ABSTRACT

Title of Thesis:	EVALUATING MALARIA AND THE IMPACT OF WATER RESOURCES DEVELOPMENT IN WESTERN ETHIOPIA THROUGH A ONE HEALTH PROSPECTIVE
	Tavis Christian Mansfield, Master of Science 2022
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In Ethiopia, the potential to be infected with malaria may increase this decade due to the expected increases in available breeding habitats created by the filling of the Grand Ethiopian Renaissance Dam (GERD) and its reservoir as well as internal displacement and forced migration of tens of thousands of people due to the flooding of local communities by the filling of the GERD's reservoir and ongoing civil conflict in the Tigray Region of northern Ethiopia. A One Health framework was used in this research along with refugee migration and resettlement information and, risk evaluation tools to assess the potential health effects of the construction and filling of the GERD and its reservoir in Western Ethiopia on the burden of malaria and the human population living in the same area. This thesis shows *Anopheles* mosquitoes that are the primary vector of malaria are present in Western Ethiopia and present an entomological surveillance tool that can be implemented in the region. The author also considers the human population movement and illustrate the current vulnerabilities of the various groups involved.

EVALUATING MALARIA AND THE IMPACT OF WATER RESOURCES DEVELOPMENT IN WESTERN ETHIOPIA THROUGH A ONE HEALTH PROSPECTIVE

by

Tavis Christian Mansfield

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Advisory Committee:
Professor Paul Turner, Chair
Professor Rachel Rosenberg Goldstein
Professor Amir Sapkota
Adjunct Lecturer Steven Ault

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Abbreviations and Acronyms

BGR	Benishangul-Gumuz Regional State
CDC	Centers for Disease Control and Prevention
CIA	Central Intelligence Agency
DHS	Demographic and Health Survey
FAO	Food and Agriculture Organization
GERD	Grand Ethiopian Renaissance Dam
HLC	Human Landing Collection Method
MIS	Malaria Indicator Survey
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OIE	World Organization for Animal Health
PMI	Presidents Malaria Initiative
PCR	Polymerase Chain Reaction Test
U.N	United Nations
UNCHR	United Nations High Commissioner for Refugees

Chapter 1 - Introduction

Ethiopia is a landlocked nation in the Horn of Africa, bordered by Kenya in the south, South Sudan and Sudan in the west, Eritrea in the north, and Djibouti in the east and Somalia in the northeast border (CIA, 2022). Ethiopia covers an estimated land area of 1,096,570 sq km and has a mean elevation of 1,330 m. The country is made up of nine ethnically affiliated regions known as regional states: Afar, Amhara, Gambela, Harari, Oromia, Somali, Benishangul-Gumuz, Tigray, and the Southern Nations, Nationalities, and Peoples' Region, as well as the Addis Ababa, the capital, and Dire Dawa (CIA, 2022). Near the western border of Ethiopia with Sudan, the Grand Ethiopian Renaissance Dam (GERD) began construction in 2011 and is built primarily to supply a massive new amount of hydroelectric power to the entire country thus driving national economic (industrial) development. Its reservoir has been filling since July 2020, will eventually cover about 1,874 km2 (724 sq mi), will extend approximately 125 km upstream from the dam, and will slowly fill over the next 5-8 years until its planned water volume capacity is reached (Wheeler et al., 2020). The dam, the largest in Africa with the Aswan High Dam in Egypt being second, has been controversial for the surrounding two down- stream nation-states which will be impacted. Sudan and Egypt might be impacted because the flow volume of the Blue Nile River below the dam is expected to be lowered on a regular or permanent basis when it reaches Sudan and subsequently Egypt after flowing to the GERD and its large reservoir, with a variety of negative environmental implications projected downstream. Downstream, millions of people rely on the Nile River for crop irrigation, drinking water and water for electrical generation and commercial uses, and Egypt estimates electricity generation from its Aswan High Dam will be reduced by 12 to 7% by the GERD (Mulat & Moges, 2014) (Wheeler et al., 2020). Upstream, thousands within the surrounding rural communities will be displaced due to changes in the GERD reservoir surface area coverage and water levels as the dam's reservoir could lead to possible flooding of 1,680 square kilometers of forest (Sierra, 2017) and small settlements.

Figure 1.. Map of Ethiopia and Neighboring Countries (Encyclopedia Britannica, 2011)

The water sources for the GERD and its reservoir begin at Lake Tana about 275 kilometers up-stream on the Blue Nile River in Ethiopia (the largest river in the country), and also include water fed by other smaller rivers in adjacent river basins such as the Didessa, Dabu, and Beles Rivers. The GERD itself resides in the Benishangul-Gumuz Region (BGR) (formerly Region 6) and the population centers closest to the dam are Bameza (at the dam), Piyabala (near the saddle dam), and the *woredas* named Guba (incl. Guba town) and Wenbera. These *woredas* are in the Metekel Zone, which is predominantly rural, where the residents rely principally upon subsistence farming and livestock management for their economic livelihood. Also adjacent to the southwestern edge of the GERD's reservoir is Sirba Abbay *woreda* in the Kamashi Zone in BGR which is a regional state that is situated along the Blue Nile River. The BGR is a Region inhabited both by long-time settlers as well as migrants, and its capital is Assosa (aka Asosa).

Previous data suggest that the BGR has the highest rural-rural in-migration in the country (CSA, 2007), explained by nearly half of rural-to-rural in-migration in Ethiopia occurring due to the search for employment (World Bank, 2001), indicating unemployment is an issue in the BGR. Some 31% of children under-five in the BGR are underweight compared to national average of 21% as well as the under-five mortality in the BGR being 98 deaths per 1000 live births compared to the national average of 67 deaths per 1000 live births (UNICEF, 2019a). The prevalence of malnutrition and high child mortality generates risk of diseases such as malaria for populations living in deficient conditions. With the *woredas* near the dam being rural and without reliable and abundant local water supply and a probable low basic sanitation coverage rate (2% of households use improved sanitation facilities) (UNICEF, 2019a), there is a presumed expected reliance of some communities on or near the Blue Nile River to use its water for domestic purposes (e.g., drinking water, cooking, laundry, bathing) and agricultural, occupational or recreational purposes (e.g., watering gardens and agricultural fields, livestock (goats, cattle) watering, washing equipment, swimming and child's play) potentially putting the surrounding population in proximity to malaria vectors.

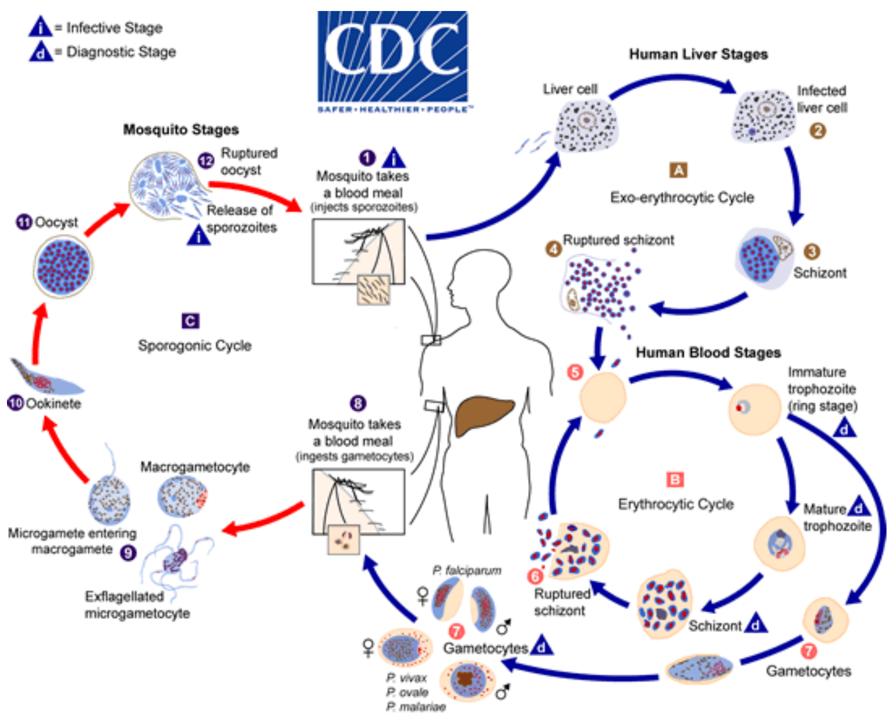

Figure 2. Life Cycle - Malaria (Source: Centers for Disease Control and Prevention, 2021)

Malaria is a serious parasitic infection endemic in much of Ethiopia and caused by being bitten by an infected female *Anopheles* mosquito which transmits microscopic malaria parasites which most commonly in Ethiopia are *Plasmodium falciparum* and *P. vivax.* When a mosquito bites a person who is infected, a small amount of blood is taken, which contains one life stage of the microscopic malaria parasite (shown in Fig.2). When the mosquito takes its next blood meal about a week or so later, another stage of these parasites mixes with the mosquito's saliva and is injected into an non-infected person being bitten thus transmitting the infection.

In this thesis, I address the possible health risk of malaria with respect to the GERD dam by conducting a risk assessment based on synthesizing research that has been previously produced and through mapping the placement of human settlements and refugee camps in relation to the GERD dam and its reservoir. Throughout the examining of older and current literature on Ethiopia and the Benishangul-Gumuz region specifically, with focus on both the environmental and socio-economic factors that may influence their health outcomes throughout this decade (2020-2030). Historically, population resettlement is difficult both on local economies and on the health of the populations displaced by large hydroelectric dams (Cernea, 1994). This thesis explores the two issues of the correlation of malaria and dams and the expected impact of human population movement on malaria burden.

To contextualize the current catalyst of human movement outside of the construction and filling of the GERD and its reservoir, since the middle of 2020 approximately 180,000 persons have been displaced due to inter-communal/ethnic violence in northern Ethiopia (OCHA, 2021a). With the northern part of BGR particularly the Wonbera *woreda* and Guba *woreda* being influenced by the ongoing humanitarian crisis (arising from civil and ethnic conflicts), the involuntary movement of people has increased and become significant with the possibility of exposure to malaria vectors during migration from endemic to non-endemic areas or through areas that may also be endemic, as more than 60% of the Ethiopian population live in malaria-risk areas (Birhanu et al., 2018). The GERD will also displace people who live in the proposed reservoir area. Because of the various forecasted reservoir volume scenarios, from 20,000 to 140,000 people will be relocated (Ahmed et al., 2015). This thesis presents that throughout the next decade there are real public health challenges related to malaria in Western Ethiopia that must be addressed through the implementation of public health measures which include but are not limited to the distribution of insecticide nets, access to anti-malarial medication and entomological surveillance.

In the two chapters that comprise this thesis, the author describes the environmental component and human population component of malaria transmission. The first chapter provides a literature review and historical overview of the association of dam and reservoir construction with higher malaria burdens over time in parts of Africa. The second chapter will geographically orient readers to refugee camps and human settlements while also describing the demographic composition of the population in connection to the GERD and the edges of its reservoir and then describe the known and potential human population displacement and increase in malaria burden. These chapters explain the issues with large hydroelectric dams as well as the strategies that should be considered to manage the prevalence of malaria in the BGR's specific region. These chapters also outline the considerations that should be assessed for the development of future dams, allowing for further investigation into how the One Health approach and risk assessment tools provides a perspective to understand the interconnected factors of the environment, human health, and malaria vectors in Ethiopia and elsewhere in the African region.

Chapter 1

The Impact of Dams on Malaria – Grand Ethiopian Renaissance Dam

Abstract

The role of large hydroelectric dams as a factor in the transmission and resurgence of malaria in the BGR has not been widely reported. This chapter aims to gain an understanding of the association between the presence of hydroelectric dams and malaria prevalence in the BGR. Then, with the integration and the use of a mapping tool to demonstrate the distance of the nearest towns and *woredas* to the reservoir's edge. Finally, this chapter will show the role of water management as a mitigation tool to reduce *Anopheles* larvae habitats surrounding the GERD reservoir thereby demonstrating the possible action that can be taken to reduce human risk for malaria.

1.1 Review of Literature

According to a 2007 report by the Food and Agriculture Organization of the United Nations, in Africa, more than half of dams (52%) were built to enable agriculture and to deliver water to towns, with another 20% of dams having various functions and with crop irrigation being one of the most common. The report's authors stated, "Although only 6% of dams were built primarily for electricity generation, hydroelectric power accounts for more than 80% of total power generation in 18 African countries, and for more than 50% in 25 countries. Only 1% of African dams have been constructed to provide flooding control …" (FAO, 2007). Dams play a role in developing and progressing economies across Northern and sub-Saharan Africa. Yet, this progress comes with altering the physical environment, including changing the ecological functions of water bodies. This change has proven to impact vector-borne disease transmission, specifically concerning malaria. Dams are classified as large by the International Commission on Large Dams if their height exceeds 15 meters or is between 5 and 15 meters (WCD 2000). One study by Kibret et al. (2019) concluded that the number of people living within 5 kilometers of large hydroelectric dams in Sub-Saharan Africa increased from 14.4 million in 2000 to 18.7 million in 2015; as well, the large dams are estimated to be responsible for between 0.7 and 1.6 million malaria cases each year in Sub-Saharan Africa.

