Environmental determinants of malaria transmission in agricultural communities around large dams in Ethiopia

By

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I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification. I certify that any help received in preparing this thesis and all sources used have been acknowledged in this thesis.

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Abstract

Dams are key to ensuring food security and promoting economic growth in sub-Saharan Africa. However, the potential adverse public health impacts of dams, such as malaria, could undermine their intended benefits. Understanding the influence of dams on the distribution of malaria transmission in different ecological settings is thus crucial to devise tailor-made malaria control tools. This study assessed the impact of dams on malaria transmission at different eco-epidemiological settings, and evaluates the potential of optimized dam management for malaria control.

To determine levels of malaria transmission around dams at different ecological settings, entomological and epidemiological surveys were conducted at three Ethiopian dams located in lowland, midland and highland areas. Larval and adult anopheline mosquitoes were collected from dam and non-dam (control) villages between October 2013 and July 2014. Female anophelines were tested for malaria sporozoite infection and blood meal sources. Five years of monthly malaria case data (2010-2014) were also analyzed. Mean monthly malaria incidence was two- and ten-fold higher at the lowland dam than at the midland and highland dams, respectively. Shoreline puddles and irrigation canals were consistently the major mosquito breeding habitats. Densities of larval and adult anophelines were also highest at the lowland dam village, followed by the midland and highland dam villages. *Anopheles arabiensis* was the predominant malaria vector species, followed by *An. pharoensis* and *An. funestus sensu lato* (*s.l.*) which were largely collected from lowland and midland dam villages. The annual Entomological Inoculation Rate (EIR) of *An. arabiensis, An. funestus s.l.* and *An. pharoensis* at the lowland dam village was 157.7, 54.6 and 48.6 infective bites per person per year, respectively. The annual EIR of *An. arabiensis* and *An. pharoensis* was 5.4 and 3.1 times higher at the lowland dam village than at the midland dam village. These data indicate that increased malaria associated with dams is higher in the lowland than midland and highland ecological settings.

Factors linked to malaria transmission around the study dams were examined using environmental (elevation, distance from the reservoir shoreline, Normalized Difference Vegetation Index (NDVI), monthly average reservoir water level and monthly changes in water level) and meteorological (precipitation, and minimum and maximum temperature) data. Multiple regression analysis demonstrated that village distance from reservoir shoreline (lagged by 1 month) was negatively associated with malaria incidence around all three dams, while average monthly reservoir water level (lagged by 2 months) and monthly precipitation (lagged by 1 or 2 months) were positively associated with malaria incidence only at the lowland and midland dams. Similarly, minimum air temperature and monthly change in reservoir water level when lagged by 2 months were positively associated with malaria incidence at the highland dam. Maximum temperature did not show any correlation with malaria incidence at any of the study dams. These results suggest that reservoir factors (monthly average reservoir water level and reservoir water level change) were important predictors of malaria incidence.

Different water level drawdown rates were tested in an experimental field setting to evaluate the potential of using reservoir water level management for larval mosquito control. Twelve experimental dams were constructed on the foreshore of the midland Koka Dam, and grouped into one of four daily water drawdown treatments: 0 (control), 10, 15 and 20 mm.day^{-1}. Larval sampling was conducted weekly during the main transmission season (October to November 2013) and subsequent dry season (February to March 2014). Mean weekly larval density was highest in the control experimental dams throughout the study, and decreased significantly with increasing water drawdown rates in both seasons. The results indicate that faster water level drawdown rates help reduce larval vector abundance around dams.

The results of the experimental work were then used to evaluate the potential of water level management for malaria control at the reservoir-scale. Digital elevation models were constructed for the three study dams to estimate reservoir parameters (surface area and perimeter of wetted shoreline) at different reservoir capacities (70, 75, 80, 85, 90, 95 and 100% full capacity). Water level drawdown rates of 10, 15 and 20 mm.day^{-1} were applied and larval abundance, entomological inoculation rate (EIR) and malaria prevalence were estimated for each reservoir capacity scenario. At the lowland dam, larval abundance increased with increasing reservoir volume and wetted shoreline area, although the opposite pattern was observed at the midland and highland dams due to differences in reservoir topography. Estimated EIR, malaria prevalence, malaria treatment and economic costs generally decreased when water level drawdown rate increased from 10 to 15 and 20 mm.day^{-1}. The results indicate that increasing water level drawdown rate will reduce malaria transmission and the associated economic impacts around dams during the main transmission season. Findings of the present study highlight that by regulating the persistence of shallow shoreline breeding habitats, reservoir water level management could serve as a potential malaria vector control tool around African dams.

This study underscores the benefits of optimized dam management by incorporating malaria vector control into reservoir management practices. Mosquito larval control using reservoir water level manipulation could therefore supplement the existing vector control measures to dramatically reduce malaria around dams. Future research should assess the practicability of dam management for malaria control in diverse African settings, including the social and economic costs of optimized dam operations on hydropower generation and downstream agriculture.

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Chapter 1

Introduction

1.1 Background

Malaria is a parasitic infection transmitted from one person to another via the bite of female *Anopheles* (Diptera: Culucidae) mosquitoes. Four *Plasmodium* species (viz. *P. falciparum, P. vivax, P. ovale* and *P. malariae*) are linked to human malaria naturally (WHO, 2015a). Among them, *P. falciparum* causes the most severe and potentially fatal forms of clinical malaria, and is the commonest malarial parasite throughout the tropics and subtropics as well as in some temperate areas (Hay *et al*. 2009). *Plasmodium vivax* has the widest geographical distribution throughout temperate regions and across the tropics, while *P. ovale* and *P. malariae* have a very limited distribution in tropical Africa and the Western Pacific (Gilles and Warrell, 1993; Gething *et al*. 2012). Human infections with the simian malarial parasite *P. knowlesi* have recently been described throughout Southeast Asia (Singh and Daneshvar, 2013), and it is now recognized as the fifth species of *Plasmodium* causing malaria in humans. However, at present, the World Health Organization does not consider that simian malaria is directly relevant to malaria elimination or eradication.

Approximately 70 (out of 465) *Anopheles* species have been shown to have the capacity to transmit human malaria parasites and 41 are considered to be dominant vector species/species complexes, capable of transmitting malaria at a level of major concern to public health (Sinka *et al*. 2012). In Africa, *Anopheles gambiae sensu stricto* Giles, *An. arabiensis* Patton *and An. funestus sensu lato* Giles are the most widely distributed malaria vector species (Gillies and De Meillon, 1968; Fontenille and Lochouam, 1999; Coetzee, 2004; Sinka *et al*. 2010).

Although *Anopheles gambiae s.s.* and *An. arabiensis* occur sympatrically throughout most of their geographical distribution in sub-Saharan Africa, *Anopheles gambiae s.s.* predominates in higher-rainfall environments (annual rainfall >1000 mm) while *An. arabiensis* is concentrated in drier regions (annual rainfall <1000 mm) (Lindsay *et al*. 1998; Moffett *et al*. 2007). In contrast, the distribution of *An. funestus s.l.* extends over much of the tropics and subtropics wherever suitable swampy breeding habitats are present (Coetzee and Koekemoer, 2013). Breeding habitat needs also vary between these species: *An. gambiae s.s.* and *An. funestus s.l.* prefer permanent or semi-permanent water bodies partly covered with vegetation while *An. arabiensis* thrives in open, sunlit, shallow transient pools (Moffett *et al*. 2007).

Like all mosquitoes, anophelines go through four stages in their life cycle: egg, larva, pupa and adult. The first three stages are aquatic and last for 6 (at 40 ^{o}C) to 47 (at 16 ^{o}C) days (Teklehaimanot *et al*. 2004). The adult stage, which lives up to a month in favorable conditions, is the only stage during which the female mosquitoes take blood meals for egg production. This provides an opportunity for the link between the human host and female *Anopheles* mosquitoes in the malaria parasite life cycle.

1.2 Global epidemiology of malaria

According to the World Health Organization (WHO), there were an average 214 million (range 149–303 million) new cases of malaria worldwide in 2015 (WHO, 2015a). The majority (90%) of these cases were from Africa, followed by Southeast Asian (7%) and Eastern Mediterranean (2%) regions. At present, malaria is generally endemic in the tropics, with extensions into the subtropics (Figure 1.1). Indigenous malaria transmission has been reported in 97 countries inhabited by around 41% of the world population.

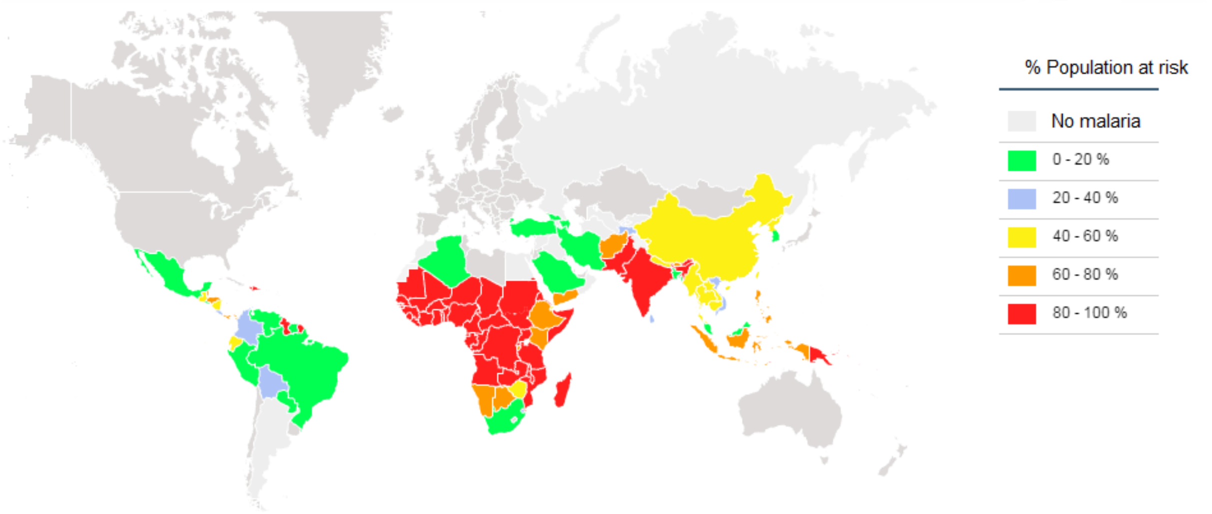

Figure 1.1. Global distribution of malaria and proportion of population at risk (Source: WHO, 2015a).

Malaria is not only a public health challenge but also a serious economic impediment to countries where the disease is endemic. The economic impact of malaria on Africa is estimated to be US$12 billion every year (RBM, 2011). This figure factors in costs of health care, absenteeism, days lost in education, decreased productivity, and loss of investment and tourism. In addition, malaria is believed to cost care-givers an average of 10 working days, adding to the economic burden in the continent (Chima *et al*. 2003). Household expenditure on malaria-related treatment includes out-of-pocket expenditures for medical consultation fees, drugs, transport and the cost of subsistence at a distant health facility. Mia *et al* (2012) found that the direct costs of treatment amounted to 32% of household income amongst very low income households, and 2% amongst the rest.

Since the year 2000, a concerted campaign against malaria has led to unprecedented levels of intervention across sub-Saharan Africa (Cibulskis *et al*. 2016). As a consequence, the number of malaria cases and deaths in the region fell by 12% (214 million in 2000 to 188 million in 2015) and 48% (from 764,000 in 2000 to 395,000 in 2015), respectively (Bhatt *et al*. 2015;

WHO, 2015a). Similarly, the annual rate of malaria incidence and mortality (per 1000 population) fell by 42% (from 427 in 2000 to 246 in 2015) and 66% (from 153 in 2000 to 52 in 2015) in the region, respectively. Such substantial progress has led the World Health Organization to shift from UN Millennium Goals to Sustainable Development Goals, with a target of reducing malaria mortality rates and clinical case incidence globally by at least 90% by 2030 compared with 2015 (WHO, 2015b).

Despite enormous global efforts to control malaria over the past decades, the risk of malaria infection, particularly in Africa, is still substantial. This is largely due to population migration (Tatem and Smith, 2010), land-use changes (O'Meara *et al*. 2010; Ermert *et al*. 2013), diversity of mosquito habitats (Rueda, 2008; Shililu *et al*. 2003), abnormal meteorological conditions (Zhou *et al*. 2004; Tompkins *et al*. 2013), poverty and drought (Worrall *et al*. 2005). In addition, other factors such as the emergence of HIV/AIDS (Abu-Raddad *et al*. 2006), antimalarial drug resistance (Phyo *et al*. 2012; Ashley *et al*. 2014), breakdown of control programs (Alilio *et al*. 2004) and insecticide resistance of *Anopheles* vectors (Knox *et al*. 2014) have contributed to the high burden of malaria, especially in sub-Saharan Africa.

1.3 Factors influencing malaria transmission

Malaria transmission involves complex interactions between *Plasmodium* parasites, anopheline mosquitoes and humans. Despite an enormous number of studies conducted during the past century, the underlying factors that determine the distribution and intensity of malaria transmission in various eco-epidemiological settings (i.e. ecological settings such as arid, high altitude, etc. that influence the level of malaria transmission) are still not clear (Cotter *et al*. 2013). Indeed, a number of factors have been shown to affect the occurrence and intensity of malaria transmission, yet the inter-relatedness of these factors make it difficult to isolate any single factor as the most significant (Figure 1.2).

Various studies on the link between weather and malaria have demonstrated that weather variables, such as temperature, rainfall and humidity, profoundly affect vector abundance and survival, and parasite maturation, which are key determinants of malaria transmission (Teklehaimanot *et al*., 2004; Zhou *et al*., 2004; Paaijmans *et al*. 2010; Mabaso *et al*. 2012; Christiansen-Jucht *et al*. 2014; Noor *et al*. 2014). For instance, temperature determines the timing and abundance of mosquitoes following adequate rainfall (Christiansen-Jucht *et al*. 2014). Furthermore, the duration of the extrinsic cycle of malaria parasites (sporogony), comprising the development of the ookinete (or the egg of the parasite) in the midgut of the female anopheline mosquito, depends on temperature (Paaijmans *et al*. 2010). For example, at an average temperature of 19°C, *P. falciparum* sporogony is completed in 37 days, but shortens at higher temperatures, to as brief as 7.9 days at 30°C (WHO, 2016). With future climate change scenarios including temperature rise, malaria transmission is likely to push to higher altitudes, resulting in increased transmission to previously unexposed, and therefore immunologically näive populations (Caminade *et al*. 2014; Siraj *et al*. 2014). However, recent modelling work (Mordecai *et al*. 2013) predicted that transmission would decrease dramatically at temperatures > 28 °C, altering predictions about how climate change will affect malaria.

Anthropogenic factors such as the construction of dams, land-use changes and agricultural practices as a consequence of human population expansion have brought new opportunities for *Anopheles* mosquitoes to breed (Hay *et al*. 2004; Muturi *et al*. 2006; Cotter *et al*. 2013). Land-use changes have been indicated to create more mosquito breeding sites and changed the water chemistry and temperature of mosquito larval habitats, substantially accelerating

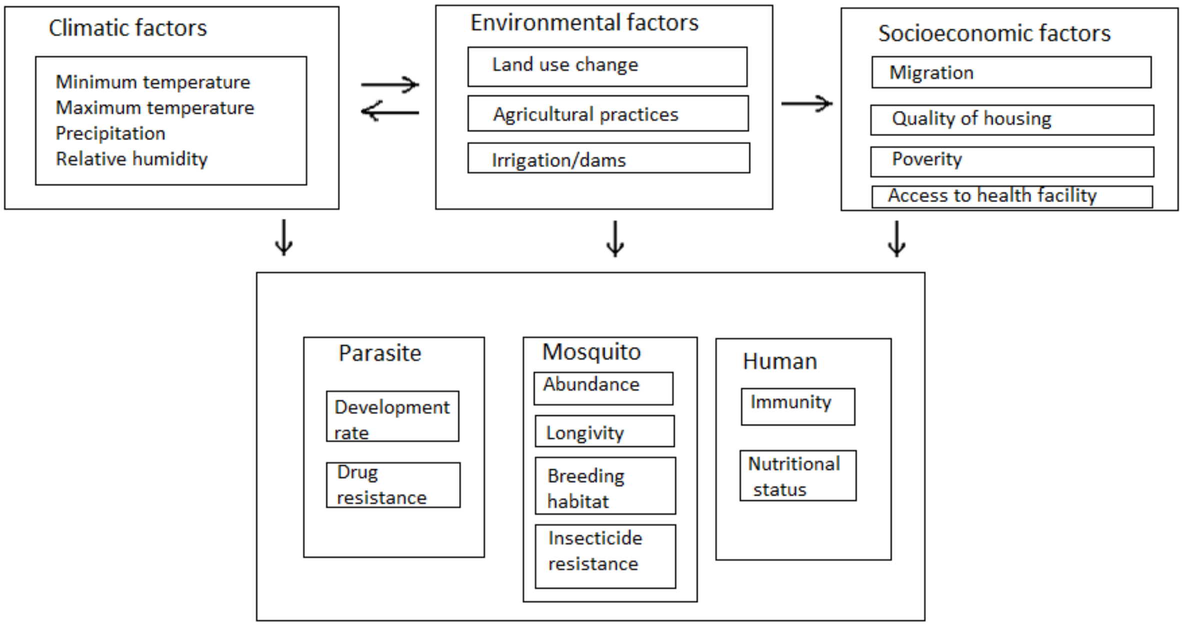

Figure 1.2 Schematic diagram of important factors affecting malaria transmission (adapted from: Lindsay and Martens, 1998).

mosquito larval development and increasing survivorship (Lindblade *et al*. 2000; Cohen *et al*. 2012). They have also altered the microclimate of the adult mosquitoes and accelerated malaria parasite development.

1.4 Malaria in Ethiopia

Ethiopia is situated in tropical zone of Africa, topographically constituting one-half of an uplifted dome girdled by the low-lying rift systems of the Great Rift Valley. Due to its diverse topography, the country experiences a wide range of climatic conditions, i.e., tropical climate prevailing in deep valleys and the lowlands, while the climate is more temperate in the highlands. Generally, the country experiences three locally known climate zones, i.e., *dega* (cold), *weyna dega* (temperate) and *kola* (warm), with elevations >2500 m above sea level, 1500-2500 m, and <1500 m, respectively. Roughly, a third of the country lies above 1500 m, of which 45% is higher than 2000 m (Tulu, 1993).

Due to the diverse topography and associated rainfall patterns, malaria transmission varies widely in Ethiopia (Figure 1.3). Generally, about two-third of the population (from a total population of 90 million) is at risk of infection (Ghebreyesus *et al*. 2006). Malaria is endemic (from moderate to high level of endemicity) in lowland areas below 1500 m. where mean annual temperature ranges between 20 to 30 ^{o}C with 100 to 1500 mm annual rainfall. Between elevations of 1500 to 2000 m where the mean annual temperature is about 20 ^{o}C and annual rainfall ranging from 400 to 2400 mm, transmission is generally unstable (seasonal) with low level of endemicity and prone to epidemic. Normally, the upper limit of malaria transmission in Ethiopia is considered to be 2000 m (MoH 2010); however, periodic epidemics and indigenous malaria transmission have been recorded above this level (Woyessa *et al*, 2004; Negash *et al*. 2005).

According to the Ethiopian Ministry of Health report (MoH, 2010), malaria affects around 4-5 million people annually in the country. It is also the leading cause of outpatient visits (15%), admissions (21%) and deaths (27%) in health facilities. All the four *Plasmodium* species that cause human malaria have long been known to occur in Ethiopia (Ghebreyesus *et al*. 2006). However, only two species, *P. falciparum* and *P. vivax*, are of epidemiological importance with a wide geographical distribution in the country (MoH, 2010). These account for around 60% and 39% of all malaria cases in the country, respectively (Ghebreyesus *et al*. 2006; MOH, 2012). The most fatal cause of malaria is infection from *P. falciparum*, with fatality rates of about 10% in hospitalized adults and up to 33% in children below 12 years of age (MoH, 2010). Moreover, epidemics of falciparum malaria that frequently strike the highland areas of the country have also been responsible for mortality and morbidity levels (Negash *et al*. 2005).

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Figure 1.3 Malaria endemicity in different parts of Ethiopia (Source: MoH 2007)

In lowland regions of the country (<1500 m a.s.l.) where malaria is endemic, the human population is still low (~18% of the total population) despite the presence of many rivers and fertile land that could be used for agriculture (Adugna, 2011). This implies that malaria may have contributed to a reduced exploitation of the productive lowland regions of the country by highland farmers and government agencies (Woube, 1997). The disease has also contributed to reduced crop productivity in rural malarious areas, since a large number of people can be prevented from work due to the debilitating illness – adding more to the economic burden of the country (Ghebreyesus *et al*. 2006).

In most highland regions of Ethiopia, recurrent epidemics of malaria of various magnitudes have been documented at interval of five to eight years since 1958 (Fountaine *et al*. 1961), mainly associated with climatic anomalies (such as El Niño) (Teklehaimanot *et al*. 2004). A retrospective study suggested that the level of malaria endemicity and the magnitude of the problem are increasing in most highland regions of the country (Negash *et al*. 2005).

1.5 Malaria vectors in Ethiopia

A total of 42 *Anopheles* species have so far been recorded in the country (Tulu, 1993). Among them, only four species, namely, *An. arabiensis*, *An. pharoensis, An. funestus s.s.* and *An. nili* have been incriminated as vectors of malaria in different parts of the country (Adugna, 2011). Among them, *An. arabiensis* is the most widely distributed and the principal vector of malaria in most parts of the country (Ghebreyesus *et al*., 2006; Adugna, 2011).

Anopheles arabiensis commonly breeds in small temporary, sunlit pools mainly formed during and immediately after the rainy seasons. The species also breeds in irrigated-field paddies, leakage pools from irrigation canals, shallow pools along streambeds, lake and river shorelines, seepages at the base of dams, and man-made pools (Table 1.1; Abose *et al*. 1998; Adugna, 2011). Unlike *An. arabiensis*, *An. funestus s.s*. and *An. nili* are more localized in their distribution as they prefer to breed around permanent and semi-permanent wetlands main located in western part of the country (Krafsur, 1977). *Anopheles pharoensis*, on the other hand, is regarded as the most important secondary vector of malaria, widely distributed in localities adjacent to permanent water bodies (Abose *et al*. 1998). This species breeds in shaded permanent water bodies such as swamps along lake and river shores, and also in rice fields and irrigation ditches.

