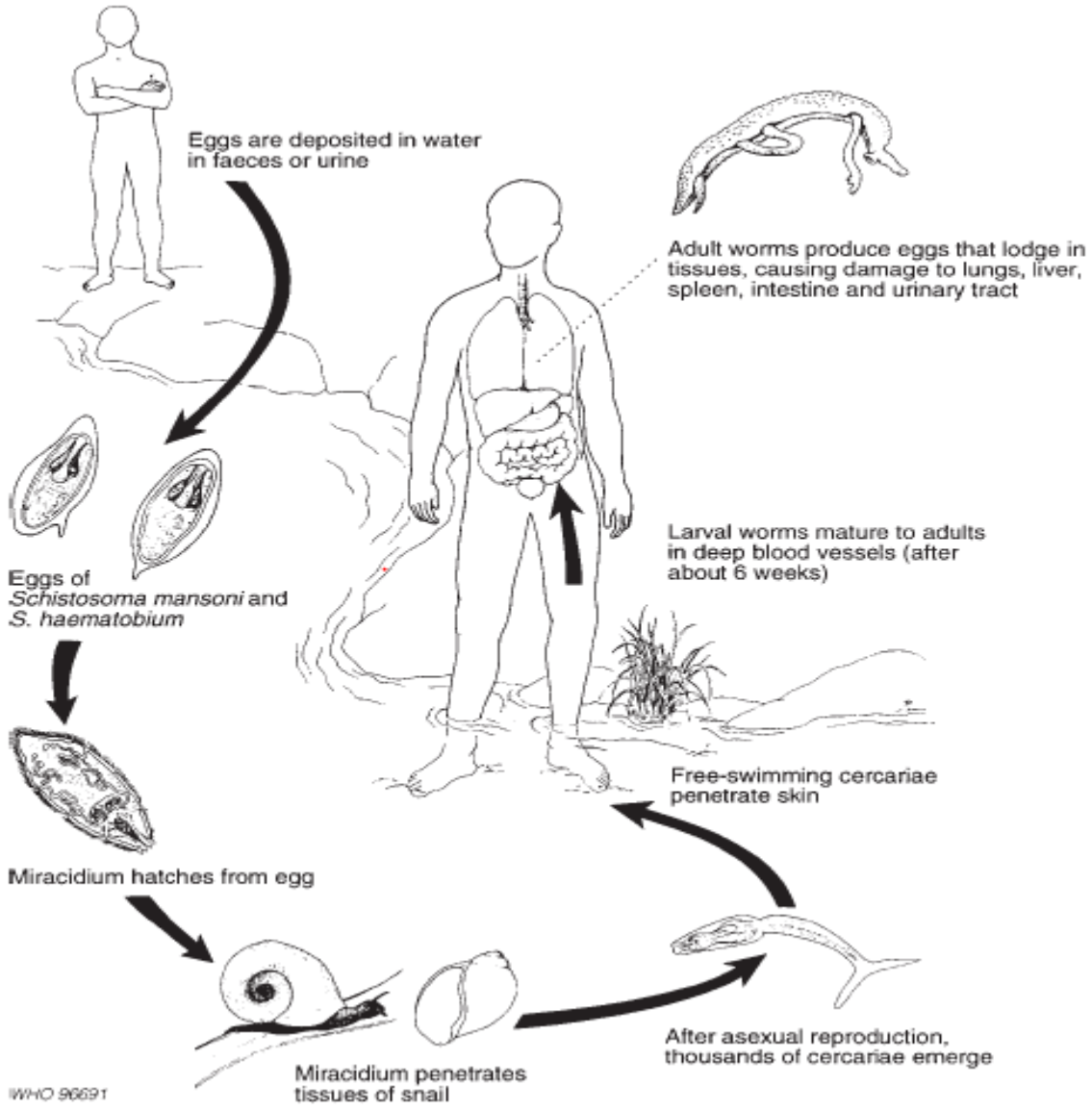

Figure 5: The life cycle of schistosomes in the *Biomphalaria* and *Bulinus* snails (intermediate hosts) and humans (definitive host). The cycle starts when humans deposit eggs (in feces or urine) in a freshwater body (Boelee and Madsen 2006).

2.3. Schistosome Snail Intermediate Hosts

2.3.1. General Classification and Biology

The intermediate hosts of *S. mansoni* and *S. haematobium* belong to the phylum Mollusca. Members of Mollusca include snails, slugs, clams, oysters, squids, and octopuses. The majority of the molluscs live in marine habitats, while the remaining ones live in fresh water and terrestrial habitats. The molluscs have soft bodies, but most are protected by a hard shell. All mollusks have the same body plan with three main parts: a muscular foot for movement; a

visceral mass containing most of their organs; and a mantle that encloses the mollusc's visceral organs (Figure 6) (Campbell and Reece, 2005). In general, molluscs have separate sexes, but snails are hermaphrodites.

Class Gastropoda is one of the many classes in the phylum Mollusca containing snails and slugs. Gastropods can be found in marine, freshwater, or terrestrial habitats with asymmetric bodies, with some members having coiled shells that can be conical or flat. They move with their foot through a rippling motion through the cilia (Campbell and Reece 2005). Most gastropods graze on plants or algae with their radula. Most marine gastropods have gills for gaseous exchange (Campbell and Reece 2005), except pulmonates that have developed a pallial lung for breathing air (Mandahl-Barth, 1957a).

Pulmonata is one of the several subclasses in class Gastropoda and order Basommatophora (snails have eyes at the base of tentacles and not at the end of tentacles as in the terrestrial pulmonates) containing schistosomiasis snail intermediate hosts. Under the subclass Pulmonata, there are several families, and schistosomiasis snail intermediate hosts belong to the family Planorbidae commonly known as the ram's horn snails. Freshwater pulmonates of Africa do not have operculum and the mantle cavity serves as an air-breathing organ since the snails do not have true gills (Brown 2002).

The shells of freshwater planorbids offer various characteristics important in taxonomy: the general shape of shells, the number, coiling, and shape of the whorls, and the shell opening (aperture). The African Planorbidae contains two subfamilies: Planorbinae and Bulininae, distinguished by the shape of the shell. The Planorbinae have lens-shaped (disc-shaped) shells while the Bulininae have ovate shells. The African Planorbinae is represented by the medically important genus *Biomphalaria* and other genera with no known medical importance, while Bulininae are represented by only one genus of medical importance, *Bulinus* (Mandahl-Barth, 1957a).

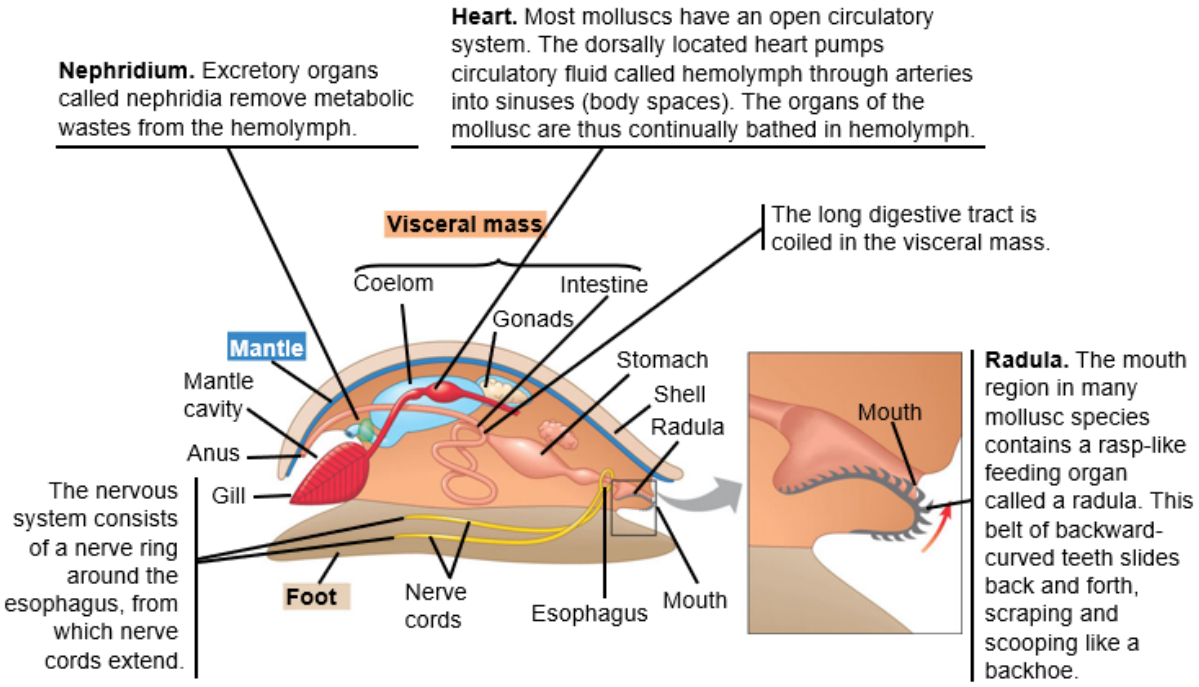

Figure 6: Molluscs general body plan with three main parts: muscular foot, visceral mass, and mantle (Campbell and Reece 2005)

2.3.2. *Biomphalaria* Snails

Biomphalaria snails have disc-shaped shells with all whorls placed in almost the same plane. The shells have varying heights ranging from 7 mm to 22 mm. The shell is dextral (right-handed) with the direction of coiling being clockwise when seen from the top. The shell dimensions in Figure 7a show the greatest diameter (line A-D) and the greatest distance between the sutures on the underside of the shell and the umbilicus (line B-C). The other shell dimensions are shown in Figure 7b. Full-grown *Bi. pfeifferi* has less than 15 mm in shell diameter with at most 5 whorls which are convex or angular on both sides (Mandahl-Barth, 1957a). However, *Bi. sudanica* has large shell diameters of up to 22 mm with five-and-a-half to six-and-a-half closely coiled whorls which are somewhat angular on the upper side and slightly angular on the underside (Brown 2002). *Biomphalaria* consists of snails with a varying number of whorls. When the shell has few whorls, they increase rapidly in width (as in *Bi. pfeifferi*) whereas, with many whorls, they increase slowly (as in *Bi. sudanica*). They all have long filiform tentacles, a secondary gill known as pseudobranch on the left side of the mantle, and a radula with central, lateral, and marginal teeth. They also have red blood with hemoglobin (Mandahl-Barth, 1957a).

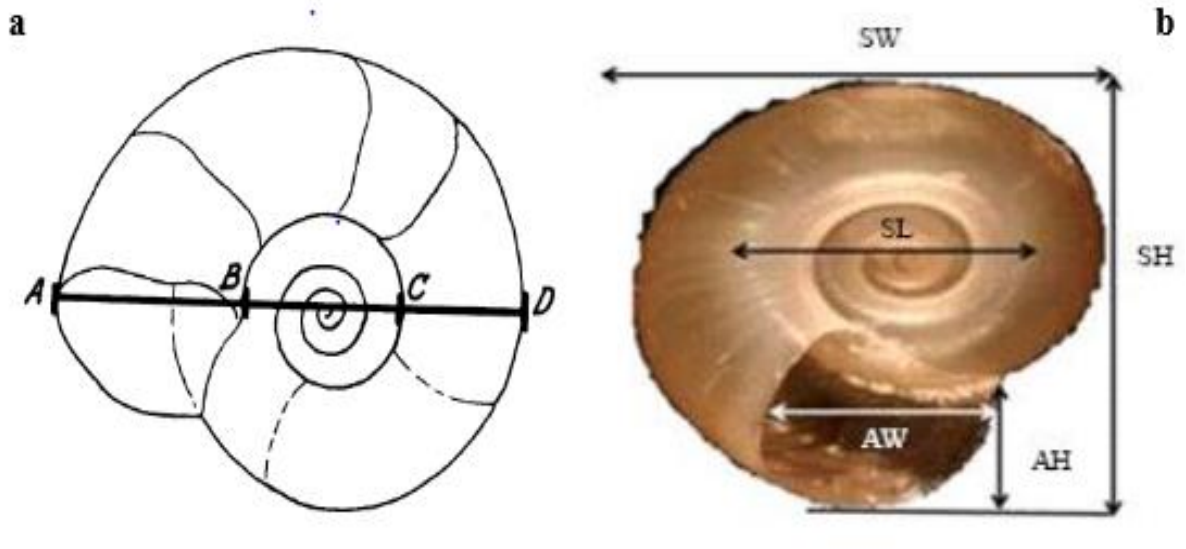

Figure 7: Disc-shaped shell of *Biomphalaria* snail showing important morphometrics: SH (shell height), SW (shell width), AW (aperture width), AH (aperture height), and SL (spiral length) (Mandahl-Barth, 1962). Shell diameter (A-D) and umbilicus (B-C).

2.3.3. *Bulinus* Snails

Bulinus snails have ovate shells which are higher than they are wide. The shells open to the left (sinistral) with coiling being anti-clockwise. The shell height varies between 4 mm and 23 mm (Mandahl 1957b). The shells may consist of 3 to 5 whorls, with a large aperture (Figure 8). *Bulinus* snails are divided into 4 species groups based on the shape and sculpture of the shell: *Bu. reticulatus* group, *Bu. africanus* group, *Bu. truncatus/tropicus* complex, and *Bu. forskalii* group. Members of the *Bu. africanus* group are the biggest species (13.4 mm by 24.5 mm) of *Bulinus* snails (Brown 2002). They are identified with a bend or truncation on the inner border of the shell opening (Figure 8). The most common and important intermediate hosts of *S. haematobium* include *Bu. globosus*, *Bu. africanus*, *Bu. nasutus*, and *Bu. ugandae.* The *Bu. africanus* group is commonly found in small dams, seasonal pools, irrigational systems, swamps, streams, rivers, and lakes where water is permanent, but *Bu. nasutus* can be found in temporary water habitats (Brown 2002). However, *Bu. africanus* and *Bu. nasutus* may be found together (Kariuki *et al*., 2004).

The *Bu. truncatus/tropicus* group (measuring 7.8 mm by 9.5 mm) is identified by the lack of truncation in the inner parts of the shell aperture. Important species in this group in Kenya include *Bu. truncatus* and *Bu. tropicus* (a potential *S. haematobium* intermediate host). The *Bu. forskalii* group is smaller and slenderer than the groups previously mentioned. The most common and widely distributed species in this group is *Bu. forskalii*. The *Bu. reticulatus* group

is very small (rarely 5 mm wide and 6 mm high) and acts as an intermediate host of *S. haematobium* under laboratory conditions. The group comprises only one species, *Bu. reticulatus* (Brown 2002).