Understanding the changes to the local ecology, and the challenging socio-economic conditions certain populations find themselves grappling with, emphasizes the importance of a multisectoral approach that the One Health framework provides. Thus, the research aims of this chapter are to identify and understand the previous and potential dynamic interactions between the distribution and burden of disease created by *Plasmodium* spp. the malaria parasite and its vector female *Anopheles* mosquitoes and considering the role of hydroelectric dams and reservoirs in disease transmission.

The newly constructed GERD is located at a longitude and latitude of 11.2183° N, 35.0941° E, and an elevation of 545 meters above mean sea level and is considered one of the two largest dams in Africa. Ethiopia plans to produce 700 megawatts (MW) from the GERD by operating the first two turbines in 2022, covering 20% of its own needs, government officials indicated (Al-Monitor, 2022). The GERD and its settlement Bameza are located 17 kilometers to the nearest town, Guba, connected by a side road of the Asosa-Guba Road. It is located approximately 96 kilometers upstream from a large dam on the Blue Nile River in Sudan named the Roseires Dam. The maximum height of the GERD when complete in the next few years will be 640 meters above mean sea level (Wheeler et al., 2020). Annual temperatures at the GERD range from 60 to 80 °F (16 to 27 °C) (Encyclopedia Britannica, 2021) but recent temperature readings from the national weather service show a range of temperatures that can reach above 100 °F (~38 °C), while relative humidity ranges around 68% to 93%. Temperature is relevant to malaria vector survival rates, and transmission potential, which will be discussed further in Chapter 2. The GERD area is located within the grassland & savannah Biome (Encyclopedia Britannica, 2021), in a local ecosystem classified in climate zone "Aw", meaning "Tropical Savannah with <100 cm mean annual precipitation, according to the Koppen-Geiger climatic classification system" (Peel et al., 2007).

Dams throughout Ethiopia have reflected the significance of the presence of dams and their impact on malaria transmission. The Gilgel-Gibe hydroelectric dam complex in Oromia, Ethiopia was previously the largest supply of power (184 Megawatts) in Ethiopia and has been operating since 2004 and was the site of the Yewhalaw et al. (2009) study observing the influence of distance from the hydroelectric dam to the nearest village to characterize malaria in the area. The study was carried out for three months between October-December 2005 where two groups of children living in three villages within 3 kilometers of the dam's reservoir (Dogosso, Budo, and Osso) and three villages 5–8 kilometers from its edge (Shakamsa, Sombo, and Yebo) were chosen at random and labeled as 'at-risk' and 'control' communities, respectively. *Plasmodium* prevalence near the reservoir was statistically greater than *Plasmodium* prevalence in further away localities (p-value = 0.013). The principal reason for the greater frequency of malaria among children living near the reservoir may be related to anthropogenic ecological modifications that impact the local abundance of mosquito-breeding sites. The time spent outside is also an important factor as smaller children tend to play in the evenings when malaria vector mosquitoes are most active (Moshi et al., 2017) (Ahmed et al., 2015).

Ethiopia is not unique when considering the influence of hydroelectric dams on the transmission of malaria in Africa, for example Kyei-Baafour et al. (2020) conducted a study in Northern Ghana around two communities, the Gowrie/Vea community by the Vea irrigation dam (dam site) and the Soe community, about 20 km away, with the predominant local vector being *An. gambiae.* The study was conducted throughout the wet and dry seasons, in which during dry periods malaria transmission is normally assumed to be quite low or non-existent. During the wet season, parasite prevalence was 54.5 % at the dam site and 33.% at the non-dam location, as determined by PCR and microscopy. It was 71% at the dam site and 49.2 % at the non-dam site during the dry season. With the very high dry season frequency discovered, the notion that very little or no transmission occurs during the dry season is incorrect when it fails to account for the existence of significant bodies of water such as dams. This may occur in the BGR, Ethiopia.

There may be a mental impression shaped by some case studies that the issue of malaria and dams is solely dependent on the behavior of human populations, however, there have been other studies conducted that highlights environmental drivers of malaria such as by Endo et al. (2018) based around the Ejersa-Dungugi-Bakele *kabele*, a village near the Koka Reservoir in Ethiopia. Their study investigated the effect of wind direction on malaria transmission around a reservoir. This study reflects the importance of the geographic placement of resettlement communities and not exclusively established communities. It was found “that the risk of malaria is higher in locations south of the reservoir than north of the reservoir”. This shows that the malaria transmission could be reduced if resettlement communities are placed downwind of reservoirs rather than upwind during dam and reservoir building.

With Ethiopia accommodating 823,000 documented refugees and asylum seekers, making it Africa's third largest refugee-hosting country, and around 62,000 whom reside in BGR, assessing malaria incidence in refugee camps is crucial due to the vast geographic backgrounds that the populations originate from (UNICEF, 2019a) (UNHCR, 2021). According to Ahmed at el. (2015), the malaria prevalence rate at the Sherkole camp (72 km from GERD) in the BGR was around 3.9% among a population of 356 children under the age of five. Though the incidence rate was low in comparison to the broader region, the study revealed three risk factors for malaria: being outside at night, being near stagnant water, and the number of under-five children per family.

Outside of the continent of Africa, malaria produces similar health outcomes when the same environmental and socio-economic factors are present such as the clearing of land for agricultural needs in Brazil wherein the Rufalco-Moutinho et al. (2016) study examined the density of *Anopheles* larvae in Remansinho, a rural settlement along the Amazon River basin. The study examined eight localities, four were in places with less intensive deforestation, and four were in a human-modified habitat. High density of Anopheline larval habitats was found in the localities near the pasture and transitional water bodies, while surrounded by forested fragments, and this related to malaria spatial distribution.

These examples illustrate that the existing literature presents evidence that hydroelectric dams have played and continue to play a significant role in malaria transmission in various places around the world. Within the course of writing this thesis, no health impact statements, environmental impact statements, or health risk assessments were found in the public domain for the GERD, though some independent groups have discussed various environmental concerns (e.g., Elagib & Basheer, 2021). A factor that has been constant within each study previously mentioned is the presence of *Anopheles* mosquitoes; their presence and distribution within the BGR is important to the potential increase of malaria burden in the region.

1.2 *Anopheles* Presence in the BGR and Entomological Surveillance

In Ethiopia, more than 40 *Anopheles* species have been identified. When compared to other species, *A. arabiensis* was the most prevalent in western Ethiopia (Adugna et al., 2021). This species has been noted to have become resistant to all four types of chemical insecticides allowed for indoor residual spraying (IRS) (Messenger et al., 2017). This mutation of a species of the *Anopheles* population poses a potential problem for Ethiopia presently and in the near future as it indicates further genetic changes may arise more widely across the genus. Genetic changes and biting behavior of *Anopheles* mosquitoes also shape malaria transmission and the preventive public health measures that will have to be taken; for example, with just 55% of the households within BGR having long-lasting insecticide mosquito nets (LLINs) (DHS, 2016), it may suggest a large portion of the population are without adequate protection.

In Bameza, Ethiopia, the area in which the GERD dam is located, there has been, but one published public health research study conducted. In a study of water quality and children's exposure to toxic heavy metals in Bameza, researchers found evidence of poor drinking water quality in town public water taps and lack of water infrastructure (Astolfi et al., 2020), which can also represent a risk factor for exposure to malaria vector if present locally, when children (and adults) may have to find alternative water sources to use. There were 81 children under the age of 18 included in the Astolfi study, demonstrating that there are already school-age children, and their families present in Bameza and the dam site itself in what is otherwise a rural and remote area of the country where no specific data has been found on the malaria burden in children and adults in Bameza, presenting a gap that needs to be filled by the Ministry of Health.

The health and entomological information in this section is based principally on other districts within the surrounding area of the GERD and the BGR in general. It's estimated that malaria prevalence in Ethiopia is 1.4% (rapid diagnostic tests) for children living in locales under 2000 m altitude yet the prevalence in BGR for the same demographic is 14%, demonstrating a higher prevalence (MIS, 2016), In Guba, Ethiopia, a town approximately 17 km from the site of the GERD and its reservoir, a study by Alkadir et al. (2020) was conducted which examined a recent five-year trend in malaria transmission. Some 16,964 suspected malaria cases were detected by microscopy, with 8,658 (51.04 %) being confirmed positive cases. Due to the intensive agricultural operations that are now taking place in districts such as Guba there has been a large influx of migrant labors from other locations of Ethiopia which plays a role in transmission (Tilaye et al., 2021).

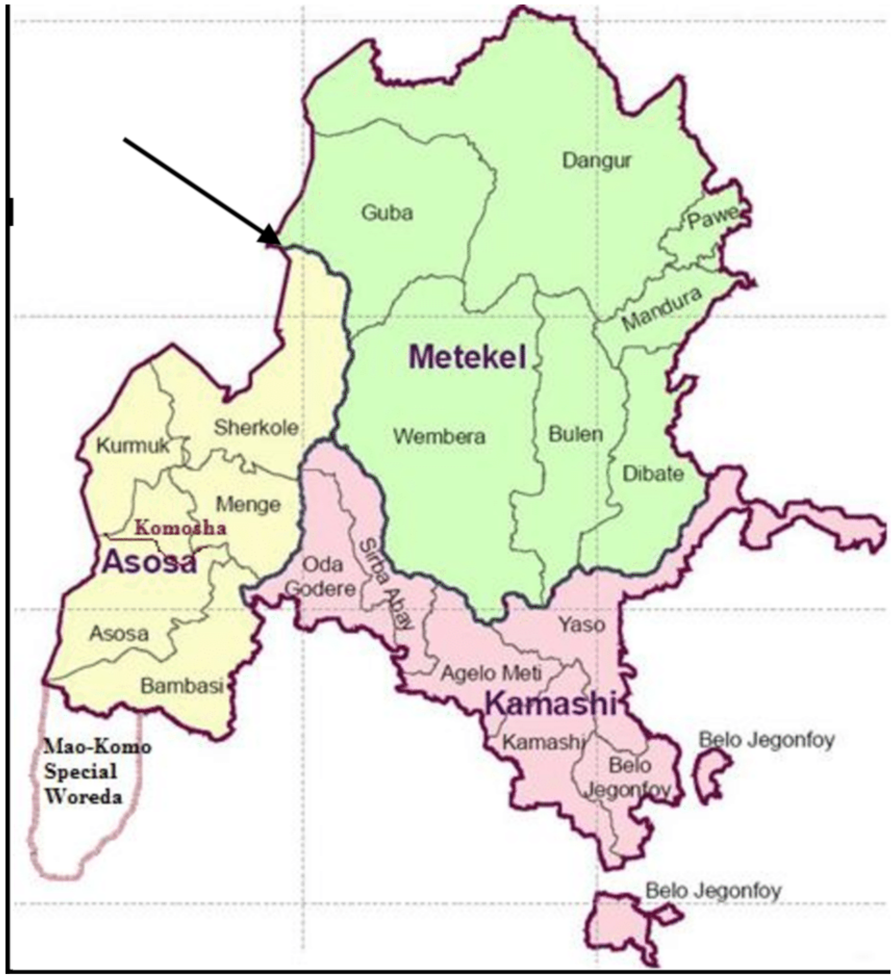

Figure 3 . Map of Benishangul-Gumuz Regional State showing three zones and 20 Woredas. Arrow shows location of GERD and its reservoir. Colors indicate political zones. (Source: Worku, 2015)

This high level of prevalence in a region in proximity to the GERD and its reservoir suggests the presence of *Anopheles* and risk of malaria transmission which was reflected in a study by Dugassa et al. (2021) based in the Dangur *woreda* of BGR (see Fig. 3) which is approximately 130 km from the edge of the GERD's reservoir. In this study, anopheline mosquitoes were collected using a human landing collection (HLC) method which captured insects as they sought to bite collectors' exposed legs. "Mosquitoes were sorted by hour of collection to calculate biting periods. *Anopheles arabiensis* (n = 1,733; 61.3% of the total *Anopheles* mosquitoes collected) was the only species identified having infective malaria sporozoites (*Plasmodium falciparum* and *P. vivax*).” This study is the second to have verified the presence of this malaria-carrying species in the BGR. Tadesse et al. (2021) observed that migrant workers in Dangur lack malaria prevention and treatment tools as less than 25% of the migrant workers slept under a mosquito net over a four-month observation period. The human movement component is important to note in relation to the presence of this malaria vector which plays a role in transmission. Dangur, though geographically distant from the GERD, was one of the *woredas* impacted by conflict in the Metekel Zone, leading to the displacement of 101,000 people in the region between the end of July 2020 and January 2021 (OCHA, 2021a).