In endemic lowland areas of southwestern, western and northwestern Ethiopia, *An. nili* was once regarded as an important vector of malaria, but with much localized distribution (Krafsur, 1970). Later studies, however, concluded that the role of this species in malaria

Table 1.1 Geographical distribution, breeding habitats, feeding and resting behaviour of major malaria vector species in Ethiopia (Adapted from: Adugna, 2011).

Species	Geographical distribution	Breeding habitat	Feeding behaviour	Resting site
An. arabiensis	Throughout the country	Shallow, sunlit, transient puddles such as rainpools, lake and river shoreline puddles, irrigated field puddles	Feeds both indoors and outdoors and highly anthropophilic	Endophilic
An. pharoensis	Western, Central and Northern parts of the country	Permanent and semi-permanent water bodies with emergent vegetation	Primarily feeds outdoors with some zoophilic tendency	Exophilic
An. funestus	Confined to western and Rift Valley regions with wetland ecosystem	Permanent and semi-permanent water bodies with emergent vegetation; common in rice paddies and irrigation canals	Primarily feeds indoors and highly anthropophilic	Mainly Endophilic
An. nili	Southwestern, western and northwestern part of the country	Permanent water bodies with emergent vegetation	Primarily feeds outdoors with some zoophilic tendency	Exophilic

transmission is negligible, partly due to ecological changes following resettlement programs in 1980s (Sehlu *et al*. 1989; Nigatu *et al*. 1994; Woube, 1997).

1.6 Malaria control in Ethiopia

Ethiopia is one of the few African countries with a long history of malaria control efforts (Ghebreyesus *et al*. 2006). The main malaria control strategy involves indoor-based vector control measures – mainly either indoor residual spraying or long-lasting insecticide-treated bed nets (LLINs) (MoH, 2014). However, the protective efficacy afforded by these intervention measures has been controversial. In some malarious-areas where the main vector feeds indoors late in the night, use of LLINs has been suggested as the best malaria vector control measure. For example, in northern and central Ethiopia, it has been reported that the efficacy of LLINs would likely be compromised as approximately 70% of bites by *An. arabiensis* occurr before 20:00 hours, before people go to sleep under their bed nets (Yohannes *et al*. 2005; Kibret *et al*. 2010). In contrast, in Sille, a hyperendemic area in southern Ethiopia, a study has suggested that if LLINs were used, 83% of the infective bites by *An. arabiensis* would probably have been prevented, as only 17% of the infective bites occurred before the local people retire to bed (Taye *et al*. 2006). This highlights the need for tailored-made intervention strategies based on mosquito behaviour and ecology in different settings.

High levels of insecticide resistance for chemicals used for IRS, mainly DDT and malathion, was also reported for *An. arabiensis* and *An. pharoensis* in several places across Ethiopia (Balkew *et al*. 2010; Yewhalaw *et al*. 2011; Fettene *et al*. 2013). To strengthen vector control efforts, larval control measures such as source reduction or environmental management has been commonly practiced in many malarious localities in the country in order to avoid (or reduce) mosquito-breeding sites, or to make them unfavorable for mosquito proliferation. The most common source reduction strategies includes draining water collections, covering water surfaces with oil, planting papyrus and reeds, and avoiding stagnant waters. A study in northern Ethiopia reported that community-led source reduction measures through filing, draining and shading potential mosquito-breeding sites within a 1 km radius of a dam village had brought a 49% relative reduction in *An. arabiensis* population compared to the pre-intervention period (Yohannes *et al*. 2005). Such measures have recently been included as a vital tool in the country's malaria control strategic plans (MoH 2014).

In addition to vector control measures, early diagnosis and treatment of malaria cases has long been a cornerstone for malaria control and prevention (MoH, 2014). However, the development of parasite resistance for malaria drugs (chloroquine and sulfadoxinepyrimethamine) has been an impediment for effective treatment of clinical cases (Getachew *et al*. 2015). Most health facilities in Ethiopia, especially those located in rural settings, do not have laboratory facilities due to which a great majority of malaria cases are treated clinically without conformatory test (MoH, 2012). This might have contributed to the development of drug resistance parasite strains in most parts of the country.

1.7 Dams and malaria

A long history of food shortage and an ever-increasing demand for electricity have challenged Ethiopia's economy for decades. To address these challenges, the country has embarked on an era of dam construction in recent years (MoWR, 2012). Despite the profound advantages of dams for ensuring food security and promoting economic growth, construction of dams in Africa have been linked to a number of adverse public health issues, such as malaria (Ghebreyesus *et al*. 1999; Sow *et al*. 2002; Keiser *et al*. 2005; McCartney and King, 2011; Kibret *et al*. 2012). Regardless, extensive dam construction is under way in Africa. In 2012, the continent's heads of state and government laid out an ambitious, long-term plan for closing Africa's water infrastructure gap (African Union, 2015). In response to this, Ethiopia has built several dams in recent years that have helped satisfy its growing energy demand, and the country is currently building an additional 8 large dams including the huge Grand Renaissance Dam (FDRE, 2015). In central Africa, the Democratic Republic of Congo has initiated the construction of several dams along the Congo River at Inga Falls, including the Grand Inga Dam – the world's largest dam (Green *et al*. 2015). In southern Africa, South Africa and Lesotho plan to build or expand six dams over the next decade to address long-term water and sanitation needs of these countries (World Commission on Dams, 2016). These include the dam on the Mzimvubu River in the Eastern Cape, expansion of the Clanwilliam Dam in Western Cape, the Nwamitwa and Tzaneen Dams in Limpopo, the

Hazelmere Dam in KwaZulu-Natal and the Polihali Dam in Lesotho. In West Africa, several dams have been planned or are under construction, including the Fomi Dam in Guinea, Toussa Dam in Mali, and Kandadji Dam in Niger (Global Water Initiative, 2012). Overall, encouraged by the recently renewed international aid for water resources development, a total of over 200 dams are currently planned or under construction throughout the continent (World Commission on Dams, 2016).

In Ethiopia, construction of dams and irrigation schemes has also been a major challenge to malaria management. The Koka Dam (Lautze *et al*. 2007; Kibret *et al*. 2012), Gilgel-Gibe Dam (Yewhalaw *et al*. 2009) and several microdams (Ghebreyesus *et al*. 1999; Dejene *et al*. 2011) have been shown to increase malaria transmission in different parts of the country. Currently, eight large dams are under construction while many more are planned in order to satisfy the country's demand of hydroelectricity generation and increased crop production. Such unprecedented water development has worried the health authorities as the country is striding for malaria elimination by 2030 (MoH, 2014). Tailor-made intervention measures are therefore required to address these challenges.

Although dams are often associated with intensified malaria transmission, no information exists on how dams affect malaria transmission. Understanding the link between dams and malaria transmission in different ecological settings will help devise tailor-made control measures. The present study is set to address this need for how to manage malaria risk from dams across ecological settings.

1.8 Research objectives

The central aim of the present study is to assess the impact of dams on malaria transmission at different eco-epidemiological settings in Ethiopia and to evaluate the potential of optimized dam management for malaria control. Its objectives are fourfold:

i) To review the available knowledge of how dams may influence the distribution of malaria incidence and vector abundance in sub-Saharan Africa;

ii) To determine the level of malaria transmission around dams at three eco-epidemiological settings;

iii) To identify the influence of environmental and meteorological factors on malaria transmission around dams at different eco-epidemiological settings; and

iv) To evaluate water level management options for larval malaria vector control around dams.

1.8 Thesis organization

The thesis is structured in seven chapters consisting of an introduction, five data chapters, and a synthesis (Figure 1.3). The thesis commences with an outline of the background, research aim and objectives in Chapter 1 (Introduction). The data chapters (Chapter 2 - 6) are written as stand-alone contributions, structured in journal format. There is thus some overlap evident in the coverage of their introduction and discussion sections. The synthesis in Chapter 7 consolidates the key findings of the thesis and examines the broader implications of these findings for the management of dams and for improved malaria control.

Chapter 2 (published in EcoHealth 2015) syntheses available information on the influence of dams on malaria incidence rates and vector abundance around dams across sub-Saharan

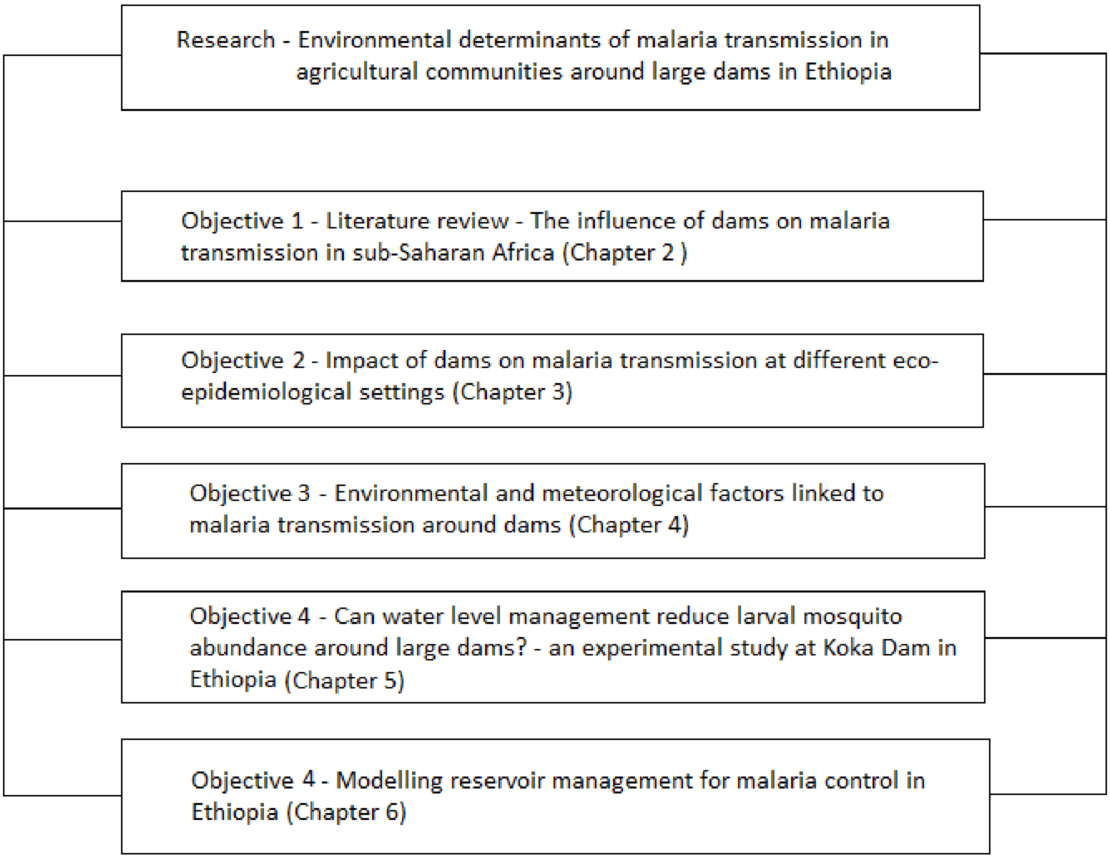

Figure 1.3. A flow diagram of the organization of this thesis and the objectives each chapter addresses.

Africa. A web-based literature search was conducted for any published or unpublished data that reported an association between dams and malaria transmission. The data were analyzed to separately demonstrate the malaria impact of dams in areas of stable (perennial) and unstable (seasonal) malaria. This chapter meets Objective 1 of the thesis, identifying clear links between dams and the current malaria distribution across sub-Saharan Africa.

Chapter 3 (under review in PLoS ONE) examines the impact of dams on malaria at different eco-epidemiological settings of Ethiopia. Epidemiological and entomological data were collected over a period of 10 months to examine the spatio-temporal variation in malaria transmission around the three study dams at different ecological settings. This chapter compares the level of malaria transmission across the three study settings. This chapter relates to Objective 2 of the thesis.

Chapter 4 analyses the influence of environmental and meteorological factors on malaria transmission across the study regions. Environmental, hydrological and meteorological data were collected and analyzed to identify factors that best explain temporal malaria transmission trends. This chapter addresses Objective 3 of the thesis.

Chapter 5 evaluates the potential of using reservoir water level management for larval control to mitigate malaria transmission around dams. Experimental dams were built in the field and faster/slower rates of water level drawdown were tested to assess their link with anopheline larval abundance. This chapter meets Objective 4 of the thesis.

Chapter 6 develops reservoir-scale models to quantify the effect of optimized water level management on malaria mosquito control. Reservoir water level scenarios were modelled and malaria risk was estimated at reservoir-scale using Digital Elevation Models and data from the experimental work (Chapter 5). This chapter analyses the risk of malaria associated with different water level drawdown rates at the three study dams. Along with Chapter 5, this chapter addresses the thesis's Objective 4.

Chapter 7 presents a synthesis of main findings of the thesis and implications for malaria management. First, it demonstrates how dams at different ecological settings influence malaria transmission. Second, it provides an overview of environmental, hydrological and meteorological factors that explain temporal malaria trends at each of the three study dams. Third, it highlights the potential opportunities of using optimized dam management for malaria control. Finally, it suggests future research directions for a better understanding of the targeted use of hydrological control for malaria vector management in sub-Saharan Africa.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Chapter 2

The influence of dams on malaria transmission in sub-Saharan Africa

Kibret S, Wilson GG, Ryder D, Tekie H, Petros B. 2015. The influence of dams on malaria transmission in sub-Saharan Africa. *EcoHealth*. DOI: 10.1007/210393-015-1029-0.

2.1 Abstract

The construction of dams in sub-Saharan Africa is pivotal for food security and alleviating poverty in the region. However, the unintended adverse public health implications of extending the spatial distribution of water infrastructure are poorly documented and may minimize the intended benefits of securing water supplies. This study reviews existing studies on the influence of dams on the spatial distribution of malaria parasites and vectors in sub-Saharan Africa. Common themes emerging from the literature were that dams intensified malaria transmission in semi-arid and highland areas with unstable malaria transmission but had little or no impact in areas with perennial transmission. Differences in the impacts of dams resulted from the types and characteristics of malaria vectors and their breeding habitats in different settings of sub-Saharan Africa. A higher abundance of a less anthropophilic *Anopheles arabiensis* than a highly efficient vector *An. gambiae* explains why dams did not increase malaria in stable areas. In unstable areas where transmission is limited by availability of water bodies for vector breeding, dams generally increase malaria by providing breeding habitats for prominent malaria vector species. Integrated vector control measures that include reservoir management, coupled with conventional malaria control strategies, could optimize a reduction of the risk of malaria transmission around dams in the region.

2.2 Introduction

With an increasing population and emerging climate change threats, demands for water storage are expected to increase, particularly in developing countries where water infrastructures are limited (World Bank, 2004*;* McCartney, 2007*;* Gleick *et al*. 2009*;* Biswas, 2012). Although construction of dams is a key to ensuring food security and alleviating poverty in sub-Saharan Africa, the negative public health effects of dams could undermine the intended benefit (McCartney and King, 2011). The public health challenges linked with water infrastructures have been mostly neglected or poorly addressed. The prominent public health problem associated with water impoundment includes malaria and other vector-borne diseases (e.g. schistosomiasis, filariasis, onchocerciasis, Rift Valley fever) (Hunter *et al*. 1999; Jobin, 1999). Malaria is a mosquito-borne parasitic disease causing between 200 and 300 million infections and over 438,000 deaths globally each year (WHO, 2015). Strikingly, over 90% of the global malaria burden occurs in sub-Saharan Africa. The presence of most efficient vector species, *Anopheles gambiae, An. funestus* and *An. arabiensis,* contribute to the prevailing high malaria transmission in the region.

There is a growing body of evidence indicating that dams influence malaria transmission in sub-Saharan Africa (Jobin, 1999; Keiser *et al*. 2005; Sanchez-Ribas *et al*. 2012). One of the major factors that determine availability of vector mosquitoes in the semi-arid areas of the tropics is the presence of areas of standing water for mosquito breeding (Bruce-Chwatt, 1980; Coetzee *et al*., 2000). The two major African malaria vectors, *An. gambiae* and *An. arabiensis,* breed in permanent and temporary shallow standing water bodies, respectively (Coetzee *et al*. 2000). Damming rivers creates stagnant shallow shoreline puddles that bring opportunities for mosquito vector breeding that could lead to increased malaria transmission in communities living adjacent to these structures (Jobin, 1999; Keiser *et al*. 2005). However, malaria transmission is a complex issue, affected by various environmental and entomological variables as well as mosquito behaviour (Lindsay and Matens, 1996). Although studies at the locality scale have demonstrated impacts of dams on malaria transmission in sub-Saharan Africa (Atangana *et al*. 1979; Oomen, 1981; Ripert and Raccurt, 1987; King, 1996; Gebreyesus *et al*. 1999; Lautze *et al*. 2007; Kibret *et al*. 2012; Yewhalaw *et al*. 2009), only one attempt (Keiser *et al*. 2005) has so far been made to review the impact of dams on malaria at a regional level. It is thus important to bring together all available information for decision-makers and dam designers so that an emphasis may be given to reduce the impact of dams on malaria while planning and designing dams. This study reviews the available evidence on the influence of dams on malaria transmission across sub-Saharan Africa, recommending potential environmental management options in different eco-epidemiological settings.

2.3 Data sources

Peer-reviewed literature, dissertations, and technical reports were systematically reviewed with an emphasis on published research findings from assessments of the impact of dams (large or small) on malaria transmission. Articles were searched mostly through PubMed using the combination of key words such as “malaria”, “*Anopheles* vector”, “dams”, “mosquito breeding”, “reservoir shoreline” and “sub-Saharan Africa”. Relevant references cited by each reviewed study were also examined. Pertinent book chapters and websites (e.g. www.dams.org) were also consulted. Only those studies that assessed epidemiological (malaria prevalence or incidence) and/or entomological (malaria mosquito bionomics, density and vectorial capacity) variables before and after the construction of a dam, or compared dam/reservoir villages and non-dam/reservoir settings with similar social and eco-epidemiological settings except for the presence or absence of dams/reservoirs were included (Figure 2.1). Studies without a control comparison design were not included in this review to ensure causality in the environmental factors responsible for changes in malaria transmission in nearby villages.

Emphasis was placed on factors associated with malaria transmission such as mosquito breeding sites, malaria vector bionomics, vectorial capacity (i.e. biological features that determine the ability of mosquitoes to transmit *Plasmodium*), human-biting tendency and entomological inoculation rate (i.e. a measure of exposure to infectious mosquitoes) in sub-Saharan Africa. This region was selected for two main reasons. First, sub-Saharan Africa has the highest malaria burden in the world, with over 90% of the global malaria cases and deaths occurring in this region (WHO, 2012). Second, this region is considered to be under-developed in terms of water infrastructures and currently is the focus for extensive further water infrastructure development (McCartney and King, 2011). To better understand the impact of dams on malaria, information on how dams in different eco-epidemiological settings affect malariologic variables is critical. A total of 24 journal articles and 3 books were found showing the effects of dams on malaria incidence and/or vector breeding and vectorial capacity in sub-Saharan Africa. The impact of dams on malaria in two major eco-epidemiological settings: unstable/seasonal (i.e. highland fringes and lowland areas with seasonal malaria transmission) and stable (i.e. lowland humid areas with perennial transmission) transmission was then analysed.

In addition, a map was developed to show the distribution of dams in countries across sub-Saharan Africa. Geo-referenced location of 1,268 dams in sub-Saharan Africa was obtained from the Food and Agriculture Organization (FAO) database (FAO, 2010) and World Register of Dams (ICOD, 2003). Raster data showing malaria stability in the region were obtained from Gething *et al*. (2011) and Malaria Atlas Project (http://www.map.ox.ac.uk).

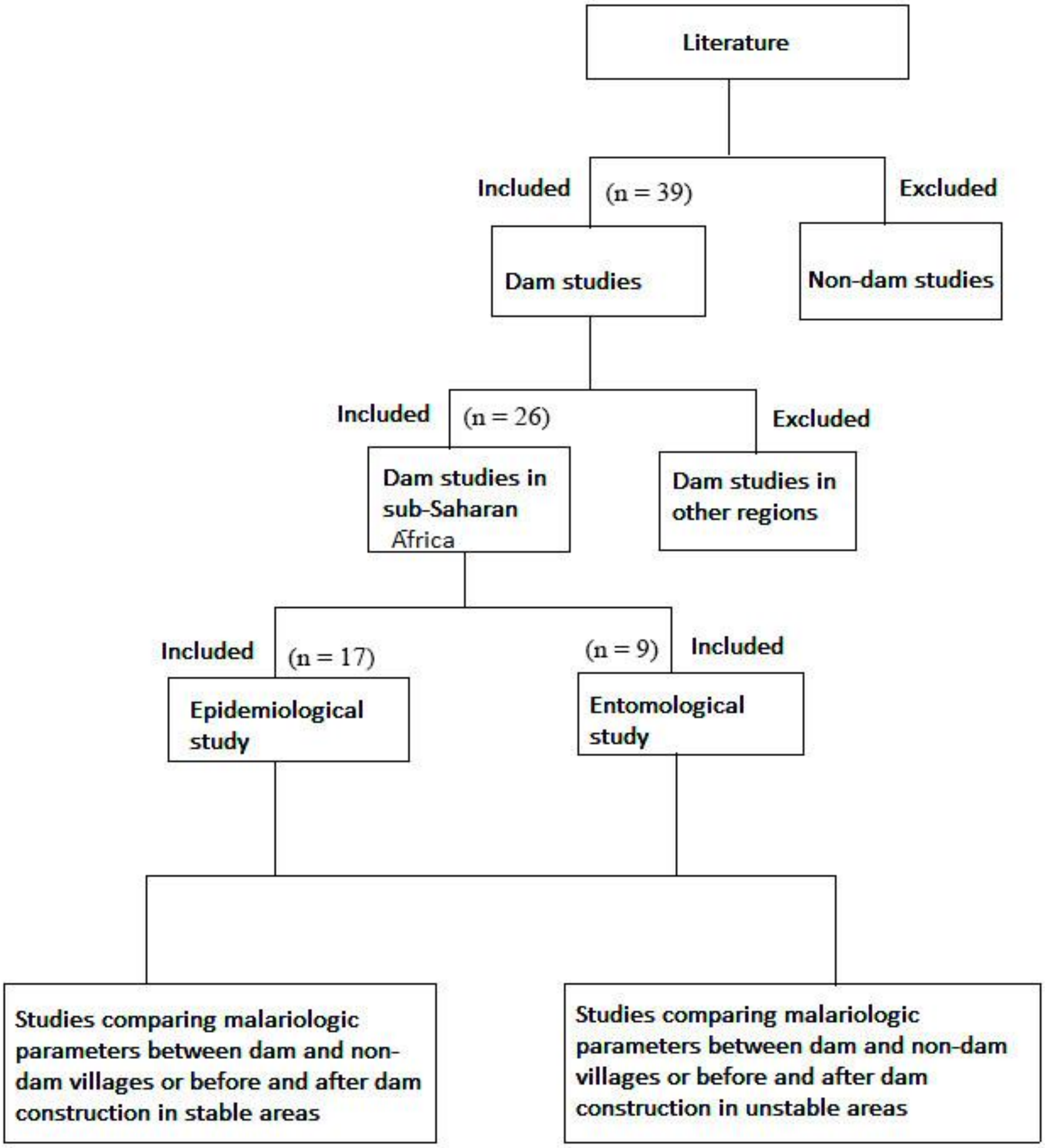

Figure 2.1. Literature review approach used in the present study, indicating inclusion and exclusion criteria for previous published studies.

