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Evaluation of Vaccine Efficacy and Snail Control on the Transmission of Schistosoma Haematobium

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Abstract

Following some successes recorded in recent clinical trials of vaccine of Schistosomiasis also known as the snail fever in mice and rodents, we present in this work a mathematical model to assess the potential impact of vaccine discovery on the spread of the disease in communities around water bodies. Also, we present the efficacy of a hybrid method that involves the combination of vaccine administration and an age old practice of controlling the population in schistosomiasis prone areas as a disease control strategy.

Keywords: Mathematical model, Schistomiasis, Vaccine Trails, Snail control

Background

Schistosomiasis also known as Bilharzia or snail fever is a chronic tropical disease caused by a parasitic worm that infects almost 258 million people in 75 countries across the world and kills approximately 280 thousand people annually [12, 23]. It is very prevalent in the Middle East, South America, Africa and Asia, particularly in regions where water infrastructure is underdeveloped [11]. Despite its prevalence, Schistosomiasis remains one of the ”neglected” tropical diseases [21]. Though not instantaneously fatal, schistosomiasis can cause complications in the urinary system and in the liver and it can also damage the brain and cause cancer of the bladder at advanced stages if it persists without an effective treatment [15, 1].

People get infected when they come into contact with the cercariae or parasitic larvae released by infected water snails into freshwater bodies, mostly, during their routine recreational, domestic, and agricultural activities in these water bodies [23]. There are

many species of the parasitic trematode worms that cause schistosomiasis and among which the schistosoma mansoni, schistosoma japonicum and the schistosoma haematobium are the most prevalent in Africa [15]. These parasitic worms have a very complicated life cycle that makes snail fever a very difficult tropical disease to tackle despite the many allocations of resources dedicated to fighting the disease. A female adult worm measures about 10 to 15mm long and they live permanently twined and lays an average of 300 eggs per day within an infected human host. These eggs are released into freshwater through urine or faeces where they hatch, create miracidia and penetrate an appropriate snail intermediate host. Within the snail host, the parasites reproduce, and this time asexual and develop into free-living organisms or cercariae which are also released by the intermediate host back into these waters. From a single egg hatched that penetrates snails, as many as 100 thousand cercariae are able to develop and are able to penetrate a human host and grow to maturity [15, 26, 28].

Ghana has many important water bodies that have contributed to the transmission and spread of schistosomiasis in the respective regions in which these water bodies are situated. According to the technical report series number 280 of the WHO (World Health Organization) [23], Ghana is one of the schistosomiasis-endemic countries in Africa and by extension the world. Most of the cases were recorded in communities around the Volta lake which is, arguably, by far the most important water body in the country. The Volta Lake was constructed to provide electricity for the diversification of the Ghanaian economy which was at the time largely dependent on cocoa. It remains to date since its construction, the largest man-made lake in the world [15]. However, the construction of the lake saw a significant rise in the number of confirmed cases of schistosomiasis. Indeed in 1968, one year into the completion of the lake, a record number of urinary schistosomiasis outbreaks was observed in communities around the volta lake and a strong correlation is observed between the water levels and the number of infections recorded periodically [15, 25]. The seasonal rise in the lake's water levels was followed by a rise in the number of urinary schistosomiasis cases recorded. In essence, the creation of the lake in such endemic regions greatly enhanced the spread of schistosomiasis in the communities along the lake. There are over 1000 communities along the Volta lake which are highly dependent on the lake for their survival and this has greatly increased the prevalence rate to over 98% since its creation in 1966 [15].

Despite the numerous successes recorded in diverse clinical trials on schistosomiasis-infected mice, rodents and baboons [29, 3] the search for a preventive vaccine against the tropical disease is still on going. However, there is currently no approved vaccine against schistosomiasis [23, 3] and the control of the disease is largely based on Mass Drug Administration (MDA) of praziquantel and other measures including snail control and regular water treatment [23]. MDA of praziquantel has proven to be very effective in the treatment of schistosomiasis and other worm infections especially in endemic regions including the communities around the Volta Lake but the administration of praziquantel does not prevent reinfections [22]. In order to maintain the disease under a specified threshold, MDAs should be undertaken at regular intervals. This presents numerous challenges particularly financial and logistical challenges considering the fact that countries that are most exposed are either third world countries or developing countries [23].