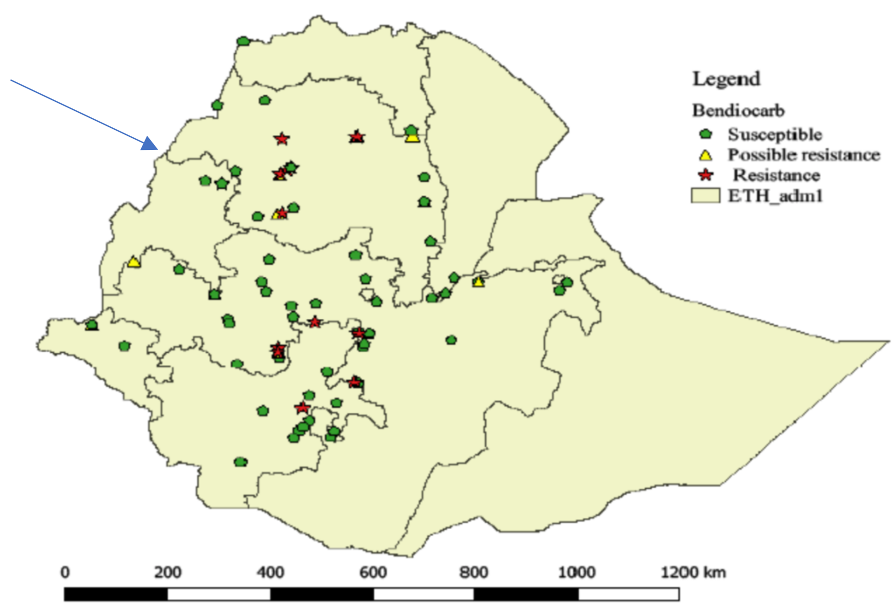

Figure 4 Map showing the distribution of resistance in An. arabiensis to fenitrathion in Ethiopia (2011 -2018) (Source: Tebeje et al, 2019)

The site of the GERD and its reservoir does not have any publicly available entomological data; however, *Figure 2* from a study on insecticide resistance in *An.*

arabiensis and the studies mentioned earlier in this chapter from within the BGR enables the logical deduction that there is a population of this malaria vector present near the reservoir's edge. When considering entomological surveillance that is needed presently and that will be needed in the future, look at the action that's been taken historically. The President's Malaria Initiative (PMI) of the United States supported the first entomological surveillance system in Ethiopia, which was developed in 2008, and has continued to fund programs in the nation. In 2018, PMI supported the spraying of 545,496 structures and the malaria protection of 1,264,189 people across 44 districts of Oromia, Gambella, and BGR, achieving a coverage rate of 97.4% (USAID, 2021). Entomological surveillance operations for vector management are comprised of three methods: the previously stated HLC, Pyrethrum spray catch (PSC), and Centers for Disease Control and Prevention (CDC) mosquito light traps (PMI, 2018). In a 2018 entomological monitoring report, the Ethiopian Government and various US governmental agencies studied three project sites in Oromia and the BGR from May 2017 to April 2018 and discovered that "a total of 1,838 adult female *Anopheles* mosquitoes were collected using PSC, HLC, and CDC light trap. *Anopheles gambiae* s.l. accounted for 42.9% of all *Anopheles* collected (n=789)" (PMI, 2018). This is significant as throughout the adult stage, *An. arabiensis* and *An. gambiae* are morphologically similar, have overlapping habitats, and contribute to malaria in Ethiopia and Africa as a whole (Zianni et al., 2013). This study provides further evidence of these two malaria-carrying species being present in western Ethiopia and specifically the BGR, which further highlights the health risk the GERD and its reservoir poses as larvae of both species can be found along the impoundment of dams in both dry and rainy seasons (McCann et al., 2018).

The Ethiopian government has focused efforts on monitoring the human population in terms of prevention and diagnostics, which is reflected in yearly reductions of malaria infections, but entomological monitoring remains a challenge as insecticide resistance persists. According to the Ethiopian Ministry of Health's "Malaria Elimination Plan for 2021-2025", their current challenges are both inadequate implementation of insecticide resistance monitoring and management strategy (IRMMS) and as well as lack of an entomologic database.

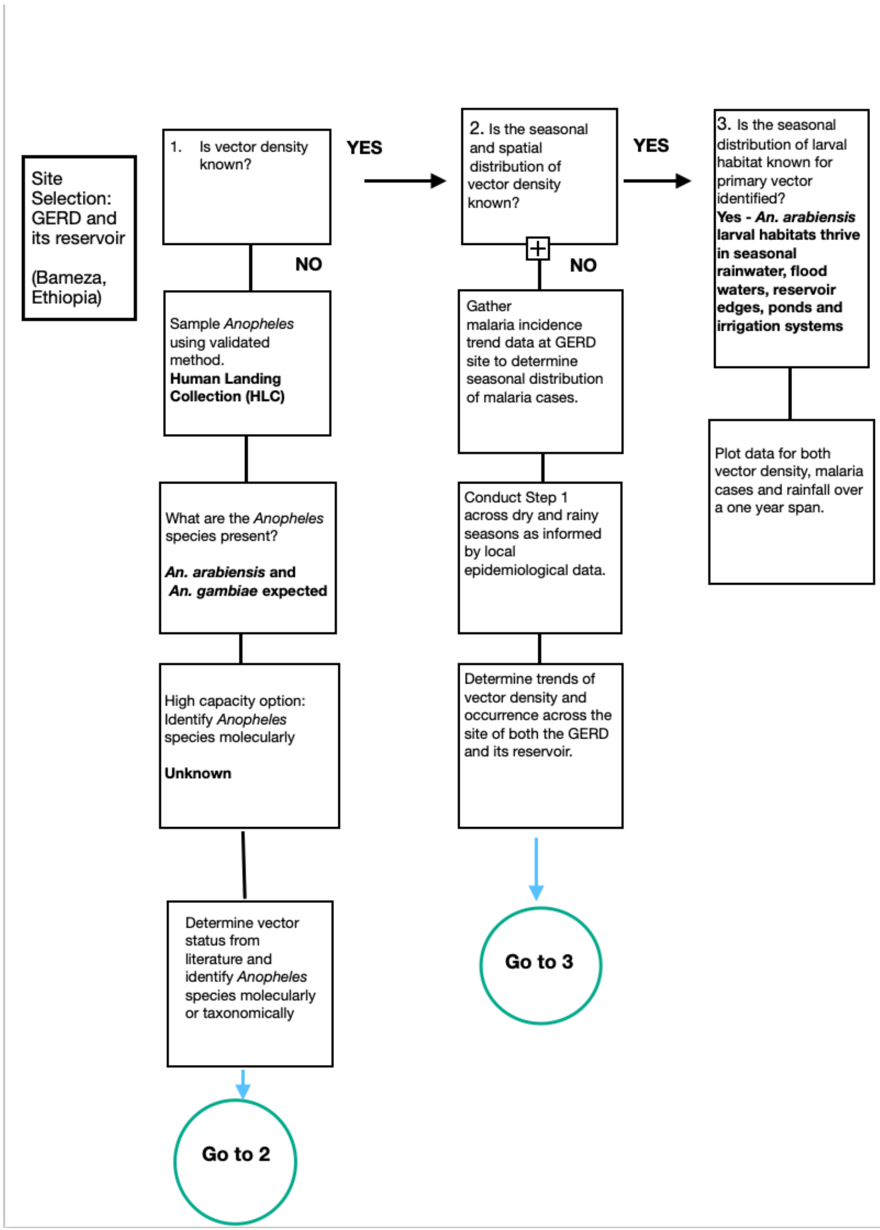

Figure 5 Decision Tree by Malaria Vector Indicator (Adapted by author from UCSF, 2020)

Risks must be presented in the decision-making process for policymakers in order to explain the health impact on the region in which they are a concern. The Decision Tree based on vector indicators adapted from the University of California at San Francisco Entomological Surveillance Tool (UCSF, 2020), presented above, enables review of what questions to examine and how the responses may influence the level of concern for vector-borne illnesses such as malaria in the GERD region if proper monitoring is not carried out. For example, with knowing that *A. arabiensis* and *A. gambiae* are now present in the GERD region, the number of species of *Anopheles* mosquitoes may expand, and the burden of malaria may rise as well, adversely influencing the area's health status and outcomes.

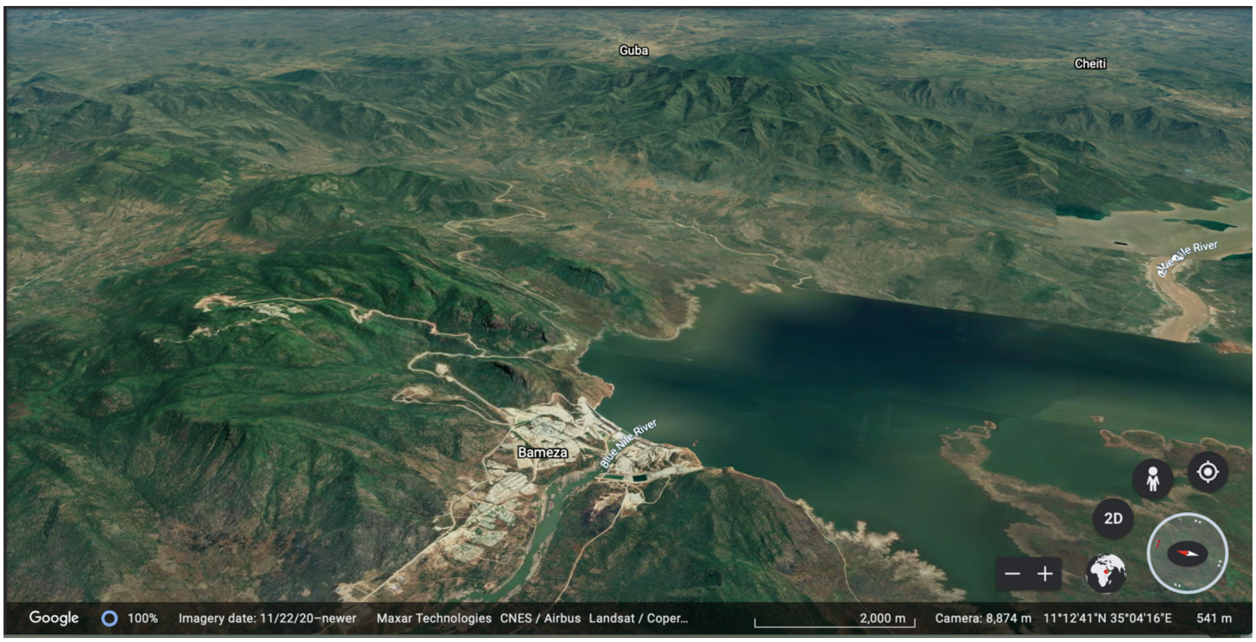

Figure 6 Satellite Imagery of the GERD area and Bameza settlement (2.1 cm =2000 m) (Google Earth)

1.3 Water Level Management and Malaria

Malaria transmission is affected by a combination of hydrologic-driven ecological variables, including the existence of appropriate habitats for the development of anopheline larvae (Kengluecha et al., 2005). Through the filling of the GERD's reservoir the edges will expand closer to human settlements making the breeding habitats of the malaria vector relevant for how habitats once not suitable for malaria vector could change due to the growing access of stagnant water that could be used for breeding. *Anopheles* spp. have been noted to breed and be abundant at the edge of rivers, dams, ponds, and streams (Zogo et al., 2019). As previously mentioned, the demographic composition and economic conditions of the BGR consist of populations that are rural and impoverished, and there is a dependence on the Blue Nile River for multiple domestic, agricultural, and economic purposes, highlighting the likelihood of people in the surrounding communities to come into contact with potential malaria vectors along the GERD's reservoir edges or for the vectors to fly and enter their villages and homes in search of blood meal.

The first and second phases of the filling of the GERD dam and its reservoir have occurred, though not without controversial actions as diplomatic relations have been muddled and tense due to concerns over water distribution of the Nile River shared between Ethiopia, Sudan, and Egypt. The Ethiopian government declared the first filling in July 2020, attributing it to significant rainfall, and the second filling took place in July 2021 with the expectation that the process of generating electricity will occur by 2023 (Rasha et al., 2021). To provide context to the rate of expansion that has taken place after the first filling, from June 2020 to November 2020, a cumulative increase of 3.584 billion cubic meters was estimated. It was also discovered that the rise in volume is substantially greater for late-July and the entire month of August (rainy season), with an increase of 1.135 and 1.39 billion cubic meters of water volume discovered between July 20 and August 14, 2020, and August 14 and 7 September 2020, correspondingly (Kansara et al., 2021).