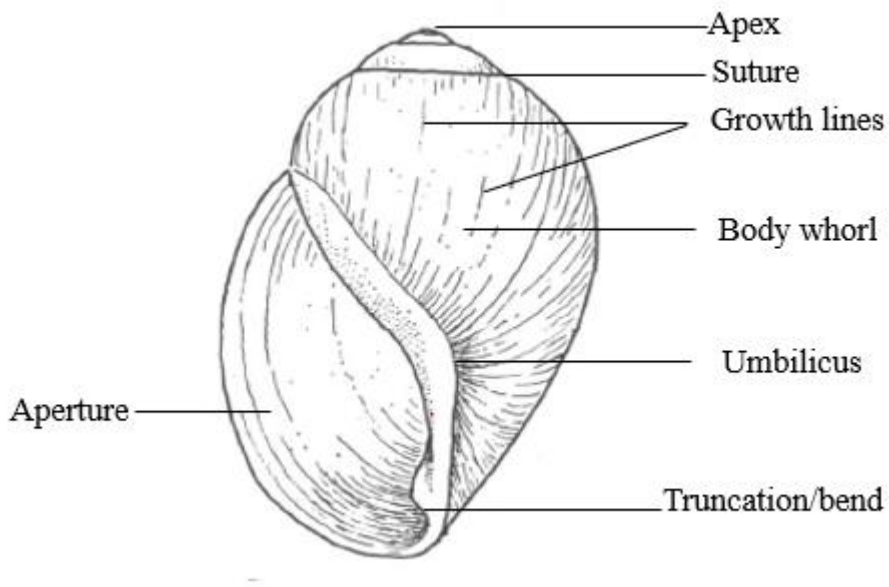

Figure 8: General morphology of *Bulinus africanus* group showing important features in taxonomy (Mandahl-Barth 1962).

2.3.4. Distribution of Schistosomiasis Snail Intermediate Hosts in Kenya

2.3.4.1. Distribution of *Biomphalaria* Snails

The distribution of *Biomphalaria* snails in Kenya follows the distribution of intestinal schistosomiasis in Kenya. There are 34 described species of the genus *Biomphalaria* out of which 12 species are presumed to transmit *S. mansoni* in Africa and the rest in tropical America (Mandahl-Barth, 1957a). They are arranged in four groups: *Pfeifferi*, *Sudanica*, *Choanomphala*, and *Alexandrina* based on shell morphology and anatomical structures (Mandahl-Barth, 1957a). In East Africa, groupings using molecular techniques have shown that the *Sudanica* and *Choanomphala* groups are ecophenotypes of one species (Standley *et al*., 2011). In Kenya, only three *Biomphalaria* species are involved in the significant transmission of intestinal schistosomiasis. They include *Bi. pfeifferi* (Krauss, 1848), *Bi. sudanica* (Martens, 1870), and *Bi. choanomphala* (Martens, 1879). *Biomphalaria sudanica* is found in swampy areas along the margins of Lake Victoria, while *Bi. choanomphala* is found exclusively in the deeper parts of Lake Victoria (Loker *et al.* 1993: Mutuku *et al*., 2019).

Biomphalaria pfeifferi is widely distributed along the tributaries feeding Lake Victoria, the canals of major irrigation schemes such as Mwea in Central Kenya and Kano plains in Western Kenya (Brown, 2002; Morgan *et al.* 2001) as well as in inland water bodies such as dams, rivers, and springs (Opisa *et al.* 2011; Dida *et al*., 2014).

2.3.4.2. Distribution of *Bulinus* Snails

The distribution of *Bulinus* snails in Kenya also follows the distribution of urinary schistosomiasis in Kenya. However, the distribution of *Biomphalaria* snails in Kenya is wider than *Bulinus* snails. There are about 30 species of *Bulinus* snails in Africa (Brown 2002), and in Kenya, only 3 species have been reported to be responsible for the transmission of *S. haematobium*. These snails include *Bu. globosus, Bu. africanus,* and *Bu. nasutus*. Other *Bulinus* snails not reported to be involved in *S. haematobium* transmission are *Bu. forskalii*, *Bu. truncatus,* and *Bu. tropicus*. In the coastal region of Kenya where the most prevalent form of schistosomiasis is *S. haematobium,* the snails responsible for the transmission of the disease are *Bu. nasutus* and *B. globosus* (Kariuki *et al*., 2004; Kariuki *et al*., 2017), as well as *Bu. forskalii,* but only a potential *S. haematobium* intermediate host. *Bulinus nasutus* is also found in Kitui (Brown 2002). In the Nyanza region of Kenya around Lake Victoria, the snails responsible for *S. haematobium* transmission include *Bu. globosus* (Opisa *et al*., 2011) and *Bu. africanus* (Ofulla *et al*., 2013). *Bulinus nasutus* and *Bu. forskalii* are also found in the Lake Victoria region. Other *Bulinus* snails found around the Lake Victoria region include *Bu. truncatus* and *Bu. tropicus* (Chibwana *et al*., 2020).

2.3.5. Factors Influencing Population Density of Schistosome Snail Intermediate Hosts

The abundance and geographical distribution of schistosomiasis snail intermediate hosts are influenced by various environmental and biotic factors which vary from one site to the next and from one region to the next. These factors are grouped as physical, chemical, and biological factors.

2.2.5.1. Physical Factors

1. Temperature

Temperature is a major factor influencing the distribution and abundance of schistosomiasis snail intermediate hosts. These snails need warm temperatures for reproduction and survivorship. During warm seasons there is an abundance of microflora used as food and aquatic plants that provide dissolved oxygen and a place to crawl and deposit eggs (Malek

1958; Olkeba et al., 2020). Most of the habitats harboring schistosomiasis snail intermediate hosts have a wide range of temperatures favoring these snails despite marked seasonal and diurnal variations. *Biomphalaria* snails can tolerate temperatures between 17 ^{o}C and 30 ^{o}C, while *Bulinus* snails can tolerate temperatures up to 33 ^{o}C (Malek 1958). However, these snails operate at an optimum temperature of 25 ^{o}C: *Biomphalaria pfeifferi* has been found to grow and survive better at 25 ^{o}C than at 19 ^{o}C (Sturrock 1966). The positive association between water temperature and snail abundance has been reported by Stensgaard *et al*., (2006), Opisa *et al*., (2011), and Ofulla *et al*., (2013).

2. Turbidity

Turbidity is a measure of the clarity of water and this can be affected by the amount of light scattered by suspended or dissolved materials. In water, suspended materials may include rich growth of planktons and suspended particulate organic matter and silt. The latter can make waters very turbid rendering the habitat unfavorable for the intermediate hosts of schistosomiasis (Malek 1958). High turbidity seems to interfere with the photosynthesis of the microflora and submerged aquatic macroflora found in snail habitats.

3. Water Current

Schistosomiasis intermediate hosts cannot withstand strong water currents and that is why they cannot be found on exposed shores of large lakes, irrigation canals with very fast water flow, or swift rivers. Under these conditions, the snails are swept away and only a few may survive by attaching to nearby plants or sheltering in quiet water pools near the bank where the water current is less swift (Malek 1958). In lotic habitats such as rivers and streams, these snails can only be found in slow or non-flowing regions such as backwaters colonized by aquatic plants (Thomas and Tait 1984). However, schistosomiasis snail intermediate hosts have varying tolerance to strong currents, the main factor being their ability to cling to a surface. *Bulinus* snails can withstand swift currents more than *Biomphalaria* snails (Malek 1958). For example, *Bi. pfeifferi and Bu. forskalii* can tolerate current velocity up to 30 cm/s. According to Thomas and Tait (1984), schistosomiasis snail intermediate hosts are commonly not found in fast-flowing water because of the following. First, it would require the snails to use a lot of energy to maintain their station. Snails such as *Bu. globosus* have hemistreamlined bodies adapted for flowing water than *Biomphalaria* snails. Second, fast-flowing water may affect the snails' physiology in terms of growth: expending a lot of energy to attach to surfaces. Third, snail food

such as epiphytic algae and detritus tend to occur in slow-flowing waters, deposited as sediments.

4. Substratum

The substratum or bottom surface of the snail habitats influences the plants and dissolved elements such as calcium and magnesium in the water. The proportion of these elements is high in waters that flow over calcareous rocks and low in waters that flow over granite rocks or sandstone. Schistosomiasis snail intermediate hosts are often found in habitats with mud and fine silt bottom surface, rich in decaying organic matter (Malek 1958; Thomas and Tait 1984; Oloyede *et al*., 2016). The substratum also supports aquatic plants on which algae and other microorganisms flourish as snail food and crawling surface for snails. However, the mud-rich substratum is not an important characteristic of *Bulinus* snails' habitats. *Bulinus* snails prefer rock or sand bottom surfaces partly filled with aquatic plants that provide decaying vegetation matter as food for the snails.

5. Water permanence and stability

Schistosomiasis snail intermediate hosts thrive in habitats that are not subject to frequent fluctuations in water level. These snails can also not be found in puddles or small pools in low rainfall zones (50-300 mm mean annual rainfall), but they can be found in larger rain pools in medium rainfall zones (500-1000 mm mean annual rainfall). Some snails such as *Bulinus* can survive dry months by aestivating in mud or vegetation (Malek 1958; Kariuki *et al*., 2004).

6. Sunlight

Sunlight affects schistosomiasis snail intermediate host indirectly. The energy obtained from the sun allows aquatic plants to carry out photosynthesis. Hence, sunlight is required in the snails' habitats to flourish and provide the snails with dissolved oxygen and food supply. Sunlight is also needed to help decompose animal and plant remains at the bottom of snail habitats, instead of polluting the habitats and rendering them unfavorable for the snails. Laboratory observations have shown that snails are active in direct sunlight (Thomas and Tait 1984), and field observations of the absence of the snails in densely shaded ponds and streams (Malek 1958). Nonetheless, the snails prefer habitats with both direct sunlight and shade (Ndifon and Ukoli 1989).

2.2.4.2. Chemical Factors

1. Salinity

Salinity is the number of dissolved salts in water mostly chlorides. According to Malek (1958), *Biomphalaria* snails have a higher tolerance for chloride than *Bulinus* snails: *Bulinus* snails can tolerate up to 2123 p.p.m. while *Biomphalaria* can tolerate up to 3641 p.p.m.

2. pH

Schistosomiasis snail intermediate hosts tolerate a wide range of pH. However, studies on the influence of pH on snail abundance are contradictory. Some studies have shown that pH has a positive relationship with snail abundance (Abdel Malek, 1958; Ofulla *et al*., 2013). Specifically, high pH ranging from 7 to 11 has been found to favor the survival of snails while lower pH is harmful to the snails and might cause the coagulation of mucus on the exposed snail surfaces (Malek 1958). Other studies report the absence of an association between pH and snail abundance (Kahigi 2000; Opisa *et al*., 2011; Oloyede *et al*., 2016).

3. Dissolved Oxygen

Schistosomiasis snail intermediate hosts are pulmonates, meaning that they have lungs that allow them to make use of atmospheric oxygen when a thin film of water covers the surface of the lung for purposes of gaseous exchange (Abdel Malek, 1958). In addition, they have a pseudobranch or a false gill that allows them to extract dissolved oxygen in the water when they are submerged. Even though these snails possess lungs, they mostly depend on dissolved oxygen in the water than on atmospheric oxygen. Dissolved oxygen in water is partly obtained from the atmosphere, but mainly from aquatic plants. Schistosomiasis snail intermediate hosts can be found in water habitats with dissolved oxygen ranging from 4.7-7 mg/L (Malek 1958) while other studies have reported a wide range of 1.6 to 8.0 mg/L (Ofulla *et al*., 2013*;* Oloyede *et al.,* 2016).

2.2.4.3. Biological Factors

Biological factors condition the habitats of schistosomiasis snail, intermediate hosts, by increasing or decreasing their abundance. The biological factors include predators, competitors, and aquatic plants.

1. Predators and Competitors

The abundance of snails in a habitat can be influenced by biological factors such as competitors and predators. Schistosomiasis snail intermediate hosts tend to occur with other snails in the same habitat (Ndifon and Ukoli 1989; Dida *et al*., 2014). Organisms occurring in the same habitat compete for food and space. *Melanoides tuberculata* has been observed to compete and in some regions outcompete the snails that transmit intestinal schistosomiasis. As a result, it has been suggested as a possible biological control for snails that transmit schistosomiasis, especially those in the genus *Biomphalaria* (Mkoji *et al*., 1992; Giovanelli *et al*., 2005). The introduction of *M. tuberculata* in field experiments helped eliminate *Bi. glabrata* in a Caribbean country (Pointier 1993). Predators of schistosomiasis snail intermediate hosts prey on adult and juvenile snails as well as their eggs masses. Studies have shown that *Marisa cornuarietis*, an ampullariid snail, can be used as a biological control of schistosomiasis snail intermediate hosts. The snail is voracious; it eats the egg masses of other snails and depletes the common food supply (Malek 1958). In the Caribbean area, *M. cornuarietis* has been used to reduce the population of *Bi. glabrata*, an intermediate host for intestinal schistosomiasis in South America (Pointier and David, 2004).

Other ampullariid snails that can control schistosomiasis intermediate hosts include *Pila ovata* and *Lanistes carinatus*. In a study by Hofkin *et al*., (1990), all adults of *M. cornuarietis*, *P. ovata*, and *L. carinatus* consumed all the egg masses of *Bi. glabrata*. However, the juveniles of *P. ovata* consumed more egg masses than the juveniles of *M. cornuarietis* and *L. carinatus*. These three species of ampullariid snails have the potential to control the population of schistosomiasis snail intermediate hosts. However, these are experimental studies done under laboratory conditions, and the biological balance might be set to the disadvantage of the prey making it possible to prove that the predator snails' prey on the prey. Additionally, under laboratory conditions, the absence of other food sources that the predator could have eaten if it were in the natural environment could also provide a biological imbalance favoring it as a predator in the laboratory (Malek 1958).

2. Aquatic Plants

Aquatic plants have been shown to play a vital role in the establishment and flourishing of schistosomiasis snail intermediate hosts (Thomas and Tait 1984; Kariuki *et al*., 2004; Plummer 2005; Ofulla *et al*., 2013; Odero *et al*. 2019). Some plants such as water hyacinth (*Eichhornia crassipes*) are good biotic indicators for certain snails. Ofulla *et al*., (2013) found significantly more *Bi. sudanica* in the Lake Victoria habitats than *Bu. africanus*. In Egypt, Dazo *et al*., (1966)

found *Bi. alexandrina* was associated with water hyacinth and none with *Bu. truncatus*. However, Opisa *et al*. (2013) did not find any significant association between aquatic plants and the abundance of *Bi. sudanica*, *Bi. pfeifferi*, and *B. globosus*, within informal settlements of Kisumu City, western Kenya. The plants increase the amount of dissolved oxygen in the water and take up carbon dioxide released by aquatic animals. The plants also provide a suitable surface for snails to lay their eggs masses and crawl. Plankton such as algae eaten by snails attaches to the submerged parts of the plants. The presence of aquatic plants makes snail habitats more favorable for establishment and breeding, but they can occur in a habitat without plants. The removal of aquatic plants in snail habitats has been recommended as one way of controlling snail abundance (Thomas and Tait 1984; Boelee and Laamrani 2004).

2.4. Compatibility of *Biomphalaria* and *Bulinus* Snails with Schistosomes

2.4.1. *Biomphalaria* Snails

In Kenya, the most important snail intermediate hosts for intestinal schistosomiasis are *Bi. pfeifferi* and *Bi. sudanica*. According to Mutuku *et al.* (2017), *Bi. pfeifferi* is the most efficient in the transmission of the disease because of its higher infection rate (39.6%-80.7%) than *Bi. sudanica* (2.4%-21.5%), "regardless of the source of *S. mansoni* or size of the snail used" (p. 1). Mutuku *et al*., (2021) also observed that *Bi. choanomphala* ((12.2% - 80.9%) was more susceptible to *S. mansoni* infection than *Bi. sudanica* (5.2% – 18.6%), regardless of the source of miracidia, and it contributed to the persistence of intestinal schistosomiasis in villages along the shores of Lake Victoria despite MDA interventions (Mutuku *et al*., 2019). Schistosomiasis is successfully transmitted because of the "compatibility of the local snail population to schistosome infection" (Mutuku *et al.*, 2014, p.2), whereas snail exposed to miracidia is likely to produce cercariae. Therefore, the greater the compatibility, the more snail infection from a given egg input into the water habitat, and the more the cercariae produced resulting in increased transmission.