Snail control is a major strategy that has been employed over several years to combat the spread of the disease. This includes the use of chemicals and the introduction of predators to reduce the snail population to an acceptable number. There are two main types of snails that act as intermediaries for the parasite in Africa. These are Biomphalaria [30, 8] and Bulinus [9] and there have been numerous studies dedicated to the control of schistosomiasis through the introduction of predators. Similarly, managing schistosomiasis in communities around the lake has been based on the administration of praziquantel to infected persons and snail control mechanisms [18].
There have been numerous research projects dedicated to the study of the epidemiology and spread of schistosomiasis and also on how to treat and eradicate the disease in the Volta Lake. These studies are based on the SIR (Susceptible, Infected, Recovered) model and are designed to study the impact and spread of the disease in a given neighbourhood. Other studies have assessed the potential impact of an efficacious vaccine that acts on the parasite's ability to live and reproduce within the human host [7, 5]. The successes recorded in various clinical trials [3, 2] may yet be an indication that an effective vaccine should be able to significantly reduce the worm population within a host and also reduce the average worm population in a community and, consequently, the number of new infections recorded annually in a specified location. The macro-parasitic framework presented by Anderson & May [19, 7] highlights different vaccination strategies that enable us to assess the impact of these strategies on infected individuals and on the spread of schistosomiasis. In recent years Anderson et al. [5] reviewed a mathematical model for the study of schistosome infections and developed a stochastic model for the transmission of the disease and the impact of MDA on its spread.
Considering the importance of the macro-parasitic framework and the significance of snail control mechanisms on the spread of schistosomiasis, we extend the models of Anderson and May [7] and [15, 25] on the snail control. Based on recent successes in clinical trials, we present a macro parasitic framework to assess the combined impact of snail control mechanisms and the administration of a potential vaccine in communities around the Volta Lake in Ghana. Similarly to [29, 7] we include snail control measures and mating probabilities of adult worms and also employ optimal control strategies to maximize the desired solution. The aim is to assess the spread of schistosomiasis in the communities around the Volta lake and present the combined impact of vaccine and snail control measures on the spread of the disease and by extension suggest solutions for adequate management of the disease in the communities considering the logistical and financial challenges.

The Model

A mathematical model is proposed to study the impact of snail control mechanisms and different vaccination strategies on the transmission of schistosomiasis in communities around the Volta Lake in Ghana. The population dynamics of the residents in the communities are presented and segmented into different groups which are administered with different vaccination strategies to analyze the impact of these strategies on the population dynamics. Similar to Stylianou et al. [29], vaccinations follow three different

vaccination strategies which are infant vaccination or mass vaccination of all age groups or a strategy involving a combination of both. These vaccinations are aimed at reducing the worm burden within the human hosts which in the long run reduces the worm burden in the community. However, in addition to these vaccination strategies, we introduce snail control techniques to manage the population of snails that serve as intermediate hosts for the miracidia in order to adequately control the levels of infectious parasites in the community. A detailed description of the strategies is presented and a thorough analysis of the strategies discussed. Our mathematical model is adequately presented and is discussed. The model is run on the data collected in the communities and the critical quantities discussed. We further investigate the combined effect of these strategies and the snail control program designed to curtail the spread of schistosomiasis in these communities. We assume that the vaccine or the vaccination methods do no impact on the life expectancy of the host.

Study Area

Constructed from 1961 to 1965 as part of the Akosombo Dam project, the Volta Lake is the largest man-made lake in the world [25, 15]. The lake lies entirely in Ghana, West Africa and it covers approximately a surface area of 8500 km^2 with a 7000km shoreline. The lake was designed to help Ghana diversify its economy which was largely dependent on cocoa and create a sustainable supply of electricity for its citizenry and the neighbouring countries [25]. Before the project, residents in the lake area numbered between 7000 and 8000 people living in about 700 villages. However, the creation of the lake saw the resettlement of these villagers into 52 new townships and over 1000 new communities whose livelihoods were now dependent on the new lake.

Before the Lake, the inhabitants of the villages were mainly farmers with only a few engaged in fishing and with a 7% prevalence rate for schistosomiasis in these communities [15, 25]. However, the creation of the lake saw a significant rise in the number of urinary schistosomiasis infections in the new settlements around the Volta lake. It was estimated that between 15 to 20% of Ghanaians were infected with Schistosoma haematobium with most of the cases recorded in communities along the Volta lake [25]. Schistosoma haematobium is endemic around the Volta lake with an average prevalence rate of 18.8% among children as reported in [25] in 1963.