With the volume of water that currently exists and that is expected as the GERD and its reservoir expands due to its scheduled fillings and to rainfall underlines the potential it has to increase the presence of breeding sites of the anopheline vectors. Understanding the human importance of the water body to local communities who may rely on it for various purposes shapes the challenge around the environmental management that will need to occur to mitigate the risk that comes with new and expanding bodies of water. Irrigation schemes and agricultural practices are among the primary factors driving the increase in the global malaria burden, as well as a significant factor in transmission in Western Ethiopia, where Jaleta et al. (2013) found entomological inoculation rates were 4.6 to 5.7-fold greater in irrigated sugarcane agro-ecosystems compared to traditional and non-irrigated agro-ecosystems. With agricultural development being an economic foundation for this rural region, the approach to water management must be sustainable and culturally sensitive while also effective in reducing malaria vector habitats.

Climate change has increased Ethiopia's vulnerability to floods and droughts (Simane et al., 2016). Warming will have an important impact on the dispersal of malaria vectors, as the temperature rise from 1948 to 2006 amounts to 1.8 °C near Ethiopia's northwestern border (Funk and Jury, 2013). With droughts forecasted in east Africa, current data shows that Ethiopia's annual rainy-day extremes exhibit high variability, with a strong trend from 1980 to 2010, revealing ambiguity when it comes to projecting how probable future flooding is for the country (Asaminew and Jie, 2019).

Understanding the malaria vectors that inhabits the region and the growing options for larval habitats due to the GERD and its reservoir as well as changes in regional climate, approaches such as the drawing down of reservoir water levels periodically could prove to be beneficial as Tusting et al. (2013) found in the countries of Kenya and India that "larval densities of malaria vector mosquitoes (*An*. *arabiensis* and *An*. *pharoensis*) were significantly lower under faster rates of water drawdown. Kibret et al. (2018) observed that quicker water drawdown rates were consistently related with lower anopheline larval abundances at the Koka reservoir in Ethiopia. This study shows how successful this technique is and how it would be appropriate to apply in the GERD area because *An. arabiensis* was present in the study as it is probable it is in the GERD area.

Water management strategies shape not only the various mosquito populations which surround lakes, reservoirs, and rivers but also the livelihood of the people such as Sudanese refugees who flee their native country into Ethiopia to escape the drought exacerbated by climate change, or also those Ethiopians whose access to safe drinking water has decreased due to funding constraints related to sanitation and hygiene (UNHCR, 2020).

Chapter 2

Current and Expected Situation of Human Population Movement, GERD filling and Malaria Burden

The movement of human populations shapes the distribution of vector borne diseases. This chapter will present the connection of the human populations at risk with data and information on the local malaria vectors and the presence of water sources (potential malaria vector breeding sites), and then conduct a risk assessment with tools, engaging all these aspects of the problem.

2.1.1 Tigray, Human Movement and Displacement

Migration has become a feature of survival across Ethiopia as the historical catalyst for population movement has often been poor economic conditions or political conflict (Berhanu & White, 2000). With the current humanitarian crisis in Northern Ethiopia's Tigray region, as well as ethnic tensions driving violence in other locations across Ethiopia, including the BGR, the extent of displacement has been alarming in terms of the afflicted people' health and food stability. The most recent conflict began in the Tigray region as a result of state elections being held in September 2020, contrary to the wishes of Ethiopian Prime Minister Ahmed Abiy, who sought to postpone the election because of the current Covid-19 pandemic. In November 2020, the National Defense Forces (ENDF) entered Tigray, escalating the war (Conte, 2022). With the conflict now sprawling across three regions of Ethiopia, more than 9 million Ethiopians are in critical need of humanitarian food support, and 40% of Tigrayans are in need of food as conflict-induced migration has disrupted diets producing mass malnutrition (WFP, 2022). With over 800,000 refugees and asylum seekers and 4.2 million internally displaced people (IDP) in Ethiopia in 2020, it was among the top three countries with the largest IDP population due to conflict, including the Democratic Republic of the Congo and Syria (UNCHR, 2021) though these figures may now be eclipsed by the IDPs and refugees fleeing the Russian military's invasion of Ukraine, which war may likely complicate the availability of refugee aid to Ethiopia.

The U.N. defines IDPs as "people who are forced to flee their homes due to armed conflict, generalized violence, violations of human rights, or natural or human-made disasters, but who remain within their own country.” (UN, 1998). In addition to these IDPs in Ethiopia, there are international refugees mainly comprised of individuals from South Sudan, Eritrea, Somalia, and Sudan (Vermura et al., 2020). With these various populations coming from different migratory routes and origins it shapes the concern for diseases such as malaria. Because population migrations have historically influenced malaria transmission, mass malaria testing and treatment in low transmission regions with a high proportion of returning migrant workers in Ethiopia has been implemented as a malaria control method (Scott et al., 2018).

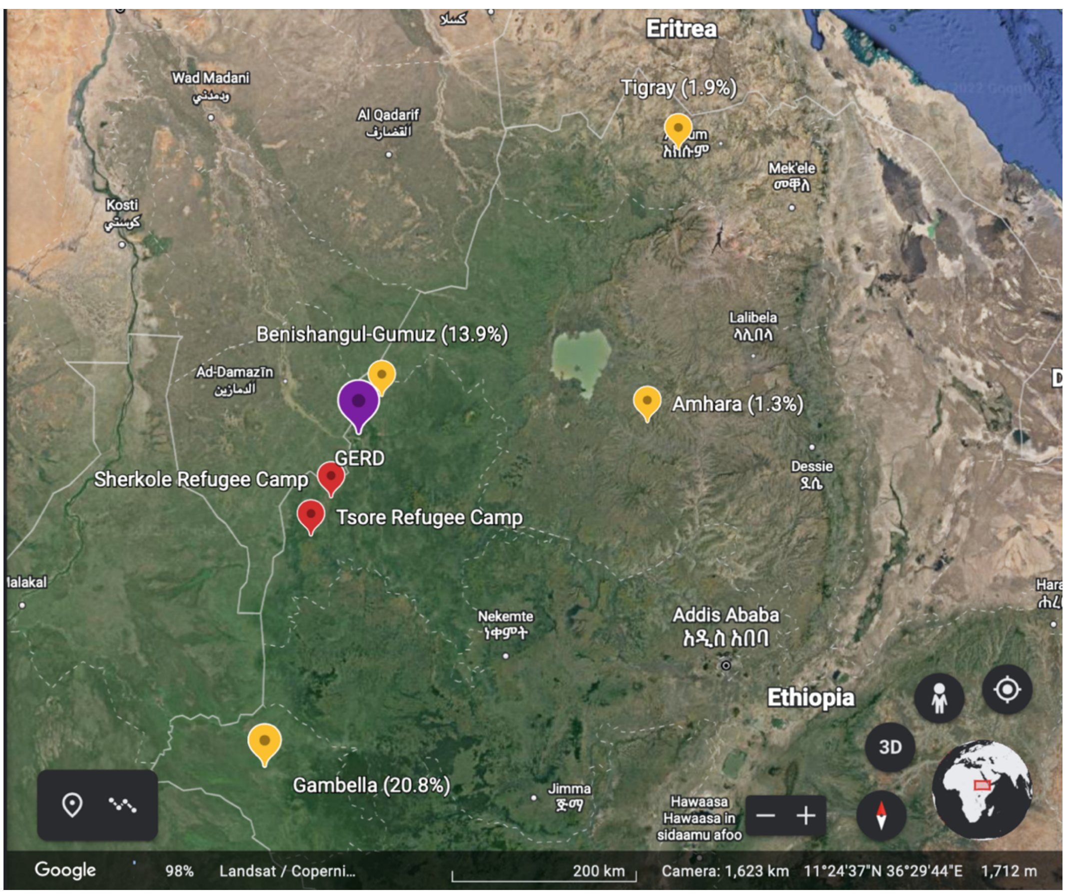

Figure 7 Satellite Imagery of Ethiopia with Malaria Prevalence based on children RDT from MIS 2016 (2.5 cm = 200 km) (Description: Yellow Point – Region, Red Point – Refugee Camp, Purple Point – GERD)

Testing is critical in efforts to reduce the burden of malaria but due to the ongoing conflict in Northern Ethiopia health services in numerous camps and facilities have been disrupted and with the influx of IDPs it has made disease surveillance limited (Gesesew et al., 2021). These interruptions in health services and the movement of people through regions where malaria is endemic (shown in Figure 7) may present a significant concern to the Ministry of Health, as Ethiopia's malaria burden as well as its refugee population is unequally distributed from the North and South. Figure 7 is a map developed based on malaria incidence noted within the 2016 Malaria Indicatory Survey among children in the labeled regions, who make up most of the refugee population in Western Ethiopian locations of concern. Several observations may be made based on this image, including the close geographical relationship between refugee camps (shown in red) and areas with high malaria incidence, as well as demonstrating how the GERD and its reservoir are inside the path of IDPs and migrants arriving from Northern Ethiopia.

Displacement is a significant yet potentially detrimental component of development initiatives, with an estimated 15 million people globally forced to leave their homes each year to make space for infrastructural developments (Cernea & Mathur, 2008). In the case of the GERD and its reservoir, it will showcase the product of development induced migration as thousands are expected to be and are currently being forced to move from the area due to its filling (Ahmed et al., 2015). This will further increase the population of IDPs as individuals look for economic opportunity and arable land to sustain local farming practices. Ethiopia has a history of resettlement or villagization schemes, Hathaway (2008) wrote, describing the problem seen at the Gibel-Gibe Dam I in Oromia, Ethiopia, "A lack of community participation is a major problem with Ethiopia's dam planning. Communities negatively affected by dams are often not consulted, and typically do not receive adequate compensation or resettlement packages. Host communities and downstream users and given little consideration regarding the negative impacts they face.". Because the Metekel Zone has historically been sparsely populated and made up of indigenous communities, the environment has been perceived to be harsh. Resettlement villages formed after the displacement caused by the Gibel-Gibe Dam I through the 1980's and 1990's were considered unsatisfying by the displaced as Kebede (2009) described resettlement village sites to be "swampy" and "waterlogged" showing an unsustainable resettlement site for an agricultural community.

As a result, this history, together with a lack of focus on malaria control prior to resettlement, highlights both disregard for the livelihoods of these impoverished communities and the importance of conducting health impact assessments for development projects (Woldemeskel, 1989) such as the GERD. The relocation of vulnerable people in the BGR because of the GERD and its reservoir jeopardizes Ethiopia's progress toward malaria elimination and eradication objectives. Vaughan and Gebremichael (2020) and ESRI (2021) present data and a map (see Figure 8 below) showing the locales of 17 resettlement villages where 5,371 Gumuz families (about 20,000 people) have been and are being resettled. Of the 17 resettlement villages, seven appear to be on or within 5 km of the reservoir's edge, and the furthest being about 125 km upstream (map, Vaughan and Gebremichael, 2020). Vaughan and Gebremichael (2020) discuss several reasons why the resettled communities face drinking water shortages and use the reservoir or river water to meet basic needs and water livestock. With the GERD area population being comprised of mostly low-income residents and migrants the flooding by the filling reservoir could prove to not only have ecological and health impacts but economic impacts as well, along with the influx of IDPs from the conflict areas of northern Ethiopia. The relocation of vulnerable people in the BGR because of the GERD and its reservoir jeopardizes Ethiopia's progress toward malaria elimination and eradication objectives. Understanding that one of the primary malaria vectors (*An. arabiensis*) is present in the region and the migration taking place in the area provides a combination that might potentially enhance contact between humans and the vector in the area, especially as GERD’s filling periods occur during the rainy season. Refugee camps, despite their distance from the GERD and its reservoir, may be impacted by malaria among the individuals escaping strife in the BGR and Tigray and those seeking sanctuary after being dispossessed from their houses.