Biomphalaria pfeifferi is inherently susceptible to *S. mansoni* without regard to the geographic origin of the parasite (Mutuku *et al.*, 2014). In a reciprocal cross-infection experiment conducted by Mutuku *et al.*, (2014) involving *Bi. pfeifferi* and *S. mansoni* from Asao in Nyakach, Kisumu County, and Mwea in Kirinyaga County, high compatibility was shown and infection rates increased with an increase in the dose of miracidia. The infection rate of snails exposed to 1 miracidium, 5, 10, and 25 miracidia was 49.5%, 71.1%, 87%, and 96.7% respectively (Mutuku *et al.*, 2014). Elsewhere, the infection rate of *Bi. pfeifferi* exposed to 1

miracidium was 56.3% and 91.6% for 5 miracidia yielding a mean total cercarial production of 18511 and 9757cercariae per snail respectively (Southgate *et al.*, 2001). Additionally, Lu *et al.*, (2016) used a polymerase chain reaction assay to detect *S. mansoni* in *Bi. pfeifferi* and *Bi. sudanica* and they found out that during 24 days of pre-patent development after exposure to 1 miracidium of *S. mansoni*, 48.3% of *Bi. pfeifferi* had successfully harbored developing parasites compared to 23.5% of *Bi. sudanica*. Additionally, at 40 days post-exposure, 47.6% of *Bi. pfeifferi* snails had shed cercariae compared to 14.7% of *Bi. sudanica*, suggesting that the former provides a more conducive environment for the development of the parasite during the pre-patent period (Lu *et al.*, 2016).

Mutuku *et al.*, (2017) did the same reciprocal cross-infection experimental study as Mutuku *et al.*, (2014) but examined the compatibility of field-derived *Bi. pfeifferi* (from Mwea in Kirinyaga County) and *Bi. sudanica* (from Nawa, Lake Victoria) to *S. mansoni* miracidia isolated from fecal samples in humans from Mwea or Nawa. They found out that the pre-patent period of *S. mansoni* was shorter in *Bi. pfeifferi* than in *Bi. sudanica*. By week 4 post-exposure, all *Bi. pfeifferi* exposed to *S. mansoni* miracidium from either Nawa in Kisumu County or Mwea in Kirinyaga County were shedding cercariae. Overall, the production of cercariae in a two-hour shedding period for *Bi. pfeifferi* was more than for *Bi. sudanica* per day (more than 2000 cercariae). Their study showed that *Bi. pfeifferi* is the most efficient in the transmission of *S. mansoni* compared to *Bi. sudanica* regardless of whether the parasite isolates came from the same regions where *Bi. pfeifferi* is the usual host or from regions where *Bi. sudanica* is the usual host.

2.4.2. *Bulinus* Snails

Just like *Biomphalaria* snails, bulinid snails also have varied susceptibility to *S. haematobium*. In Msambweni, coastal Kenya, *Bu. nasutus* is highly susceptible to *S. haematobium* infection than *Bu. globosus* (Kariuki *et al*., 2004), but the vice versa is true in Unguja, Zanzibar (Stothard and Rollinson 1997). In Unguja, *Bu. nasutus* was not observed to be naturally infected with *S. haematobium*, but 7 out of 17 *B. globosus* were naturally infected (Stothard and Rollinson 1997). In a study done by Kariuki and others (2017) in Msambweni, Kenya, the rate of survival of exposed *Bu. globosus* with *S. haematobium* miracidia was half that of unexposed *Bu. nasutus* with miracidia, and unaffected when exposed. Both snails are capable of transmitting *S. haematobium* in Msambweni, Kenya, but *Bu. globosus* was the most efficient intermediate host by having a greater proportion of exposed snails shedding cercariae per day, a finding different from that of Kariuki and others (2004). In the coastal region of Kenya, the geographic

distribution of *Bu. globosus* and *Bu. nasutus* are different, with the former being found at distances of 30 km or more away from the Indian Ocean, while the latter is found in habitats close to the ocean (Clennon *et al*., 2006). Additionally, *Bu. nasutus* is usually the only *S. haematobium*-shedding snail in endemic regions of coastal Kenya. Therefore, it is thought that *Bu. nasutus* might be effective in transmitting *S. haematobium* in coastal Kenya because of its ability to tolerate salinity compared to *Bu. globosus*, and aestivate in its habitats during dry seasons (Kariuki *et al*., 2004; Brown 2002).

2.5. Cercarial Shedding and Implications for Transmission

The transmission of schistosomiasis is usually determined by the shedding of cercariae from schistosomiasis snail intermediate hosts. In high schistosomiasis transmission areas, very few or none of the collected snails are usually found to shed cercariae. In a study conducted by Opisa *et al*., (2011), only 1.8% of all the collected snails (*Biomphalaria* and *Bulinus*) shed cercariae. However, the prevalence of shedding was high in *Bulinus* species (2.2%) than in *Biomphalaria* species (1.7%). The finding of the low prevalence of cercarial shedding is not new. In a study done by Kariuki *et al*., (2004) in the Msambweni area in Kwale County, the proportion of *Bulinus* snails that shed cercariae was only 1.2%. Similarly, in a study done by Hamburger *et al*., (2004) in coastal Kenya, the rates of cercarial shedding were either low (0.14-3.4%) or altogether absent. Additionally, a study conducted on the Sesse Island of Uganda, a low transmission area, reported that none of the collected snails shed any cercariae (Standley *et al*., 2010).

Several explanations have been put forward to explain the absence or low numbers of snails shedding cercariae. First, cercariae may be shed for a limited period and the percentage of infected snails may be very low (McClelland, 1956). This explanation is also confounded with the focal nature of schistosomiasis and the difficulties that come with sampling vast areas where snails may be dispersed, making it very hard to accurately identify which sites would contain high numbers of infected snails. Second, snail population abundance, snail infection rates, and cercarial shedding are all under the seasonal influence (Kariuki *et al*., 2004). Third, it has been suggested that in high endemic areas, field snails are not continuously infected with miracidia (Sturrock *et al*., 1979). Given the fact that the prepatent period of infection takes at least four weeks with only a few snails reaching the patent period of cercarial shedding, it is possible to collect snails with prepatent infection. As a result, it is important to use other methods such as snail crushing or repeated shedding in the laboratory over time (Opisa *et al*.,

2011). But the use of these methods may be unsuitable for large-scale snail sampling. However, molecular methods for the detection of schistosomes cercariae in snails can be used.

2.5.1. Detection of Snails Infected with Schistosomes

Schistosomiasis transmission control cannot be done without evaluating the rate of infection of the snail intermediate hosts (Appleton and Miranda 2015). Snails infected with schistosomes are routinely identified by cercarial shedding when the snails are exposed to artificial or indirect sunlight, or by examining crashed preparations of snails through the microscope. These procedures are time-consuming and often result in an inaccurate and insensitive determination of rates of infection, especially when levels of schistosome infection in snails are low (Lardans and Dissous 1998). Additionally, these procedures may fail to detect prepatent infections and do not aid in the identification of cercariae (Lardans and Dissous, 1998). This might explain why in areas where schistosomiasis is endemic, studies of the snails' intermediate hosts to detect the proportion of infected snails is usually very low (McClelland, 1956; Kariuki *et al.*, 2004 Hamburger *et al*., 2004; Opisa *et* al., 2011) or absent (Standley *et al.*, 2010).

To overcome the foregoing challenges, sensitive detection methods for snail infection have been developed. Immunodiagnostic of *S. mansoni* antigens in snail hemolymph using Enzyme-linked immunosorbent assay (ELISA) has been used to detect schistosome cercariae in field snails with a 100% sensitivity and specificity (Hamburger *et al*., 1989). The detection of schistosome DNA sequence in snail tissues is also useful in diagnosing infected snails during the prepatent period. Some of the parasite DNA sequencing methods such as 18S ribosomal RNA gene sequencing using dot blot hybridization yield very low sensitivity detection concerning discriminating *S. mansoni*-infected and uninfected snails (Rollinson *et al*., 1986). Amplification of *S. mansoni* 18S rDNA sequences using polymerase chain reaction (PCR) is good at detecting prepatent infection; but the high homology of the 18S rDNA sequences from different schistosomes does not allow differentiation of the different species of schistosomes (Hanelt, *et al*., 1997). However, the use of PCR amplification of the minisatellite repeat of mitochondrial DNA from *S. mansoni* has been shown to detect prepatent infection in snails with high specificity for *S. mansoni* but with relatively lower sensitivity detection compared to that of rDNA amplification (Jannotti-Passos, *et al*., 2006). Loop-mediated isothermal amplification (LAMP) assay has been shown to detect schistosomes in snails one day after exposure to miracidia (Abbasi *et* al., 2010). Moreover, the method has detected one snail infected with *S. mansoni* in a pool of 1000 uninfected snails thus attesting to the high sensitivity and specificity of the parasite (Caldeira *et al*., 2017).

Molecular techniques for detecting schistosome parasites in snails are sensitive and specific. But they are relatively expensive compared to the traditional methods of shedding cercariae by exposing snails to indirect sunlight or artificial light. In addition, molecular methods detect schistosomes in pooled samples of snails; making it very difficult to identify the proportion of snails in a given sample that shed cercariae. Nonetheless, the molecular methods are a quick way of monitoring infected snails in a given freshwater habitat for purposes of improving schistosomiasis surveillance, especially in areas where control interventions are geared toward the elimination of the disease (Caldeira *et al*., 2017).

CHAPTER 3: MATERIALS AND METHODS

Schistosomiasis is one of the most prevalent water-borne diseases causing the greatest risk to health in rural areas of developing countries. The disease is endemic in areas where people frequently come into contact with water through their everyday quest for livelihood. In Mageta Island, the most common livelihood activity is fishing which exposes the local inhabitants to schistosome infections. Lake Victoria water provides suitable habitat for the intermediate snail host to thrive. Communities in the Lake Victoria region are highly mobile (Nunan, 2010); a person with schistosomiasis infection can move into Mageta Island in response to the fluctuating fish productivity. When fishing or carrying out household chores very few people bother to use the toilets, instead they urinate or defecate in water or near the shores of the lake, depositing schistosome eggs that hatch into miracidia and infect potential intermediate snail hosts.

3.1. The Study Area

This study was conducted on Mageta Island located inside Lake Victoria in Siaya County in Western Kenya (Figure 9). Administratively, Mageta Island together with the adjacent Magare Island, and the uninhabited Sirigombe Island, form Mageta location which has a population of about 7000 individuals (Mukabana *et al*., 2019). Mageta Island lies at an altitude of 1,140 m above sea level between 33° 59′15″–34° 2′30″ E and 0°7′15″–0°8′15″ N within a surface area of 7.02 square kilometers. The Island receives long rains from March to May and short rains from October to December.

The main socio-economic activity carried out by the community in the Mageta location is fishing. The fishing activities are mainly conducted through artisanal capture around six landing beaches which include, Wakawaka, Sika, Mitundu, Kuoyo, Mahanga, and Magare. There are various fish species caught around the Mageta location, but the main ones include Nile tilapia (*Oreochromis niloticus*), Nile perch (*Lates niloticus*), and the silver cyprinid (*Rastrioneobola argentae*). Very few fishermen, mostly the elderly, practice small-scale fishing of fishes in the genera *Mormyrus* and *Protopterus* along the muddy northern swamps of the Island.

The community in Mageta Island also practices small-scale farming of crops and animals. The people on the Island mainly domesticate cattle, chickens, goats, sheep, pigs, donkeys, cats, and dogs. Crop farming involves maize, beans, tomatoes, and kale of the cultivar *Acephala*

(Mukabana *et al*., 2019). The shores of Lake Victoria also harbor various species of snails some of which are known intermediate hosts for schistosomiasis. Some snails such as *Pila ovata* are collected to be used as fish baits, an activity that exposes the collectors to schistosomiasis.

Most people in Mageta Island practice open defecation. Very few homes have pit latrines, and those with latrines rarely use them because as one walks around on the Island, it is common to smell or see feces on farms, fields, and bushes. The behavior of open defecation is also encouraged by the reliance on Lake Victoria water for all household chores such as washing clothes, utensils, bathing, and fetching water for cooking and drinking. Additionally, the occupation of fishing also encourages open defecation. An individual might not think about using a pit latrine when fishing or fetching water. They can either urinate or defecate in water or offshore. The practice of open defecation is a risk factor that contributes to the transmission and persistence of schistosomiasis (Musuva *et al*., 2021) since the habitats of schistosomiasis snail intermediate hosts are around the lake.

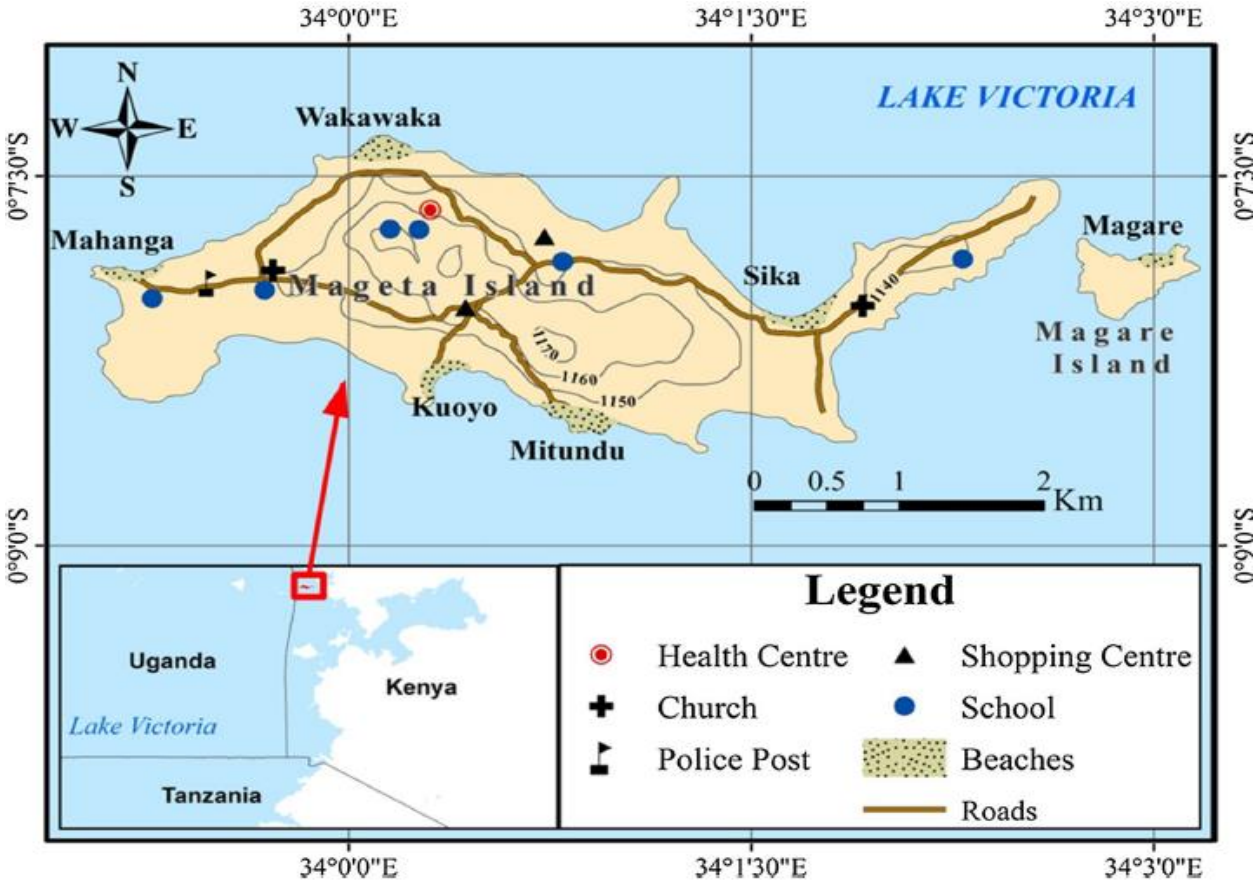

Figure 9: Map of Mageta location showing Mageta and Magare Islands in Lake Victoria, Western Kenya (Mukabana *et al*., 2019).