The location of dams over the malaria stability map was developed using ArcView Geographical Information System (GIS) software version 10.1. In this study, a “dam” refers to the physical infrastructure while “reservoir” refers to the water impoundment.

2.4 Results

Impact of dams on malaria in areas with unstable malaria transmission

A total of 15 studies around 11 dams investigated the impact of dams on malaria in semi-arid areas and highland fringes with seasonal malaria transmission in sub-Saharan Africa (Table 2.1). These studies generally indicated that malaria prevalence was higher in dam villages than non-dam villages (Table 2.2). In Kenya, the malaria parasite rate in dam communities increased from 4.5% before Kamburu Dam's construction to 55.3% after construction (Oomen, 1981). The main malaria vectors in the region are *An. arabiensis* that prefer breeding along the shorelines in temporary puddles. The same vector species also flourished in shallow reservoir shoreline puddles in the semi-arid Bamendjin Dam in Cameroon (Atangana *et al*. 1979). Similarly, microdams (i.e. dams with less than 1million cubic meter water holding capacity) in northern Ethiopia (Ghebreyesus *et al*. 1999) and large dams (Yewhalaw *et al*. 2009; Lautze *et al*. 2007*;* Kibret *et al*. 2012) in semi-arid parts of the country with seasonal malaria were found to significantly increase malaria prevalence in adjacent (<3 km) human populations when compared with those further away (8-10 km) from the dams. *Anopheles arabiensis* was indicated as the primary malaria vector, breeding in shallow sunlit reservoir-shoreline and irrigation canals, and seepages under the dam (Yohannes *et al*. 2005; Kibret *et al*. 2012). Lautze *et al*. (2007) used a model that included virtually all major variables (including climate variables) that might affect malaria risk. Proximity to the reservoir appeared as a highly significant explanatory variable.

Human-induced environmental modifications normally exert a great impact on vector population dynamics, which could possibly lead to malaria epidemics in areas where people

Table 2.1. Characteristics of dam study areas with unstable malaria in sub-Saharan Africa.

Country	Name of the dam	Dam capacity (Mm^3)	Elevation (m, asl)	Climate	Source
Cameroon	Bamendjin Dam	1,847	1500	Semi-arid area	Atangana *et al*. 1979; Ripert and Raccurt, 1987
Ethiopia	Gilgel-Gibe Dam	168	700	Sub-humid hot climate	Yewhalaw *et al*. 2009
	Koka Dam	1,850	1600	Semi-arid; mean temp 24 ^{o}C	Lautze *et al*. 2007; Kibret *et al*. 2009; 2012
	Koga Dam	83.1	2000	Highland area; mean temp 19 ^{o}C	Zeleke, 2007
	Mai Nigus, Mai Sessela and Mai Seye microdams	0.5-4.5	1900-2100	Degraded highland	Dejene *et al*. 2011; 2012
	Tigray microdams	2.7	1790	Semi-arid; mean temp 20 ^{o}C	Gebreyesus *et al*. 1999; Yohannes *et al*. 2005
Ghana	Akosombo Dam	148,960	920	Semi-arid wetland	Sam, 1993
Kenya	Kamburu Dam	123	1671	Semi-arid area; Annual rainfall between 550 and 750 mm; annual min temperature between 14 and 18 ^{o} C; annual max temperature between 26 and 30 ^{o} C	Ooman, 1981
Nigeria	Usuma Dam	120		Semi-arid wet land	Ujoh *et al*. 2012
Tanzania	Mtera Dam	125	698	Semi-arid	Njunwa, 2000
Zimbabwe	Manyuchi Dam	319	800	Mean temp between 16 and 25 ^{o}C	Freeman, 1994

have low immunity to the disease. For malaria epidemics to occur, both people and the parasite and the vector mosquito must come into frequent contact (Smith and McKenzie, 2004). In Zimbabwe, malaria epidemics occurred in 1991 following construction of Manuynch Dam in the Mwenzi district that was once considered to be free of malaria

(Freeman, 1994). The author believed that movement of people and vectors carrying malaria parasites from neighboring endemic areas could have contributed to the establishment of malaria transmission around Manyunch Dam.

Whilst the Koga Dam (2000 m above sea level) in northwest Ethiopia intensified malaria transmission (Zeleke, 2007), at least three microdams in the northern highlands of Ethiopia (>2000 m above sea level) did not result in increased malaria prevalence despite an increased density of *An. arabiensis* (Dejene *et al*. 2011; Dejene *et al*. 2012). Air temperature was indicated as a limiting factor to support malaria transmission in the latter studies.

Generally, malaria vector species distribution seems to influence the nature of the interaction between dams and malaria across sub-Saharan Africa. *Anopheles arabiensis* was the predominant species followed by *An. pharoensis* around the dams in Ethiopia (Yohannes *et al*. 2005; Zeleke, 2007; Kibret *et al*. 2012), Kenya (Oomen, 1981) and Zimbabwe (Freeman, 1994), while *An. gambiae* was the most common malaria vector found around dams in Ghana (Sam, 1993), Nigeria (Ujoh *et al*., 2012) and Tanzania (Njunwa, 2000). *Anopheles funestus* was the dominant species around the Bamendjin Dam of Cameroon (Atangana *et al*. 1979). While *An. arabiensis* was predominantly found in sunlit temporary breeding habitats created by water-level changes, *An. gambiae* and *An. funestus* were common in wetlands created by receding reservoir water. *Anopheles gambiae* and *An. funestus* are highly anthropophilic and endophagic while *An. arabiensis* exhibits partial zoophilic and exophagic behaviour.

Impact of dams on malaria in areas with perennial transmission

There have been only three studies that have assessed the impact of dams in areas where malaria transmission occurs throughout the year (Table 2.3). Malaria prevalence was not

Table 2.2. Documented impact of dams on malaria in areas with unstable malaria in sub-Saharan Africa.

Name of the dam and location	Malaria situation	Primary malaria vector species and breeding	Source
Bamendjin Dam , Cameroon	Malaria prevalence was 36% and 25% in communities at close proximity and farther away (14 km) from the reservoir, respectively.	*An. funustus* flourished in shallow vegetation-covered waters	Atangana *et al*. 1979; Ripert and Raccurt, 1987
Gilgel-Gibe Dam, Ethiopia	The *P. vivax* prevalence was significantly higher in communities within 3 km from the dam as compared to those 5-8 km from the dam (OR = 2.00, 95% CI = 1.38, 2.92)	*An. arabiensis*; shoreline puddles	Yewhalaw *et al*. 2009,
Tigray microdams, Ethiopia	Malaria incidence was 14.0 episodes/ 1000 child months in communities within 3 km radius from dams as compared to 1.9 in villages 8-10 km from the dams	*An. arabiensis* and *An. pharoensis*; shoreline puddles and seepage below the dam	Gebreyesus *et al*. 1999; Yohannes *et al*. 2005
Koka Dam , Ethiopia	Malaria infection rate was 90.4 cases/1000 person in communities within 1 km from the reservoir compared to 5.3 at a distance 5-9 km away	*An. arabiensis* and *An. pharoensis*; shoreline puddles and seepage below the dam	Lautze *et al*. 2007; Kibret *et al*. 2009; 2012
Koga Dam, Ethiopia	Malaria prevalence was significantly higher (9.5%) in dam villages than the non-dam villages (0.5%)	Larvae of *An. arabiensis* were found around the reservoir shoreline	Zeleke, 2007
Mai Nigus, Mai Sessela and Mai Seye microdams, Ethiopia	The dams did not result in significant increase in malaria incidence	Two-fold increase in *An. arabiensis* density in dam communities following dam construction	Dejene *et al*. 2011; 2012
Akosombo Dam, Ghana	The dam resulted in perennial malaria transmission	*An. gambiae* breeds on the shorelines of the reservoir (Lake Volta)	Sam, 1993

Kamburu Dam, Kenya	Before dam construction = 4.5% and 1.8% malaria prevalence in children living within 4 km from the dam and Inland (4-11 km from the dam) communities, respectively; After dam construction = 55.3% and 22.2%, respectively. 80-85% of all cases are due to *P. falciparum* and 10-15% are due to P. *malariae*	*An.gambiae* (principal vector); *An. funestus* (secondary vector); *An. gambiae* was found breeding in almost all water collections examined while *An. funetus* preferred permanent vegetation-covered pools	Ooman, 1981
Usuma dam, Nigeria	Malaria prevalence was higher in the dam villages when compared to non-dam villages	*An. gambiae*	Ujoh *et al*. 2012
Mtera dam, Tanzania	Malaria prevalence increased from 23.5% before construction to 50.4% after construction of the dam	Adult densities of *An. gambiae* were higher after construction of the dam	Njunwa, 2000
Manyuchi dam , Zimbabwe	The area used to be malaria free but surrounded by malarious districts before dam construction. The dam was blamed for malaria epidemics (35 deaths & 5,804 *P. falciparum* clinical cases) in 1994.	*An. arabiensis*	Freeman, 1994

enhanced following the construction of the Gleita Dam in Mauritania (Baudon *et al*. 1986). *Anopheles pharoensis,* with a short longevity and thus poor vectorial capacity, is the main vector around Gleita Dam (Table 4). Although the density of this vector increased due to abundant breeding grounds associated with the reservoir, its short lifespan appeared to limit its role in malaria transmission. The Diama Dam in Senegal was also found to have had no impact on malaria transmission rates, despite an increase in vector abundance (Sow *et al*. 2002*;* Sanchez-Ribas *et al*. 2012). *Anopheles gambiae,* a highly anthropophilic species with high vectorial capacity, was replaced by the less anthropophilic *An. pharoensis* with its lower vectorial capacity following dam constructions in semi-arid areas.

Distribution of dams related to malaria stability in sub-Saharan Africa

The location of a total of 1,268 dams was examined in relation to malaria stability across sub-Saharan Africa (Figure 2.2). Over half of these dams were located in areas with either unstable or stable malaria, while 43% (n=545) were located in areas where malaria transmission does not exist (mainly in South Africa). Of the dams located in malarious areas, 33% (n=416) and 24% (n=307) were located in areas with unstable and stable malaria, respectively. The majority of the dams in stable malarious areas were located in western Africa, while the majority of dams in unstable areas were situated in southern and eastern Africa.

2.5 Discussion

This review indicated that the effects of dams on malaria transmission vary depending on the ecology of the vector mosquito and malaria endemicity of a given area. Whilst dams could increase malaria in semi-arid areas where the transmission is seasonal, dams built in stable

Table 2.3. Characteristics of dam study areas with stable malaria in sub-Saharan Africa

Country	Name of the dam	Water capacity (Mm^3)	Climate and topography	Vector bionomics and breeding	Source
Senegal	Diama Dam	250	Semi-arid	*An. pharoensis* breeds in temporary puddles and has a low survival rate which limits its role in malaria transmission. Even in some villages where *An. gambiae* and *An. arabiensis* are common, they prefer irrigated areas and their anthropophilic index remains low.	Sow *et al*. 2002
Mauritania	Foum Glaita Dam	500	Area of reservoir is 10 by 15 km; Sahelian climate between humid area and desert;	*An. gambiae;* While there were several puddles formed, it was suggested that harsh winds and high temperatures negatively affected larval development	Baudon *et al*. 1986
Mali	Manantali Dam	11,300	Dry sahelian climate with annual rainfall of 360 mm and mean temperatures ranging 28 ^{o}C	*An. arabiensis* and *An. gambiae* and vector densities were correlated with ditches, but not the river	Ndiath *et al*. 2012

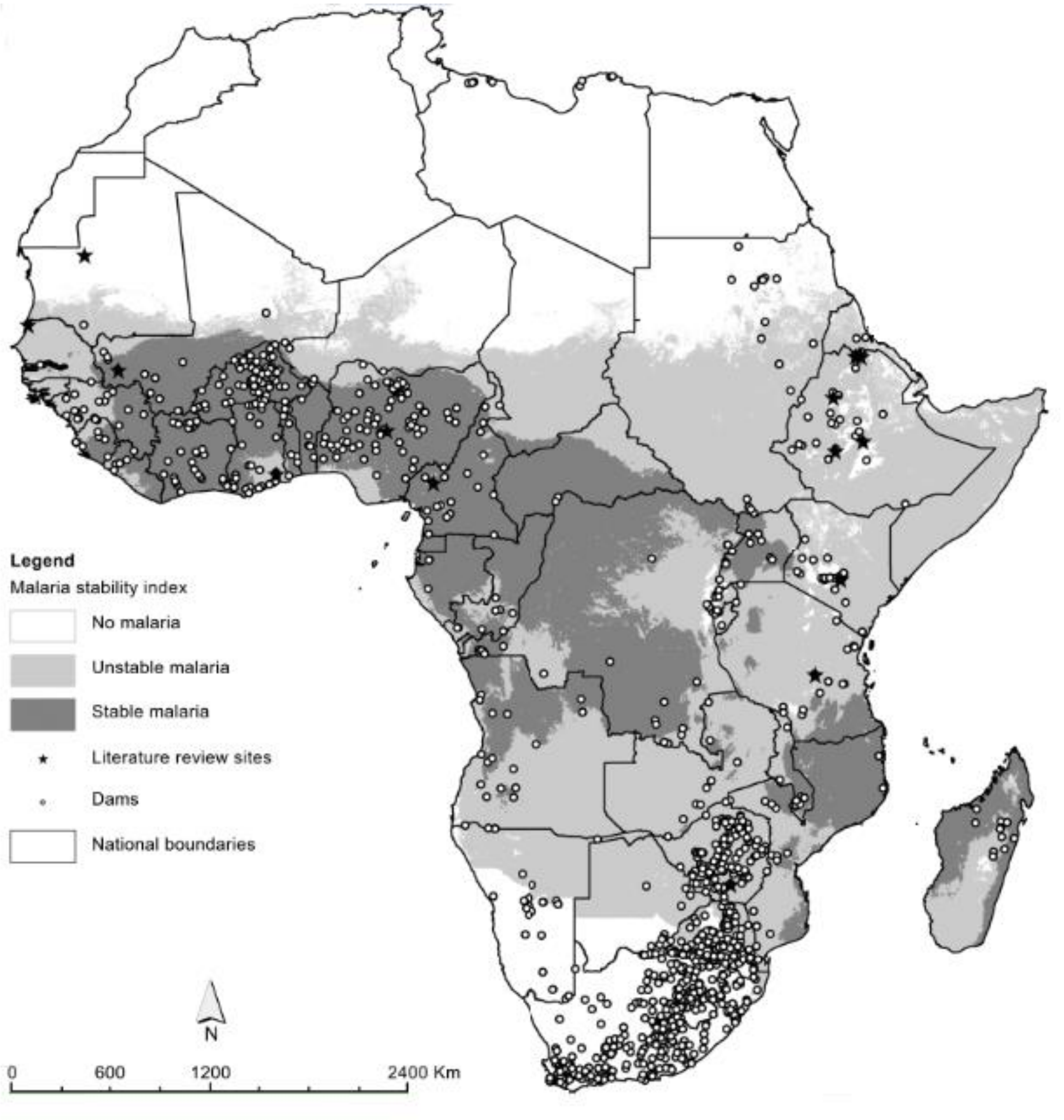

Figure 2.2. Map showing spatial distribution of dams in the sub-Saharan Africa related to the 2010 malaria stability indexing, and locations of study sites used in the review.

areas (i.e. areas with year-round malaria transmission) showed no effect of enhanced malaria intensity. This is mainly attributed to the differences in larval breeding habitat preferences and distribution of *An. arabiensis* and *An. gambiae* across sub-Saharan Africa (Gilles and De Meillon, 1968).

Anopheles arabiensis predominately occurs in semi-arid areas with limited rainfall while *An. gambiae* commonly exists in tropical rainforest regions and prefers permanent breeding sites unlike *An. arabiensis* that flourishes in sunlit shallow temporary breeding habitats such as reservoir shoreline puddles (Coetzee *et al*. 2000). In semi-arid unstable malarious areas, availability of water for mosquito vector breeding is the key environmental variable that determines the force of malaria transmission (Craig *et al*. 1999; Teklehaimanot *et al*. 2004). In these settings, dams result in a proliferation of *An. arabiensis*, leading to intensified malaria transmission.

On the other hand, in stable areas with perennial transmission, *An. arabiensis* and *An. pharoensis* with lesser anthropophilic behavior thrive much better than the highly anthropophilic *An. gambiae* and *An. funestus* around water reservoirs, resulting in insignificant change in local malaria prevalence. This scenario was documented in studies of Malian and Senegalese villages near Manatali Dam. Interestingly, the dam increased malaria in the Senegalese villages (King, 1996) but not at those in Mali (Ndiath *et al*. 2012). The explanation for this difference was that *An. arabiensis* was the major vector along the Senegalese shoreline of the reservoir with unstable malaria while *An. arabiensis* displaced the more efficient vector *An. gambiae* in the Malian villages adjacent to the reservoir shoreline where stable malaria exists. Similarly, Ijumba and Lindsay (2001) reported displacement of the most endophilic and anthropophilic malaria vector *An. funestus* by *An. arabiensis* with lower vectorial capacity, as the latter thrives more than the former in puddles associated with water impoundments in stable areas. In a previous global review, Keiser *et al*. (2005) indicated that whether an individual water project triggers an increase in malaria transmission depends on the contextual determinants of malaria including the epidemiologic setting, socioeconomic factors, vector management, and health-seeking behaviour. Dams also attract people for farming, fishing and domestic water use resulting in higher human density around them. With higher vector abundance and increased availability of bloodmeal for the vector, dams could intensify malaria in such highly populated dam communities (Hunter, 1993). Moreover, the distribution and ecology of malaria vector species are among the important factors that determine the potential influence of dams on malaria.

Increased malaria in unstable areas following dam construction was also documented elsewhere (Keiser *et al*. 2005); for example at the Bargi Dam (Singh *et al*. 1999) and Sathanaur Reservoir of India (Hyma and Ramesh, 1980), the Three Gorges Reservoir in China (Quan *et al*. 2013), and the Itapu Dam in Brazil (Flavigna-Gulmerme *et al*. 2005). These studies indicated that ecological changes due to water storage led to the formation of suitable mosquito vector breeding grounds. In contrast, construction of small dams in the Sandargarh district of India has led to a decrease in malaria prevalence in dam communities (Sharma *et al*. 2008). This was due to altered flow conditions in the river downstream of the dams that resulted in unfavorable breeding conditions for *An. fluviatilis* which requires slow-flowing streams. The link between dams and malaria is thus generally associated with environmental changes that influence mosquito vector species abundance.

Anthropogenic conditions may modify the malaria stability index by influencing the distribution, survival rate, and feeding habits of vectors (Kiszewski *et al*. 2004). Insecticide use, improved house construction and land-use changes would reduce the force of transmission. Anthropogenic changes that increase transmission would include the accumulation of ground puddles and enhanced mosquito resting-sites that affect mosquito longevity. Irrigation has been indicated to exacerbate dam impacts on malaria (Keiser *et al*.

2005) and rice irrigation has led to increased malaria in unstable areas of sub-Saharan Africa (Ijumba and Lindsay, 2001). Lindsay *et al*. (2000) indicated that both minimum and maximum air temperatures were higher in irrigated villages than non-irrigated villages in the highlands of Uganda. Similar microclimate change may contribute to an increase in malaria in the irrigation dams in the highlands of sub-Saharan Africa. Temperature is a key determinant of several malaria transmission parameters, including the rate of parasite and mosquito development and biting rates (Beck-Johnson *et al*. 2013; Christiansen-Jucht *et al*. 2014). Around Lake Bunyonyi in the highlands of Uganda, Lindblade *et al*. (2000) found that temperatures were significantly higher in villages close to the lake than in those further away, and that *An. gambiae* was abundant around the lake. This explains why *An. arabiensis* appears to have become abundant around the highland dams. Lindblade *et al*. (2000) also demonstrated that the duration of malaria parasite development was reduced by 17.3 days (from 55.5 to 38.2 days) when mean temperatures increased from 18.0 to 18.9 ^{o}C. A similar relationship with temperature exists for larval mosquito development (Beck-Jonson *et al*., 2013) and adult biting rate (Lindsay and Barley, 1996). Further studies are necessary to understand the existing microclimate changes that favour malaria transmission around highland dams in sub-Saharan Africa.