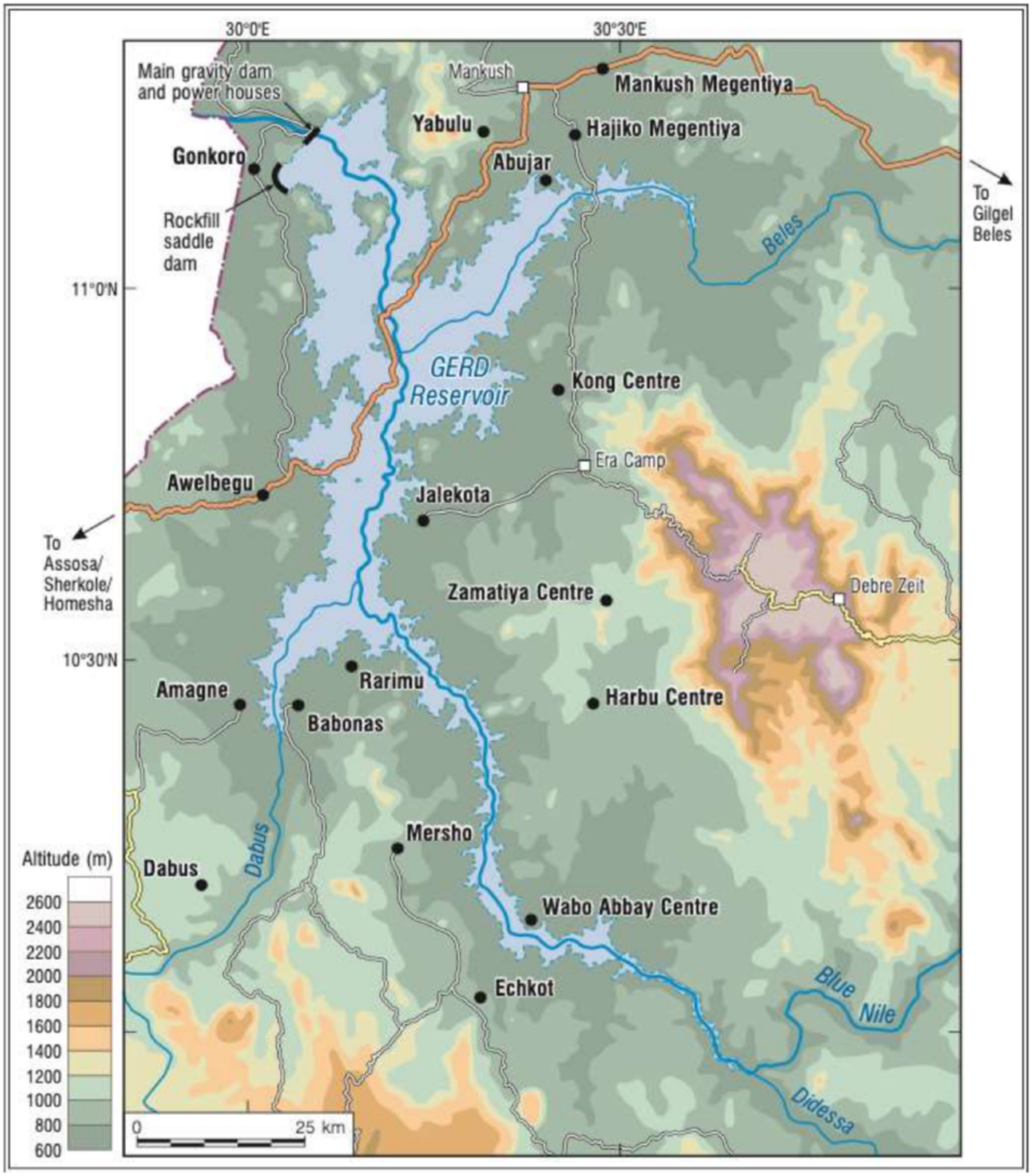

Figure 8 Approximate location of 17 resettlement sites for the Gumuz people in relation to the Blue Nile River and the GERD dam and reservoir. (Scale 2.5cm=25 km) Source: Vaughan and Gebremichael (2020)

2.1.2 Refugee Camps and Ethnic Groups in the BGR

As a result of malnutrition, contaminated water, inadequate sanitation, overcrowding, and limited access to health care, refugees are more prone to infectious illnesses. Diseases such as malaria might endanger migrants who lack sufficient personal protective equipment, or insecticide netting or antimalarial medications (Anderson et al., 2011).
In BGR, refugee livelihoods are the most constricted, leading to resource competition, environmental degradation, internal insecurity, and thievery (Vemuru et al., 2020). Refugees are more likely than hosts to rely on assistance, as agriculture and wage-earning labor are their principal sources of income (Vemuru et al., 2020). While initially designed to accommodate Sudanese and South Sudanese refugees, BGR's refugee camps (Sherkole and Tsore) now are responsible for hosting some of Ethiopia's internally displaced indigenous people. This has resulted in a rise in the camps' population. Over 100,000 Ethiopian IDPs are already housed in the BGR regional refugee camps (OCHA, 2018). The Gumuz and Berta are Ethiopian ethnic groups that are heavily represented in this IDP population. The Gumuz inhabitants live in a part of the Metekel Zone that is defined as lowland and will be displaced by the GERD's reservoir on its northern bank, as they live in these low, humid, wooded plains that descend downhill towards the Sudanese border in the west (Vaughan and Gebremichael, 2020). According to the Ethiopian government's "Environmental Impact Assessment Proclamation", new projects must be reviewed to ensure that there will be no negative effects on the environment surrounding the project area (Abebe, 2012), however, without a specific need to include addressing human needs in EIAs the human health impact may become ignored. For

example, in 2013, an estimated 5,110 individuals were evacuated from the downstream area, and almost 20,000 people are projected to be relocated. The indigenous people of Gumuz and Berta, who were living in some of the worst economic conditions before this recent development-induced displacement, make up the vast majority of those impacted (International Rivers, 2012).

The Sherkole and Tsore refugee camps today host a varied population of international refugees and IDPs, wherein the primary countries represented are Kenyans and South Sudanese, indicating a migration of people to the north due to the BGR's location northwest of both countries. With this travel, the possibility of these refugees passing through malaria-endemic areas to reach these refugee camps is high, as Gambella, Ethiopia, which is south of the BGR is more malarious (see *Fig*. 7). With more than half of these refugees being children the malaria prevalence amongst that demographic is significant as the refugee camps are situated between high prevalence regions (shown in Fig.7). Children under the age of five account for around 86 % of malaria fatalities worldwide. In fact, children are most vulnerable to severe disease and death between the ages of six months and five years old: during this time, children have lost maternal immunity and have not yet developed protective immunity to infection (Schumacher and Spinelli, 2012). Data on the current malaria prevalence more recent than 2015 rates in these refugee camps are unavailable since conflict has led to decreased levels of health services and disease surveillance.

2.1.3 Movement, Malaria Burden and Future Population Growth

Malaria is one of the most widely documented causes of mortality among refugees, with significant rates of sickness and death among refugees and displaced people in disease-endemic countries or regions (Martens & Hall, 2000). Several of the border regions within Ethiopia that are accepting refugees have obstacles such as poor infrastructure, widespread poverty, deteriorating environmental conditions, and lack of spatial capacity. The unit cost of water supplied in the camps is rather high, and compliance with international minimum requirements varies by region (AFRO, 2018). In 2019, a United Nations Children's Fund (UNICEF) Situation Report noted that "Underfunding of UNICEF's Humanitarian Action for Children (HAC) appeal has hampered provision of long-lasting insecticide treated nets to vulnerable communities, thus posing a challenge to containing malaria outbreaks. Some 2,200 IDP households living in a high malaria risk area in Metekel Zone in Benishangul-Gumuz Region were given nets." (UNICEF, 2019b). With challenges that come with humanitarian situations, migrants in sub-Saharan Africa frequently lack constant access to good housing and potable water, and the link between drinking water, sanitation, and malaria is underlined in the economic situation of moving groups such as IDPs and refugees (Yang et al., 2020). These conditions make this population vulnerable to malaria as they do not have adequate protection from the outside environment therefore malaria vector have opportunities to bite.

The environmental exposure component of malaria transmission for this population underlines the importance of One Health. A One Health perspective allows us to consider evolutionary changes that may occur among parasites that impact host range and parasite population genetics (Webster et al., 2015). For example, the influence of climate change on the *Anopheles* species within Ethiopia is what may allow the species to expand to higher elevation (Ryan et al., 2020).With this perspective we are able to see both what happens on a micro level such as poor hygiene or lack of sanitation facilities and what happens on a macro level such as mass migration and war, which both play a significant role in health outcomes (Heukelbach, 2020). Keeping with the context of parasites, malaria is a disease that globally has a multiple agent such as the previously mentioned *P. falciparum* and *P. vivax* as well as *P. ovale and P. knowlesi.* Refugees and IDPs may introduce malaria parasites from an endemic area to the host region, or they may be more vulnerable if they travel from a non-endemic area to an endemic location, where they may lack natural immunity to local strains. When non-immune immigrants settle in areas conducive to mosquito breeding, epidemic conditions may develop (Gautret et al., 2009).

The consequence of conflict is often not solely the loss of life from war but the long-term breakdown of national health systems leading to low vaccination rates, malnutrition and reductions in access to healthcare (Gayer et al., 2007). This is particularly important when considering that malaria infections are observed in the Tigray region (MIS, 2016) yet with the health infrastructure under pressure from conflict those with malaria may not seek help. Paulander et al. (2009) noted a little less than half of Tigrayans were aware that mosquitoes caused malaria infections, highlighting the need for more advance malaria control programs in the region. This also highlights the risk that these individuals may pose as they move through or towards BGR.

Approximately 15,000 IDPs are in the Wenbera *woreda* and around 6,000 IDPs are in the Guba *woreda* both of which both have relatively high malaria prevalence; the nutritional needs of these individuals have yet to be fully met by the national government and these individuals are continuing to move as ethnic violence continues even in the Metekel Zone (OCHA, 2021b) to the north especially near the border of Tigray. Within the month of January 2021, 1,256 ethnic asylum seekers arrived within Sudan's Blue Nile Province (OCHA, 2021b) which borders BGR. This represents probable evidence of migration through the GERD region as Sudan's Blue Nile Province is on the western side of the dam while the IDPs fled from the North and Northeast to the Northwest and West likely through BGR.

Not only does the migration through the *kebeles* or towns surrounding the GERD and its reservoir pose concern for refugees in regard to malaria burden but also the residents of the Guba *woreda* who reside in close proximity of the reservoir who will be displaced between now and 2030 (Table 1 below)

Kebeles in Guba Woreda	Number of households (2012)	Predicted number of children (Based on current fertility rate and number of households in 2012)	Estimated number of children in 2020	Predicted number of children in 2025	Predicted number of children in 2030
Bamza	205	850	1,035	1,171	1,325
Fanguso	282	1,170	1,425	1,612	1,824
Yarenja	506	2,099	2,557	2,893	3,273
Jadiya	116	481	586	663	750
Babi Zenda	223	925	1,127	1,275	1,443

Table 1. Population Projection of Kebeles in Guba Woreda (Adapted and with calculated estimates 2012, 2020, 2025, 2030 by the author from: International Rivers, 2013)

The population information is drawn from the International Rivers GERD Field Report from 2013 as baseline information in Table 1 which presents some of the rural communities expected to be displaced by the filling of GERD and reservoir. Table 1 presents child population projections from the time periods of 2020, 2025, and 2030 to demonstrate a growing population within the Guba woreda showing the potential for regional malaria burden to rise as this agricultural region is likely to have a fertility rate higher than the overall country. Using a household size of 4.15 in Guba instead of

Ethiopia's overall current 4.1 to account for the difference in region and the pace of population growth which is 2.5%, the author produced projections showing a net gain of almost 2,000 children over the next decade.

The current population of Ethiopia is estimated to include over 114 million people and is growing at a rate of 2.5 % per year and is expected to more than double by 2050 (United Nations, 2019).With the movement of people internally and the current pace of population growth the total population of BGR is expected to grow from the current 1.1 million to approximately 1.4 million people with 463,000 living in the urban areas and about 1 million people living in the rural areas by 2030 (CSA, 2013). The population growth of school aged children (SAC) in BGR grouped by ages is about 193,000 (7-12 yrs old), 63,000 (13-14 yrs old) and 123,000 (15-18 yrs old) respectively, by 2030 (CSA, 2013).

Population growth is relevant to the current malaria burden in Ethiopia as growing population demand more of the physical environmental particularly as agriculture is vital to economic growth in Western Ethiopia, considering activity such as deforestation to clear land for agriculture. The Blue Nile River which is a feeder river to the main Nile River (which is also fed by the White Nile River) and covers 250,000 km of watershed in the Ethiopian Plateau. The GERD will contribute to changes in downstream flow of river water, in Sudan and Egypt (El-Bastawesy et al., 2015, Wheeler et al., 2020). The Blue Nile River plays a very important role in Ethiopia, originating in Lake Tana and also fed by several smaller tributary rivers, and it fosters vegetation in the Ethiopian Plateau (El-Bastawesy et al., 2015). There have been reductions in vegetation along the Blue Nile

River basin due to deforestation, livestock grazing and other human-caused factors which have generated concern due to the dependence of the local populations on subsistence agriculture and the protective role that forest cover plays in buffering communities from floodwaters (Gebrehiwot et al., 2010).