3.2. Investigation of snail diversity in natural and manmade habitats on Mageta Island

This first objective was achieved through a cross-sectional survey aimed at sampling snails from different habitat types characterized by frequent human water contact activities such as fishing, washing, and fetching water and water-drinking points for livestock such as cattle, donkeys, sheep, and goats. The habitats were classified as either natural or manmade.

3.2.1. Snail Sampling

Sampling of snails was conducted in August 2020 in habitats with water and vegetation either around the shores of Lake Victoria or in-land. From each habitat type (e.g., lakeshore, swamp, trench, or lagoon), snails were sampled using a scoop made of a stainless-steel sieve with a mesh size of 2 mm by 2 mm, embedded in a triangular-shaped frame measuring 40 cm on each of the three sides, and mounted on a 1.5-meter-long wooden handle (Figure 10). In sites with low water levels preventing the use of the scoop, snails were picked by a long pair of forceps. The selection of each sampling area per site was done by approximation of a 10-meter length along the lakeshore or of 5 m^2 in swamps, water puddles, or ponds (Opisa *et al*., 2011). The number of scoops per site was 10. It was suspected that schistosomiasis transmission could take place in any sampling site, therefore, gumboots and rubber gloves were worn to prevent infection.

The scoop was pushed underneath vegetation and shaken forward and upward to dislodge snails attached to vegetation. The content of each scoop was emptied into a white plastic tray for easier identification, counting, and recording of snails. A pair of forceps was used to sort through the content of each scoop while picking and sorting snails based on their shell morphology. Each snail species, including those known to transmit schistosomiasis (Genera: *Biomphalaria* and *Bulinus*), were placed in 35 ml clear plastic poly pots or 150 ml plastic containers and labeled to the genus level with information on GPS site number and collection date. In each poly pot or container, a small amount of snail habitat source water was placed to keep the snails moist, and covered with white perforated lids to provide aeration and prevent the snails from crawling out during transportation. All the containers with snails were arranged in plastic trays and taken to the Mageta Health Centre, where the process of cercarial shedding was performed. In addition to the snail sampling, there were several predictor variables recorded at each site. These included the village name and description of the snail habitat (see Appendix 2).

Figure 10: Scoop used to sample snails from habitats on Mageta Island, Lake Victoria, Kenya.

3.2.2. Identification of snails

Snails were identified using morphological keys provided by Brown (2002). The book provides identification of freshwater snails found in Africa. Identification begins with looking at the shell opening of the snail. Snails with shell openings covered with operculum are known as prosobranchs (e.g. *Melanoides tuberculata* and *Pila ovata*). Snails such as *Biomphalaria*, *Bulinus*, and *Physa*, do not have operculum and are grouped as pulmonates. The next step is looking at the shape of the shell: *Biomphalaria* snails have disc-shaped/flat-shaped shells while *Bulinus* snails possess ovate shape (see sections 2.3.2 and 2.3.3).

3.3. Assessment of trematode infection in snails in habitats

At the health clinic, the content of each poly pot or container was emptied into a petri dish and observed under a dissecting microscope for identification of the snails to the species level. Each snail was given a specific identification number based on GPS site number and snail name (e.g., *Biom.s* 5-1 or *Bul* 5-1): *Biom.s* for *Biomphalaria sudanica,* GPS site number 5, and snail number 1. Larger snails such as *Pila ovata* were placed in plastic containers of approximately 150 ml in capacity, containing snail's habitat source water. Each snail from each site was placed in a poly pot containing about 5 ml of lake water and exposed to indirect sunlight for 2 hours to induce cercarial shedding (Figure 11).

Thereafter, the content of each poly pot/container was emptied into a petri dish one at a time, stained with Lugol's Iodine, and examined for the presence of bifurcate and non-bifurcate cercariae under dissecting microscope. Bifurcate and non-bifurcate cercariae were

differentiated based on the morphology of the tail (Frandsen and Christensen, 1984). The snails that shed cercariae from each site on the first day of the collection were discarded. Snails that did not shed on the first day of the collection were kept for 5 days and observed daily after exposure to indirect sunlight for 2 hours for cercarial shedding. Snails in the genus of *Pila* were observed until they died. This snail is of interest because it is sometimes used by fishermen on Mageta Island as bait for fish species in the genus *Protopterus*.

Figure 11: Poly pots containing snails with grass as food.

3.4. Development of schistosomiasis risk map of Mageta Island

This objective aimed to map schistosomiasis transmission sites on Mageta Island. To achieve this, geographic coordinates of snail habitats were recorded using a hand-held GPS receiver (Garmin eTrex® 10). The GPS coordinates were downloaded into Microsoft Excel. QGIS Desktop (version 3.16.4) was used to create point layers from the Microsoft Excel file. Overlaying analysis was used to create transmission sites based on snails infected with schistosome cercariae.

3.5. Investigation of the association between plant species and the occurrence of snails

This objective was achieved by identifying plants in snail habitats. Plant identification was done using the Google Lens software application. The application was downloaded into an android smartphone from the Google Play store. The application was opened and a picture of the main plant on a snail habitat containing identifying features such as flowers, leaves, and stem was taken. The application automatically searched the internet for similar images with names. The searched plant images were compared with the plant(s) on the snail habitats and the name recorded. Image recognition technology has improved to the extent that there are several automated plant identification applications available for smartphones, and one of them

is Google Lens. The accuracy of Google Lens has been recorded at 71% in the identification of British flora, with a reliability score of 2.9 (out of 4.0 score) (Jones 2020). However, the use of Google Lens has a few limitations. One, when used with an individual without or less botanical skill, the application provides shortcuts to the otherwise technical keys used in botany to identify plants. Therefore, the confirmation of plant identity should be done with the help of a botanical expert. In this study, the help of a botanical expert was used to confirm the identity of the collected plants. Second, the application limits the accurate identification of rare plants that might be absent in the database used for identification (Jones 2020).

3.6. Data Analysis

All the collected data in this study (see Appendix 2) were entered in Microsoft Excel. A pivot table was used to explore the trends and patterns in the data. The data were analyzed using SPSS statistical software (version 20). Generalized Linear Models (GLM) were used to fit the count data to a Poisson distribution with a log link function to test whether habitat types (categorized as natural or manmade) and bottom surface types (categorized as mud, sand, rock, and wood), influenced the abundance of snail species in habitats. Binomial logistic regression was used to find out the effect of habitat categories (manmade and natural), habitats with human activities, and plant species on the probability of finding schistosomiasis snail intermediate hosts in habitats. Before all analyses were done, the assumptions of each model were checked. For Poisson distribution, over-dispersion was checked for all the dependent variables (snails collected from the field and snails exposed to shed cercariae) in the data. The outcomes of the analyses were considered to be statistically significant at $P < 0.05$.

CHAPTER 4. RESULTS

The cross-sectional survey was carried out in August 2020 on Mageta Island. This was in the dry season. The sampling of the snails during the dry season in Mageta Island was preferable because, during the rainy season, an increase in water level in the snail habitat sweeps away the snails and this potentially interferes with data measurements. The results of this study revealed that the residents of Mageta Island are at an increased risk of schistosomiasis transmission given the presence of schistosome snail intermediate hosts (*Biomphalaria sudanica*, *Biomphalaria pfeifferi*, *Bulinus tropicus, Bulinus nasutus*, and *Bulinus forskalii*) and frequent human water contact. As a result, these habitats are potential sites for schistosomiasis transmission given that schistosome cercariae were recovered from snail intermediate hosts.

4.1. Diversity of snail species in natural and manmade habitats on Mageta Island

A total of 9,779 freshwater snails representing 7 genera and 10 species (Class Gastropoda) were collected from 116 habitats on Mageta Island. Based on shell morphology (see section 2.3), the snails were identified as *Biomphalaria sudanica*, *Bulinus tropicus, Melanoides tuberculata*, *Bellamya* spp., *Lymnaea natalensis*, *Physa acuta, Pila ovata, Biomphalaria pfeifferi*, *Bulinus nasutus,* and *Bulinus forskalii*. There were also 111 clams (Class Bivalvia) collected from the study area. The habitats, grouped into six different habitat types, included Lake shoreline (N = 83), swamps (N = 24), banana plant holes (N = 3), lagoons (N = 3), ditches (N = 2), and boat (N = 1). Lake shoreline, swamps, and lagoons were classified as natural habitats, while banana plant holes, ditches, and boats were classified as manmade (Table 2). Habitats classified as natural comprised 94.82% (N = 110) of the habitats and contained 96.32% (n = 9419) of the sampled snails. Manmade habitats comprised 5.17% (N =6) of habitats and contained 3.68% (n = 360) of the sampled snails. *Biomphalaria sudanica* was the most abundant snail species (86.94%; n = 8502) followed by *Bulinus tropicus* (6.23%; n = 609). Figure 12 displays the percent abundance of fresh water snails on Mageta Island. The mean numbers displayed at the bottom of the figure show that *Physa acuta* was the second most abundant snail species and this is not true. Hence the use of the percentages was the best option for representing the abundance of the snail species on Mageta Island and not the means of the snail species. *Biomphalaria sudanica* was still the dominant snail species (48.05%) even after 7,321 individuals collected from one site and forming the outlier in this study's analysis, were removed. The mean of *Bi. sudanica* with the outlier removed was 32.81 ± 0.96 compared with 229.78 ± 2.49 with the outlier. The Shannon-Weiner diversity index for snails in natural

(*H* = 0.65) and manmade (*H* = 0.49) habitat types, was very low. This means that the diversity of snails on Mageta Island is low. The value of equitability or evenness for the two groups of habitats was the same (*E* = 0.27), meaning that the total number of snails on Mageta Island was concentrated on only one species, that is *Bi. sudanica*.

Of the collected 10 species of snails, only 5 were intermediate hosts for intestinal (*Bi. sudanica* and *Bi. pfeifferi*) and urinary (*Bu. tropicus, Bu. nasutus,* and *Bu. forskalii*) schistosomiasis (Figure 13a). *Lymnaea natalensis,* an intermediate host for *Fasciola hepatica*, which causes a parasitic disease known as fascioliasis, was also present. The rest (*M. tuberculata*, *Bellamya* spp., *P. acuta,* and *P. ovata*) are not known to harbor trematodes infective to humans (Figure 13b).

The mean number of *Bi. sudanica* in manmade habitat types was significantly lower (54.67 ± 3.02) than those collected from natural habitat types (74.31 ± 0.82) ($P < 0.05$). However, when the single outlier was removed from the analysis, *Bi. sudanica* was significantly higher in manmade habitats (54.67 ± 3.02) than in natural habitats ((7.83 ± 0.27) ($P < 0.05$). *Biomphalaria pfeifferi* (0.18 ± 0.04), *Bu. tropicus* (5.54 ± 0.22), *M. tubercculata* (1.71 ± 0.13), *P. acuta* (0.69 ± 0.08), and *Bellamya* spp. (1.57 ± 0.12) were absent from manmade habitat types. The mean number of *Bu. nasutus* in manmade habitats (2.67 ± 0.67) was significantly higher than in natural habitats (0.02 ± 0.01) ($P < 0.05$). The mean number of *Bu. forskalii* was not significantly different between natural (0.17 ± 0.17) and manmade habitat types (0.12 ± 0.03) ($P > 0.05$), but the natural habitat type, had the highest mean number of snails. The mean number of *L. natalensis* in natural habitats (0.95 ± 0.09) was significantly higher than in manmade habitats (2.33 ± 0.62) ($P = 0.03$). The mean number of *P. ovata* in natural habitats (0.95 ± 0.09) was significantly higher than in manmade habitats (2.33 ± 0.62) ($P = 0.04$) (Figure 14). Whereas the chance of finding freshwater snails in natural habitats was twice higher than that of finding them in manmade habitats (OR = 2.052, 95% CI = 0.237– 17.776), the difference was not significant ($P = 0.514$).

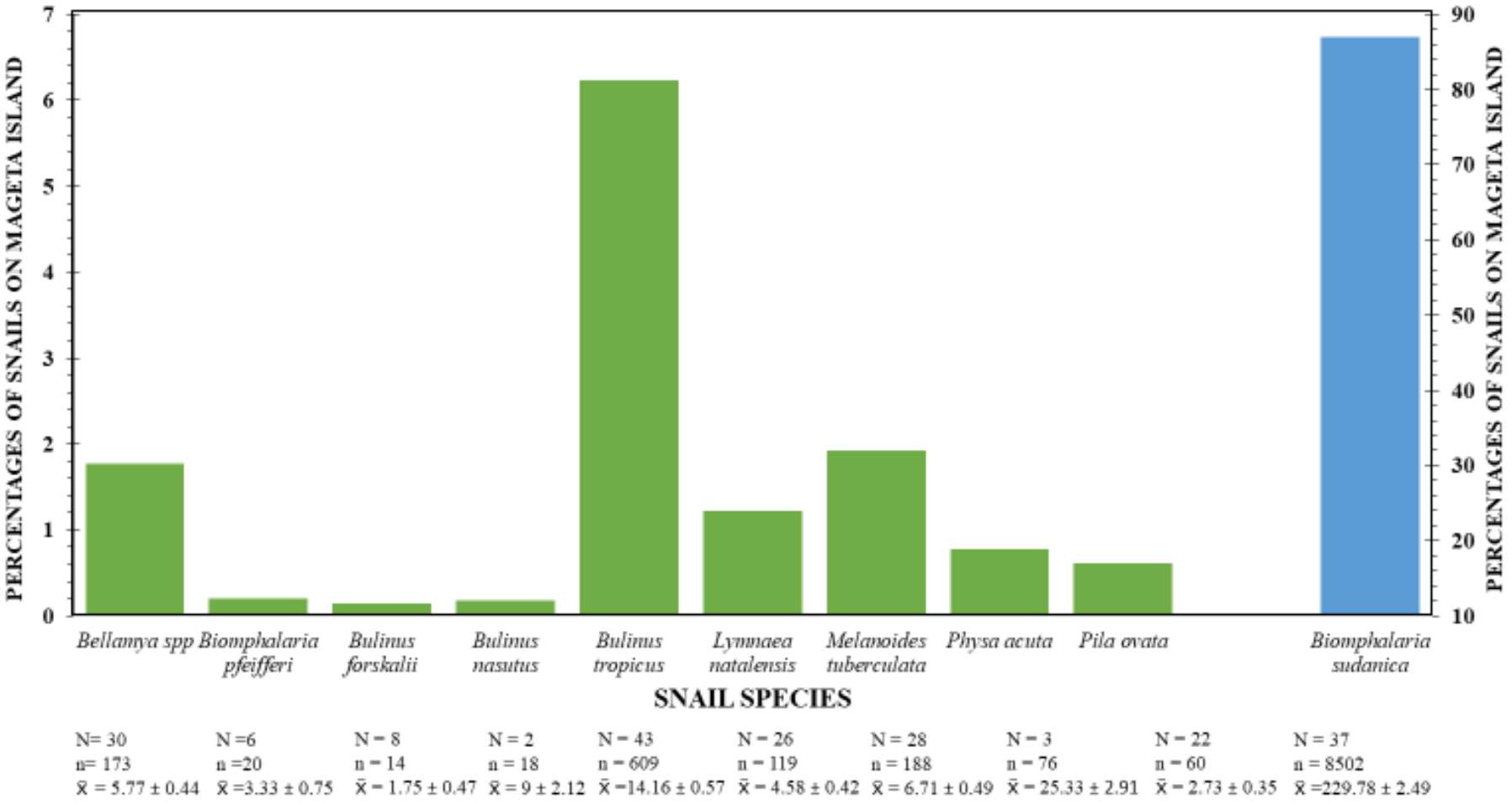

Figure 12: The Percentages of snail species on Mageta Island. N denotes the number of habitats, n the total number of species, and $\bar{x}$ is the mean

Figure 13a: Snails of medical importance collected from Mageta Island, Western Kenya. The black bars indicate the height of the snail shell and the values in millimeters indicate the shell diameter.