Over 20 million people live around dams in sub-Saharan Africa (Kibret *et al*., 2015). It was also estimated that a total of 1.1 million malaria cases annually were associated with dams. Several new dams have been proposed for irrigation and hydropower generation in this region (FAO, 2007; Dumas *et al*., 2010; Zarfl *et al*. 2015). Yet, the risk of malaria could compromise the intended benefits of these dams. There is no doubt that integrated malaria interventions are necessary in order for the reservoir communities to enjoy the intended benefits derived from water infrastructures (Brewster, 1999; Russell *et al*. 2011). Among the most common malaria intervention strategies, vector control measures (using insecticide treated bed nets and indoor residual spraying), coupled with environmental control through disrupting mosquito larval breeding sites, have been advocated as a cost-effective measure in water resources development schemes such as large dams (Utzinger *et al*., 2001; Walker, 2002). Dam management protocols using water level manipulation during peak malaria transmission seasons have been shown to suppress mosquito larval breeding and malaria around dam communities in the United States (Kitchens, 2013). With recent intensive dam construction activities in sub-Saharan Africa, it is essential to explore such water management options to mitigate malaria around large water impoundments. Recent studies in Ethiopia found that faster drawdown of the Koka reservoir during the main malaria transmission season could reduce malaria vector abundance and improve downstream flood control (Kibret *et al*. 2009; Reis *et al*., 2012). However, this has never been tested for its applicability in African settings. Future studies should focus on developing dam operation tools that incorporate malaria control to suppress vector mosquito breeding and malaria transmission in unstable regions of sub-Saharan Africa.

In conclusion, water storage infrastructures are essential to ensure food security and address the development needs. However, poor consideration of the negative public health effects of such structures could compromise the intended outcomes. This study indicates the negative impact of dams on malaria particularly in areas with unstable/seasonal transmission in sub-Saharan Africa. The effects of dams on malaria should be well understood before implementing such projects and appropriate mitigation measures should be taken during operation. Research is required to further assess environmental factors that lead to intensified malaria transmission in unstable malaria areas of sub-Saharan Africa. Integrated vector control measures that include protocols for reservoir management, coupled with conventional malaria control strategies, will reduce the risk of malaria transmission in dam communities across the region.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Chapter 3

Malaria impact of large dams at different eco-epidemiological settings in Ethiopia

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3.1 Abstract

Background: Dams are important to ensure food security and promote economic development in sub-Saharan Africa. However, a poor understanding of the negative public health consequences from issues such as malaria could affect their intended advantages. This study investigates the impact of dams on malaria transmission at three different eco-epidemiological settings in Ethiopia.

Methods: Larval and adult mosquitoes were collected from dam and non-dam villages around the Kesem (lowland), Koka (midland) and Koga (highland) dams in Ethiopia between October 2013 and July 2014. Determination of blood meal sources and detection of *Plasmodium falciparum* sporozoites was done using Enzyme-linked Immunosorbent Assay (ELISA). Five years of monthly malaria case data (2010-2014) were also collected from health centers in the study villages.

Results: Mean monthly malaria incidence was two- and ten-fold higher in the lowland dam village than in midland and highland dam villages, respectively. The total surface area of anopheline breeding habitats and the mean larval density was significantly higher in the lowland dam village compared with the midland and highland dam villages. Similarly, the mean monthly malaria incidence and anopheline larval density was generally higher in the dam villages than the non-dam villages in all the three dam settings. *Anopheles arabiensis*, *An. pharoensis* and *An. funestus* were the most common species, largely collected from lowland and midland dam villages. Larvae of these species were mainly found in reservoir shoreline puddles and irrigation canals. The mean adult anopheline density was significantly higher in the lowland dam village than the midland and highland dam villages. The annual Entomological Inoculation Rate (EIR) of *An. arabiensis*, *An. funestus* and *An. pharoensis* in the lowland dam village was 157.7, 54.6 and 48.6 infective bites per person per annum, respectively. The annual EIR of *An. arabiensis* and *An. pharoensis* was 5.4 and 3.1 times higher in the lowland dam village than the midland dam village.

Conclusion: The present study found that the presence of dams intensifies malaria transmission in lowland and midland ecological settings. Dam and irrigation management practices that could reduce vector abundance and malaria transmission need to be developed for these regions.

3.2 Introduction

The sub-Saharan Africa region is ranked lowest in the world for average water withdrawal (World Bank, 2004), suggesting the pressing need for targeted development of water resource infrastructure. New water storages are currently being extensively developed to help improve the region’s food security and promote sustainable economic development (ICOD, 2003; Rosegrant and Perez 1997). However, the link between dams and malaria has been widely recognized as a public health challenge (Keiser *et al*. 2005; Kibret *et al*. 2015a; Kibret *et al*. 2015b) which could hamper the intended advantages provided by these water infrastructures.

Ninety percent of the global malaria burden occurs in sub-Saharan Africa, resulting in transmission and disease management being a leading public health challenge (WHO, 2015). With the current high level of dam construction in the region (Cole and Elliott, 2014), links between the spatial distribution of dams in the landscape and malaria outcomes must be better understood for an assessment of any potential negative public health outcomes from dam development. Previous studies have indicated that dams increase malaria by providing breeding sites for malaria-transmitting mosquitoes in areas with unstable/seasonal malaria (Atangana *et al*. 1979; Oomen, 1981; Baudon *et al*. 1986; Ghebreyesus *et al*. 1999; Yohannes *et al*. 2005; Lautze *et al*. 2007; Mba and Aboh, 2007; Kibret *et al*. 2009; Yewhalaw *et al*. 2009; Kibret *et al*. 2012; Ndiath *et al*. 2012). For example, a study around the Akosombo Dam in Ghana documented a 20% increase in malaria incidence in populations within a 3 km radius of the reservoir compared with those residing more than 7 km from the reservoir (Mba and Aboh, 2007). The occurrence and persistence of shallow shoreline puddles around the edge of the reservoir providing breeding habitats for the primary malaria vector species, *Anopheles gambiae sensu stricto*, was indicated to underpin the increased malaria incidence (Badu *et al*. 2013).

A number of environmental factors determine the degree of intensity of malaria transmission in Africa. Elevation has long been known for its effect on malaria transmission, mainly due to its influence on ecological and climatic drivers. A study in Tanzania found that malaria prevalence decreases by 21% in every 100 m increase in elevation (Drakeley *et al*. 2005). Higher temperatures and other ecological characteristics associated with lower altitudes have been indicated to support higher rates of malaria transmission in the lowlands than the highlands.

Although dams can increase malaria in unstable areas (i.e. areas with seasonal malaria), it is not clear whether the impact of dams on malaria varies in different ecological settings. As Africa is experiencing a new era of dam building, with numerous dams planned or currently under construction (Kibret *et al*. 2015a), understanding the link between dams and malaria transmission across different eco-epidemiological settings is crucial in order to devise malaria control strategies and enable appropriate allocation of limited resources for intervention around water resources development schemes.

The present study assessed the link between three dams and malaria at different eco-epidemiological settings in Ethiopia. The objective of this study was to identify mosquito breeding sites and compare adult and larval abundances around three dams in highland, midland and lowland settings of Ethiopia. The study also aimed to determine and compare the level of malaria transmission across the three eco-epidemiological settings.

3.3 Methods

Study area

This study was conducted around three large dams in Ethiopia: the Kesem Dam (9^{o}9’1”N 39o51’32”E; 975 m above sea level (asl)), Koka Dam (8^{o}46’80”N, 39^{o}15’32”E; 1551 m asl) and Koga Dam (11^{o}39’35”N, 37^{o}17’44”E; 1980 m asl) (Figure 3.1). The Kesem Dam (hereafter referred as the lowland dam) is located on the Awash River in the lowlands of the Ethiopian Rift Valley, 225 km east of Addis Ababa, the capital of Ethiopia. Its crest height of 25 m, stores a maximum of 500 million m^3 of water, covering an area of 200 km^2. The maximum length of the shoreline at full capacity is 55.4 km (Ministry of Water Resources, 1987). The primary purpose of the dam is to irrigate 20,000 ha of land for sugarcane production downstream. The area is characterized as semi-arid with a mean daily temperature of 27°C. The hottest month is May (average daily temperature is 38 °C) and the coldest is December (average daily temperature is 18 °C) (Ethiopian Meteorological Agency, unpublished data). The area receives an average annual total rainfall of 600 mm: the main rainy season (June-August) accounts for 80% of the total rainfall. An estimated population of 35,000 lives within a 5 km radius of the Kesem reservoir (Central Statistics Agency, 2010). Sabure, hereafter referred as the lowland dam village, is the nearest settlement (<1 km) to the dam with a population of 3,608 in 2012 (Sabure Health Center, unpublished report). Meli, hereafter referred as lowland non-dam village, is located 15 km from the Kesem reservoir shoreline and was selected as a control village. Most of the inhabitants of both villages are agrarians and irrigation laborers.

Koka Dam (hereafter referred as the midland dam) is located in the Ethiopian Rift Valley in Central Ethiopia, 100 km south of Addis Ababa. It has a crest height of 42 m, and a full water storage capacity of 1,188 million m^3. The surface area of the reservoir at full capacity is 236 km^2 and the length of the reservoir at full storage capacity is 86 km. The primary purpose of the dam is to generate 43.2 MW of electricity from three turbines (approximately 6% of the current total grid-based generating capacity of the country). Currently, the Wonji sugarcane irrigation scheme (6,000 ha), located approximately 12 km downstream of the dam, is also dependent on releases from the dam. In addition, the dam is also used for flood control. The area receives a total annual rainfall of 850 mm and the mean daily temperature is 24 °C (National Meteorological Agency, unpublished report). The area is characterized as semi-arid with a mean daily temperature of 22°C. The hottest month is May (average daily temperature is 32 °C) and the coldest is December (average daily temperature is 12 °C). An estimated population of 29,000 lives within 5 km from the reservoir (Central Statistics Agency, 2010).

Ejersa (population 4,236), hereafter referred to as the midland dam village, is a rural village located adjacent (<1 km) to the Koka reservoir shoreline. Jogo (population 3,421; Adama Health Center, unpublished report), hereafter referred as the midland non-dam village, is located about 10 km from Koka reservoir, and was used as a control village. The inhabitants of both villages are largely agrarians. Malaria is an important public health concern in both villages, with the main transmission season occurring from September to December, immediately following the long rainy season (June-August).

Koga Dam (hereafter referred as the highland dam) is located on the Koga River, one of the major tributaries of the Blue Nile River, 560 km northwest of Addis Ababa. The dam has a storage capacity of 83.1 million m^3 and surface area of 175 km^2. It was commissioned in 2009 to irrigate 7,000 ha of wheat, corn and teff crops. The rainy season (June-August) generates about 70% of the runoff feeding the Koga River (Birhanu *et al*. 2014). The length of the reservoir shoreline at full capacity is 120 km. The area is characterized as highland with a mean daily temperature of 19 ^oC and receives an average annual rainfall of 1500 mm. The hottest month is May (average daily temperature is 26 ^oC) and the coldest is January (average daily temperature is 10 ^oC) (Ethiopian Meteorological Agency, unpublished data). An estimated 32,680 people live within 5 km of the reservoir (Central Statistical Agency of Ethiopia, 2010). Endemir, hereafter referred as the highland dam village, is located adjacent (<1 km) to the reservoir shoreline and had a population of 2,907 in 2013 (Merawi Health Center, unpublished report). Sira Behibret, hereafter referred as the highland non-dam village, is located 12 km from the reservoir shoreline and had a population of 3,241 in 2013 (Merawi Health Center, unpublished report). The inhabitants of both villages are agrarians, and cattle herding is also common.

Malaria is the leading public health challenge in all study villages, mainly following the months of the rainy season (September to November). *Plasmodium falciparum* is the predominant malaria-causing parasite, accounting for 70-80% of malaria infections (Oromia Health Bureau, unpublished report). The remaining malaria infections are due to *P. vivax*. *Anopheles arabiensis* is the major malaria vector species in the study area while *An. pharoensis* plays secondary role (Kibret *et al*. 2009). Potential mosquito breeding habitats in the study area include shoreline puddles, irrigation canals, rain pools and manmade pools (Plate 3.1).

Clinical malaria data collection

To assess the risk of malaria around dams, monthly data of retrospective microscope-confirmed malaria cases were obtained from health centers in each of the three dam sites (2010–2014). The malaria dataset was sorted for each of the 6 villages (3 dam and 3 non-dam villages), and species of malaria parasite as confirmed by microscopy.

Mosquito sampling

Larval and adult mosquitoes were sampled every three weeks for a total of 14 nights (n=14) in each of the study villages from October 2013 to July 2014. Larval stages were sampled from any water body such as rain pools, manmade pools, reservoir shoreline puddles, and irrigation canals. During each survey, all potential mosquito breeding habitats within a 1 km radius of the study village were sampled using 350 mL standard dippers (Silver, 2007). One km radius of each study village was initially marked and two teams covered the whole village in each survey. First, the surface area of the each potential mosquito breeding site was estimated in square meters (m^2) and sampling was undertaken at a rate of six dips per m^2

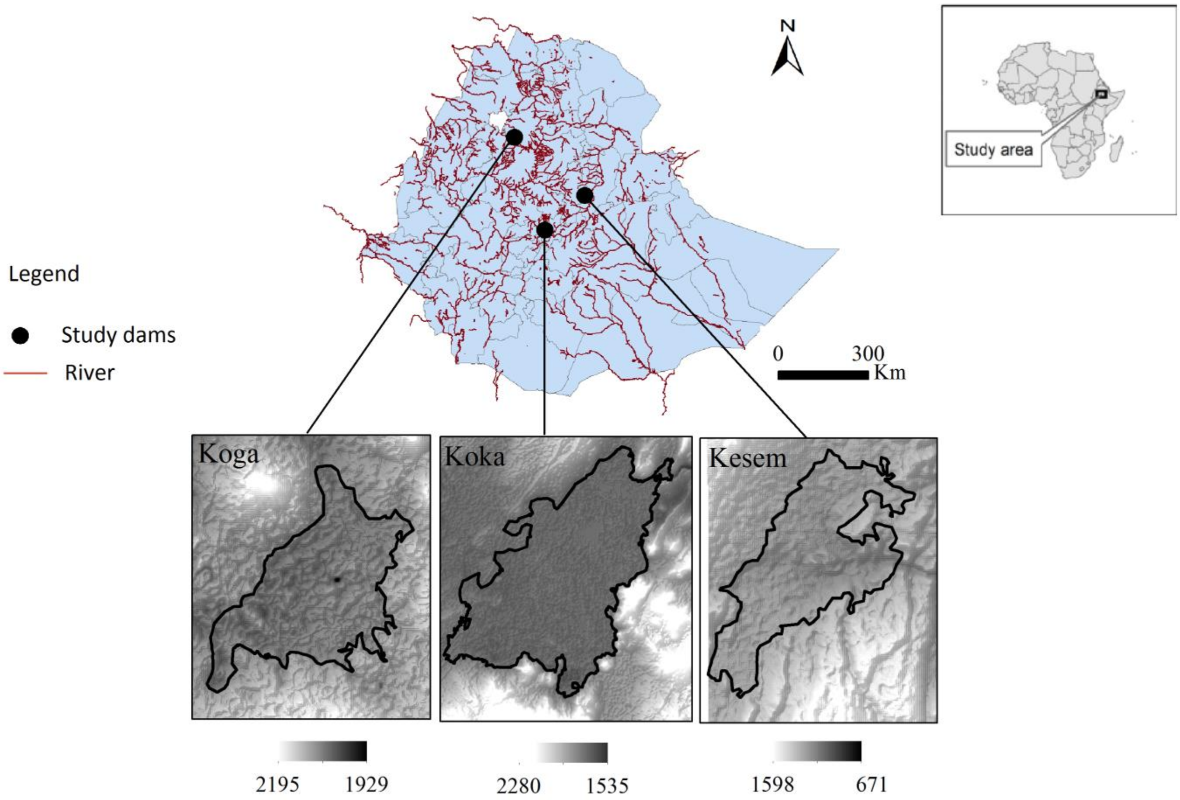

Figure 3.1. The study area in Ethiopia, showing the lowland Kesem Dam (975 m above sea level in the Rift Valley), the midland Koka Dam (1,551 m asl), the highland Koga Dam (1,980 m asl) and the dam and non-dam villages near each of these sites.

(Silver, 2007). Standard dips were taken uniformly around the edges and in the middle. All available larval habitats (whether new or old ones) were sampled in each survey. Larval anophelines samples were then counted and stored in vials by direct pipetting, killed by gentle heating and preserved in 70% alcohol for later taxonomic identification. Larval samples from each mosquito habitat were placed in separate vials. Preserved larval anophelines were identified to species by microscope in the laboratory using morphological characteristics (Verrone, 1962a).

Adult mosquitoes were collected using CDC light traps (Model 512; J W Hock Co, Atlanta, USA) (Plate 1.2). In each study village, a total of 10 light traps were deployed for overnight

Plate 3.1. Potential mosquito breeding habitats in the study area. A) shoreline puddle; B) manmade pool; C) irrigation canal; and D) rain pools.

mosquito collection from 1800 to 0630 hours. Five of the light traps were deployed inside human homesteads and the other five were installed outdoors. Houses for light trap mosquito collection were randomly selected, and sampling was conducted in the same houses throughout the period of the study. Each indoor light trap was placed in a bedroom, near a wall, with the bulb about 50 cm above a person sleeping under an untreated bed net (Yohannes *et al*. 2005). The outdoor light traps were installed on trees nearby open cattle enclosures where some of the villagers spent the evening. The same outdoor locations were used throughout the survey. The following morning, light traps were collected and emptied

Plate 3.2. CDC light trap installed for overnight adult mosquito collection.

into paper boxes containing a silica gel desiccant. Anophelines were kept at room temperature (20-22^{o}C) until processed.

Mosquito processing

The head-thorax portion of each dried female anopheline was processed to detect *P. falciparum* circumsporozoite antigens using Enzyme-linked Imminosorbent Assay (ELISA) (Wirtz *et al*. 1987). To determine mosquito blood meal sources (human vs bovine), the abdomen portion of blood-engorged female anophelines was tested using the direct ELISA technique (Beier *et al*. 1988).

Statistical analysis

Monthly malaria incidence was express as the number of microscope-confirmed malaria cases in a given month per 1000 population (Webb and Bain, 2010). Anopheline larval density was determined as the mean number of anopheline larvae per m^2 in each eco-epidemiological setting. Adult mosquito density was expressed as the mean number of adult mosquitoes per light trap per night, separated for indoor and outdoor traps within each eco-epidemiological region. Differences in malaria incidence, larval and adult mosquito densities were tested among the elevation settings (pairing reservoir and non-reservoir villages at each site) using one-way Analysis of Variance (ANOVA), followed by a post-hoc HSD Tukey test.

The sporozoite rate was expressed as the proportion of mosquitoes positive for *Plasmodium* sporozoites from the total number of mosquitoes of a species tested by ELISA. Human biting rates were derived from light trap catches by dividing adult anopheline density by a factor of 1.5, to match light trap catches with human landing catches, as determined by Yohannes *et al*. (2005). The human-biting rate was then multiplied by the sporozoite rate and the number of days in a year (365) to estimate the annual Entomological Inoculation Rate (EIR). A Chi-square test was used to analyse the difference in annual EIR among the dam sites and between the dam and non-dam villages. For each *Anopheles* species, the human blood index (HBI) was determined as the proportion of samples positive for human blood from the total samples tested by blood meal ELISA. All analyses were done using Microsoft Excel 2010 and SPSS statistical software version 22 (SPSS Inc, Chicago, IL, USA). The level of significance used for all tests was 0.05.

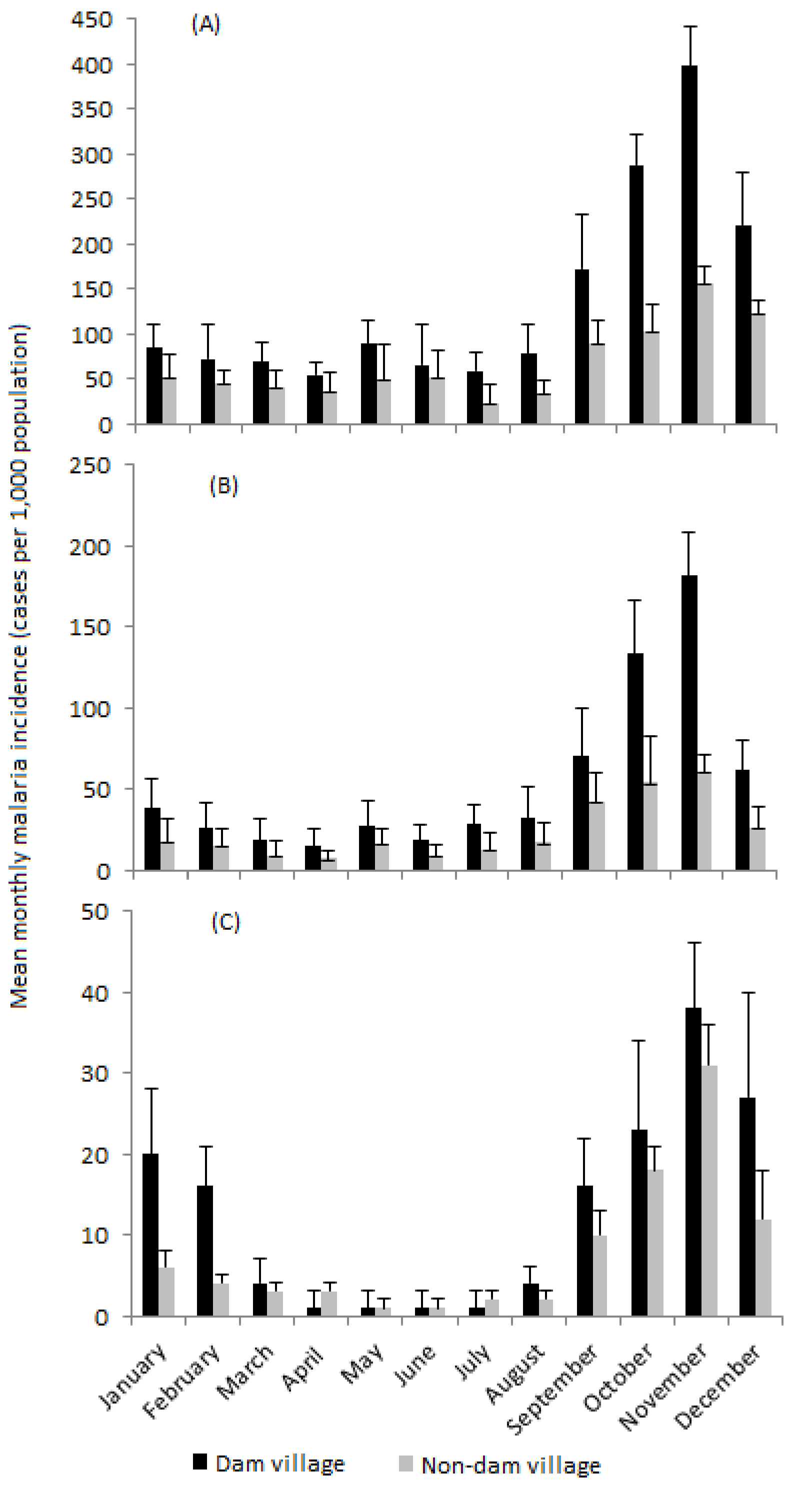

Figure 3.2. Mean monthly malaria incidence (cases per 1,000 population) in the (A) lowland, (B) midland and (C) highland dam and non-dam villages in Ethiopia, 2010 – 2014. Note different scales on the Y-axes. Error bars are the standard error.