Effect of Snail Control on the Worm Population in the Environmental Reservoir and on Schistosomiasis

The use of snail control mechanisms to control the population of snails and interrupt the life cycle of the schistosoma parasite as a combat strategy against schistosomiasis has been used for many years [17, 4]. Even though there has been neglect of this method in favour of MDAs and in favor of the search for a vaccine, the importance of snail control seems to be regaining more attention as an important combat strategy against schistosomiasis [17, 4, 27, 16] particularly in endemic areas such as the Volta lake and in many other developing countries. This is because the use of snail control strategies has yielded many successes in the fight against schistosomiasis. Charles et al. [16] used niclosamide, a chemical-based snail control method, to control the average worm burden in snails which was found to be very effective in reducing schistosomiasis

infections and prevalence rates. Generally, the prevalence rates of schistosomiasis in snail control regions is much lesser than those in regions where snail populations are not controlled [27] and these findings were corroborated by findings made in some part of Africa and Asia [15, 24]. It is important to note that snail control doesn't always involve the application of chemicals which may be toxic to the water bodies. Snails are a delicacy in many parts of Africa and Asia and controlling the population of snails in these regions may involve catching them in large quantities for the food market.
Despite the many potential benefits of snail control in tackling schistosomiasis, the strategy is very expensive to implement and may also be toxic to the environment with serious consequences for the water bodies [20, 18]. However the combination of vaccines with snail control strategies may be an optimal strategy.

Vaccination effect on worm population

The spread and persistence of schistosomiasis in a region is mainly based on its ability to survive up to sexual maturity and reproduce within a human host and its ability to find an intermediate snail host and reproduce as the schistosoma life cycle clearly explains [15]. An effective vaccine against schistosomiasis ideally contains antigens that stimulates the host's immune system to disrupt the worm's ability to live up to sexual maturity in a host. For our model setup, we consider the following quantities: The per capita mortality rate of an adult μ_w, the number of eggs produced per female worm per unit time σ_w, and the rate at which the cercariae larvae is able to infect and grow to sexual maturity within a human host, β_w respectively. These vaccine quantities are such that $v_1 = v_2 = v_3 = 0$ represent an ineffective vaccine and $v_1 = v_2 = v_3 = 1$ being a vaccine with 100% efficacy. We suppose that after administration of the vaccine, the rates μ_w, σ_w and β_w become:

$$\mu^*_w = \left(\frac{1}{1-v_1}\right)\mu_w,\ 0 \le v_1 < 1 \tag{1}$$

$$\sigma^*_w = (1 - v_2)\,\sigma_w,\ 0 \le v_2 \le 1 \tag{2}$$

$$\beta^*_w = (1 - v_3)\,\beta_w,\ 0 \le v_3 \le 1 \tag{3}$$

Population Dynamics

To adequately measure the efficacy of a potential vaccine on a human host and generally on a specified community, every individual in the community is assigned to either the vaccinated class, N_v, or the unvaccinated N_u. We consider the approach of MDAs of praziquantel [22, 13] in the administration of the vaccine. The first model we consider is a mass vaccination of a significant proportion say ρ of school-going-age children at regular intervals in the case where the vaccine does not provide permanent protection against schistosomiasis. This is because children are most vulnerable to the parasitic worm with high rates of reinfection [22]. The second model considers random vaccination of individuals within the community at a per capita rate of q annually. Our third vaccination strategy considers a combination of the previous models that is the immunization of children and adult individuals which is repeated on regular intervals

to prevent reinfection after the vaccine wanes away.
In our vaccination program, a homogeneous population is assumed and the selection of individuals to partake in the vaccination scheme is not biased in all aspects. We suppose further that the vaccine-induced immunity is lost at a rate of ω and hence $\tau = {}^{1}/_{\omega}$ represents the average duration of vaccine protection. We assume also that vaccinated individuals enjoy with immediate effect the benefits associated with the vaccine and a vaccinated individual moves from the unvaccinated class to the vaccinated class when the immunity is lost. The population dynamics of worms depends on whether they reside within a vaccinated host or within an unvaccinated host which we represent respectively by M_v and M_u.
According to the schistosoma parasite life cycle, humans get infected when they come into contact with the parasitic larvae also known as the cercarae which represents the initial point of interaction between the worms and a human host. Therefore humans get infected through their interactions with infected snails in water bodies and we present this transmission by the quantity β_u or β_v depending on whether the interaction follows a vaccination. A much more detailed description of the parameters in our model is described in table (1) of the table section. Our model set-up introduces a snail control strategy that significantly reduces the average worm burden or worm population in the miracidia and cercariae which are assumed to be turning over really fast. This strategy disrupts the worm population or the parasite's life cycle and reduces significantly the worm's population in the environmental reservoir.