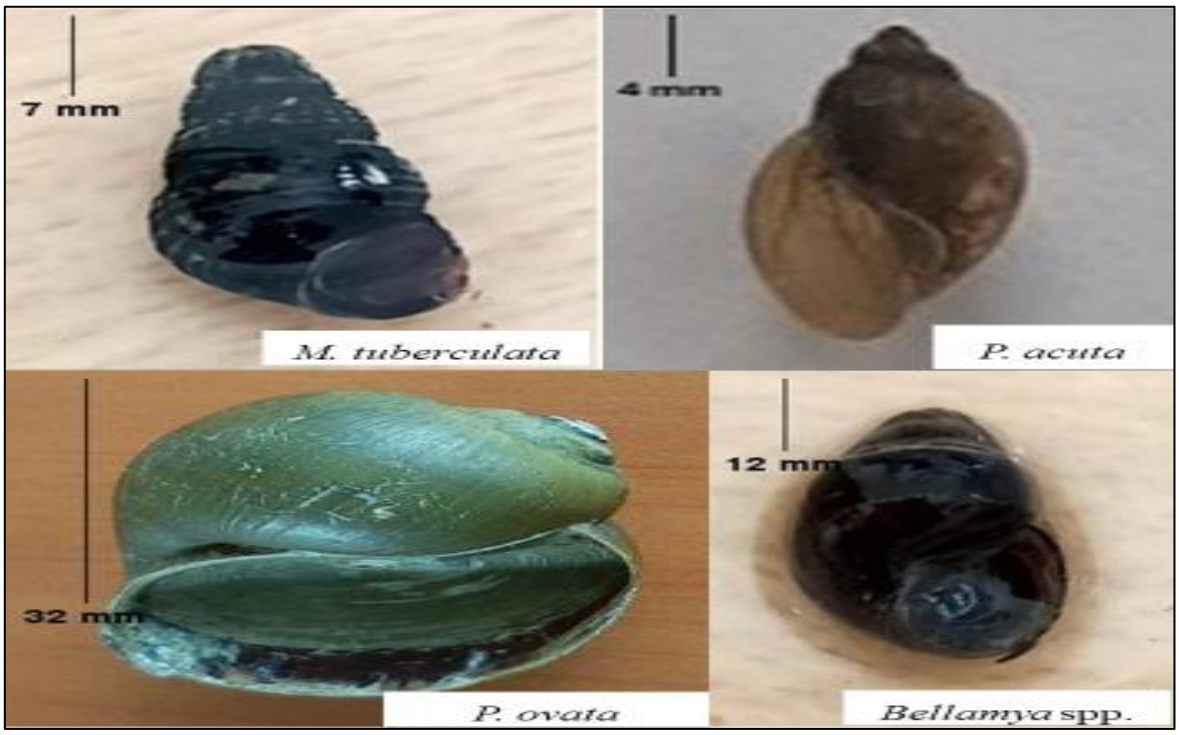

Figure 13b: Snails of non-medical importance collected from Mageta Island, Western Kenya. The black bars indicate the height of the snail shell and the values in millimeters indicate the shell diameter

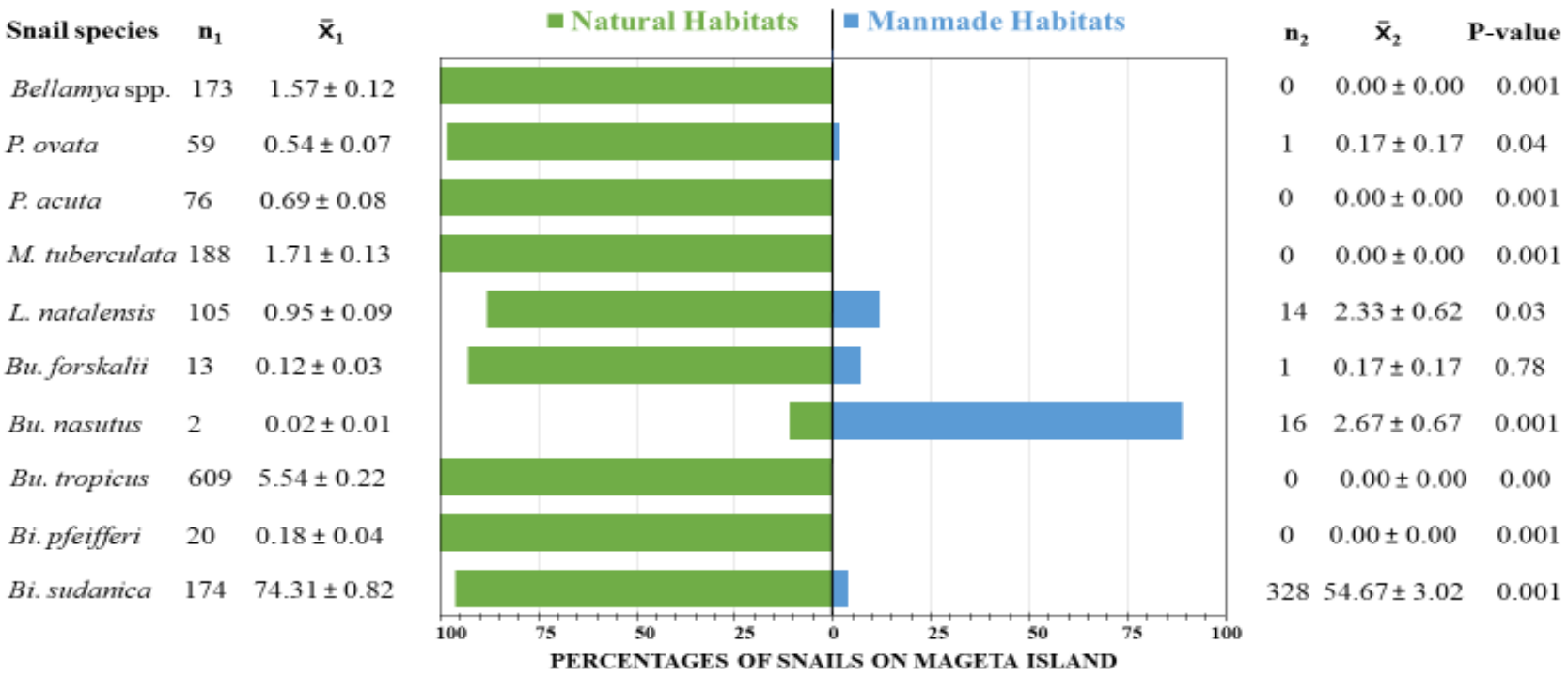

Figure 14: The percentage and mean number of snail species in natural and manmade habitat types on Mageta Island. The total number of individual snails in natural habitats (n_1) and manmade habitats (n_2) is represented by green and blue bars, respectively. The $\bar{x}$ is the mean of each snail species

Table 2: Summary of the mean number (±S.E) of snail species diversity in different habitat types collected on Mageta Island in Western Kenya.

Habitat Types	Snail Species	Mean no. of snails ± S.E.
Banana plant holes (3)	*Biomphalaria sudanica*	108.67 ± 6.02
	Bulinus nasutus	5.33 ± 1.33
Boat (1)	*Biomphalaria sudanica*	2.00*
	Bulinus forskalii	1.00*
	Lymnaea natalensis	14.00*
Ditch (2)	*Pila ovata*	0.50 ± 0.50
Lagoon (3)	*Biomphalaria sudanica*	0.33 ± 0.33
	Bulinus tropicus	11.00 ± 1.92
	Lymnaea natalensis	0.67 ± 0.47
	Melanoides tuberculata	1.00 ± 0.58
	Physa acuta	25.00 ± 2.89
Lake shoreline (83)	*Bellamya* spp	2.02 ± 0.16
	Biomphalaria pfeifferi	0.01 ± 0.01
	Biomphalaria sudanica	1.40 ± 0.13
	Bulinus forskalii	0.08 ± 0.03
	Bulinus tropicus	6.82 ± 0.29
	Lymnaea natalensis	1.01 ± 0.11
	Melanoides tuberculata	1.88 ± 0.15
	Pila ovata	0.67 ± 0.09
Swamp (24)	*Bellamya* spp	0.21 ± 0.09
	Biomphalaria pfeifferi	0.79 ± 0.18
	Biomphalaria sudanica	335.71 ± 3.74
	Bulinus forskalii	0.25 ± 0.10
	Bulinus nasutus	0.08 ± 0.06
	Bulinus tropicus	0.42 ± 0.13
	Lymnaea natalensis	0.79 ± 0.18
	Melanoides tuberculata	1.21 ± 0.22
	Physa acuta	0.04 ± 0.04
	Pila ovata	0.13 ± 0.07

The numbers in brackets are the number of habitats. The asterisk (*) denotes the undefined S.E (standard error of the mean) since the value of n for the boat was 1.

4.1.1. Density of snails in habitats of different bottom surface types

A total of 4 bottom surface types (mud, rock, sand, and wood) of the sampled habitats were found on Mageta Island. Sixty-two habitats (33 Lake shoreline, 24 swamp, 3 banana plant holes, and 2 ditch) had bottom surfaces made up of mud, 32 habitats had rock bottom surfaces (30 Lake shoreline and 2 lagoons), 21 had sand (20 Lake shoreline and 1 lagoon), and 1 wooden (boat). Habitats with bottom surfaces made up of mud had the highest mean number of snails (83.08 ± 0.89) but with a mean of 14.14 ± 0.37 without the outlier, followed by habitats with rocks (11.41 ± 0.43). The mean number of snails in habitats with sand and wood bottom surfaces was 7.18 ± 0.47 and 5.67 ± 1.37, respectively. All of the 10 snail species were recovered from habitats with mud bottom surfaces and 7 and 5 from habitats with rock and sand bottom surfaces, respectively. Wood-bottomed habitats had 3 snail species (Table 3).

The mean of *Bi. sudanica* found in habitats with mud bottom surfaces (137.06 ± 1.49 and 19.30 ± 0.56) was significantly higher than those found in habitats with rock (0.06 ± 0.04) and wood (2.00 ± 1.41) bottom surfaces ($P < 0.05$). *Biomphalaria pfeifferi* and *Bu. nasutus* were only found in habitats with mud bottom surfaces. *Bulinus forskalii* was found in both mud and wood-bottomed habitats but without a significant difference in the mean number of snails (Table 3). *Bulinus tropicus* collected from rock bottom surfaces were significantly higher than those found in mud and sand ($P < 0.05$). The mean number of *L. natalensis* in habitats with wood bottom surfaces was significantly higher than those in mud, rock, and sand ($P < 0.05$). The mean number of *M. tuberculata* was significantly higher in habitats with sand bottom surfaces than in mud and rock bottom surfaces ($P < 0.05$). *Physa acuta* was only present in habitats with rock and mud bottom surfaces with the former's mean being significantly higher than the latter ($P < 0.05$). The mean number of *P. ovata* and *Bellamya* spp. were significantly higher in habitats with sand bottom surfaces than rock and mud bottom surfaces ($P < 0.05$).

Table 3: Mean number of snail species collected from habitats with different bottom surfaces

Habitat bottom surface types	Mud	Rock	Sand	Wood
Snail species	N= 62	N= 32	N= 21	N = 1
Bi. sudanica	137.061 ± 1.49^{a}	0.06 ± 0.04^{bd}	0.00	2.00
Bi. pfeifferi	0.32 ± 0.07	0.00	0.00	0.00
Bu. tropicus	0.58 ± 0.1^{a}	14.53 ± 0.67^{b}	5.14 ± 0.50^{c}	0.00
Bu. nasutus	0.29 ± 0.70	0.00	0.00	0.00
Bu. forskalii	0.21 ± 0.06^{a}	0.00	0.00	1.00
L. natalensis	0.61 ± 0.10^{a}	1.50 ± 0.22^{b}	0.90 ± 0.21^{ac}	14.00
M. tuberculata	0.89 ± 0.12^{a}	1.75 ± 0.23^{b}	3.67 ± 0.42^{c}	0.00
P. acuta	0.02 ± 0.01^{a}	2.34 ± 0.27^{b}	0.00	0.00
P. ovata	0.34 ± 0.07^{a}	0.66 ± 0.14^{b}	0.86 ± 0.20^{bc}	0.00
Bellamya spp.	1.71 ± 0.17^{a}	1.63 ± 0.23^{ab}	0.71 ± 0.18^{c}	0.00

Different letter superscripts within the same raw denote a significant difference in the mean number of snails collected in habitats of different bottom surface types ($P < 0.05$), while the same letter superscript denotes no significant difference in the mean of snails ($P > 0.05$) collected. N denotes the number of sites from where the snails were collected. The values on the Wood column are the numbers of snails collected and not mean value since the value of N = 1.

4.1.2. Geographical distribution of snails collected from Mageta Island

The snails collected from Mageta Island were found along or near the shores of Lake Victoria, with none found inland (Figure 15). The distribution of the snails was concentrated on the northern, eastern, and western parts of Mageta Island. Out of the 116 habitats, only 13 (5.5%) habitats did not have snails. The southern part of the Island harbored very few snails because the place is rocky and inaccessible for sampling.