3.4 Results

Malaria incidence across dams

The mean monthly malaria incidence was higher in the dam villages than the non-dam villages in all three study dam sites (df = 2; $P < 0.05$) (Figure 3.2). The mean monthly malaria incidence at the lowland dam village (mean = 137.4; 95% CI = 86.3–188.5) was two-fold higher than at the midland dam village (54.4; 95% CI = 38.2–70.6) and over ten-fold higher than at the highland dam village (12.7; 95% CI = 10.2–15.2). Significant difference in malaria incidence among the three dam sites was found (ANOVA: df = 2; F = 15.673; $P < 0.05$). The peak period of malaria incidence at all study sites was between September and November.

Mosquito breeding sites and larval density

A total of 1,838 potential mosquito larval sites were surveyed during the study period (Table 3.1). Of these, 1,556 (84.7%) were encountered in the dam villages while only 282 (15.3%) were in non-dam villages. Anopheline larvae were detected at 454 (29.2%) and 43 (15.2%) of these sites at dam and non-dam villages, respectively. At the lowland dam site, the number of positive anopheline breeding sites was over 12 times higher in the dam village (n = 271) than in the non-dam village (n = 22). At the midland dam site, the number of positive anopheline breeding sites was nearly nine times higher in the dam village (n = 115) than in the non-dam village (n = 16). Similarly, the number of anopheline breeding sites was six times higher in the dam village (n = 68) than in the non-dam village (n = 11).

Table 3.1. Summary of anopheline larval surveys conducted in the lowland (Kesem), midland (Koka) and highland (Koga) dam and non-dam villages in Ethiopia between October 2013 and July 2014.

	Village	No. potential anopheline breeding sites	No. positive anopheline breeding sites	Total area of positive anopheline breeding sites (m^2)	Total no. of anopheline larvae sampled	Mean larval density (no. larvae m^2)
Lowland dam	Dam village	712	271	353.4	793	10.8
	Non-dam village	148	22	56.3	398	3.7
Midland dam	Dam village	508	115	156.5	308	5.1
	Non-dam village	83	16	48.1	122	1.4
Highland dam	Dam village	336	68	84.2	165	0.5
	Non-dam village	51	11	18.5	74	0.2

A total of 594.1 and 122.9 m^2 of water body was found supporting anopheline mosquito breeding in the dam and non-dam villages, respectively (Table 3.1). The area of anopheline breeding sites was 2.3 and 4.2 times higher in the lowland dam village compared to the midland and highland dam villages, respectively. The surface area of anopheline larval sites in the dam villages was generally 10–13 times higher than at the non-dam villages.

A total of 1,860 anopheline larvae were sampled during the period of the study (Table 3.1). Of which, the majority (64%; n = 1,191) were sampled from the lowland dam site while the rest 24% (n = 430) and 13% (n = 239) were from the midland and highland dam sites, respectively. Anopheline larval abundance was generally higher in the dam villages than the non-dam villages at all study dam sites. The mean larval density (larvae per m^2) was significantly higher in the lowland dam village (mean = 10.8; 95% CI = 7.9–13.7; df = 2;

Table 3.2. Distribution of *Anopheles* species across different types of larval breeding habitats in the lowland (Kesem), midland (Koka) and highland (Koga) dam and non-dam villages in Ethiopia, between October 2013 and July 2014.

Site	Village	Type of breeding habitat	Number of positive mosquito breeding sites	Area of positive mosquito breeding sites sampled (m^2)	*An. arabiensis*	*An. pharoensis*	*An. coustani*	*An. funestus s.l.*	*An. cinereus*	Total no. *Anopheles* larvae found
Lowland dam	Dam village	Shoreline puddle	188	77.3	164	75	10	61	0	310
		Rain pools	12	15.2	26	6	5	0	2	39
		Manmade pools	8	4.9	8	0	9	0	1	18
		Irrigation canals	63	256	248	89	26	63	0	426
		Total	271	353.4	446	170	50	124	3	793
	Non-dam village	Shoreline puddle	-*	-	-	-	-	-	-	-
		Rain pools	18	49	177	110	51	0	0	338
		Manmade pools	4	7.3	31	17	12	0	0	60
		Irrigation canals	-	-	-	-	-	-	-	-
		Total	22	56.3	208	127	63	0	0	398
Midland dam	Dam village	Shoreline puddle	90	124.8	129	84	19	4	0	236
		Rain pools	10	17.2	18	2	3	0	0	23
		Manmade pools	15	14.5	37	3	8	0	1	49
		Irrigation canals	-	-	-	-	-	-	-	-
		Total	115	156.5	184	89	30	4	1	308
	Non-dam village	Shoreline puddle	-	-	-	-	-	-	-	-
		Rain pools	12	37.1	47	27	9	0	0	83
		Manmade pools	4	11	32	5	2	0	0	39
		Irrigation canals	-	-	-	-	-	-	-	-
		Total	16	48.1	79	32	11	0	0	122

Site	Village	Type of breeding habitat	Number of positive mosquito breeding sites	Area of positive mosquito breeding sites sampled (m^2)	*An. arabiensis*	*An. pharoensis*	*An. coustani*	*An. funestus s.l.*	*An. cinereus*	Total no. *Anoph-eles* larvae found
Highland dam	Dam village	Rain pools	17	15.8	28	0	10	0	0	38
		Manmade pools	2	1.5	4	0	2	0	0	6
		Irrigation canals	28	54.8	65	17	14	2	0	98
		Total	57	84.2	111	19	32	3	0	165
	Non-dam village	Shoreline puddle	-	-	-	-	-	-	-	-
		Rain pools	8	12.4	47	11	3	0	0	61
		Manmade pools	3	6.1	8	5	0	0	0	13
		Irrigation canals	0	0	0	0	0	0	0	0
		Total	11	18.5	55	16	3	0	0	74

* - indicates that this type of breeding habitat did not exist.

$X^2 = 7.413$; $P < 0.01$) than the midland (mean = 5.1; 95% CI = 4.0–6.2) and highland (mean = 0.5; 95% CI= 0.3–0.7) dam villages. Overall, controlling for elevation differences, the variation in mean larval density among the three dam sites was significant (df = 2; F= 8.453; $P < 0.01$). Five *Anopheles* species were identified as larvae across the study area: *An. arabiensis, An. pharoensis, An. funestus sensu lato* (s.l.), *An. coustani* and *An. cinereus* (Table 3.2). Among these, larvae of *An. arabiensis* was predominant in all study villages, accounting for 58% (n = 1,083) of total larval collections, followed by *An. pharoensis* (24%; n = 453), *An. coustani* (10%; n = 189) and *An. funestus s.l.* (7%; n = 131). Larvae of *An. funestus s.l.* were found only in the lowland dam village, predominantly in the shoreline puddles and irrigation canals. At the lowland site, *An. arabiensis* was predominately found in irrigation canals and shoreline puddles, contributing to 56% and 37% of the total larval collection from these habitats, respectively. Shoreline puddles accounted for 70.1% of this species' larvae in the midland dam village, while irrigation canals and shoreline puddles accounted for 49.5% and 12.6% in the highland dam village, respectively. Similarly, *An. pharoensis* larvae were primarily found within irrigation canals and/or shoreline puddles at each of the dam villages. In control villages, larval *An. arabiensis* was predominant, commonly found in rain pools and manmade pools. Overall, whilst anopheline larvae at the midland dam village were collected mainly from shoreline puddles, both shoreline puddles and irrigation canals were the dominant larval habitats at the lowland and highland dam villages.

Anopheline larval density peaked between October and November, dropping during the dry season, and building-up to the wet season in all study villages (Figure 3.3). However, overall mean larval density was generally higher in the dam villages than non-dam villages at all three study areas.

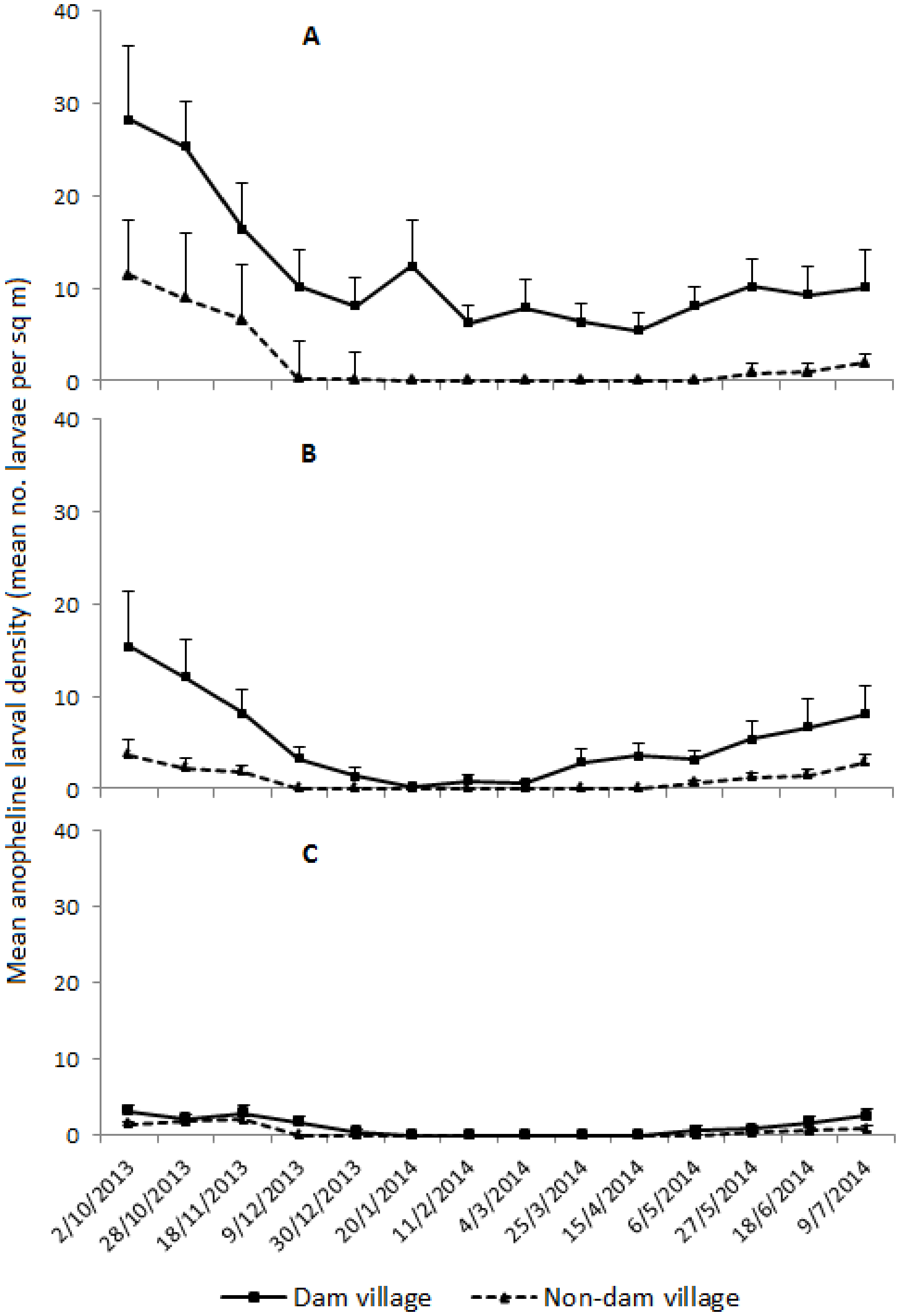

Figure 3.3. Mean anopheline larval density (no. larvae per sq m) in the (A) lowland, (B) midland and (C) highland dam and non-dam villages in Ethiopia, between October 2013 and July 2014.

Table 3.3. Number and mean density of adult anophelines and collected in the lowland (Kesem), midland (Koka) and highland (Koga) dam and non-dam villages in Ethiopia, between October 2013 and July 2014.

		An. arabiensis		*An. pharoensis*		*An. coustani*		*An. funestus s.l.*		*An. cinereus*		Total anophelines	
		No. (%)	Mean density*	No. (%)	Mean density	No. (%)	Mean density	No. (%)	Mean density	No. (%)	Mean density	No. (%)	Mean density
Lowland dam	Dam village	1423	15.81	782	8.69	99	1.10	449	4.99	2	0.02	2755	30.61
	Non-dam village	466	5.18	251	2.79	31	0.34	0	0.00	0	0.00	748	8.31
Midland dam	Dam village	541	6.01	421	4.68	103	1.14	36	0.40	8	0.09	1109	12.32
	Non-dam village	205	2.28	126	1.40	66	0.73	0	0.00	0	0.00	397	4.41
Highland dam	Dam village	64	0.71	16	0.18	12	0.13	0	0.00	0	0.00	92	1.02
	Non-dam village	23	0.26	0	0.00	16	0.18	0	0.00	0	0.00	39	0.43
Total	Dam village	2028	7.51	1219	4.51	214	0.79	485	1.80	10	0.04	3,956	14.65
	Non-dam village	694	2.57	377	1.40	113	0.42	-	-	0	0.00	1,184	4.39

* Mean density refers to the mean number of adult anophelines per trap per night during the sampling period.

Adult mosquito abundance

A total 5,140 adult anopheline mosquitoes were collected during the study period (Table 3.3). Of these, 68% (n = 3,503), 29% (n = 1,506) and 3% (n = 131) were from lowland, midland and highland dam sites, respectively. *Anopheles arabiensis* was the predominant species in all villages, accounting for 53% of the total adult anopheline collections. *Anopheles pharoensis* was the next most abundant species (31%), followed by *An. funestus s.l.* (9.4%), *An. coustani* (6.4%) and *An. cinereus* (0.2%). Similar to larvae, anopheline adult density peaked between October and November, fell during the dry season and increased again in June with the commencement of the wet season in all study villages (Figure 3.4). Overall mean adult anopheline density varied significantly across villages (df = 5; X^2 = 12.89; $P < 0.001$), and was generally higher at the dam villages than the non-dam villages in all three study areas. The highest density was recorded at the lowland dam village (mean = 10.8 anopheline per trap per night; 95% CI = 6.2 – 15.4) and the lowest at the highland non-dam village (mean = 0.2; 95% = CI 0.1 – 0.4). Similarly, the overall mean adult anopheline density at the lowland dam village was 2.2 times higher than at the midland dam village and 22 times higher than at the highland dam village.

Indoor and outdoor adult mosquito sampling detected *An. arabiensis* predominately indoors in all study villages (Table 3.4). The density of *An. pharoensis* was also higher indoors than outdoors at the lowland dam site, but not at the midland and highland dam sites. In contrast, *An. coustani* and *An. funestus s.l.* were predominately sampled from outdoor traps in all study sites.

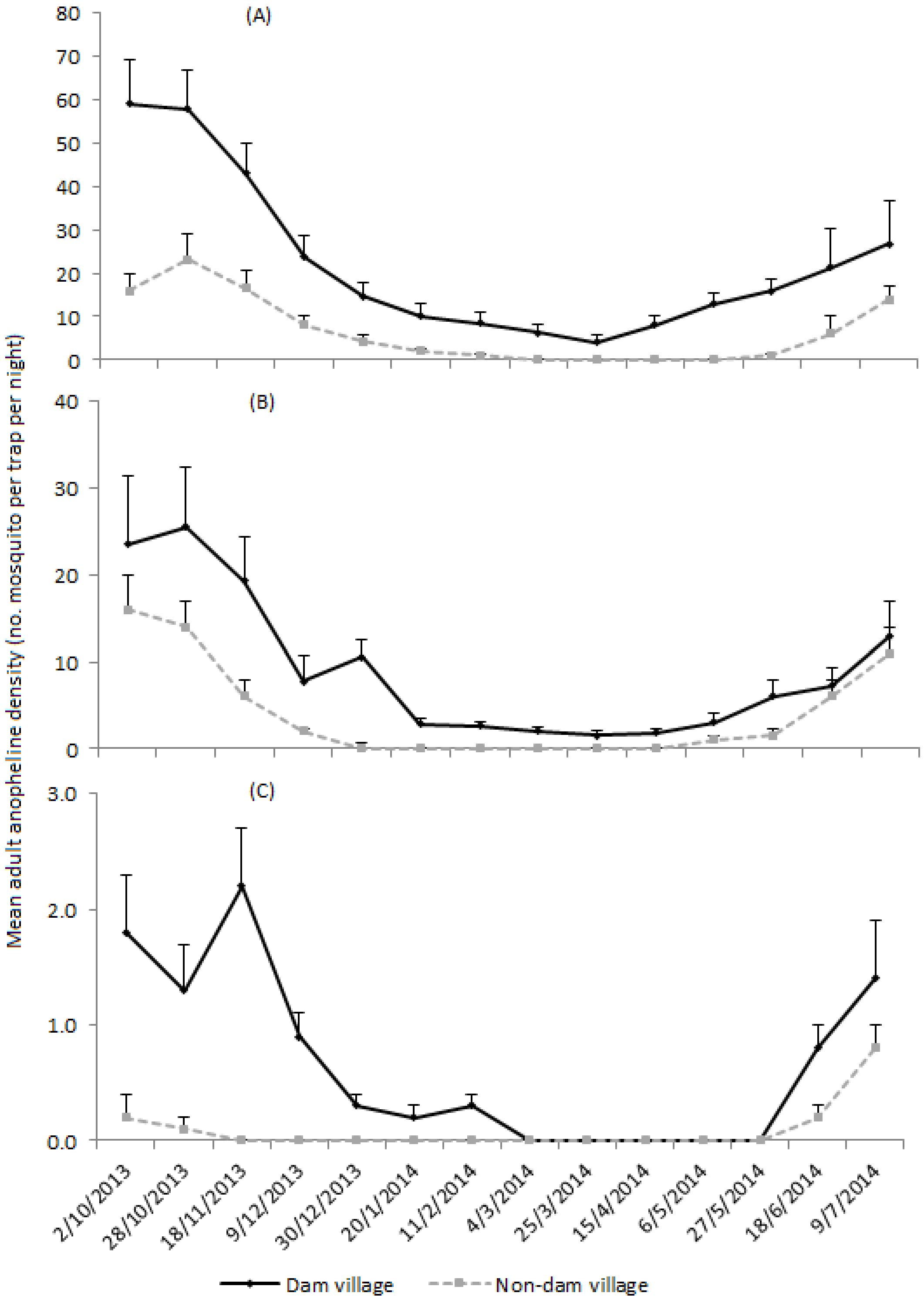

Figure 3.4. Mean adult anopheline density (number of mosquitos per trap per night) in the (A) lowland, (B) midland and (C) highland dam villages and non-dam villages in Ethiopia, between October 2013 and July 2014. Note different scales on the Y-axes. Error bars are the standard error.

Table 3.4. Indoor and outdoor mean adult anopheline density (no. mosquitoes per trap per night) in the lowland (Kesem), midland (Koka) and highland (Koga) dam and non-dam villages in Ethiopia, between October 2013 and July 2014.

Study site		*An. arabiensis*		*An. pharoensis*		*An. coustani*		*An. funestus s.l.*		*An. cinereus*		Total	
		Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Lowland	Dam village	20.87	10.76	10.13	7.24	0.71	1.49	0.91	9.07	0.00	0.04	32.62	28.60
	Non-dam village	6.89	3.47	4.18	1.40	0.22	0.47	0.00	0.00	0.00	0.00	11.29	5.33
Midland	Dam village	7.20	4.82	2.51	6.84	0.47	1.82	0.16	0.64	0.00	0.18	10.33	14.31
	Non-dam village	3.11	1.44	1.04	1.76	0.53	0.93	0.00	0.00	0.00	0.00	4.69	4.13
Highland	Dam village	1.13	0.29	0.13	0.22	0.07	0.20	0.00	0.00	0.00	0.00	1.33	0.71
	Non-dam village	0.31	0.20	0.00	0.00	0.09	0.27	0.00	0.00	0.00	0.00	0.40	0.47
Total	Dam village	29.20	15.87	12.78	14.31	1.24	3.51	1.07	9.71	0.00	0.22	44.29	43.62
	Non-dam village	10.31	5.11	5.22	3.16	0.84	1.67	0.00	0.00	0.00	0.00	16.38	9.93

Blood meal sources and Entomological Inoculation Rate

ELISA results indicated that *An. funestus s.l.* (Human Blood Index (HBI) = 87.2%) and *An. arabiensis* (HBI = 82.4%) were the most anthropophagic species in the lowland dam village (Table 3.5). Slightly lower HBI values (70.7–72.7%) were recorded for *An. arabiensis* in theother dam villages. In contrast, the proportion of blood meals of *An. arabiensis* originating from bovine sources appeared to increase from lowland (22%) to midland (34%) and highland (36%) dam sites. *An. pharoensis* preferred human blood meals over bovine sources while *An. coustani* preferred bovine over human blood in all study villages.