Deforestation can engender population migration as well as propagate malaria outbreaks as discussed in Chapter 1. Large hydroelectric dams are largely products of maladaptive efforts as sub-Saharan Africa faces continuance effects of climate change yet projects such as the GERD and its reservoir displace and disturb physical environments possibly making the livelihood of those receiving electricity better while shifting vulnerability to those in the surrounding communities (Schipper, 2020). Refugee hosting areas often experience changes to the surrounding landscape as forested areas become converted to needed cropland due to subsistence agricultural needs (Maystadt et al., 2020). Also, the primary energy source for activities such as cooking for refugee populations is firewood which is another factor that influences deforestation (Lynch, 2002).

2.2.1 Methodology to Develop a Risk assessment of Greater Malaria Burden in BGR

The primary objectives of this research consisted of 1) to investigate the potential effects of the construction and filling of the Grand Ethiopian Renaissance Dam (GERD) and its reservoir on the burden of malaria and 2) to evaluate the living conditions and known malaria burden in the current human settlements in the BGR including internally displaced people, residents, Eritrean and other refugees, and those who have been involuntarily resettled in the region as the GERD is filled. These objectives aided in the formulation of the overall hypothesis, which stated that upon completion of the Grand

Ethiopian Renaissance Dam and filling of its main reservoir during this decade, as well as a series of human population changes, and in the absence of specific local interventions to improve local malaria vector control and increased access to primary health care services, including malaria surveillance and treatment, a portion of the estimated population of 1.1 million people now living in the Benishangul-Gumuz region would experience a greater burden of malaria.

Aligned with the Objectives stated above, a *One Health perspective* serves as the conceptual and research framework for this study. One Health is defined as "the collaborative effort of multiple disciplines, working locally, nationally, and globally to attain optimal health for people, animals and the environment" (Deem et al., 2019).

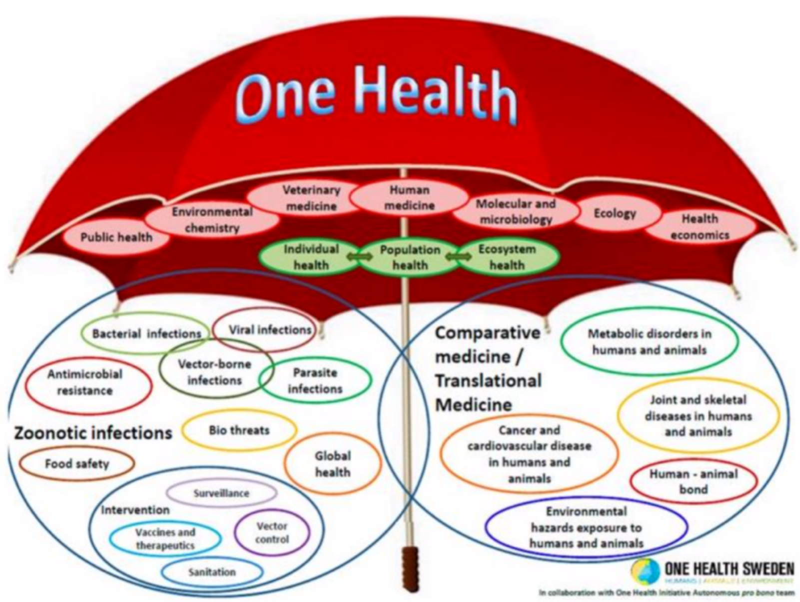

Figure 9 The One Health Umbrella, as developed by One Health Sweden (Mackenzie et al., 2019)

One Health has grown in importance in the scientific community as vector borne and zoonotic diseases emerging through anthropogenic influence have been found to make up the majority of known infectious diseases (Gibb et al., 2020). Some 75% of emerging infectious diseases in humans have animal origins (are zoonotic); these diseases do not just burden humans but impacts numerous populations of animals as well (Deem et al., 2019). For human populations that live in proximity to wildlife and bodies of water it is important to understand the ecological conditions and surroundings of their living spaces because that can inform one's perspective on the health and health risks of various communities. Human activity such as deforestation or water resource development can change physical landscapes which influences the chain of infection of vector borne diseases and other infectious diseases and raise health risks; such changes can result in the change of the size of a host population, either increasing or decreasing it (Keresh et al., 2012), as well as change geographic distribution.

Synthesis research consists of using existing knowledge from prior research projects and building on the topic to offer new interpretations (Jacobsen, 2021). This thesis was developed based principally on Synthesis Research particularly conducted as an Integrative Review (Snyder 2019; Torraco 2005). The integrative review was chosen in this One Health context because the interdisciplinary nature of the study requires pulling data and information from various subjects and articles to tackle the objective and aims of the study.

This thesis was developed and complemented by the use of select tools, particularly the Tripartite Zoonotic Diseases Guide and Tool of WHO/FAO/OIE (2019, 2020). In the

Tripartite Zoonotic Disease Tool, its Annex G and Annex I were used in particular to construct the framework for assessing exposure pathways and risk management and construct a risk matrix. Using tools such as the UCSF entomological surveillance planning tool (UCSF, 2020), allowed for the simulation of questions and actions that could be taken to investigate methods of successful intervention as it allows data on malaria vectors to be tracked in time and place. Google Maps, Google Earth, Google Earth Pro and MinDat were used to locate maps and settlements of the BGR and GERD area and used for simple spatial analysis of distances and geolocation of communities and rivers. Literature searches were conducted using the bibliographic databases PubMed and ScienceDirect, BioMed Central, Google and Google Scholar to obtain peer-reviewed scientific articles, Ethiopian government census surveys and reports, the Nile Basin Water Research Atlas, and reports from non-governmental organization and international agencies such as the World Bank, World Health Organization, FAO, UNICEF, OCHA and other United Nations agencies. For national demographic data and projections (population growth to 2030), the Central Statistical Agency databases of the government of Ethiopia were accessed and used, together with information from the United Nations Population Fund databank.

Key searches used the terms (words or phrases) malaria*, Plasmodium falciparum, P. vivax, Anopheles gambiae Anopheles arabiensis,* GERD, Benishangul-Gumuz, mosquitoes*,* Ethiopia, dam, reservoir, water resource development, health impact, resettlement, environmental impact, among other words and phrases. There was a general focus on BGR with a more specific focus on the GERD for Chapter 1 and for Chapter 2.

2.2.2 Analysis

Within the research conducted, the author made use of both singular peer review articles as well as systematic review articles regarding malaria infections, particularly those that evaluated the disease burden and health and living conditions of U5 in Ethiopia. This demographic has proven to be more vulnerable to infection due to their less developed immune system and this demographic seem to be more prominent in the public health literature (Tsegaye et al, 2021). Economic status has been shown to influence malaria prevalence amongst U5 and adults as those who are considered poor are more exposed to malaria vectors due to the lack of ability to afford or access long lasting insecticide nets, inadequate housing infrastructure and occupational activities such as farming (Degarege et al., 2019). The systematic reviews consulted for this study revealed that multiple regions of Ethiopia are endemic for *P. falciparum* but the geographic study area focused on within their papers did not present a large amount of case studies in the BGR, arguing that the BGR is under surveyed and understudied. Reports of suspected malaria infections from hospitals and other health centers studied along the Blue Nile River were considered as risk indicators where the presence of *P. falciparum* or *P. vivax* occurred.

Factors such as date of publication, study population and study location were a part of the criteria to identify and select articles. Most of the studies used clinical diagnosis and/or analyzed blood samples taken from U5 for malaria. Several peer reviewed articles indicated the prevalence of malaria in the nine regional states of Ethiopia. As noted earlier, there was no evidence found that a health impact assessment or health risk analysis for the GERD has been conducted and published by the Government of Ethiopia in publicly available documents on the internet, nor any government-generated environmental impact statement (ESRI, 2021).

Malaria burden studies of vulnerable populations in regions in both the north and south of the GERD study area were sought and considered, and some of these areas presented evidence of the geographic distribution of *both P. falciparum and P. vivax* being present in infections in proximity to the Blue Nile River which will be influenced by construction of the GERD and creation of its reservoir. At least five studies which include data on malaria and in the BGR have been published; see Table 2.

Author and Year of Publication	**Title (Shortened)**	**Locale**	**Key Content (Prevalence by age group, occupation or gender)**
Alkadir et al., 2020	"A five year trend analysis of malaria prevalence in Guba district, Benishangul-Gumuz regional state…"	Guba, Ethiopia (BGR)	51% prevalence (all ages)
Gontie et al., 2020	"Prevalence and associated factors of malaria among pregnant women in Sherkole district…"	Sherkole, Ethiopia (BGR)	10% prevalence (Pregnant Women)
Ahmed et al., 2015	"Prevalence of malaria and associated factors among under-five children in Sherkole refugee camp…"	Sherkole, Ethiopia (BGR)	3.9% prevalence (U5)
Tilaye et al., 2021	"Malaria Infection is High at Transit and Destination Phases Among Seasonal Migrant Workers…"	Northwest Ethiopia (9 districts in the Amhara Region)	16.1% prevalence (seasonal migrant workers)
Ethiopian Public Health Institute, 2015	Ethiopian National Malaria Indicator Survey 2015	Ethiopia (including BGR)	1.2% prevalence (Ethiopia, all ages) 10.4% prevalence (BGR, all ages)
Geleta & Ketema, 2016	"Severe Malaria Associated with *Plasmodium falciparum* and *P. vivax* among Children in Pawe Hospital…"	Pawe, Ethiopia (BGR)	2009 - 41% prevalence 2013 - 25% Prevalence (≤ 10 years old)

Table 2. Prevalence Table of Malaria in Western Ethiopia

The data cited in the table above present malaria prevalence primarily in the Metekel Zone within the BGR, except two studies that looked at two vulnerable groups, U5 and pregnant women in Sherkole, Ethiopia (altitude 780 m), which is approximately 73 km southwest of the GERD and 280 km from Lake Tana which is the source of the Blue Nile River. Also, one study highlights malaria prevalence amongst migrant workers in the Amhara Region, which is essential as it's the bordering regional state to BGR and is also where Tigrayans will travel through to get to the refugee camps in southern BGR. The Sherkole *woreda* is outside the Metekel Zone but is vital as it contains the previously mentioned Sherkole refugee camp, which currently holds Tigrayan IDPs. The Metekel Zone is the political zone in which the GERD and reservoir reside. The table reflects the literature on malaria prevalence as other published articles that may have been found carried no mention of malaria prevalence in the relevant *woredas* within this zone.

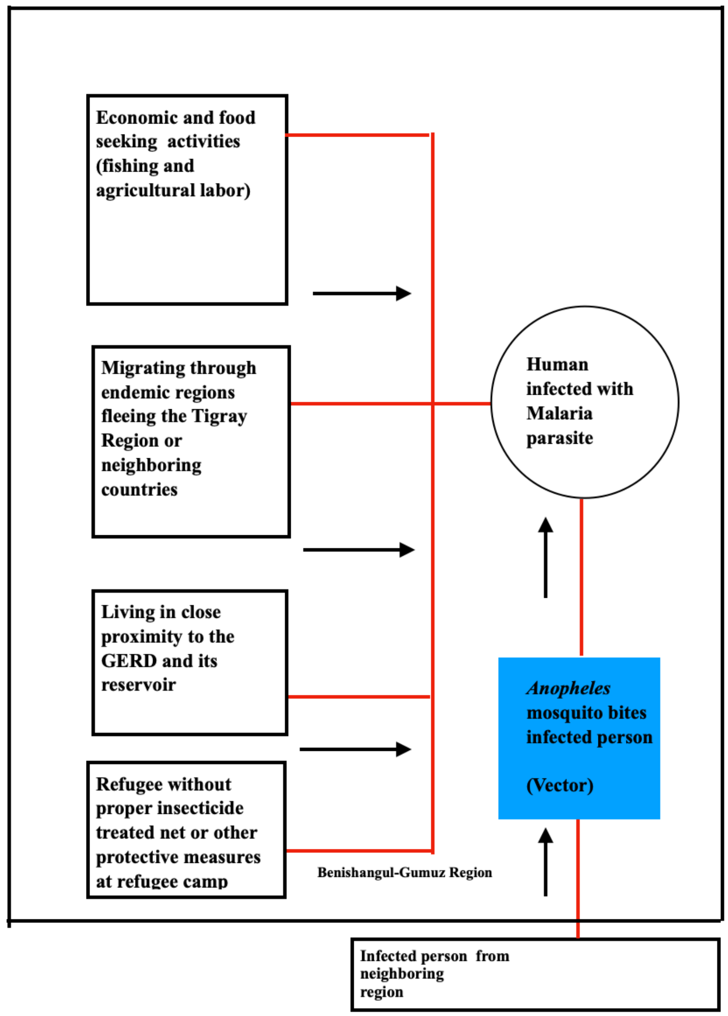

Figure 10 Risk Pathways for Malaria (Adapted by author from WHO/FAO/OIE, 2020)

Due to the disparities in access to malaria prevention tools such as insecticide nets and lack of access to healthcare within the semi-arid GERD area, it is essential to demonstrate the potential pathways for human exposure to malaria vectors. Using Module 3 of the Joint Risk Assessment Operational Tool (WHO/FAO/OIE, 2020), the visualization of risk pathways (see *Fig. 10*) was conducted to better understand the transmission pathways of disease, which is vital to the mitigation of the geographic spread and prevention of outbreaks of disease. With the *Anopheles* species being present in the Blue

Nile River and its source and principal tributaries, it is important to note that the uses of this body of water vary from economic activity such as fishing to more daily activities such as bathing. For this vector, the pathways involve various waterways, so the ranges of the exposure pathways are not as expansive as interface-relevant sources for airborne diseases such as avian influenza (where sources can range from live animal markets to household poultry) and human influenza.