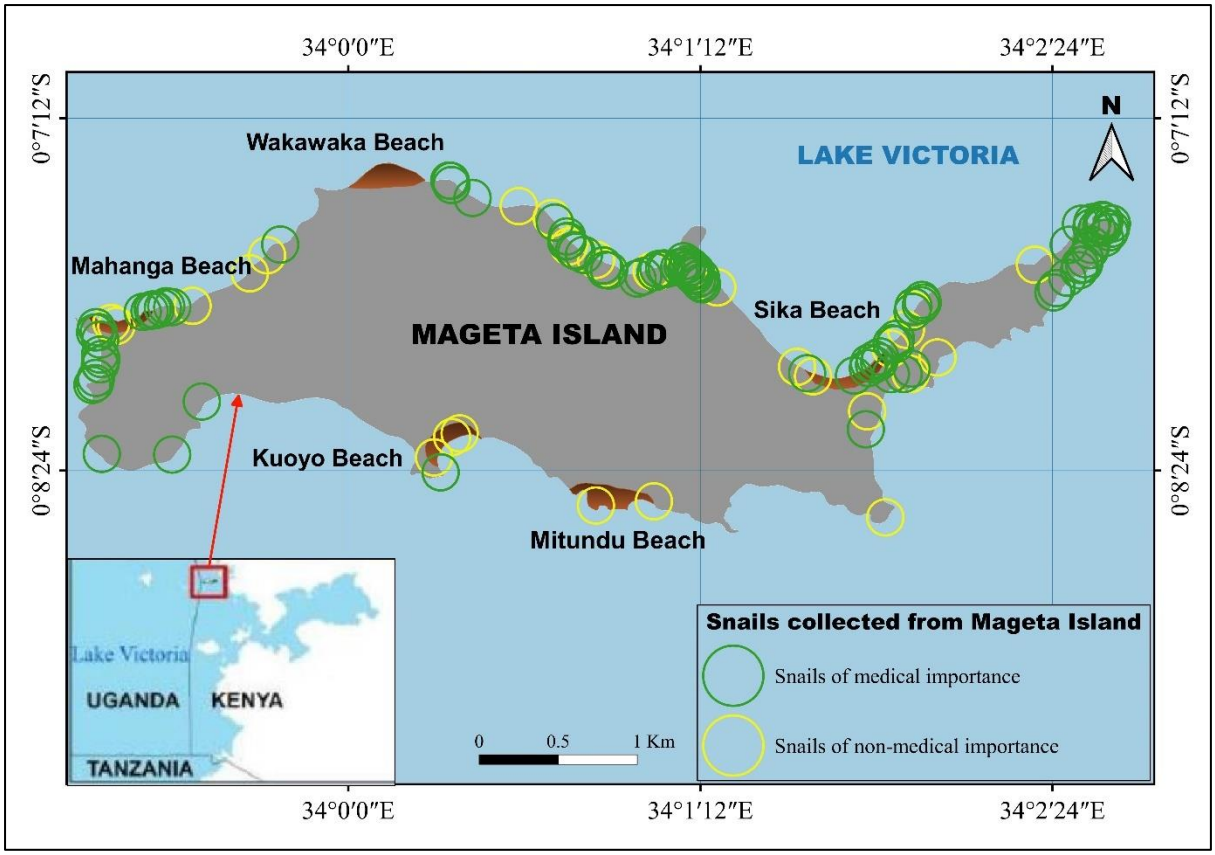

Figure 15: Spot map showing the spatial distribution of snails of medical (green circles) and non-medical (yellow circles) importance on Mageta Island, Western Kenya

4.2. Prevalence of trematode infection in snails on Mageta Island

A total of 2,014 freshwater snails representing 7 genera and 10 species (Class Gastropoda) were exposed to indirect sunlight for a maximum of four hours to facilitate the shedding of cercariae. Overall, 69 (3.43%) of the snails shed some type of cercariae. Six snail species were found to be infected with cercariae and they included *Bi. sudanica* (6.28%; n = 47), *Bu. tropicus* (1.81%; n = 11), *M. tuberculata* (2.78%; n = 5), *Bu. forskalii* (14.29%; n= 2), *L. natalensis* (1.74%; n = 2), and *Bi. pfeifferi* (10%; n = 2) (Figure 16).

Snail species that did not shed any cercariae included *Bu. nasutus*, *P. acuta*, *P. ovata*, and *Bellamya* spp. Out of 2,014 snails, 27 (1.34%) were infected with bifurcate cercariae, while 42 (2.09%) were infected with non-bifurcate cercariae. *Bulinus forskalii* and *L. natalensis* both shed the same proportion of bifurcate cercariae. The proportion of *Bi. sudanica* infected with bifurcate cercariae (1.74%) was less than that infected with non-bifurcate cercariae (4.54%). However, the proportion of *Bu. tropicus* that shed bifurcate cercariae (1.64%) was more than

the proportion that shed non-bifurcate cercariae (0.16%). *Melanoides tuberculata* only shed non-bifurcate cercariae.

Overall, the proportion of snails that shed non-bifurcate cercariae was highest than the snails that shed bifurcate cercariae. However, the proportion of snails that shed cercariae was highest in natural habitats (3.38%) than in manmade habitats (0.05%). Snails that shed bifurcate cercariae were collected from natural habitats but none from manmade habitats. The proportion of snails that shed bifurcate cercariae was highest in swamps (0.70%) followed by the lagoon (0.40%) and lake shoreline (0.40%) (Table 4). Snails that shed non-bifurcate cercariae were only found on banana plant holes (manmade habitat) and swamps and Lake shorelines (natural habitats). The proportion of snails that shed non-bifurcate cercariae was highest on swamps (1.19%) followed by Lake shoreline (0.84%) habitats.

Table 4: Prevalence of trematode infection in snails from different habitat categories and habitat types on Mageta Island, Western Kenya

Habitat Category	Habitat Types (N)	Prevalence of trematode Infections		Prevalence
		Snails infected with bifurcate cercariae (n)	Snails infected with non-bifurcate cercariae (n)	
Manmade	Boat (1)	0.00	0.00	0.05
	Ditch (2)	0.00	0.00	
	Banana plant holes	0.00	0.05 (1)	
Natural	Lagoon (3)	0.40 (8)	0.00	3.38
	Lake shoreline (24)	0.25 (5)	0.84 (17)	
	Swamp (32)	0.70 (14)	1.19 (24)	
Total		1.35	2.08	3.43

N is (numbers in bracket) are the number of habitat types while n is the number of snails that shed either bifurcate or non-bifurcate cercariae

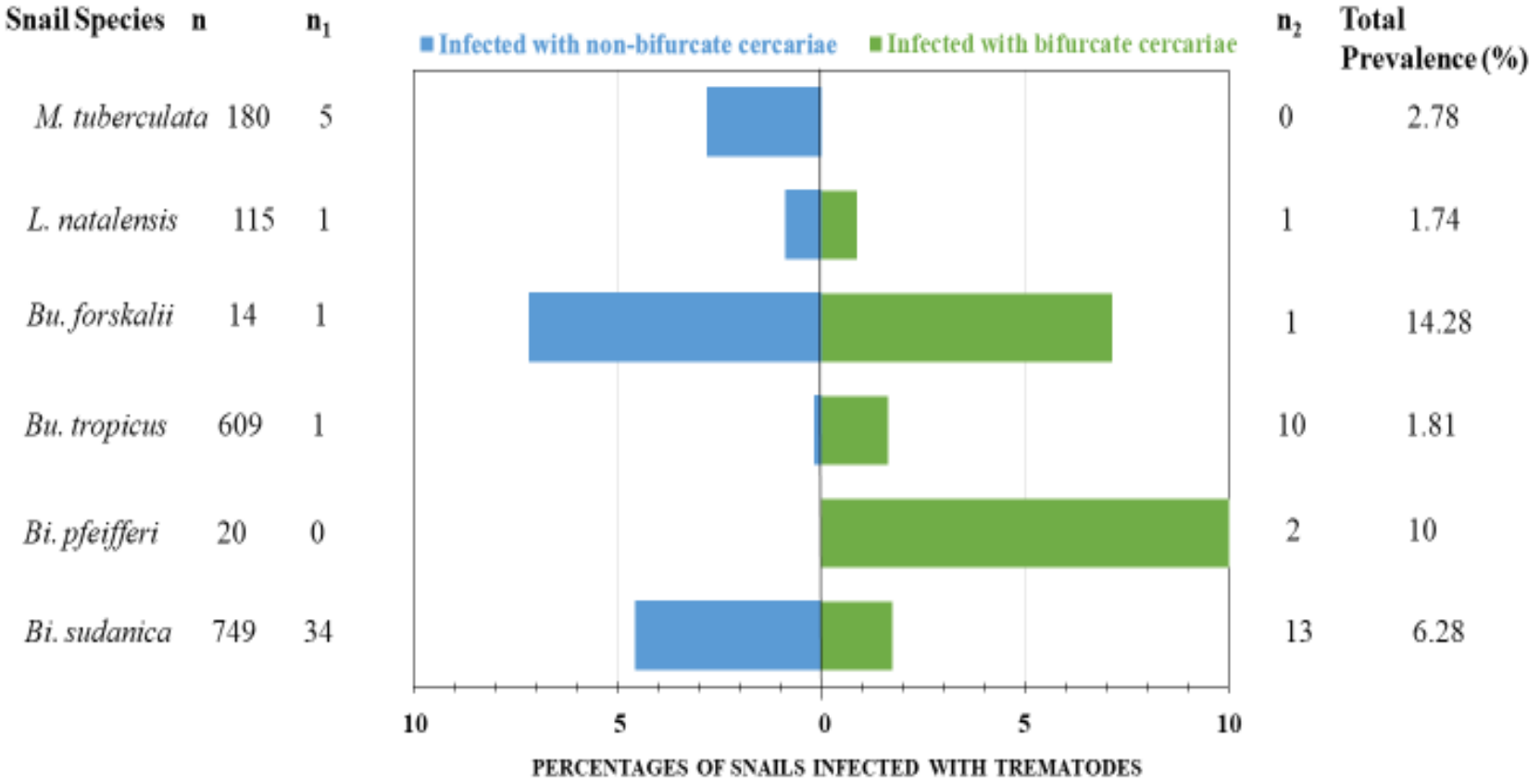

Figure 16: Percentages of snails infected with bifurcate cercariae (green bars) and infected with non-bifurcate cercariae (blue bars). n represents the total number of snails exposed to shed cercariae while n_1 represents the total number of snails that shed non-bifurcate cercariae and n_2 snails that shed bifurcate cercariae. The total prevalence is the combined prevalence for both snails that shed bifurcate and non-bifurcate cercariae

4.2.1. The association between human activities and cercarial shedding in schistosome snail intermediate hosts

Schistosome snail intermediate hosts that shed cercariae included *Bi. sudanica*, *Bi. pfeifferi*, *Bu. tropicus*, and *Bu. forskalii*. Although snails collected from habitats with human activities had the highest infection rates, the shedding of cercariae was not associated with the presence or absence of human activities in habitats. The odds of finding *Bi. sudanica*-infected snails in habitats with human activities were 1.143 times (95% CI = 0.599 - 2.183) than in habitats without human activities. However, this difference was not significant (P = 0.685). The odds of finding *Bu. tropicus*-infected snails in habitats with human activities were 72.386 times (95% CI = 15.063 - 347.848) higher than in habitats without human activities (P = 0.001). *Biomphalaria pfeifferi* and *Bu. forskalii* were only present in habitats with human activities.

4.2.2. Geographical distribution of snails that shed schistosome cercariae on Mageta Island

Out of 116 habitats, only 13 (11.2%) were found to have snails shedding bifurcate cercariae. The distribution of snails infected with schistosome cercariae was mostly concentrated around Sika beach (Figure 17).

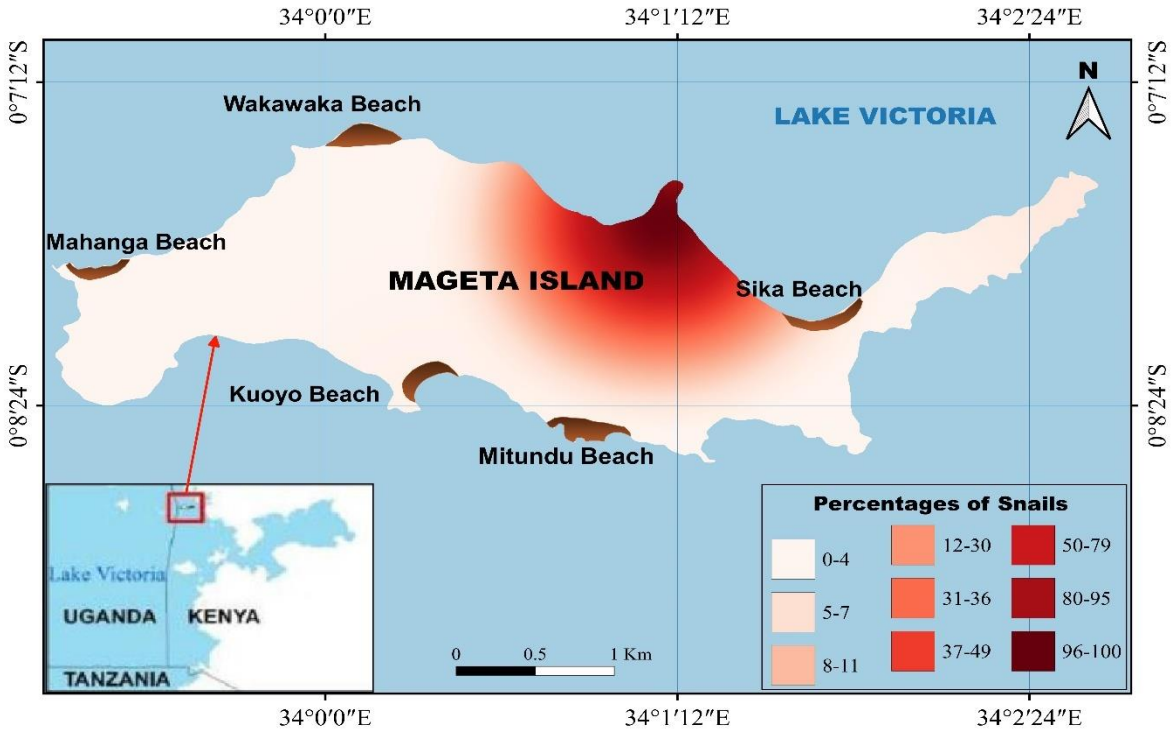

Figure 17: Risk map showing the geographical distribution of snails infected with schistosome bifurcate cercariae

4.3. Association between plant species and occurrence of snails in habitats

4.3.1. Density of snails in habitats with different plant species

The majority of the snails (n = 8915; 91.16%) collected from Mageta Island were found in habitats with vegetation (n = 70; 60.34%). Table 5 contains the mean number of each snail species and the plant species found in their respective habitats. The highest mean number of *Bi. sudanica* were found in habitats with *Lemna minor* (3715 ± 43.10) which included one of the habitats with 7,321 snails (the outlier), followed by a combination of *Eichhornia crassipes* and *Azolla caroliniana* (301.00 ± 17.35). The mean abundance of *Bu. tropicus* (11.52 ± 0.49) and *P. acuta* (1.56 ± 0.18) were highest in habitats without plants. The mean number of *Bu. nasutus* (16.00 ± 4.00) and *Bu. forskalii* (1.00 ±1.00) was highest in habitats with a combination of *Lemna minor* and *Azolla filliculoides* and *Ludwigia grandiflora*, respectively. Habitats with *Ipomoea cairica* harbored the highest mean abundance of *L. natalensis* (4.00 ± 2.00), while the highest mean abundance of *M. tuberculata* (20.50 ± 3.20) was found in habitats with *Cyperus esculentus* and *Potamogeton pusillus*(17.00 ± 4.12). The highest mean abundance of *P. ovata* (4.00 ± 1.41) was found in habitats with *Leersia oryzoides*. The highest mean abundance of *Bellamya* spp. (14.00 ± 3.74) was found in habitats with *Mimosa pigra*.