A total of 4,848 female anophelines were tested for *P. falciparum* sporozoite infections (Table 3.6). The highest sporozoite infection rate was detected in the lowland dam village where 4.5% (20/449), 4.1% (59/1423) and 2.3% (18/782) of *An. funestus s.l.*, *An. arabiensis* and *An. pharoensis*, respectively, were found to be positive. In the lowland non-dam village, 1.7% (8/466) of *An. arabiensis* and 1.2% (3/251) of *An. pharoensis* tested positive for *P. falciparum* sporozoites. In the midland dam village, the sporozoite rate of *An. arabiensis* and *An. pharoensis* was 2% (11/541) and 1.4% (6/421), respectively, while only a single female *An. arabiensis* (0.5%, 1/205) tested positive for *P. falciparum* sporozoite in the midland non-dam village. All sporozoite-infected anophelines were collected between September and November during the main transmission season. None of the samples from the highland dam villages tested positive for *P. falciparum* sporozoites.

The annual Entomological Inoculation Rate (EIR) for *An. arabiensis, An. funestus s.l.* and *An. pharoensis* at the lowland dam village was found to be 157.7, 54.6 and 48.6 infective bites per person per year (ib/p/y), respectively (Table 3.6). In contrast, the annual EIR of *An.*

Table 3.5. Blood meal sources of female anophelines in the lowland (Kesem), midland (Koka) and highland (Koga) dam and non-dam villages in Ethiopia, between October 2013 and July 2014.

Site	Village	*An. arabiensis*	*An. pharoensis*	*An. funestus s.l.*	*An. coustani*
Lowland dam	**Dam village**				
	No. tested	924	508	311	47
	Positive for human blood (%)	761 (82.4)	348 (68.5)	272 (87.5)	18 (38.3)
	Positive for bovine blood (%)	203 (22.0)	209 (41.1)	40 (12.9)	32 (68.1)
	Unidentified (%)	9 (1.0)	5 (1.0)	2 (0.6)	3 (6.4)
	Non-dam village				
	No. tested	278	199	0	20
	Positive for human blood (%)	202 (72.7)	122 (61.3)	0	6 (30.0)
	Positive for bovine blood (%)	88 (31.7)	72 (36.2)	0	15 (75.0)
	Unidentified (%)	4 (1.4)	7 (3.5)	0	1 (5.0)
Midland dam	**Dam village**				
	No. tested	392	314	18	73
	Positive for human blood (%)	277 (70.7)	201 (64.0)	11 (61.1)	28 (38.4)
	Positive for bovine blood (%)	135 (34.4)	123 (39.2)	7 (38.9)	54 (74.0)
	Unidentified (%)	14 (3.6)	17 (5.4)	0 (0)	3 (4.1)
	Non-dam village				
	No. tested	168	91	0	44
	Positive for human blood (%)	118 (70.2)	61 (67.0)	0	18 (40.9)
	Positive for bovine blood (%)	62 (36.9)	32 (35.2)	0	34 (77.3)
	Unidentified (%)	7 (4.2)	3 (3.3)	0	2 (4.5)
Highland dam	**Dam village**				
	No. tested	45	9	0	5
	Positive for human blood (%)	32 (71.1)	6 (66.7)	0	2 (40.0)
	Positive for bovine blood (%)	16 (35.6)	4 (44.4)	0	3 (60.0)
	Unidentified (%)	0 (0.0)	1 (11.1)	0	0 (0.0)
	Non-dam village			0	
	No. tested	11	0	0	16
	Positive for human blood (%)	8 (72.7)	0	0	7 (43.8)
	Positive for bovine blood (%)	4 (36.4)	0	0	9 (56.3)
	Unidentified (%)	1 (9.1)	0	0	1 (6.3)

Table 3.6. *Plasmodium falciparum* sporozoite rate and annual Entomological Inoculation Rate (EIR) of *Anopheles* mosquitoes in the lowland (Kesem), midland (Koka) and highland (Koga) dam and non-dam villages in Ethiopia, between October 2013 and July 2014.

Site	Village	*An. arabiensis*	*An. pharoensis*	*An. funestus s.l.*	*An. coustani*
Lowland dam	**Dam village**				
	No. tested	1423	782	449	99
	No. positive (%)	59 (4.1)	18 (2.3)	20 (4.5)	0 (0.0)
	Annual EIR	157.7	48.6	54.6	0
	Non-dam village				
	No. tested	466	251	36	103
	No. positive (%)	8 (1.7)	3 (1.2)	0 (0.0)	0 (0.0)
	Annual EIR	21.4	15.9	0	0
Midland dam	**Dam village**				
	No. tested	541	421	36	103
	No. positive (%)	11 (2.0)	6 (1.4)	0 (0.0)	0 (0.0)
	Annual EIR	29.2	15.9	0	0
	Non-dam village				
	No. tested	205	126	-*	66
	No. positive (%)	1 (0.5)	0 (0.0)	-	0 (0.0)
	Annual EIR	1.7	0	-	0
Highland dam	**Dam village**				
	No. tested	64	16	-	12
	No. positive (%)	0 (0.0)	0 (0.0)	-	0 (0.0)
	Annual EIR	0	0		0
	Non-dam village				
	No. tested	23	0	0	16
	No. positive	0 (0.0)	-	-	0 (0.0)
	Annual EIR	0	0	0	0

EIR refers to the number of infective bites per person per year.

- (minus) refers to absence of the species in that area.

arabiensis and *An. pharoensis* at the lowland non-dam village was 21.4 and 8.1 ib/p/y. At the midland dam village, the annual EIR was found to be 29.2 and 15.9 ib/p/y by *An. arabiensis* and *An. pharoensis*, respectively, while the annual EIR in the midland non-dam village was 1.7 ib/p/y by *An. arabiensis*. Overall, the data revealed that dams resulted in 7.4 and 6.0-fold increases in EIR in the lowland and midland areas, respectively, compared to the non-dam villages in the same settings.

3.5 Discussion

The present study found that dams intensify malaria (i.e. a greater abundance of mosquitoes with a propensity to bite humans, together with higher infection rates and EIR) in the lowland and midland eco-epidemiological settings of Ethiopia. Reservoir shoreline puddles and irrigation canals were the major malaria vector breeding habitats, contributing 70-80% of the anopheline larval breeding sites. *Anopheles arabiensis* and *An. pharoensis* were the major malaria vectors, occurring in higher abundance at lowland and midland dam villages than at the highland dam villages.

Anopheles arabiensis and *An. pharoensis* were primarily breeding in shoreline puddles and irrigation canals in the lowland, midland and highland dam villages, although their abundance differed among villages. The abundance of these vector species peaked between October and November when the dams were full and their inundated shorelines were closest to villages. A previous study around the Koka Dam indicated that while *An. arabiensis* prefers shallow sunlit shoreline puddles, *An. pharoensis* breeds in semi-permanent and partly covered large water pools (Kibret *et al*. 2012). A preference for similar breeding habitats was documented for these species in the neighboring Zeway area (Kibret *et al*. 2010), around microdams in northern Ethiopia (Yohannes *et al*. 2005) and elsewhere in Ethiopia (Woube, 1997; Yewhalaw *et al*. 2009).

A number of local factors such as vegetation cover and cattle trampling on the shoreline (creating hoof prints ideal for mosquito breeding) might also affect the productivity of larval habitats around the shoreline of the reservoirs (personal observation). Most of the larval anopheline positive shoreline puddles were isolated from the main reservoir. This apparently reduces predation risk by fish and other vertebrates. Local factors are thus important in determining the distribution of larval habitats around a water impoundment.

Larval and adult vector densities decreased from the lowland to midland to highland dam villages. Climate variables such as temperature are the major factors that determine rates of mosquito breeding, adult longevity and malaria parasite development at different elevation settings (Zhou *et al*. 2004). Dams in lowland areas create ideal breeding sites for mosquitoes where rainfall is the limiting factor underpinning the availability of mosquito breeding habitats. Moreover, irrigation activities increase vector breeding habitats by creating waterlogged sites in the irrigated fields as well as irrigation canals. A previous study in central Ethiopia where irrigation is commonly practiced indicated that poor irrigation water management led to increased mosquito breeding habitats with a high risk of malaria transmission (Kibret *et al*. 2014). Moreover, people migrate from lowland malarious areas to less malarious irrigation sites looking for daily employment, particularly during the harvest season (December - February) (McCann, 2015). This could have been the reason for a slight increase in malaria cases at the highland dam observed during this period (Figure 3.2). A number of studies in sub-Saharan Africa have also shown the link between irrigation and malaria, and the need for targeted planning and implementation of mosquito control measures in order to reduce mosquito breeding (Robert *et al*. 1992; Ijumba and Lindasay, 2001; Dolo *et al*. 2004; Mutero *et al*. 2004; Muturi *et al*. 2006; Mwangangi *et al*. 2010). Similarly, the present study identified that the lowland irrigation dam had increased mosquito vector abundance and malaria transmission.

A higher vector density along with a high HBI and EIR in the lowland dam village revealed the serious potential negative impact of dams on malaria in lowland Ethiopia. Moreover, the presence of three vector species (*An. arabiensis, An. pharoensis* and *An. funestus s.l.*) with a combined annual EIR of 261 per person per year around the Kesem Dam highlights the pressing need to devise vector control strategies around lowland dams. Nevertheless, the annual EIR of *An. arabiensis* (157.7) and *An. funestus s.l.* (54.6) in the lowland dam village was lower than those reported (314 and 88, respectively) from the Lower Moshi irrigation area of northern Tanzania for the same species (Ijumba *et al*. 2002). The annual EIR in the midland dam village was comparable to previously documented EIR in the same study area (Kibret *et al*. 2012), and in western (Woube, 1997) and southwestern Ethiopia (Massebo *et al*. 2013). In fact, the EIRs results in the present study might have underestimated the actual EIR since no data for September, which lies in the main transmission season, were obtained. The higher EIR and malaria incidence in the lowland dam village is likely to have been driven by the greater climatic suitability of lowland areas for malaria transmission. Moreover, due to high humidity during the day in the lowland dam area, people often prefer to work on their farms during the early hours of the night (personal observation), which increases the chance of mosquito bites. Additional malaria intervention measures such as personal protection are thus required, particularly for outdoor-dominant *An. funestus s.l.* in the lowland dam village and *An. pharoensis* in the midland dam village since the current malaria intervention strategies entirely target indoor mosquitoes.

The present study has documented for the first time in four decades the role of *An. funestus s.l.* in malaria transmission in the lowland Ethiopia. This species disappeared from several wetland areas of Ethiopia in the 1970s due to land use changes (Woube, 1997). The presence of *P. falciparum* sporozoite infected *An. funestus* along with a high HBI confirms the role of this species in malaria transmission in the lowland dam area. The reported high sporozoite rate of *An. funestus s.l.* (4.5%) in the lowland dam village was comparable to that reported from Uganda (5.3%) (Mulamba *et al*. 2014), but lower than that documented in Eritrea (9.5%) (Shililu *et al*. 1998). Krafsur (1971) reported a lower sporozoite rate (1.1%) for this species in the wetlands of the Gambella Region in western Ethiopia. Erlanger *et al*. (2005) reported that the density of *An. funestus s.l.* was 25-fold higher in the irrigated sites as compared to non-irrigated sites in the sub-Saharan Africa. The present study documented the link between *An. funestus s.l.* and irrigation dams in the lowland areas of Ethiopia which otherwise would not have been identified.

Malaria incidence and vector density peaked in all study villages between October and November immediately after the main wet season. The impact of the dams was to intensify the malaria transmission instead of extending the period of transmission. Similar findings were documented in the Gilgel-Gibe Dam in south Ethiopia (Yewhalaw *et al*. 2009), the Bemendjin Dam of Cameroon (Atangana *et al*. 1979), the Kamburu Dam of Kenya (Oomen, 1981), the Mthera Dam of Tanzania (Njunwa *et al*. 2000), and the Usuma Reservoir of Nigeria (Ujoh *et al*. 2012). A recent review work reported that dams intensify malaria transmission in seasonally unstable areas since they provide breeding habitats for mosquito vectors (Kibret *et al*. 2015a) Reservoir shoreline puddles and irrigation canals provide suitable breeding habitats for malaria vector mosquitoes around dam sites. A previous study around Koka Dam indicated that lower water level drawdown rates between September and November led to increased formation of reservoir shoreline puddles (Kibret *et al*. 2012). Reservoir water management is thus crucial to minimize the presence and persistence of reservoir shoreline puddles. In addition, irrigation canals do not operate during the wet season as farmers use rain-fed agriculture during this period, leaving irrigation canals waterlogged from rainfall and thus providing ideal breeding grounds for malaria vector mosquitoes (personal observation). Draining irrigation canals and reducing water logging in agricultural fields were previously shown to be effective in reducing larval breeding habitats around microdams in northern Ethiopia (Yohannes *et al*. 2005).

In conclusion, the link between dams and malaria must be considered while planning, designing and operating large dams in sub-Saharan Africa where malaria is a primary public health challenge. The present study confirmed that dams in semi-arid lowland and midland areas intensify malaria transmission due to mosquito vector breeding in associated shoreline and irrigation habitats. However, such an effect was not detected at the highland dam area. Proper management of dams and associated shallow shoreline and canal habitats is thus essential to reduce malaria vector breeding around these economically important water infrastructures. Such environmental management techniques along with conventional vector interventions should be targeted to reduce malaria transmission around these critical infrastructures.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Chapter 4

Environmental and meteorological factors linked to malaria transmission around large dams at three ecological settings in Ethiopia

Kibret S, Wilson GG, Ryder D, Tekie H, Petros B. Environmental and meteorological factors linked to malaria transmission around large dams at three ecological settings in Ethiopia.

4.1 Abstract

Background: A growing body of evidence suggests that dams intensify malaria transmission in sub-Saharan Africa. However, the site characteristics underpinning patterns in malaria transmission around dams are poorly understood. This study investigated local-scale environmental and meteorological variables linked to malaria transmission around three large dams in Ethiopia.

Methods: Monthly malaria incidence data (2010-2014) were collected from health centers around three dams located at lowland, midland and highland elevations in Ethiopia. Environmental (elevation, distance from the reservoir shoreline, Normalized Difference Vegetation Index (NDVI), monthly reservoir water level and monthly changes in water level) and meteorological (precipitation, and minimum and maximum temperature) data were analyzed to determine their relationship with monthly malaria transmission at each of the study sites using correlation and stepwise multiple regression analysis.

Results: Village distance to reservoir shoreline (lagged by 1 and 2 months) and monthly change in water level (lagged by 1 month) were significantly correlated with malaria incidence at all the three dams, while NDVI (lagged by 1 and 2 months) and monthly reservoir water-level (lagged by 2 months) were found to have a significant influence only at the lowland and midland dams. Precipitation (lagged by 1 and 2 months) was also significantly associated with malaria incidence, but only at the lowland dam while minimum and maximum temperatures (lagged by 1 and 2 months) were important factors only at the highland dam. Village distance from reservoir shoreline (lagged by 1 month), monthly average change in reservoir water level (lagged by 2 months) and monthly total precipitation (lagged by 1 month) were the most important variables that explained 81.3% of the monthly variability in malaria incidence at the lowland dam. At the midland dam, village distance from reservoir shoreline (lagged by 1 month), monthly reservoir water level (lagged by 2 months) and monthly total precipitation (lagged by 2 months) explained 71.1% of the monthly malaria incidence. At the highland dam, village distance from reservoir shoreline (lagged by 1 month), monthly mean minimum temperature (lagged by 2 months) and monthly change in reservoir water level (lagged by 2 months) explained 76.5% variability in monthly malaria incidence.

Conclusion: The findings of this study confirmed that reservoir associated factors (distance from reservoir shoreline, monthly average reservoir water level and monthly water level change) were important predictors of increased malaria incidence in villages around Ethiopian dams in all elevation settings. Reservoir water level management should be considered as an additional malaria vector control tool to help reduce malaria transmission rates.

4.2 Introduction

Malaria is a serious public health challenge in sub-Saharan Africa, where over 90% of the global burden (214 million cases) occurs (WHO, 2015). A number of environmental, climatic, seasonal and ecological factors determine the occurrence and intensity of malaria transmission. For instance, while rainfall limits the availability of breeding habitats for mosquito vectors, temperature determines the length of mosquito larvae development and the rate of growth of the malaria parasites inside the vector (Patz and Olson, 2006; Stern *et al*. 2011). In addition, environmental modifications such as the construction of dams and irrigation schemes also affect the type and distribution of mosquito breeding habitats (Jobin, 1999; Keiser *et al*. 2005).

In Africa, dams have been demonstrated to enhance malaria transmission in areas of unstable transmission (Keiser *et al*. 2005; Kibret *et al*. 2015a). Increased malaria incidence following dam construction was reported around several African dams (Atangana *et al*. 1979; Oomen, 1981; Freeman, 1994; Lautze *et al*. 2007; Mba and Aboh, 2007; Kibret *et al*. 2012; Yewhalaw *et al*. 2013). Overall, dams have been shown to contribute to over 1 million malaria cases annually in sub-Saharan Africa (Kibret *et al*. 2015b). However, the extent to which various environmental and climatic factors may have contributed to enhanced rates of malaria transmission around these sites remains poorly understood.

Climatic variables such as precipitation and air temperature are important determinants of the spatial distribution and relative abundance of malaria vector species in Africa (Lindblade *et al*. 2000). For instance, in Africa, *Anopheles gambiae* is usually the predominant species in high rainfall environments, while *Anopheles arabiensis* is more common in arid areas (Coetzee, 2000; Sinka *et al*. 2010). However, climatic conditions are also inter-related with elevation. For example, temperature decreases as elevation increases, and consequently the abundance and species composition of malaria vectors may change significantly with elevation (e.g. Lindblade *et al*. 2000).

In Ethiopia, local increases in malaria rates have been blamed on the establishment of new dams (Ghebreyesus *et al*. 1999; Lautze *et al*. 2007; Kibret *et al*. 2012; Yewhalaw *et al*. 2013). A new era of dam construction currently underway in Ethiopia (Ministry of Water Resources, 2012) has also elevated concerns for the public health impact of these infrastructures. Yet, dams are important contributors to Ethiopia’s economic development and food security. However, a poor understanding of their effects on malaria rates in different ecological settings represents a critical barrier to the sustainability of water storage infrastructures.

Establishing how different environmental and climatic factors affect rates of malaria transmission is required to develop appropriate disease control tools. A recent review suggested that the relationship between dams and malaria incidence varies across ecological settings (Kibret *et al*. 2015a). However, the study did not investigate how environmental (other than the presence of dams) and climatic factors vary across these ecological settings and, in turn, affect rates of malaria incidence around dams. The present study aims to investigate relationships among a number of environmental and climatic factors associated with malaria transmission around Ethiopian dams in three ecological settings – highland, midland and lowland.

4.3 Methods

The present study was conducted around three dams in Ethiopia (the Kesem Dam (975 m asl); referred as lowland dam), Koka Dam (1551 m asl; referred as midland dam) and Koga

Dam (1980 m asl; referred as highland dam) (Figure 4.1). The details of the characteristic of the study area are presented in Chapter 3. At each dam, stratified random sampling was used to select six villages at similar disatances from the reservoir shoreline (2 were <1 km, one each in 1-2 km, 2-3 km and 3-4 km and 4-5 km) for this study. Time series malaria case data as well as environmental and meteorological data were analyzed to determine factors linked to malaria transmission at each dam setting.

Retrospective malaria case data

Five years (January 2010 to December 2014) of weekly malaria data were collected from the health center at each of the dam sites. At each health center, each febrile case was tested by a trained laboratory technician for malaria using microscopic blood screening and distinguished between *P. falciparum* and *P. vivax*. Test results were recorded in the laboratory registry, along with data of outpatient name, age, gender, and residency. The data showed malaria case incidence. These data were de-identified and exported to Microsoft Excel and SPSS for analysis.

Environmental data

The environmental data used for this study comprised village elevation, village distance from reservoir shoreline, Normalized Difference Vegetation Index (NDVI) and reservoir water level. Village elevation was recorded using a handheld Geographical Positioning System receiver (GPSMAP 60CSx, Garmin International Inc., USA*)*. For each study village, data on monthly distance from reservoir shoreline were acquired from the European Space Agency image repository. These images had a resolution of 150 x 150 m, were geo-referenced, and taken in the first week of each month between January 2010 and December 2014. These were

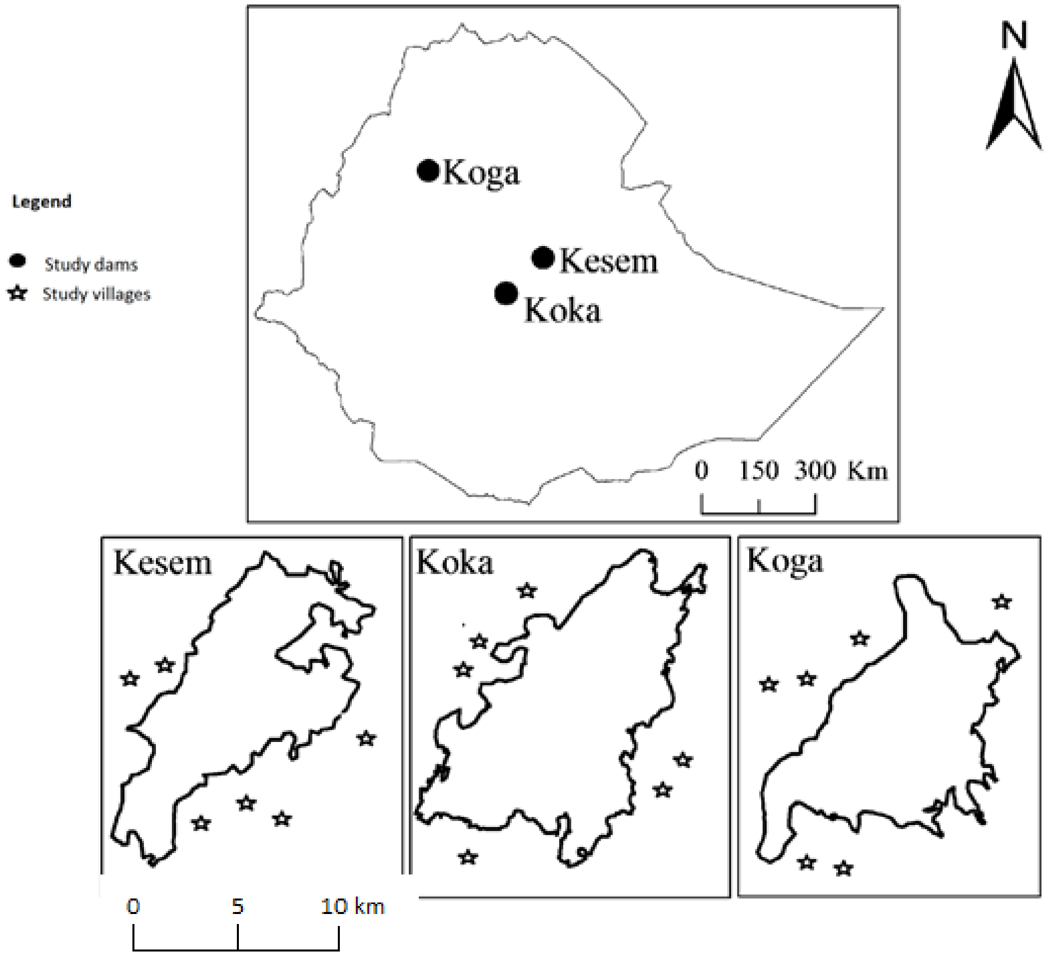

Figure 4.1. Map of the study area and location of study villages in relation to the reservoir shorelines.

then imported to ArcGIS 9.2 to estimate the distance between the center of each study village and the nearest reservoir shoreline for each month of the study period.