Table 1: Model Parameters and estimates

Variable/ Parameter	**Interpretation**	**Values**
N	Host population size	–
M	Mean Number of worms	Model dependent
L	Environmental reservoir	–
d^d	Human host death rate	1/50yrs^{-1}
b	Human host birth rate	–
μ	The intrinsic growth rate	–
$\sigma^b{}_W$	Parasite mortality rate	1/4yrs^{-1} [7]
μ_2	Free-living larvae mortality rate	365/7yrs^{-1} [7]
λ^b	Egg production rate per female worm	0.14 [14]
ψ	Flow of infectious material into the environment	–
k	Negative binomial clumping parameter	0.24
γ	Density dependence fecundity parameter	0.0006/ female worm
p	Proportion of infants vaccinated per unit time	[0,1]

q^b	Rate of mass vaccination	–
ω	Rate of loss of vaccine induced immunity per unit time	$[0, \infty]$
v_1	Vaccine efficacy with an effect on worm life expectancy	[0,1]
v_2	Vaccine efficacy with an effect on worm life fecundity	[0,1]
v_3	Vaccine efficacy with an effect on worm establishment	[0,1]
Γ_H	Recruitment into unvaccinated host population	–

Host population dynamics

Unlike the regular SIR model, our model assesses the impact of a potential vaccine and therefore the subdivision of individuals into the vaccinated and the unvaccinated groups. We assume further without loss of generality that the vaccines have no impact on the host's intrinsic growth rate, μ_H and we assume further that all rates in our model are time, age and space independent and that the vaccine has similar effects regardless of the community in which they are administered.

Due to feedback effects of MDAs on both the vaccinated and the unvaccinated, we assume in the same light that vaccination programmes will have an indirect impact on the unvaccinated hosts and also an indirect impact on the average number of eggs within the community. We describe the dynamics of the human groups as:

$$\frac{dN_u}{dt} = \Gamma_H - qN_u + \omega N_v - \mu_H N_u \tag{4}$$

$$\frac{dN_v}{dt} = qN_u - \omega N_v - \mu_H N_v \tag{5}$$

$$N(t) = N_u(t) + N_v(t) \tag{6}$$

where $N(t) = e^{-\mu_H t}$ and Γ_H representing the recruitment rate of the susceptible humans.

Observe also that the dynamics of the host population in equation (6) does not include vaccination at birth which will be incorporated into the model through our initial conditions. For example if we vaccinate a population ρ at birth, then the initial condition of the ODE is given by $N_v(0) = \rho$ and $N(t = 0) = \rho + N_u(0)$. As already described models are as follows;

- **Model 1**:The vaccination of a proportion ρ of children between the ages of $[0,1)(q = 0)$.
- **Model 2**: The vaccination of a general population at a per capita rate of q per year $(p = 0)$.
- **Model 3**: Vaccination of either the general or infant population combined with an effective snail control programme.

Worm Population Dynamics

We denote the dynamics of the worm population within a vaccinated and unvaccinated human host and the environment reservoir respectively as M_v, M_u, L which we describe

in the equations as follows:

$$\frac{dM_u}{dt} = L\beta_u - (\mu_H + \mu_W)M_u - qM_u + \omega M_v, \quad (7)$$

$$\frac{dM_v}{dt} = L\beta_v - (\mu_H + \mu^*{}_W)M_v + qM_u - \omega M_v, \quad (8)$$

$$\frac{dL}{dt} = \psi(\sigma_W M_u + \sigma^*{}_W M_v) - \mu L, \quad (9)$$

where

$$\beta_u = \beta \int_{t=0}^{\infty} N_u(t) = \frac{\beta(\mu_H+\omega-\rho\mu_H)}{\mu_H(\omega+q+\mu_H)}, \beta_v = \beta^* \int_{t=0}^{\infty} N_v(t) = \frac{\beta^*(q-\rho\mu_H)}{\mu_H(\omega+q+\mu_H)},$$

subjected to the initial conditions $M_v(t=0) = M_0 N_v(t=0) = (p+q)M_0$ and $M_u(t=0) = M_0 N_u(t=0) = (1-(\rho+q))M_0$.