4.3.2. The association between the presence of vegetation and schistosome snail intermediate hosts

There was a significant association between the presence of vegetation in habitats and the presence of schistosome snail intermediate hosts (Figure 18). The mean abundance of *Bi. sudanica, Bi. pfeifferi, Bu. nasutus,* and *Bu. forskalii* in habitats with vegetation was significantly higher than in habitats without vegetation (P= 0.001) (Figure 18). However, the mean abundance of *Bu. tropicus, L. natalensis, M. tuberculata, P. acuta, P. ovata*, and *Bellamya* spp. were significantly higher in habitats without vegetation than in habitats with vegetation (P = 0.001) (Figure 18).

The odds of finding *Bi. sudanica* in habitats with vegetation was 2.585 times (95% CI = 1.002 – 6.667) more than in habitats without vegetation (P = 0.050). *Biomphalaria pfeifferi* and *Bu. nasutus* were only present in habitats with vegetation. The odds of finding *Bu. tropicus* in habitats with vegetation was 0.919 times (95% CI = 0.871 – 0.970) than in habitats without vegetation, with a significant difference (P = 0.002). The odds of finding *Bu. forskalii* in habitats with vegetation was 3.354 times (95% CI = 0.449 – 25.020) higher than in habitats without vegetation (P = 0.238).

Table 5: Snail abundance (mean ± S.E) from habitats with different plant species collected from Mageta Island

Plant Name	*Bi. sudanica*	*Bi. pfeifferi*	*Bu. tropicus*	*Bu. nasutus*	*Bu. forskalii*	*L. natalensis*	*M. tuberculata*	*P. acuta*	*P. ovata*	*Bellamya* spp.
Azolla filliculoides	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00 ± 0.71	1.00 ± 0.71
Ceratophyllum demersum	0.00	0.00	0.00	0.00	0.00	2.00 ± 1.41	2.00 ± 1.41	0.00	0.00	0.00
Cyperus esculentus	0.00	0.00	2.50 ± 1.12	0.00	0.00	0.00	20.50 ± 3.20	0.00	0.00	0.00
Cyperus papyrus	10.00 ± 3.16	0.00	3.00 ± 1.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dulichium arundinaceum	0.50 ± 0.50	0.00	0.00	0.00	0.50 ±0.50	0.50 ± 0.50	0.00	0.00	0.50 ± 0.50	0.00
E. crassipes	7.63 ± 0.50	0.43 ± 0.12	1.43 ± 0.22	0.07 ± 0.05	0.30 ±0.10	0.87 ± 0.17	0.83 ± 0.17	0.00	0.30 ± 0.10	1.33 ± 0.21
E. crassipes + A. caroliniana	301.00 ± 17.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00 ± 1.00	0.00
E.crassipes+C.demersum+Paspalum distichum	116.00 ± 10.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E. crassipes+Commelina benghalensis	136.00 ± 11.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E. crassipes +Ipomea aquatica	30.00 ± 5.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I. cairica	0.00	0.00	1.00 ± 1.00	0.00	0.00	4.00 ± 2.00	1.00 ± 1.00	0.00	0.00	0.00
Leersia oryzoides	10.5 ± 2.29	0.00	0.00	0.00	0.00	1.00 ± 0.71	0.00	0.00	4.00 ± .41	2.00 ± 1.00
Lemna minor	3715 ± 43.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L. minor+A. filliculoides	81.00 ± 9.00	0.00	0.00	16.00 ± 4.00	0.00	0.00	0.00	0.00	0.00	0.00
Ludwigia grandiflora	5.00 ± 2.24	0.00	0.00	0.00	1.00 ± 1.00	1.00 ± 1.00	0.00	0.00	0.00	0.00
Ludwigia peploides	0.33 ± 0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.33 ± 0.33	0.00	0.00
Mimosa pigra	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	14.00 ± 3.74
Panicum repens	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00 ± .00	0.00
Pistia stratiotes	22.00 ± 3.43	0.75 ± 0.43	0.00	0.00	0.00	0.25 ± 0.25	0.5 ± 0.35	0.00	0.00	0.00
P. stratiotes+A. filliculoides	14.33 ± 2.19	1.33 ± 0.67	0.00	0.00	0.33 ± 0.33	1.00 ± 0.58	0.00	0.00	0.00	0.00
P. stratiotes+ Salvinia auriculata	0.00	0.00	0.00	0.00	1.00 ± 1.00	0.00	0.00	0.00	0.00	0.00
Potamogeton pusillus	0.00	0.00	2.00 ± 1.41	0.00	0.00	0.00	17.00 ±4.12	0.00	0.00	4.00 ± 2.00
Ruppia maritima	0.00	0.00	2.00 ± 1.41	0.00	0.00	0.00	4.00 ± 2.00	0.00	0.00	0.00
No Plant	0.21 ± 0.07	0.00	11.52 ± 0.49	0.00	0.02 ± 0.02	1.65 ± 0.19	2.00 ± 0.20	1.56 ± 0.18	0.79 ±0 .13	2.27 ± 0.22

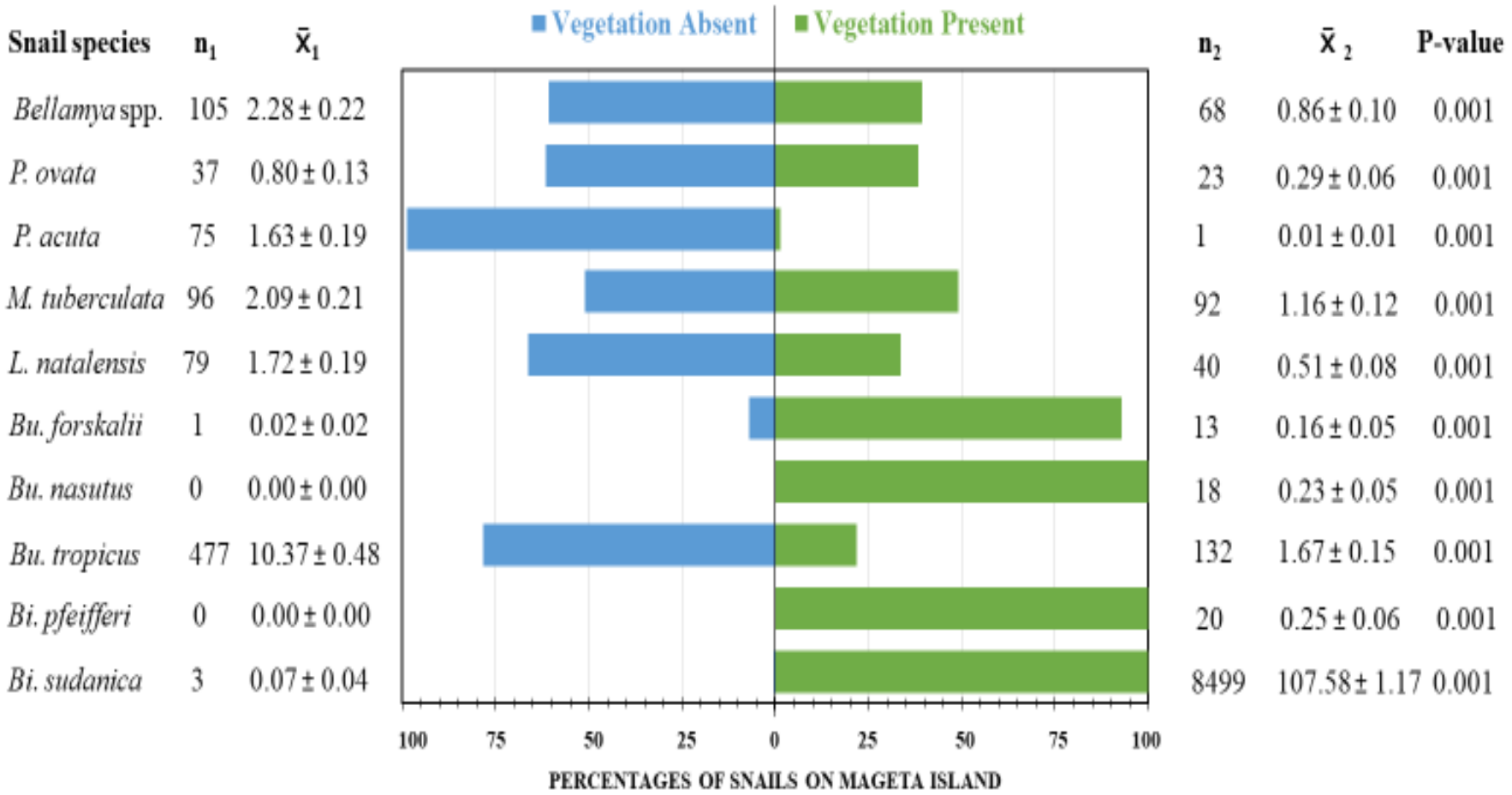

Figure 18: Percentages and the mean number of snail species in habitats with vegetation (green bars) and without vegetation (blue bars). The total number of individual snails in habitats without vegetation (n_1) and habitats with vegetation (n_2). The $\bar{x}$ is the mean of each snail species.

CHAPTER 5: DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

5.1. Discussion

This cross-sectional study demonstrated that Mageta Island harbors habitats that support snail intermediate hosts infected with schistosome cercariae. Examination of 10 snail species, namely *Bi. sudanica, Bi. pfeifferi, Bu. tropicus, Bu. nasutus, Bu. forskalii, L. natalensis, M. tuberculata, P. acuta, P. ovata*, and *Bellamya* spp., revealed that *Bi. sudanica* (86.9%) followed by *Bu. tropicus* (6.2%) were the most abundant snail species on Mageta Island. These snails were collected from 6 habitat types grouped as natural (Lake shorelines, swamps, and lagoons) or manmade (boats, ditches, and banana plant holes). Most snails (96.3%) came from natural habitat types (94.8%) with swamps containing all of the 10 species of snails. Habitats with mud bottom surfaces harbored the highest mean number of snails followed by rock, sand, and wood. *Biomphalaria sudanica, Bi.* pfeifferi, Bu. *nasutus* and *Bu. forskalii*, preferred habitats with mud bottom surfaces, while *Bu. tropicus* preferred habitats with rock bottom surfaces. The distribution of snails was mostly on the northern, eastern, and western shorelines of Lake Victoria on Mageta Island. A very small proportion of snails (3.4%) were infected with trematodes, with only 1.3% being infected with bifurcate cercariae. Vegetation was an important predictor for finding snails in habitats identified in this study. Overall, snails were found where there were *Eichhornia crassipes* (water hyacinth) plants on Mageta Island. This study revealed that habitat types played an important role in supporting snail species involved in the transmission of schistosomiasis.

In this study, the diversity of snail species was recorded with *Bi. sudanica* being the most abundant followed by *Bu. tropicus*. Only 6 snail species were found to be of medical importance and they included *Bi. sudanica, Bi. pfeifferi, Bu. tropicus, Bu. nasutus, Bu. forskalii, L. natalensis,* while the remaining 4 namely *M. tuberculata, P. acuta, P. ovata*, and *Bellamya* spp., were of non-medical importance (Brown 2002). A study done near the site of the current study by Lange and others (2013) reported collecting 15 species of snails at the Ndere and Mbita region of the Winam Gulf section of Lake Victoria region of Kenya, including the same snail species diversity found in this study, with *M. tuberculata* being the most abundant species (95.5%). The only exception was that they collected *Bi. choanomphala* and *Bulinus* species of the *tropicus*/*truncatus* group, unlike in this study where *Bu. nasutus* of the *Bulinus africanus* group and *Bu. forskalii* of the *Bu. forskalii* group was collected. Similar studies that focused on schistosomiasis snail intermediate hosts

conducted around Lake Victoria, found *Bi. sudanica* to be more abundant than *Bulinus* snails (Opisa *et al*., 2011; Ofulla *et al.*, 2013). These studies, unlike this study, recorded *Bu. globosus* (Opisa *et al*., 2011) and *Bu. africanus* (Ofulla *et al.*, 2013). In the coastal region of Kenya, the most abundant snail species are *Bu. nasutus* (Kariuki *et al*., 2004; Clennon *et al*., 2006). Elsewhere, the most abundant snail species were found to be *Bi. pfeifferi, L. natalensis* (Kock *et al*., 2004; Utzinger and Tanner 2000) and *M. tuberculata* (Oloyede *et al*., 2016). The findings of this study revealed that schistosomiasis snail intermediate hosts are present on Mageta Island.

The six habitat types had a varying abundance of snail species. Out of the 6 habitat types, swamps supported the majority of the snail species. The mean abundance of *Biomphalaria* snails and *M. tuberculata* were higher in swamps followed by Lake shorelines, while that of *Bu. tropicus* was most abundant in lagoons followed by Lake shoreline habitats. The mean abundance of *Bu. nasutus, Bu. forskalii,* and *L. natalensis* were highest in banana plant holes and boats respectively. *Physa acuta, P. ovata,* and *Bellamya* spp. were abundant in lagoons and Lake shorelines respectively. These findings are contrary to similar studies that found *Bi. sudanica* to be abundant in ponds (Ofulla *et al*., 2013) and Lake shoreline habitats (Opisa *et al*., 2011), and *Bi. pfeifferi* to be abundant in rivers (Opisa *et al*., 2011). *Bulinus nasutus* has also been found to be abundant in ponds in the coastal region of Kenya (Kariuki *et al*., 2004). *Lymnaea natalensis, M. tuberculata, P. acuta*, *P. ovata,* and *Bellamya* spp., have been found to share the same habitat types as schistosomiasis snail intermediate hosts with a difference in abundance (Malek 1958; Kariuki *et al*., 2004; Kock *et al*., 2004; Giovanelli *et al*., 2005; Olkeba *et al*., 2020). The habitats found in this study support the establishment of snails involved in the transmission of schistosomiasis.

Schistosomiasis snail intermediate hosts inhabit a wide range of natural as well as manmade habitats. In this study, natural habitats harbored more snails than manmade habitats probably due to the availability of conditions preferred by these snails. Contrary to this finding, Utzinger and Tanner (2000) in Tanzania found that snails were abundant in both natural and manmade habitats because both habitats provided favorable conditions such as water depth that allowed the establishment of the snails. They found that a layer of concrete on a manmade habitat was covered with algae that provided food for the snails. Sturrock and others (2001) found *Bi. pfeifferi* to be abundant in smaller manmade habitats (smaller canals) but peaked in larger natural (rivers) and manmade (larger canals) habitats in Richard Toll town in Senegal. They found *Bulinus* spp. to be

more abundant in larger natural habitats where their population peaked than *Bi. pfeifferi*. Interestingly, in this study, *Bu. nasutus* was the only snail species with a significantly high mean abundance in manmade habitats than in natural habitats (see Figure 12). This is not surprising because *Bulinus* snails have been observed to withstand harsh conditions in temporary habitats such as ponds and water pools when the water dries up (Perez-Saez *et al*., 2016). *Bulinus* snails can aestivate under vegetation and burrow in mud in a condition of reduced metabolic activity triggered by the drying of water pools (Brown 2002). In this study, *Bu. nasutus* was abundant in banana plant holes, a finding that agrees with reports of the snail being abundant in seasonal water bodies such as ditches, burrow-pits, and ponds (Brown 1992; Kariuki *et al*., 2004).