Monthly NDVI data for the study villages were acquired from the U.S. National Oceanic and Atmospheric Administration (NOAA) that documents data of the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on-board the Terra and Aqua Satellites. These satellites provide a vegetation survey at a 250 m spatial resolution every 16 days (United States Geological Survey, 2015). The MODIS NDVI products are computed from atmospherically–corrected, bi-directional surface reflectances that have been masked for water, clouds, heavy aerosols, and cloud shadows. NDVI is a measure of vegetation condition – used here as a proxy for mosquito habitat availability (Hay *et al*. 1998). NDVI values vary between +1.00 and −1.00; the higher the NDVI value, the denser the green vegetation.

Daily reservoir water level data were obtained for each dam from the Ethiopian Electricity and Power Corporation, and the Ministry of Water Resources for the duration of the study period (January 2010 and December 2014). These were then exported to Microsoft Excel and SPSS for analysis. The data were aggregated to monthly averages and monthly changes in water level (i.e calculated by subtracting the amount of the reservoir water level at the end of a month from its figure at the beginning of the month; negative values indicate receding water level while positive values indicate increasing water levels) for each of the three dams. The objective of including monthly changes in water level was to determine how the magnitude of change in water level correlates with malaria incidence as it directly affects the nature of the shoreline for mosquito breeding.

Meteorological data

Five years (January 2010 to December 2014) of daily meteorological data including total rainfall (mm), and mean daily minimum and maximum temperature (^{o}C), were obtained from three meteorological stations at each of the three study dam sites. Any missing values were replaced with daily average data from the closest neighboring station. The data were then aggregated to monthly averages and exported to Microsoft Excel and SPSS for analysis.

Statistical analysis

To satisfy the assumptions of individual statistical analyses, we first tested for normality in the distribution of monthly malaria incidence, environmental and meteorological data sets using SPSS. Temperatures (both minimum and maximum), reservoir water level (and change in water level) and NDVI values were normally distributed while malaria incidence and precipitation data were log-transformed.

For each village, malaria incidence was calculated as the number of cases per 1,000 population (Webb and Bain, 2010). A one-way Analysis of Variance (ANOVA), followed by Tukey's test, was used to test for the differences in malaria incidence between the three dam sites.

Average monthly meteorological data (precipitation, minimum and maximum air temperature) were calculated and lagged by one and two months to allow time for mosquitoes and malaria parasites to complete their lifecycle prior to the expression of any malaria incidence. Similarly, monthly NDVI data were also lagged by one and two months to allow time for mosquito development. The same number of lags was used previously elsewhere in Africa (Reiner *et al*. 2015; Chirebvu *et al*. 2016). Monthly relative humidity data were not included in the analysis due to there being too many missing values for the duration of the study period.

To determine any correlation between meteorological/environmental variables and malaria incidence at each dam site, univariate associations were first examined between malaria incidence and potential explanatory factors (i.e. environmental and meteorological variables) by regressing a single factor against malaria incidences for each dam site. Since there might be cross-correlation between independent variables over time, cross-correlation analyses were conducted. When the correlation coefficient for the association between the independent variables was greater than 0.5, these variables were analysed in Autoregressive Integrated Moving Averages (ARIMA) to avoid multicollinearity. After the effect of any auto-correlation had been removed by the ARIMA procedure, stepwise forward multiple regression analyses were used to identify the meteorological/environmental factors that best explain malaria incidence at each dam site. Only those variables with a significant correlation ($P < 0.05$) with malaria incidence were added in the multiple regression models. In the case of lagged variables, only the data series with the highest correlation were included in these analyses. All analyses were performed using Microsoft Excel and SPSS Version 21 software.

4.4 Results

Spatial and temporal variation in malaria incidence

Mean monthly malaria incidence was 1.7- and 5.6-time higher at the lowland (mean = 96.3; 95% CI = 81.5-111.0; ANOVA: F = 54.7; $P < 0.001$) than the midland (mean = 56.7; 95% CI = 45.9-67.4) and highland (mean = 17.2; 95% CI = 13.9-20.4) dams, respectively (Table 4.1). The temporal variation in malaria incidence at the three dams showed a seasonal peak between September and November at all study dams (Figure 4.2). Differences in malaria incidence between villages and years at each dam site, however, were not statistically significant (ANOVA, $P > 0.05$). Malaria incidence was generally strongly correlated with elevation ($r^2 = 0.97$; $P < 0.05$): malaria incidence decreased as elevation increased (Figure 4.3).

Table 4.1. Summary of monthly mean malaria incidence at the three study dams in Ethiopia, 2010-2014

Dam location	Mean malaria incidence	95% CI	Odds ratio	*P**
Lowland	96.3	81.5-111.0	1	-
Midland	56.7	45.9-67.4	1.7	<0.01
Highland	17.2	13.9-20.4	5.6	<0.01

* ANOVA test. Tthe difference in malaria incidence between midland and highland dam was also significant (Tukey test, *P* < 0.01).

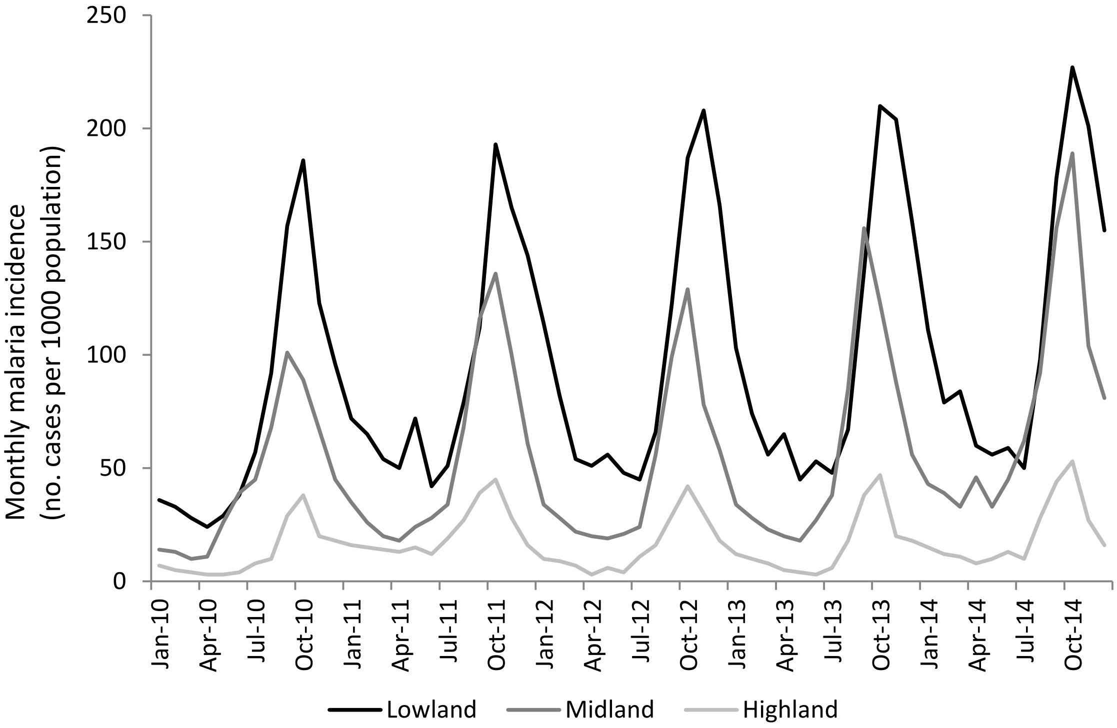

Figure 4.2. Temporal variation in monthly malaria incidence in reservoir communities at the lowland, midland and highland dams in Ethiopia, 2010-2014.

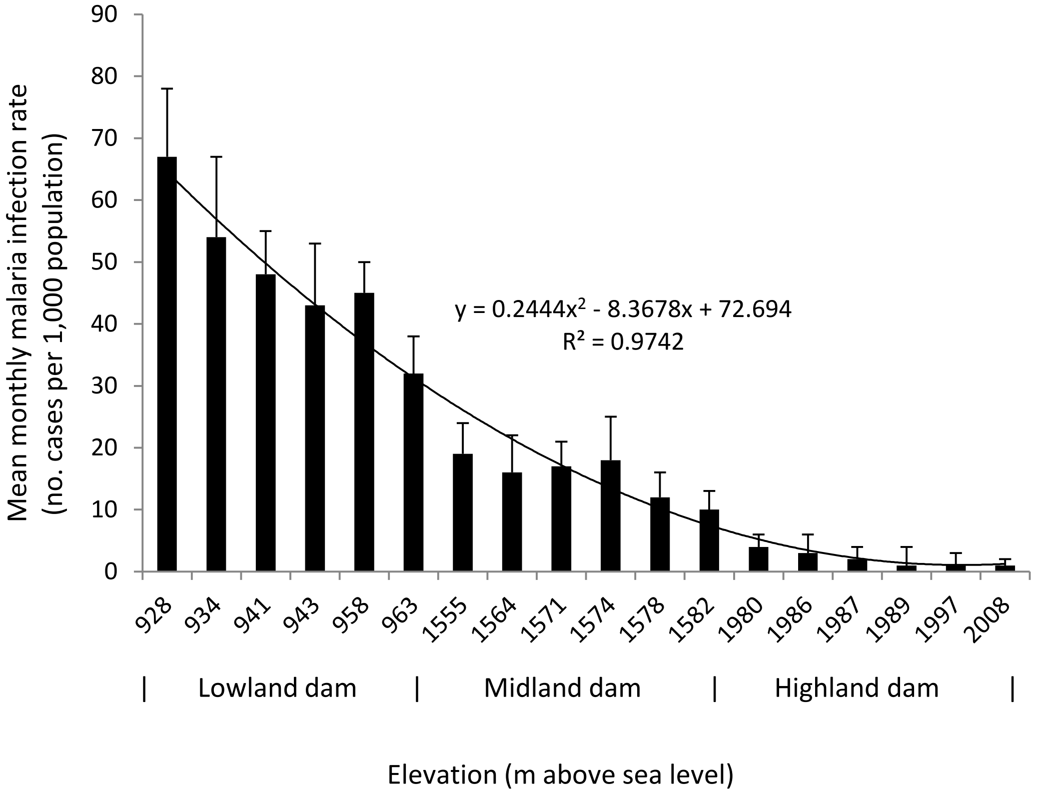

Figure 4.3. Relationship between malaria incidence and village elevation at the lowland, midland and highland dams in Ethiopia.

Impact of environmental factors on malaria incidence

Village proximity to a reservoir shoreline was negatively correlated with malaria incidence inall the three dam sites: the shorter a village's distance to the shoreline, the higher the malaria incidence in the following month (Figure 4.4). Indeed, approximately 69% (annual average from 51-86%) of annual malaria cases occurred when a village's distance was less than 2 km from the shoreline. This trend was consistent across the three dam sites.

Malaria incidence peaked following the months of high reservoir water level (Figure 4.5). There was generally a 2-month lag-time between peak water level and malaria incidence,

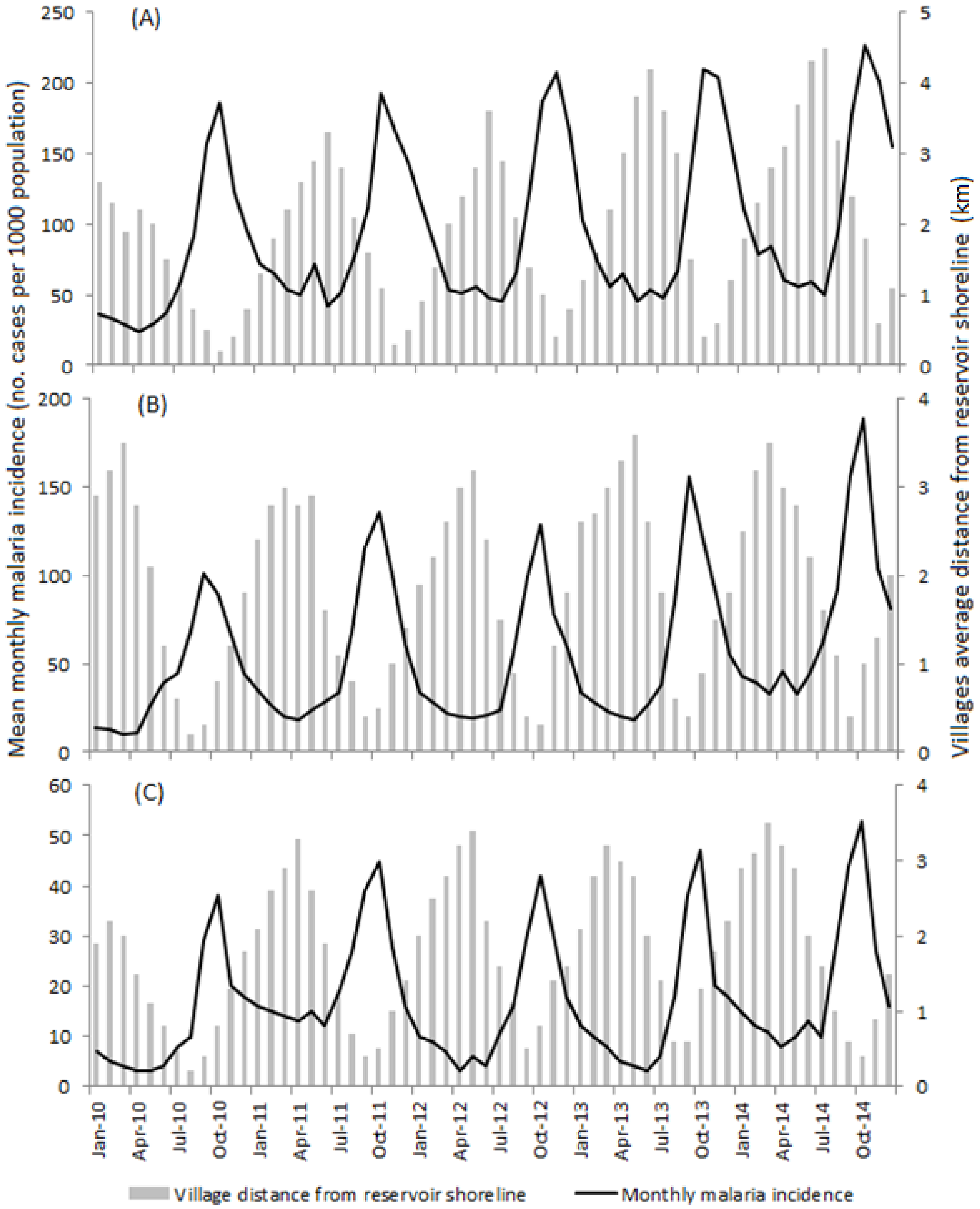

Figure 4.4. Temporal variation in monthly malaria incidence and villages distance from reservoir shoreline at (A) lowland, (B) midland and (C) highland dams in Ethiopia. Please note, Y-axis scales vary between the three plots.

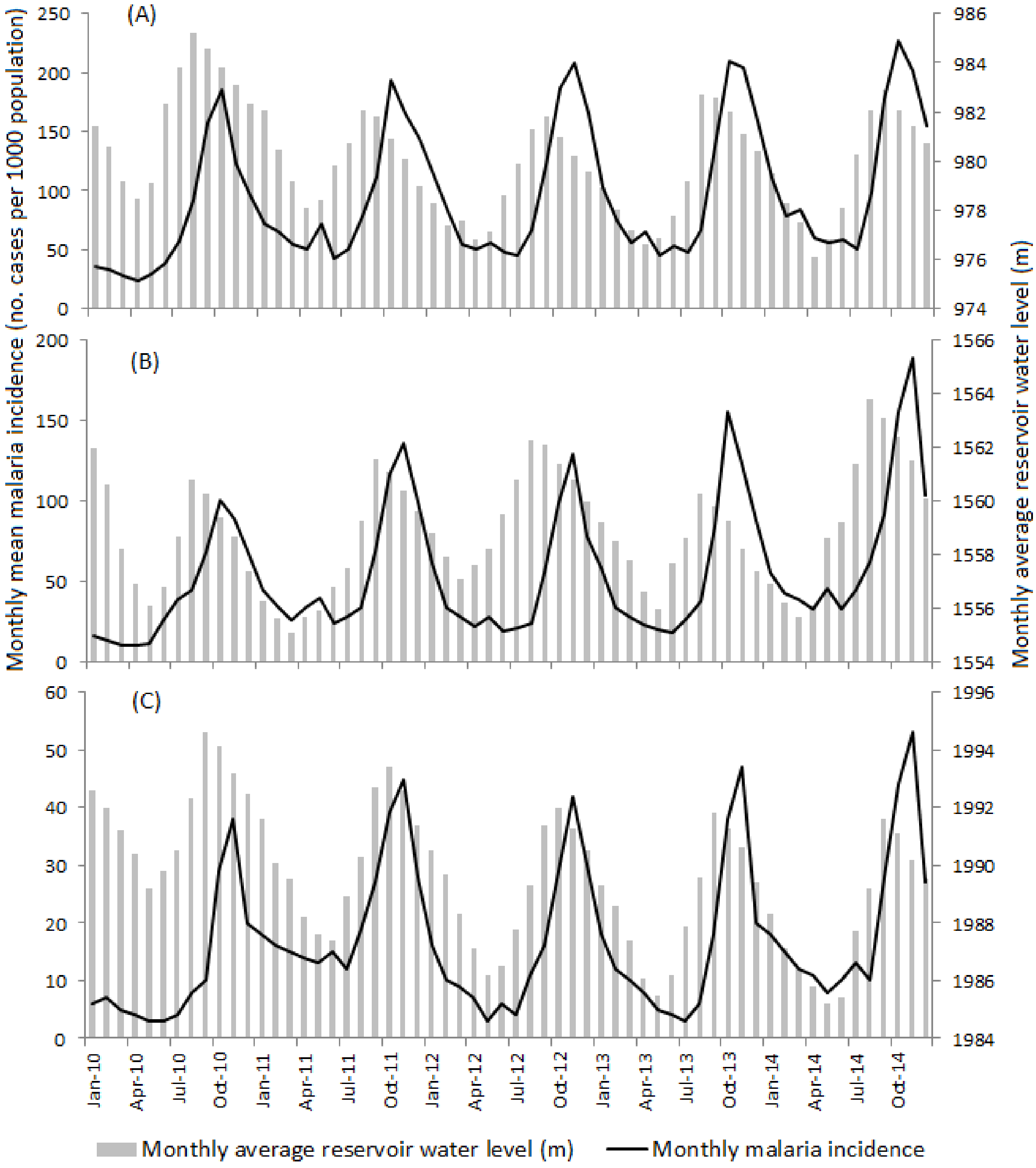

Figure 4.5. Temporal variation in monthly malaria incidence and monthly average reservoir water level at (A) the lowland, (B) midland and (C) highland study dams in Ethiopia, 2010-2014. Please note, Y-axis scales vary between the three plots.