The parameter ψ represents the flow of infectious materials into the environment as defined in [29] which can be regulated in our model through snail control strategies. We note that β_u and β_v represent respectively the transmission functions to an unvaccinated and a vaccinated host which we define as the product of the respective coefficients with the analytic solutions of the host's population dynamics below:

$$N_u(t) = \left(\frac{\omega}{\omega+q}\right) e^{-\mu_H t} - \left(p - \frac{\omega}{\omega+q}\right) e^{-(\mu_H+\omega+q)t} \quad (10)$$

$$N_v(t) = \left(\frac{q}{\omega+q}\right) e^{-\mu_H t} - \left(p - \frac{q}{\omega+q}\right) e^{-(\mu_H+\omega+q)t} \quad (11)$$

The mean parasitic worm burden within a community is therefore defined as the weighted average of worms within a vaccinated and unvaccinated individuals:

$$M = (1-(\rho+q))M_u + (\rho+q)M_v \quad (12)$$

Similarly to Anderson & May in [7] and to Stylianou [29], we assume the parasites are monogamous in nature with a fixed aggregation parameter k and they follow a negative binomial distribution with a mating probability $\varphi(M,k)$. For each individual in the population we define $F(M)$ as the product of φ and the density dependence function $f(M)$.

$$\frac{dL}{dt} = \psi(\sigma_W M_u F(M_u) + \sigma^*{}_W M_v F(M_v)) - \mu, \quad (13)$$

Basic and effective reproductive numbers (R_0, R_e)

The basic and effective reproductive numbers are very important decision-making quantities and an indicator of the continual growth or otherwise of the worm's

population within a given community. We define it as the average population of female worm's that survive to reproductive maturity with minimal or no constraints [7]. A basic reproductive number $R_0 > 1$ indicates that the worms will survive within the human host and therefore persist in the community. On the other hand a basic reproductive number of R_0 below 1 indicates that the worm's population will continue to drop and die out of the community. Therefore R_0 of 1 represents a threshold and an effective vaccine should be maintain this quantity below the threshold [7, 13]. The reproductive number is very critical in determining the persistence and spread of the parasite within the host population and consequently the community. Similarly the effective reproductive number is obtained as the new value for the basic reproductive number after the necessary interventions to curtail the spread of the infections. To compute the effective reproductive number, we consider the dynamics of the worm population as follows:

$$\frac{d}{dt}\begin{pmatrix}M_u\\M_v\end{pmatrix} = \begin{pmatrix}-\mu_u & \omega\\ q & -\mu_v\end{pmatrix}\begin{pmatrix}M_u\\M_v\end{pmatrix} = M\begin{pmatrix}M_u\\M_v\end{pmatrix} \Longrightarrow M = \begin{pmatrix}-\mu_u & \omega\\ q & -\mu_v\end{pmatrix}$$

and

$$M^{-1}\frac{d}{dt}\begin{pmatrix}M_u\\M_v\end{pmatrix} = \begin{pmatrix}M_u\\M_v\end{pmatrix},$$

where

$$\mu_u = \mu_H + \mu_W + q \text{ and } \mu_v = \mu_H + \mu_W + \omega.$$

The basic reproduction number is, therefore, given by the positive eigenvalues of M. Using the eigen-decomposition of the matrix M, we get the eigenvalues to be

$$e_{1,2} = \frac{-(\mu_u+\mu_v)\pm\sqrt{(\mu_u-\mu_v)^2+4q\omega}}{2}.$$

Using the egg productions of the two states, vaccinated and unvaccinated, $\Lambda = (\sigma_W, \sigma^*{}_W)$, the contribution of eggs from an established worm, Q, will be:

$$Q = -\psi\int_0^\infty \Lambda\begin{pmatrix}M_u\\M_v\end{pmatrix}dt = -\psi\Lambda\int_0^\infty M^{-1}\frac{d}{dt}\begin{pmatrix}M_u\\M_v\end{pmatrix}dt = -\psi\Lambda M^{-1}\Pi,$$

where $\Pi = (\pi_u, \pi_v)$ are the initial conditions of (M_u, M_v). For n eggs in the environment, on average of $\frac{n(\beta_u+\beta_v)}{\mu}$ will establish and hence the probability split between the two types of hosts will be;

$$\begin{pmatrix}\pi_u\\\pi_v\end{pmatrix} = \frac{1}{\beta_u+\beta_v}\begin{pmatrix}\beta_u\\\beta_v\end{pmatrix},$$

thus,

$$R_e = -\frac{\psi}{\mu}\Lambda^T M^{-1} B, \tag{14}$$

where

$$\Lambda = (\sigma_W, \sigma^*{}_W)\ M = \begin{pmatrix} -\mu_u & \omega \\ q & -\mu_v \end{pmatrix}\ B = \begin{pmatrix} \beta_u \\ \beta_v \end{pmatrix}. \tag{15}$$