Different snail species in this study preferred habitats with different bottom surfaces. Schistosomiasis snail intermediate hosts are generally associated with mud bottom surfaces rich in decaying organic matter. The mud provides support for aquatic plants, a surface on which algae and other microorganisms flourish, thus providing food for the snails and a surface to crawl. In this study, the majority of snail species were found in habitats with mud bottom surfaces, but the most abundant snail species was *Bi. sudanica*. These findings are in agreement with other studies that found a majority of the snails occur on fine silt and mud in both fast-flowing and slow-flowing water (Malek 1958; Thomas and Tait 1984; Lydig and Lehtila 2009). However, mud rich in decaying matter appears to be a usual but not an essential habitat preference for *Bulinus* snails (Malek 1958). This explains why *Bu. tropicus* was most abundant in habitats with rock and sand substratum. *Lymnaea natalensis* was most abundant in habitats with wood bottom surfaces, but in other studies, it has been found in the same habitat as *Biomphalaria* snails (Malek 1958; Utzinger and Tanner 2000; Lydig and Lehtila 2009). Habitats with coarse sand in fast-flowing water favor prosobranchs such as *M. tuberculata* and *P. ovata* where they can withstand harsh wave action by closing their opercula.

The results of this study showed that snails are significantly associated with aquatic vegetation. Nonetheless, some of the aquatic macrophytes are good biotic indicators for certain snail species. Similar studies have found a significant association between aquatic vegetation and snail species of medical importance (Malek 1958; Thomas 1987; Oloyede *et al*., 2017), with schistosomiasis snail intermediate hosts mostly being associated with *Eichhornia crassipes* plants (Ofulla *et al*., 2010, 2013; Odero *et al*., 2019). Most of the snails in this study were found in habitats with *E.*

crassipes (water hyacinth), with *Bi. sudanica* being the most abundant. In this study, water hyacinth was accompanied by other aquatic plants such as *Azolla filliculoides*, *Azolla caroliniana, Ceratophyllum demersum, Paspalum distichum, Commelina benghalensis, Ipomoea aquatica,* and *Lemna minor* (see table 4). In a study by Ofulla *et al*., (2010) on the other hand, water hyacinth was accompanied by hippo grass (*Vossia cuspidata*), *Phragmites mauritanius,* paper reed (*Cyperus papyrus*), short grasses, and water lily (*Nymphaea* spp.) (Opisa *et al*., 2011), along the shores of Lake Victoria and nearby inland waters. Elsewhere, plants associated with schistosomiasis snail intermediate hosts and other freshwater snails included *Acroceras zizanioides, Ludwigia leptocarpa, Commelina* spp., *Pistia stratiotes, Salvinia nymphellula, Nymphaea lotus, Utricularia reflexa*, *Lemna pausicotata* (Ndifon and Ukoli 1989).

The water hyacinth is an invasive plant that has spread in Lake Victoria creating serious economic, social, and ecological challenges in recent times (Villamagna and Murphy 2010). Water hyacinth has been shown to contribute to an increase in the population of snails that transmit schistosomiasis, particularly *Bi. sudanica* (Plummer 2005). The plant's complex root structure and leaves create a habitat for snails where they find food such as plant detritus and phytoplankton (Plummer 2005). Moreover, the dense mats of water hyacinth are likely to reduce water current and wave action, since high water velocity can remove snails from their substratum and sweep them away, restrict growth, feeding, and reproduction by sweeping away egg masses deposited on plant leaves or roots (Plummer 2005). *Lemna minor*, also an invasive plant species were found to harbor a high population of *Bi. sudanica* in this study, particularly in one site. A study that looked at the interaction of macrophytes with *Bi. glabrata*, an intermediate host that transmits intestinal schistosomiasis in South America, found out that *L. minor* was among the plant species least preferred as a food source (Thomas 1987). Interestingly, in this study, *L. minor* harbored the highest abundance of *Bi. sudanica*, albeit from just one site. This might be a result of the snails not feeding on the plant *per se*, but on the plant detritus and phytoplankton that embed in the plant roots. Conversely, *Bu. tropicus* was found to be abundant in habitats without plants, explained by the rock and sand habitat bottom surface that *Bulinus* snails in general prefer. But algae can also grow on rock substratum providing food for the snails. Additionally, *Bulinus* snails are not exclusively found in habitats without vegetation. The rock substratum might be next to aquatic plants that deposit decaying plant matter on it as a source of food for snails.

In this study, a very small proportion of snails were found to be infected with trematodes including those that are known to transmit schistosomiasis. This is a finding that is not surprising because other similar studies done nearby have found the same results whereby few (Kariuki *et al*., 2004; Opisa *et al*., 2011; Luka and Mbaya 2015) or none (Standley *et al* ., 2010) of the sampled snails were infected with cercariae. The low or absence of snails shedding cercariae may be due to several reasons. First, the release of schistosome cercariae from field-collected snails may be inhibited by the shedding of other trematodes from a single snail (Laidemitt *et al*., 2019). In this study, *Bi. sudanica* and *Bu. forskalii* did shed more of non-bifurcate cercariae than bifurcate cercariae. Second, the prepatent infection in snails takes more than four weeks, and by the time a snail is exposed to shed cercariae, it might still be in the prepatent period. In this study, after the first exposure, snails were re-exposed for only five days to increase the chances of shedding cercariae. Thus, confirmation of snail infection with trematodes by exposing snails to indirect sunlight was a limitation of this study. Future studies should use molecular techniques to confirm infection in snails.

Molecular techniques help to accurately identify schistosome species infecting snail intermediate hosts important for understanding schistosomiasis transmission, control, and elimination (Tian-Bi *et al*., 2019). The identification of schistosome cercariae using morphological keys as provided by Frandsen and Christensen (1984), can be misleading since both animal and human schistosomes have bifurcate cercariae. In this study, the highest number of snails that shed bifurcate cercariae were *Bi. sudanica* and *Bu. tropicus*. In a study by Tian-Bi and others (2019) only 1% of *Bulinus* spp. were found to be shedding mammalian schistosomes, and out of this, 44% were infected with *S. bovis* (cattle intestinal blood-fluke), 36% with hybrids of *S. haematobium* and *S. bovis*, while only 20% infected with *S. haematobium*, identified using nuclear and mitochondrial amplification methods. Additionally, in a study by Bakuza *et al.*, (2017), 12.3% infection prevalence was observed in snails using cercarial shedding, while 47% was observed using the PCR (polymerase chain reaction) technique. In this study, it is possible that the prevalence of bifurcate cercariae in snails that transmit human schistosomiasis was higher because some snails might have been in the prepatent stage. These studies highlighted the importance of using molecular techniques to accurately identify infection in snail intermediate hosts of schistosomiasis and avoid the possibility of overestimating or underestimating the level of human schistosomiasis transmission if animal schistosomes are not considered.

Although snail cercarial infection was low and the identity of the bifurcate cercariae is questionable, residents of Mageta Island may still be at risk of intestinal schistosomiasis given the presence of *Bi. sudanica* and *Bi. pfeifferi*, and urinary schistosomiasis given the presence of *Bu. nasutus*, a known intermediate snail host of *S. haematobium* and *Bu. tropicus* and *Bu. forskalii* as potential *S. haematobium* intermediate snail hosts (Brown 2002; Labbo *et al*., 2007; Sang *et al*., 2014). This assumption can be confirmed by the presence of both *S. mansoni* and *S. haematobium* eggs in samples of feces (7 out of 41 samples) and urine (1 out of 47 samples) respectively, collected from humans in Mageta Island during a preliminary study. The prevalence of *S. mansoni* and *S. haematobium* was 17.07% and 2.13%, respectively. Further investigations are needed due to the small sample size used.

5.2. Conclusion

The following conclusions were made in this study:

1. Mageta Island harbors schistosomiasis snail intermediate hosts with *Biomphalaria sudanica* (intermediate host for *Schistosoma mansoni*) being the most abundant in natural habitats followed by *Bulinus tropicus* (potential intermediate hosts for *Schistosoma haematobium*) that was only found in natural habitats.
2. Residents of Mageta Island are at risk of schistosomiasis infection because of the presence of snail intermediate hosts infected with schistosomiasis cercariae.
3. Habitat types and vegetation play an important role in the establishment of schistosomiasis snail intermediate hosts on Mageta Island.

5.3. Recommendations

1. Studies on Mageta Island residents should be done to determine the prevalence of human schistosomiasis.

2. Residents of Mageta Island should be included in the schistosomiasis national-wide mass drug administration (MDA) treatment with praziquantel.

3. Future studies should use molecular techniques to identify cercariae on schistosomiasis snail intermediate hosts, for purposes of confirming disease transmission points.

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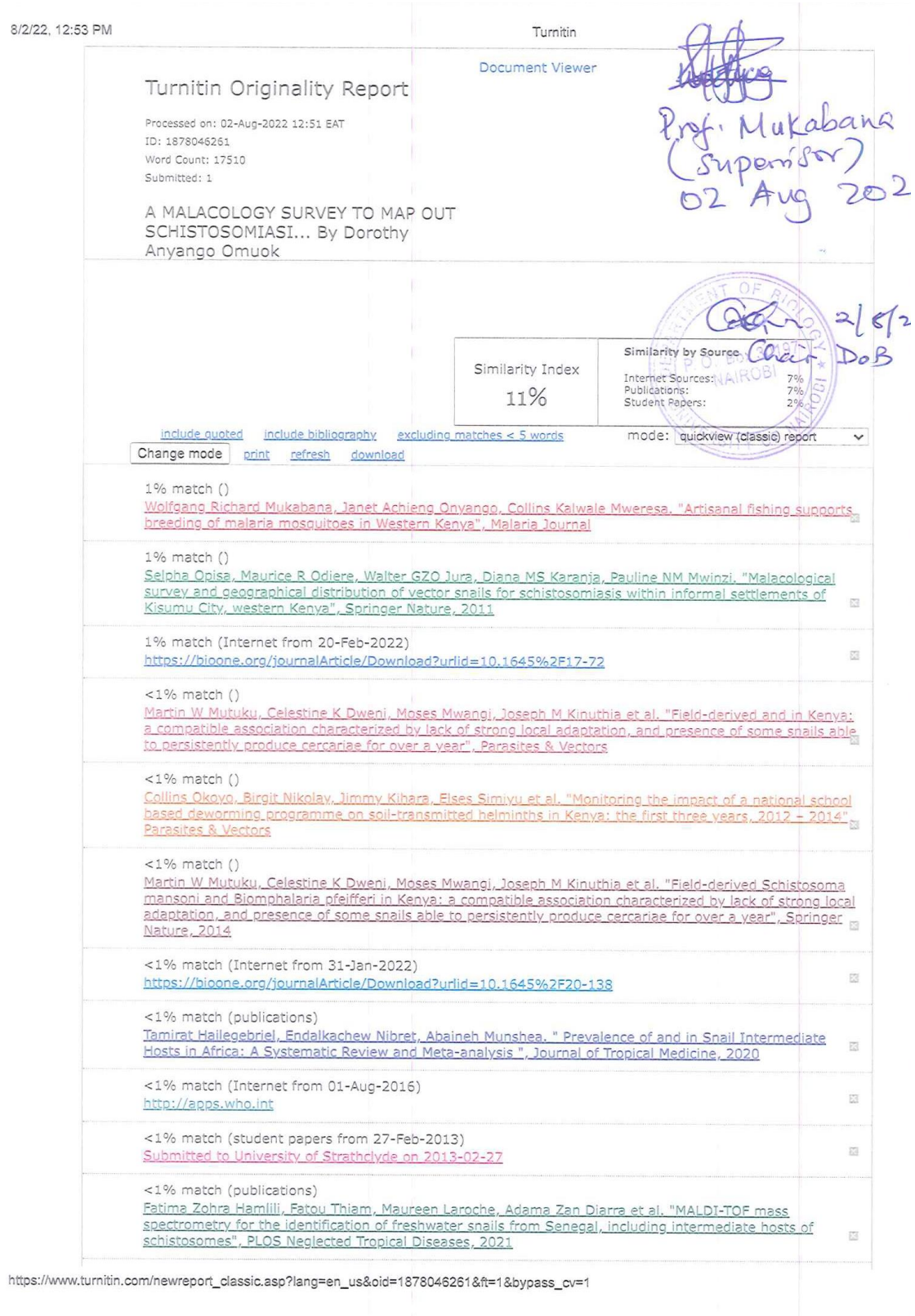
APPENDIX 1: Originality Report



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APPENDIX 2

1. DATA SHEET: SNAIL SURVEY – MAGETA ISLAND

1.0. General Information:

Date _____ Village _____ GPS site # _____

Name of Community Health Volunteer (CHV) _____

2.0. GPS co-ordinates of snail habitat:

Latitude _____ Longitude _____ Elevation (m) _____

3.0. Description of Snail habitat:

Habitat location (e.g. trench arising from Sika fish Banda): _____

Habitat type (e.g. swamp, lake shoreline): _____ Snails present (Y/N): _____

Is snail used as fish bait?	Y/N	Snail Name	Name of fish targeted:
Snail type 1	_____	_____	1 _____
Snail type 2	_____	_____	2 _____
Snail type 3	_____	_____	3 _____
Snail type 4	_____	_____	4 _____
Snail type 5	_____	_____	5 _____
Snail type 6	_____	_____	6 _____

Human activities present (Y/N): _____ Identity of human activities: _____ Is vegetation present (Y/N)? _____

Is algae present? (Y/N): _____ Is habitat open to direct sunlight? (Y/N): _____ Habitat bottom surface type e.g. wood, sand, mud, rock etc.: _____

Is the habitat permanent? (Y/N): _____ Is the habitat manmade? (Y/N): _____ Sex of person who created the habitat? (Male/Female): _____

Does habitat support livelihoods? (Y/N): _____ Type(s) of livelihood(s) supported e.g. ACF etc.: _____

4.0. Snail host(s) present in the habitat:

Name of snail	Plant host		# collected
	Name	Type	
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			

Name of snail	Plant host		# collected
	Name	Type	
11.			
12.			
13.			
14.			
15.			
16.			
17.			
18.			
19.			
20.			

Comments:

_____

_____

_____

Enumerator (names): _____ Signature: _____

APPENDIX 3

2. DATA SHEET: MAGETA SNAIL CERCARIAL INFECTIONS

NAME OF SNAIL			GPS SITE #	SNAIL ID # (e.g. *B.globosus*127-A)	Plant part*	INFECTED (Y/N)	
Local name	Genus	Species				Human	Animal

* Part of plant (e.g. leaf back, stem, root, flowers, fruits, seeds etc.) from where the snail was collected

APPENDIX 4

3. DATA SHEET: HUMAN SCHISTOSOME INFECTIONS ON MAGETA ISLAND

DATE: _____

PATIENT INFORMATION:

Name of patient: _____

Village Name: _____

Age: _____

Sex: _____

Occupation: _____

Education Level: _____

Place of residence (last 3 or 4 months): _____

HELMINTH INFECTION STATUS:

Infected (Y/N): _____

Parasite name(s): 1. _____

2. _____

3. _____

COMMENTS:

_____

_____

Enumerator (names): _____ Signature: _____