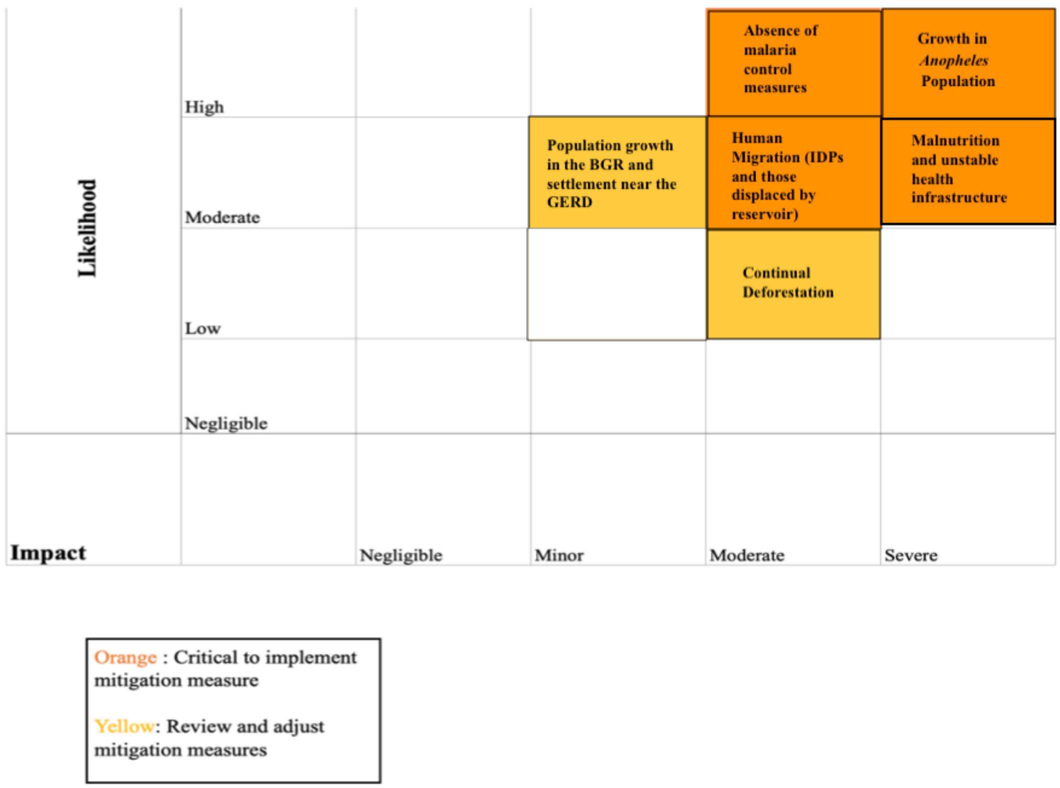

Figure 11 Risk Matrix of the selective likelihood and Impact off factors affecting malaria burden in the BGR and GERD area (Adapted by the author from WHO/FAO/OIE, 2020)

Within the decision-making process for policymakers, it is important for risks to be illustrated in order to express the impact to the region in which they are a concern. The Risk Matrix shown above (*Fig*. 11) allows for the evaluation of what risk may have the most severe impact to the region if it goes unaddressed. For example, without surveillance and control of the mosquito population that is currently present in the GERD area the population of these mosquito population will grow and the prevalence of malaria may increase as well, shaping the health outcomes for the area. The risk matrix was developed through the use of the Joint Risk Assessment Operational Tool (WHO/FAO/OIE, 2020), and the risks were placed and based upon literature related to the studies previously mentioned, as well as risks that may arise if there are no intervention approaches between now through 2030. In Figure 11, the key indicates that risks in orange need critical mitigation measures, while the risk in yellow means a need to adjust mitigation measures. Risks such as population growth were noted previously in this thesis. The population within BGR is growing, and their proximity to the GERD and its reservoir may influence future malaria transmission. Deforestation is a risk to future malaria transmission as land cover changes play a role in the growth and distribution of the *Anopheles* mosquito population (Kweka et al., 2016) (Rufalco-Moutinho et al., 2016). Growth in the Anopheles population is a risk that is highly likely due to the presence of the GERD, and its reservoir creating a breeding habitat will have a severe impact as vector density plays a role in the increase of malaria transmission (O'meara et al., 2020). Growth of this population may pose future control challenges depending on the duration of reduced monitoring programs (Yewhalaw et al.,2013). Human migration is a risk significant for the BGR as migrants seeking employment move throughout the region and IDPs move due to displacement and conflict in the surrounding regions, posing a threat for future malaria transmission as human population movement can facilitate transmission as populations move through areas of low transmission to moderate and high transmission (Martens & Hall, 2000).

Malnutrition among children poses a significant risk to future malaria transmission as it influences the severity of malaria and children's immune system to fight malaria. Das et al. (2018) conducted a systematic review finding 33 articles highlighting the association between malnutrition and the risk of malaria and the impact of malnutrition on antimalarial treatment efficacy. This risk had a considerable amount of evidence available particularly evidence suggesting malnutrition may negatively impact child malaria mortality, therefore making this risk severe. Malnutrition, particularly for child refugees experiencing undernutrition and children in regions such as BGR that experience severe wasting (UNICEF, 2019a), can effectively impact the Ministry of Health's ability to treat this vulnerable demographic. Shikur et al. (2016) observed that in a study involving 428 children under-five, severely wasted children in Ethiopia were three times more likely than non-wasted children to experience a malaria episode. With the continuation of the humanitarian crisis in the Tigray region of Ethiopia, the future population of those experiencing malnutrition may reasonably grow.

The absence of malaria control measures poses a risk to malaria transmission currently and in the near future. Its control measures are partially responsible for reducing infections in the past five decades throughout sub-Saharan Africa (Bridges et al.,2012). Measures such as the distribution of insecticide-treated nets and indoor spraying have proven effective, yet the failure to invest in these programs could reduce the previous gains made. Malaria control measures such as diagnostics and testing are vital particularly for those who are infected but do not present symptoms (Hemingway et al., 2016). The risk of BGR continuing without surveillance and control programs will prove to be severe as the Ethiopian government health expenditure has varied in the past. From 2014 to 2019 Ethiopia's health expenditure has gone from 4% to 3.2% of the GDP (World Bank, 2022).

Red: **Very high risk.** Could result in high levels of excess mortality/morbidity.

Orange: **High risk.** Could result in considerable levels of excess mortality/morbidity.

Yellow: **Moderate risk.** Could make a minor contribution to excess mortality/morbidity.

Green: **Low risk.** Will probably not result in excess mortality/morbidity.

Key health risks now through 2030

Public Health Risk	Level of risk			Rationale
Years starting now	**Current**	**2025**	**2030**	
Population Growth in BGR and near the GERD	Yellow	Yellow	Orange	As the population grows in BGR and specifically near the GERD, the proximity of settlements to water will grow closer possibly increasing exposure to mosquito biting (Kibret et al., 2017)
Deforestation	Orange	Orange	Orange	In some environments, deforestation can raise malaria risk factors such as mosquito population growth rates and biting rates, as deforestation impacts more than just mosquitoes; it is linked to socioeconomic changes that affect malaria rates in humans (Rufalco-Moutinh et al., 2016)
Human Migration (IDPs, Refugees, and population displaced by the reservoir	Orange	Orange	Orange	Movement of people from moderate to high-transmission areas can lead to imported cases and the possible reintroduction of malaria into low-transmission or malaria-free areas. Ethiopia holds a growing population of refugees and IDPs (Martens & Hall, 2000)
Growth in *Anopheles* Populations	Orange	Orange	Red	Anopheles population will grow harder to control and increase due to the creation of the GERD and its reservoir where water edges create suitable habitats (Yewhalaw et al., 2013)
Malnutrition and unstable healthcare infrastructure	Red	Red	Red	With the needs of children and women going unmet during the conflict and displacement, the health outcomes will grow worse as healthcare access is disrupted (World Food Programme, 2022)
Absence of malaria control measures	Orange	Red	Red	BGR has a high malaria prevalence currently so if preventive measures are not implemented the rate of prevalence will grow further (Tizifa et al., 2018)

Figure 12 Key health risks for the BGR population and GERD area through 2030 (Adapted by the author from WHO, 2022

)

Figure 12 shown above, summarizes the common threats throughout this decade. These threats vary from moderate risks to very high risks. The severity of some of the threats will be shaped by the duration in which they are not mitigated by change of policy or change of conditions, such as the conflict currently taking place in Ethiopia. Demonstrating the threats with a temporal feature allows policymakers to understand and observe the time-sensitivity of these threats, such as the growth in the *Anopheles* population, which are growing resistant to pesticide and currently present in the GERD area. The public health risks presented in Figure 12 build off the potential dangers presented in Figure 11, showing impact, likelihood, and time all inform how these risks should be prioritized by a ministry of health and local government.

Concerns captured in risk framing	Risk assessment questions	Technical Consideration	Possible management options	Rationale
Public fear and perception, negative impacts on travel	Will the human population movement near the GERD and reservoir lead to increase malaria infections?	Capacity of human healthcare system to detect the prevalence of infection in certain communities and regions. ______________ Capacity of Ministry of Health to maintain and update entomological database	1.Health surveillance for rural/agricultural communities ______________ 2.Educate and improve awareness around *Anopheles* presence and malaria symptoms ______________ 3.Reduce and manage water levels and water sources which act as anopheline breeding sites	1.Active case screening may be needed for difficult-to-reach groups that do not frequent health facilities, as well as asymptomatic individuals that continue to spread the parasite despite the absence of symptoms (Hemingway et al., 2016). ______________ 2.Health education campaigns have influenced the elimination of malaria in certain countries (Tang et al., 2016). ______________ 3.Water level management has proven to reduce Anopheline larvae (Kibret et al., 2018)
Disease coming across a border	Is it likely that a lack of malaria preventive measures and agricultural necessities for refugees/migrants exposes them to *Anopheles* mosquito bites at and around the GERD and its reservoir?	Population of migrants in GERD region ______________ Frequency of migration between GERD region and surrounding countries ______________ Frequency of *woreda* to *woreda* migration	1.Monitor malaria prevalence in all regional states ______________ 2.Medical evaluations (including malaria) of migrants from endemic regions ______________ 3.Monitor border communities for malaria burden	1 & 3. Because of the existence of various economic activities , highly mobile populations contribute to the importation of malaria for various nations and regions (Abdallah et al., 2022). __________ 2.Monitoring inter-regional migration can provide health information (Wen et al., 2016).

Figure 13 Risk-Framing Table: Linking the risk framing, the risk assessment questions, and risk management of Malaria in the BGR and GERD area (Adapted by the author from Annex I, WHO/FAO/OIE, 2020)

To effectively manage risk of malaria, there are risk assessment questions to ask and risk considerations which need to be evaluated, as one identifies disease management tools for malaria burden in BGR. Malaria presence in the BGR (which is currently present throughout western Ethiopia) makes a risk assessment of the trends in prevalence of infection all the regional states more pressing. The concern of increased risk is also fueled by current migration patterns, particularly by IDPs (see OCHA reports) and communities displaced by the GERD reservoir (Vaughan & Gebrimichael 2020; ESRI 2021), which will shape or influence the geographical distribution of infection between now and 2030.