And also substituting the vectors and the matrix, we have

$$R_e = -\frac{\psi}{\mu}(\sigma_W, \sigma^*{}_W)^T \begin{pmatrix} -(\mu_H + \mu_W + q) & \omega \\ q & -(\mu_H + \mu^*{}_W + \omega) \end{pmatrix}^{-1} \begin{pmatrix} \beta_u \\ \beta_v \end{pmatrix} \tag{16}$$

$$R_e = \frac{\psi}{\mu(\mu_u\mu_v - q\omega)}[\sigma_w, (\mu_v\beta_u + \omega\beta_v) + \sigma^*{}_W(q\beta_u + \mu_u + \beta_v)]. \tag{17}$$

Without any vaccine or without an effective vaccine, we have that $\mu_W = \mu^*{}_W, \beta_W = \beta^*{}_W, \sigma_W = \sigma^*{}_W, \rho = 0, q = 0$. Thus Reproductive number of the unvaccinated is given by:

$$R_0 = \frac{\psi\sigma_W\beta}{\mu(\mu_H + \mu_W)}. \tag{18}$$

We derive $R^v{}_0$, the basic reproductive number of the vaccinated, from the effective reproductive number in equation (17) by setting $p = 1$ and $q = 0$ i.e.

$$R^v{}_0 = \frac{\omega\psi\sigma_W\beta_v}{\omega + \mu_H\mu(\mu_H + \mu_W)} + \frac{\sigma^*{}_W\beta_v\mu_H\psi}{\mu(\omega + \mu_H)(\omega + \mu_H + \mu_W)} + \frac{\sigma^*{}_W\beta_v\mu_H\psi\omega}{\mu(\omega + \mu_H)(\mu_H + \mu_W)(\omega + \mu_H + \mu_W)}$$

$$R^v{}_0 = \frac{\omega}{\omega + \mu_H} R_0 + \frac{\sigma^*{}_W\beta_v\mu_H\psi}{\mu(\omega + \mu_H)(\omega + \mu_H + \mu_W)} + \frac{\sigma^*{}_W\beta_v\mu_H\psi\omega}{\mu(\omega + \mu_H)(\mu_H + \mu_W)(\omega + \mu_H + \mu_W)}$$

Depending on a given value of R_0, a transmission setting of schistosomiasis in a community could be classified as high, medium or low. A transmission setting with an R_0 between the values of $[1, 1.4]$ is classified as low, whereas a setting in the range of $[1.5, 2.4]$ and any transmission setting with R_0 greater than 2.5 is classified as a very high transmission setting $[6, 5]$. In fact the farther the value of R_0 from 1 the worse the situation. Generally, we can define the effective reproductive number as a weighted mean of the basic reproductive number of the vaccinated and the unvaccinated.

$$R_e = (1 - (p + q))R_0 + (p + q)R^v{}_0, \tag{19}$$

Critical Infant Vaccination Coverage, ρ_c, q_c

The main aim of our study is to investigate the spread of schistosomiasis in communities

around the Volta Lake and to propose a vaccination strategy that best curtails the spread of the disease in the community. We are primarily interested in the proportion of individuals in the community that must be vaccinated in order to cut short the high levels of transmissions and to prevent reinfection of individuals. We do this by restricting the value of the effective reproductive number in equation (17) to derive the required proportion. That is

$$(\rho + q)_c = \frac{1-\frac{1}{R_0}}{1-\frac{R^v{}_0}{R_0}}. \tag{20}$$

Our results are based on simulated parameter values from epidemiological and empirical studies of schistosomiasis [7, 29] which may vary slightly from one community to the other. We acknowledge that, changes in parameter values can cause great disruptions but these variations will not be significant enough to change the results.