The risk framing table (*Fig*.13) adapted by me from the Joint Risk Assessment Operational Tool (WHO/FAO/OIE, 2020) allows a demonstration of the complexity of the technical considerations that have to be addressed such as the capacity of a healthcare system in a particular isolated region such as BGR where its childhood malaria prevalence rate of 14% is relatively high compared to the overall childhood malaria prevalence for the country which was 0.6% (MIS, 2016). The risk-framing table allows for preventive measures to be constructed because though the infection risk may not be currently present in any given area, the risks may remain significant for populations in the BGR now or by 2030, as the population grows, and population migration and displacement continues. It is recommended that the Ethiopian government should strongly consider the management options proposed here as timely implementation of these strategies could mitigate future exposure to malaria, its geographic expansion and risk of an increased disease burden.

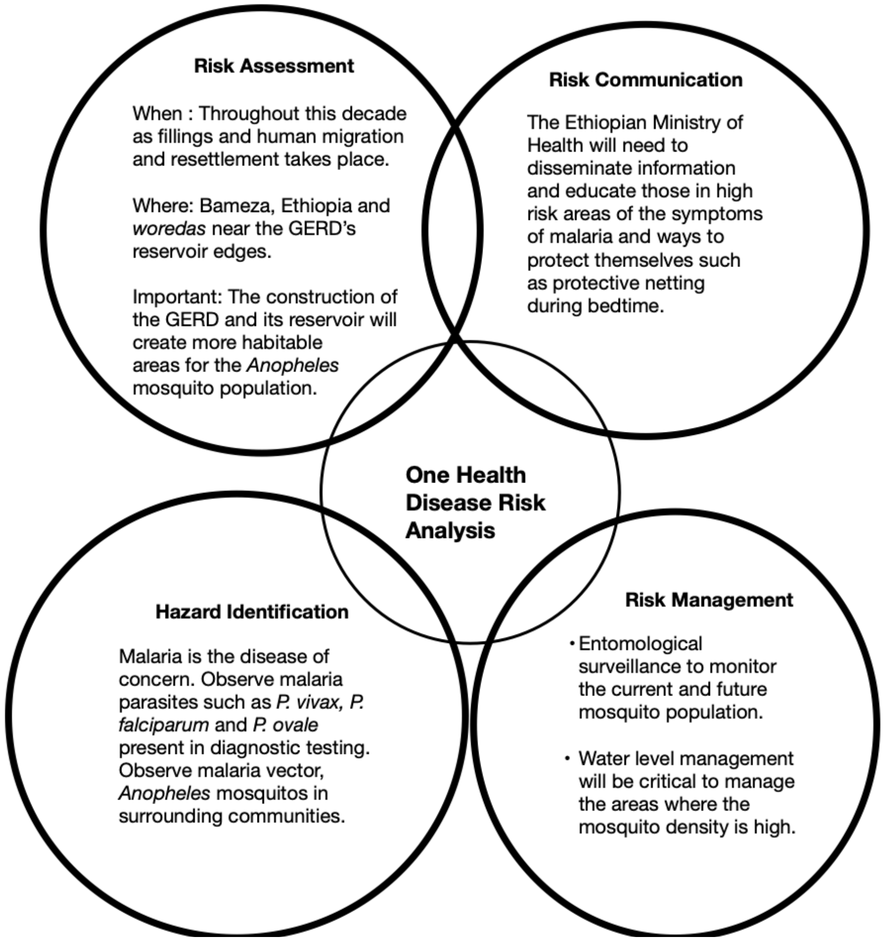

Figure 14 One Health Disease Risk Analysis for Malaria in the GERD area and BGR (Adapted by the author from: Deem et al.,2019)

Figure 14 above shows how the four components of risk analysis enable the implementation of the One Health approach. The risk assessment component of the figure depicts the area and duration of the evaluation, which informs the other three components. As previously stated, identifying the presence of malaria infections and the vector of malaria allows for risk management. The Ethiopian government intends to manage entomological databases to keep up to date information pertaining to disease vectors to educate both the public and policymakers. This thesis focuses primarily on three of the four risk components of this diagram.

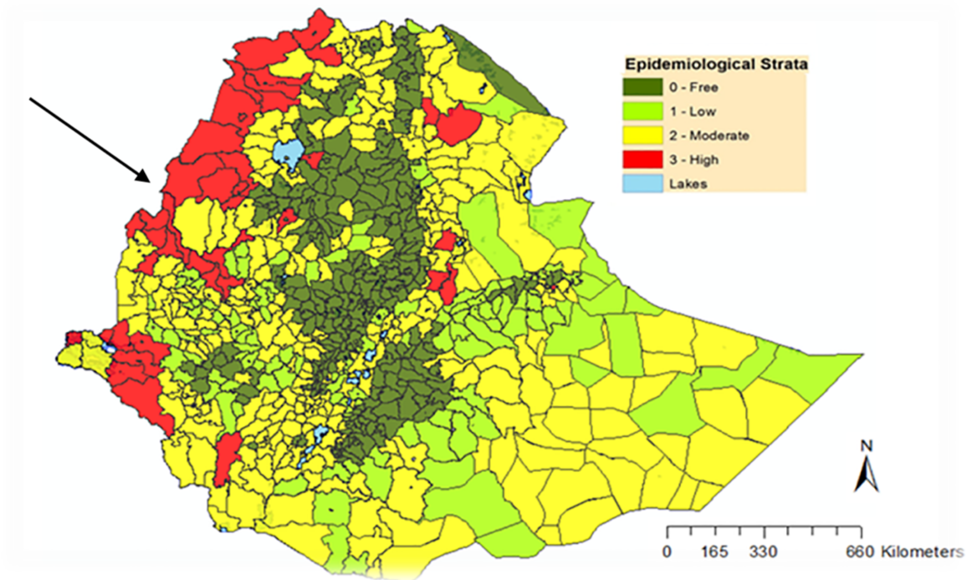

Figure 15 Malaria risk map of districts by annual parasite incidence in Ethiopia (Source: Federal Ministry of Health National Strategic Plan 2017–2020) (Arrow shows location of the GERD)

The western and southern part of Ethiopia consistently present a higher prevalence of malaria infection which is reflected in Figure 15 presenting parasite incidence based on districts. According to Ethiopia's Ministry of Health, malaria is present in around 68 % of the country's total land, and 60 % (63,495,055) of the whole population is at risk of infection (Federal Ministry of Health, 2018). In 2017/18, 1,206,892 verified and clinical malaria cases, as well as 158 fatalities, were recorded. Of the total confirmed cases, 883,886 (69.2%) were *P. falciparum*, whereas 181,964 (30.8%) were *P. vivax* (Federal Ministry of Health, 2018). Though malaria incidence has decreased over the last decade the western part of Ethiopia has struggled to reduce rate of infection due to the region being understudied (Taffese et al., 2018).

2.2.3 Discussion

Understanding that malaria vectors, *Anopheles* species is present within proximity to the GERD and with knowledge of the historical influence that the creation of hydroelectric dams has had on malaria transmission, vector control needs to be highlighted and investments should be made. Political will and funding for vector surveillance and control are vital for controlling future malaria outbreaks. A study noted that about 91% of malaria resurgence occurrences worldwide between the 1930s and early 2000s was due to deteriorating vector control programs (Cohen et al., 2012). With more entomological surveillance, there will be a need to increase human resource capacity to manage the vector populations, which is an issue the Ethiopian government has noted is a part of their long-term strategy (Woyessa et al., 2013). Resistance to pyrethroid insecticides, the type used to treat bed nets, is already widespread in malaria vectors throughout Africa. Resistance to many other insecticide classes used to control adult mosquitoes is growing (Ranson & Lissenden, 2016). This issue, along with the environmental disturbances that come with water resource development projects, can cause concern and create risks for numerous countries hoping to construct dams, as hydropower is Africa's primary source of renewable energy (IHA, 2021)

The role of hydroelectric energy in Ethiopia and, more broadly in Africa, reflects the pursuit to provide electricity to more people and increase economic development (IEA, 2019). The possible benefits of the GERD and its reservoir may consist of controlling future flooding events, providing electricity for communities for the first time and potentially boost the fishing industry which were the products of the construction of the

High Aswan Dam in Egypt (Fahim, 1981). The Confluent and Niandouba dams were built in the south of Senegal in 1984 and 1997, respectively. They are made up of a succession of reservoirs, the largest of which is the Niandouba reservoir (85 million m3), followed by the Confluent reservoir (34 million m3) and lastly the Lac Waima reservoir (25 million m3). This volume of water has allowed for the development of irrigated agriculture over a total area of 5,000 hectares at Anambé, Senegal. With the construction of these reservoirs, rice planting yields increased from 500 ha in 1985 to 2,500 ha in 2009, with significant variances over the time (Bazin et al.,2017). This is evidence that water resource development projects can provide benefits to countries, but the potential health impact must be considered. BGR historically has had challenges reducing malaria transmission (Federal Ministry of Health, 2018) and with the construction of the GERD and its reservoir it exacerbates those challenges which would need to be evaluated not in regards to the GERD but generally for this hard-to-reach population.

Low and middle-income nations frequently have inadequate institutional social policies to address some of the social consequences of massive infrastructure projects such as dams (Nordensvard et al., 2015). With a lack of communication between national governments and local governments there is a need for procedural justice. The capacity of individuals and communities whose environment and health are at stake in a siting choice to participate as equal stakeholders with governmental officials in the decision-making process is referred to as procedural justice (Schlosberg, 2007). This approach in future development projects could allow rural populations to have autonomy over their health and local environment. Historically in African countries, urban dwellers are more concentrated, visible, and better able to express their thoughts and unhappiness, and they wielded more political power (Sandbrook, 1982). Since 2005, the lowest 10% of the Ethiopian population has not risen in terms of consumption, largely in rural regions, and inequality is on the rise, attributable mostly to the growing discrepancy between urban and rural areas (World Bank, 2021)

Development in rural areas without attention to vulnerable communities and without resources to mitigate future outbreak will lead to malaria's burden in the BGR to rise if entomological surveillance and infrastructure improvements (including water and sanitation, and health care infrastructure and services) are not made, and the growing population in the region will continue to use the water resources most readily available to them (such as the reservoir of the GERD). The need to access to surface waters increases human population movement around areas like the GERD and its reservoir putting them at risk of encountering malaria vectors. Contributing factors to the risk of adverse health effects to the communities in the GERD area include biodiversity loss and water pollution from the construction of the GERD and reservoir in a region that already faces water-related issues (Soliman et al., 2016) such as shortages, increased agricultural demand, flooding and drought.

2.2.4 Conclusion

This thesis has presented multiple examples which reflect the influence of dams on malaria transmission, current geographic distribution of malaria infections, its multiple vectors, and the various types of human populations moving about or settled near or around the region of the GERD and the BGR, and allowed for the conclusion that there will be a possible increase in the burden of malaria arising by 2030 due to a set of human population changes including resettlement, environmental changes, and involuntary human displacement and forced migration due to ongoing civil strife. Seen altogether from a One Health perspective, the data presented, and the conditions and circumstance described, the author concludes there will be a rise in expected human exposure to the malaria parasite and its vectors in the BGR and the GERD area.

In a wider look, observing and analyzing the significant changes taking place in the BGR through a One Health perspective has allowed for a cumulative assessment of the multiple risks that are emerging from the construction of the Grand Ethiopian Renaissance Dam and reservoir and the presence of malaria within communities along the Blue Nile River and its feeder rivers. For example, the dearth of insecticide treated nets (for protection against malaria vector bites in indoor conditions) in the BRG have continued to make malaria a reoccurring issue over decades (MIS, 2016), and the malaria infection clusters (foci) located near agricultural regions (Federal Ministry of Health, 2018), illustrate the outcomes of human behavior and mosquito ecology which arise from the absence of economic stability, as well as lack of natural resource management and point to the need to provide basic health and infrastructure service to the BGR communities. With ecological changes taking place within the BGR due to agricultural practices leading to deforestation, high flow runoff and river siltation and the construction of the GERD itself and expansion of its reservoir, malaria vector mosquitoes are expected to have more suitable habitats available which allows these mosquito populations to grow. The growth of these populations poses a threat to humans, making the surveillance and monitoring of the *Anopheles* mosquito population and human malaria cases vital to recognize and mitigate any future exposure to the prominent malaria parasites *P. falciparum* and *P. vivax.*

This decade and the next will prove to be crucial for the BGR region that is being influenced by poverty and an ongoing humanitarian crisis with internal displacement and forced migration of tens of thousands of people, as well as expected impacts of climate change (e.g., Gidey et al., 2018). It is the large proportion of U5 children who show the highest prevalence and burden of malaria; this burden will shape their future in the country and confirm their need to be protected from the disease. If governmental delays in enacting preventive and treatment measures in rural areas accompanied by adequate investment in basic sanitary infrastructure and health services to protect the health of this population, we can expect a similar result that has been observed in other countries, which is a population and a generation devastated by malaria infections and the multiple health and societal burdens they create.

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