Results

A vaccination strategy may take into account numerous factors if it is to achieve its aims. Factors including the severity of transmission i.e. the R_0 value for the community or the transmission intensity in the community, the efficacy of the vaccine being administered and its side effects, and the duration of the vaccine protection. For example, a vaccine with life-time protection may not require periodic immunization or even of snail control to ensure the eradication of the disease. However, a vaccine with a fixed periodic duration of protection may require periodic re-vaccination in order to break transmission and a snail control strategy to ensure an even longer protection against the virus. Figure 1 shows the exponential growth of the worm population within an infected human host in the absence of any effective intervention. The legend captures accurately the intensity of the population growth with respect to the reproductive number R_0 which corroborates epidemiological research [7], that is the higher the reproductive number the greater the exponential growth of infection. Also, Figure 2 clearly shows the impact of an effective vaccine on the worm population with a host in the community. In the plot of Figure 2 we notice that the initial worm population of 100 grows sharply in a higher transmission setting but reduces sharply due to vaccine and dies out completely after about 100 unit time. However, for a much more effective vaccine in Figure b of Figure 2 with an efficacy of 80% which is 30% more potent, we brief sharp rise in the worm population in higher transmission setting with $R_0 > 2.5$ and much faster reduction in the worm population which dies out after a shorter period of 60 unit time. Figure 3 shows the impact of snail population control strategy on the number of schistosome that are able to infect and grow to sexual maturity within a human host. Observe that in both plots in Figure 3, we have reduced by 40% the number of schistosomes that are able to infect its host. In such a situation, a vaccine efficacy of about 20% or less on the worm's ability to survive up to sexual maturity is able to break transmission and eradicate the worms within the host after about 100 unit time. In the

second plot of Figure 3, in the same model 3 setting, a much more potent vaccine achieves a faster eradication,i.e. over 2 times faster, of the schistosomes.

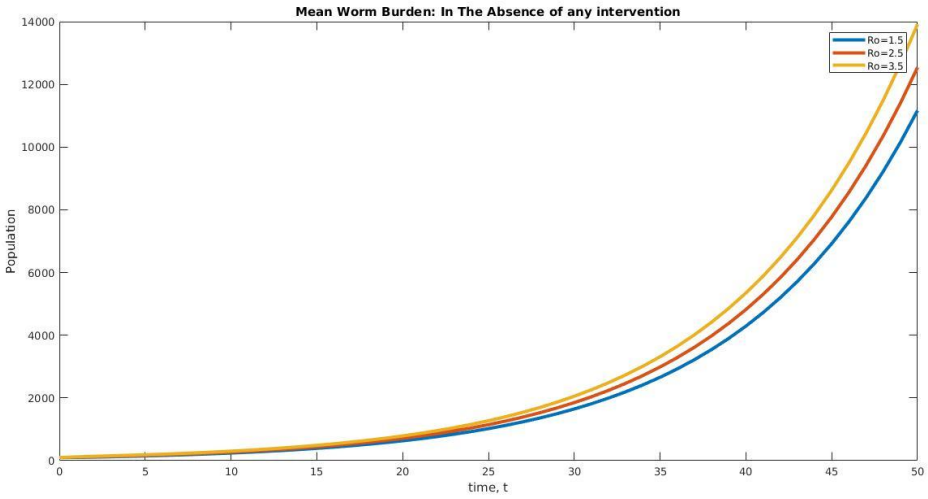
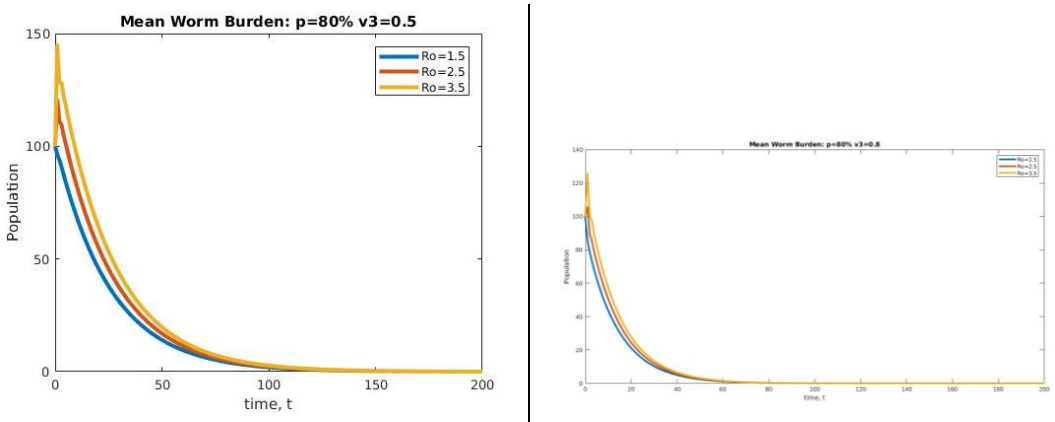
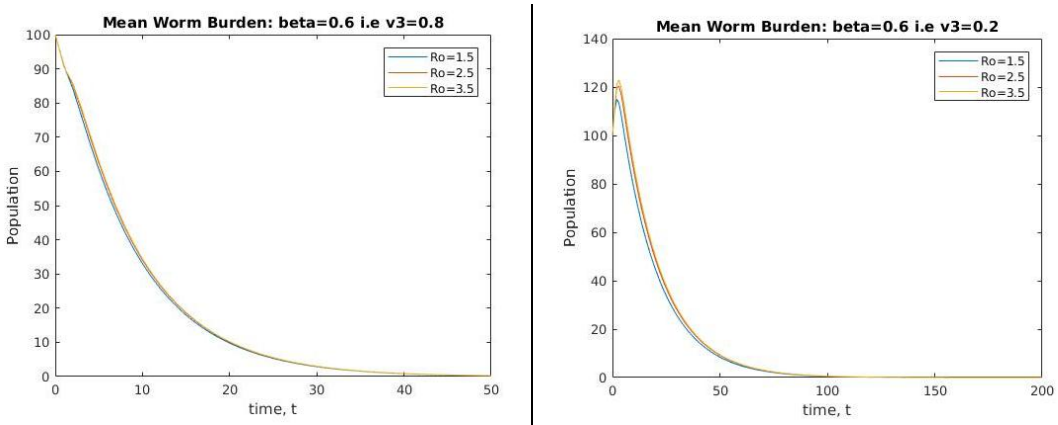


Figure 1: Mean worm burden within a human host in the absence of any intervention i.e. vaccine, MDA of praziquantel.



(a) $v_1 = 0, v_2 = 0, v_3 = 0.5$ (b) $v_1 = 0, v_2 = 0, v_3 = 0.8$

Figure 2: The vaccine impact on the worm's ability to infect and grow up to sexual maturity within a host using infant vaccination of model 1 with $\rho = 0.8$



(a) $v_1 = 0, v_2 = 0, v_3 = 0.8$ (b) $v_1 = 0, v_2 = 0, v_3 = 0.2$

Figure 3: The vaccine impact on the number of eggs produced per female worm per unit time in vaccination of the general population in model 2 with $q = 0.5$

Discussion

From our graphs, it is clear that the vaccination coverage needed to interrupt the transmission of schistosomiasis the community is largely dependent on the efficacy of the vaccine, the vaccination strategy, the transmission levels in the community and also the application of other snail control measures. As observed from the graphs, higher transmission levels,i.e. $R_0 > 2.5$, require stronger vaccine efficacy to break transmission. For example if we consider a high transmission setting, then a vaccine efficacy of 80% and a vaccination coverage of at least 90% is required to break transmission or reduce the basic reproductive number to below one. However, a vaccine efficacy of 50% will break transmission but requires 100% vaccination coverage and a longer period of time to eradicate the disease. As expected and as observed in the graphs, the higher the efficacy of the vaccine the shorter the time required to break transmission. In a medium to low transmission settings, a vaccine efficacy of 50% and a vaccination coverage of 80% is required to interrupt the transmission. A higher coverage leads to a faster desired result.

With an effective snail control strategy or program, a vaccine with an efficacy of 20% leads to a break in transmission in low and medium transmission setting even in with a smaller vaccination coverage. This combined strategy could prove very useful and cheaper in endemic regions with financial and logistical challenges.

Conclusion

Our mathematical model provides us with numerous information necessary to combat schistosomiasis in communities around the Volta lake and other communities where schisto-somiasis is endemic. In communities with high basic reproductive number or a high transmission setting, a very effective vaccine with a huge vaccination coverage is required to contain the disease within the community. However, combining the

vaccination with snail control programs does not reduce the vaccination but also shortens the time required to break transmission. A cost and benefit analysis with consideration for the severity of the infection is important to chose an optimal strategy that is financially and logistically prudent.

Competing interests
The authors declare that they have no competing interests.

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