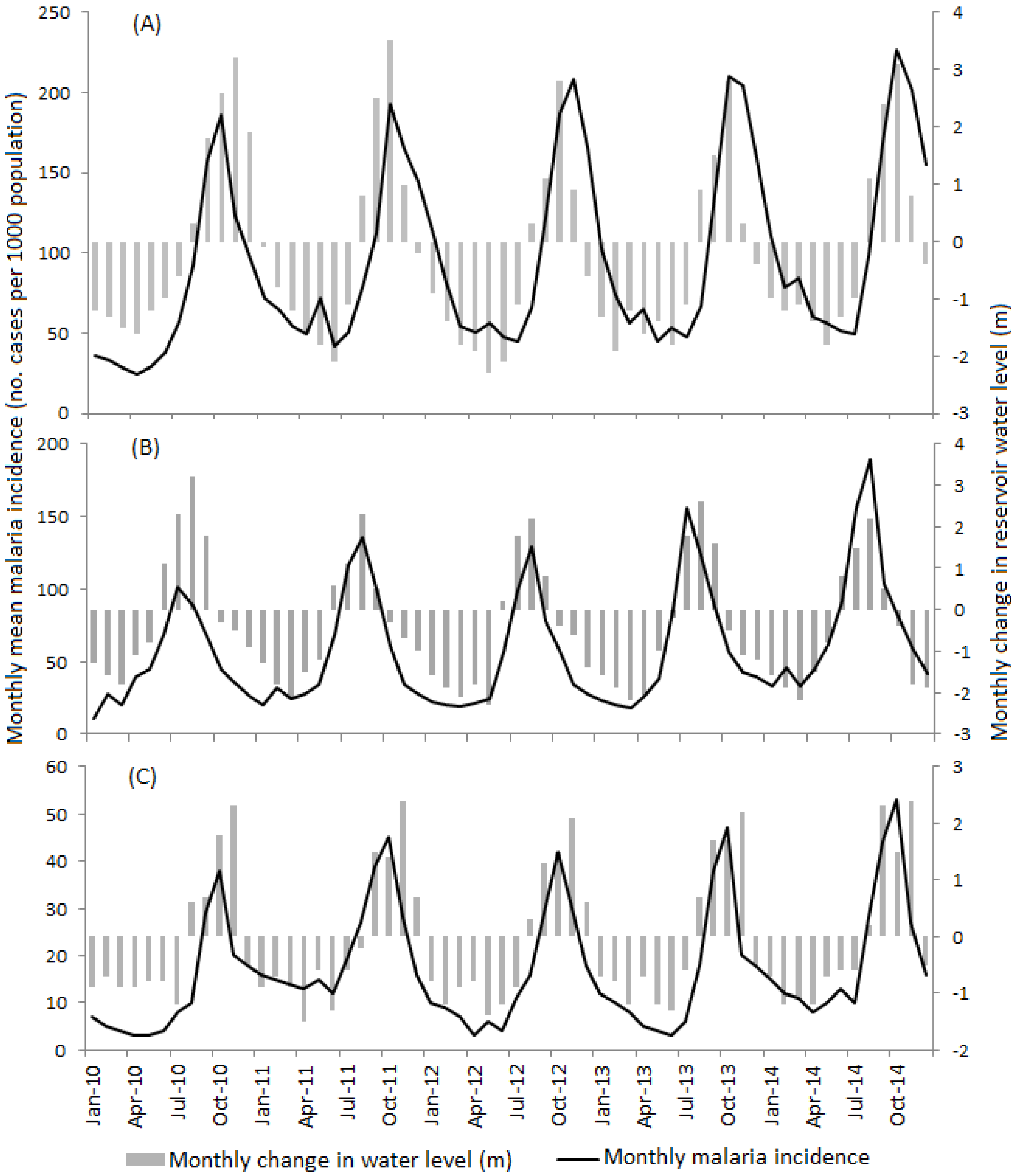

Figure 4.6. Temporal variation in monthly malaria incidence and monthly change in reservoir water level at the (A) lowland, (B) midland and (C) highland study dams, Ethiopia. Please note, Y-axis scales vary between the three plots. Negative water level changes refer to receding water levels.

which was consistent between dams. Similarly, malaria peaks also followed peaks in positive water level change at each dam (Figure 4.6), with a lag-time ranging from 1 month (highland dam) to 2-3 months (midland and lowland dams). Likewise, high NDVI levels were associated with peaks in malaria incidence either 1-2 (lowland and midland dams) or 3 months (highland dam) later (Figure 4.7).

Univariate analysis detected significant relationships between environmental variables and malaria incidence across the three dams (Table 4.2). NDVI (lagged by 1 and 2 months; r = 0.567 and 0.669, respectively), village distance from the reservoir shoreline (lagged by 1 and 2 months; r = -0.598 and -0.441, respectively), monthly average reservoir water level (lagged by 2 months; r = 0.362) and monthly change in reservoir water level (lagged by 1 month; r = -0.616) were significantly associated with monthly malaria incidence at the lowland dam. At the midland dam, distance from reservoir shoreline (lagged by 1 and 2 months; r = -0.455 and -0.368, respectively), NDVI (lagged by 2 months; r = 0.452), monthly average reservoir water level (lagged by 2 month; r = 0.408) and monthly change in reservoir water level (lagged by 1 and 2 months; r = -0.481 and -0.366, respectively) were significantly associated with malaria incidence. At the highland dam, a strong correlation was found between monthly malaria incidence and distance from reservoir shoreline (lagged by 1 and 2 months; r = -0.487 and -0.377, respectively) and monthly changes in reservoir water level (lagged by 1 month; r = -0.301).

Impact of meteorological variables on malaria incidence

A peak in malaria incidence followed mid-year peaks in rainfall at each of the three dams (Figure 4.8). Lag times were relatively consistent between dams, ranging from an average of 2.4 or 2.6 months at the lowland and midland dams to 2.0 months at the highland dam.

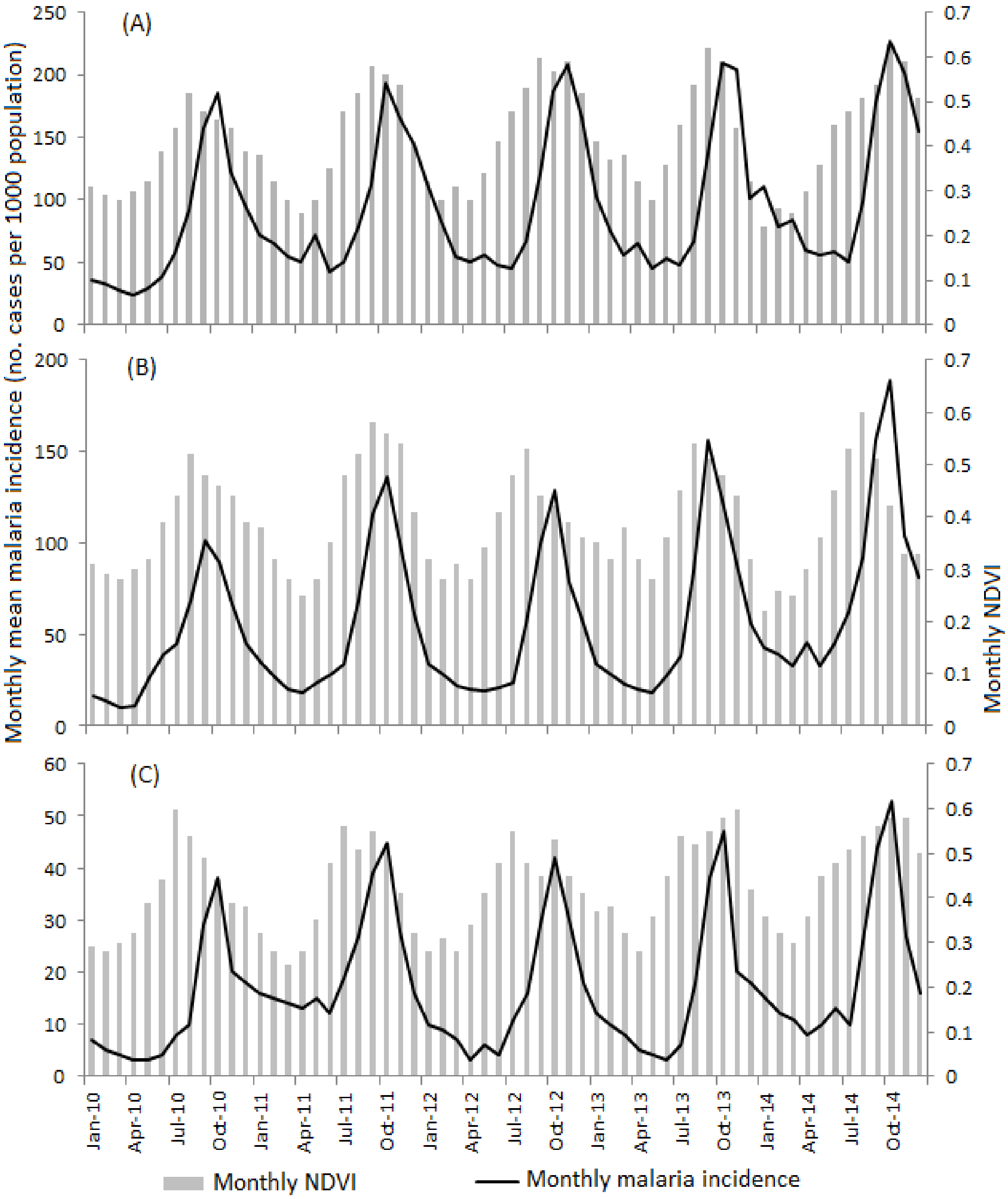

Figure 4.7. Relationship between monthly malaria incidence and monthly NDVI at (A) lowland, (B) midland and (C) highland dams in Ethiopia. Please note, Y-axis scales vary between the three plots.

Table 4.2. Correlation between environmental variables and monthly malaria incidence at the lowland, midland and highland dams in Ethiopia.

	Pearson's correlation with mean monthly malaria incidence		
Environmental variable	Lowland dam	Midland dam	Highland dam
NDVI	0.341	0.255	0.127
NDVI lagged by a month	0.567*	0.303	0.239
NDVI lagged by two month	0.669*	0.452*	0.302
Village distance from reservoir shoreline	-0.252	-0.132	-0.103
Village distance from reservoir shoreline lagged by a month	-0.598*	-0.455*	-0.487*
Village distance from reservoir shoreline lagged by two months	-0.441*	-0.368*	-0.377*
Monthly average reservoir water level	0.231	0.312	0.121
Monthly average reservoir water level lagged by one month	0.296	0.324	0.209
Monthly average reservoir water level lagged by two months	0.362*	0.408*	0.299
Monthly change in reservoir water level	-0.124	-0.235	-0.191
Monthly change in reservoir water level lagged by one month	-0.616*	-0.481*	-0.694*
Monthly change in reservoir water level lagged by two months	-0.244	-0.366*	-0.301

* Significant correlation at $P < 0.05$

Malaria peaks tended to occur a month following peaks in minimum air temperature at the lowland and highland dams, but from 1 to 2 months following the same peaks at the midland lowland and highland dams, but from 1 to 2 months following the same peaks at the midland dam (Figure 4.9). However, the relationship between seasonal malaria incidence and variation in maximum air temperature was less clear. At the lowland dam, malaria peaks occurred 2 to 4 months following late-summer troughs in maximum air temperature, but from 0 to 3 months following similar troughs at the midland dam. The same pattern was less

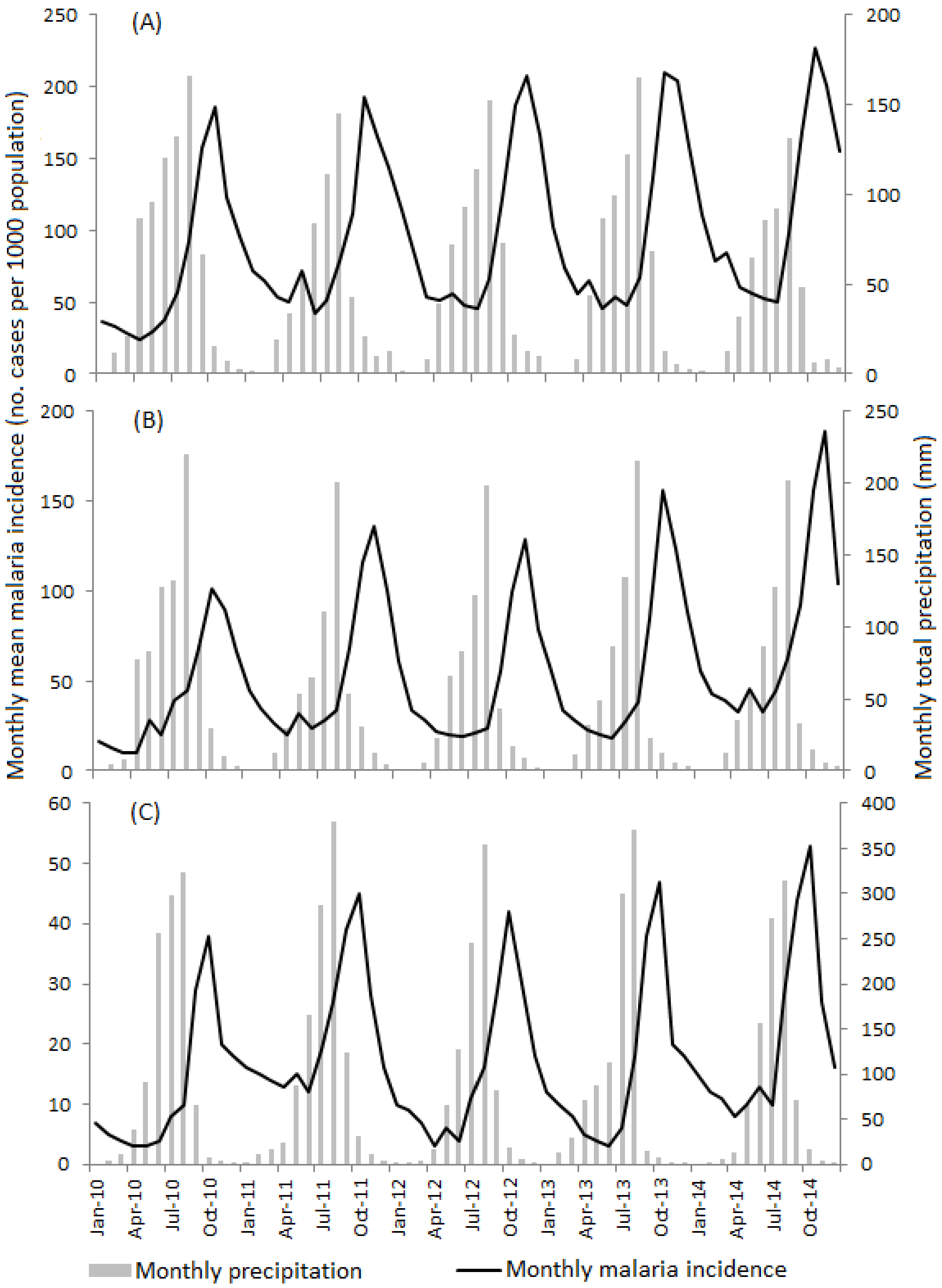

Figure 4.8. Temporal variation in monthly malaria incidence and monthly total precipitation at the (A) lowland, (B) midland and (C) highland study dams, Ethiopia. Please note, Y-axis scales vary between the three plots.

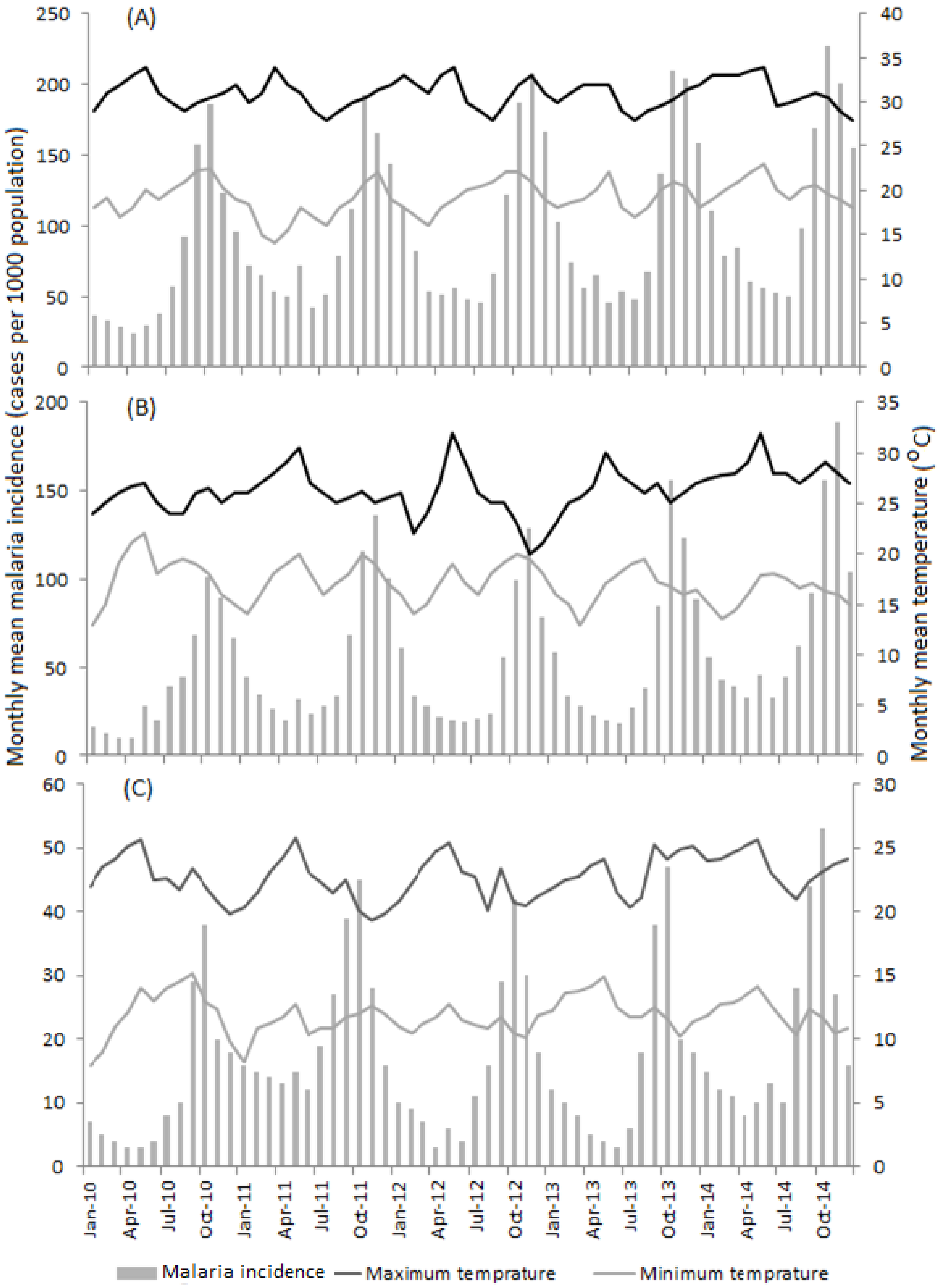

Figure 4.9. Temporal variation in malaria incidence and minimum and maximum air temperatures at the (A) lowland, (B) midland and (C) highland study dams, Ethiopia. Please note, Y-axis scales vary between the three plots.

consistent at the highland dam, with malaria incidence peaks tending to follow minor September peaks in maximum air temperature.

Univariate analysis of the influence of meteorological variables on seasonal malaria incidence indicated differences in variables that were significantly associated with malaria incidence between the three dam sites (Table 4.3). At the lowland dam, monthly total precipitation lagged by 1 and 2 months (r = 0.414; r = 0.672, respectively) was the only variables with a significant correlation with monthly malaria incidence. At the midland dam, monthly total precipitation lagged by 2 months (r = 0.329) and monthly mean minimum temperature lagged by 1 and 2 months (r = 0.501; r = 0.612, respectively) were significantly correlated with monthly malaria incidence. At the highland dam, monthly mean minimum (r = 0.419; r = 0634) and maximum (r = 364; r = 0.451) air temperature lagged by 1 and 2 months were significantly correlated with monthly malaria incidence.

Regression models

Cross-correlation analysis showed that a number of environmental and meteorological variables were significantly correlated with each other (Appendix 1). For instance, maximum temperature was significantly correlated with NDVI, monthly reservoir water level and reservoir water level change at each of the three dams.

Stepwise multiple regression analyses selected few environmental and meteorological variables as factors most explaining malaria incidence across the three study dams (Table 4.4). At the low land dam, village distance to reservoir shoreline lagged by 1 month (r^2=0.468; $P < 0.001$), monthly average change in reservoir water level lagged by 2 months

Table 4.3. Correlation between climatic variables and monthly malaria incidence at the lowland, midland and highland dams in Ethiopia.

	Pearson's correlation with mean monthly malaria incidence		
Climate variable	Lowland dam	Midland dam	Highland dam
Monthly total precipitation	0.213	0.107	0.042
Monthly total precipitation lagged by one month	0.414*	0.268	0.211
Monthly total precipitation by two months	0.672*	0.376*	0.282
Monthly mean minimum temperature	0.231	0.184	0.302
Monthly mean minimum temperature lagged by one month	0.195	0.342*	0.419*
Monthly mean minimum temperature lagged by two months	0.232	0.399*	0.634*
Monthly mean maximum temperature	0.161	0.103	0.147
Monthly mean maximum temperature lagged by one month	0.208	0.198	0.364*
Monthly mean maximum temperature lagged by two months	0.279	0.233	0.451*

* Significance ($P < 0.05$)

(r^2 change = 0.189; $P < 0.001$) and monthly total precipitation lagged by 1 month (r^2 change = 0.156; $P < 0.001$) together explained 81% of the monthly variability in malaria incidence. At the midland dam, village distance to reservoir shoreline lagged by 1 month ($r^2 = 0.398$; $P < 0.001$), monthly reservoir water level lagged by 2 months (r^2 change = 0.266; $P < 0.001$) and monthly total precipitation lagged by 2 months ($r^2 = 0.221$; $P < 0.001$) explained 71.1% of variation in monthly malaria incidence. At the highland dam, village distance to reservoir shoreline lagged by 1 month ($r^2 = 0.324$; $P < 0.001$), monthly change in reservoir water level lagged by 2 months (r^2 change = 0.374; $P < 0.001$) and monthly mean minimum temperature lagged by 2 months (r^2 change = 0.068; $P < 0.001$) explained 76.5% of variation in monthly malaria incidence. Overall, dam-associated factors, such as distance to shoreline or the

Table 4.4. Optimum stepwise multiple regression models relating monthly malaria incidence with environmental and climatic factors at the three dam sites.

Model	Predictors	Non-standardized coefficient*	Adjusted R^2	Sig.
Lowland dam				
1	Village distance from reservoir shoreline (lagged by 1 month)	-9.46	0.468	<0.001
2	Village distance from reservoir shoreline (lagged by 1 month), monthly change in reservoir water level (lagged by 1 month)	4..61	0.657	<0.001
3	Village distance from reservoir shoreline (lagged by a month), monthly change in reservoir water level (lagged by 1 month), monthly total precipitation (lagged by 2 months)	2.49	0.813	<0.001
Midland dam				
1	Village distance from reservoir shoreline (lagged by 1 month)	-5.47	0.398	<0.001
2	Village distance from reservoir shoreline (lagged by 1 month), monthly reservoir water level (lagged by 2 month)	3.89	0.532	<0.001
3	Village distance from reservoir shoreline (lagged by 1 month), monthly reservoir water level (lagged by 2 months), monthly total precipitation (lagged by 2 month)	0.66	0.711	<0.001
Highland dam				
1	Village distance from reservoir shoreline (lagged by 1 month)	-1.98	0.324	<0.001
2	Village distance from reservoir shoreline (lagged by 1 month), monthly change in reservoir water level	2.04	0.698	<0.001
3	Village distance from reservoir shoreline (lagged by 1 month), monthly change in reservoir water level (lagged by 2 months), monthly minimum temperature (lagged by 1 month)	2.75	0.765	<0.001

* The non-standardized coefficient of a variable is also referred as “effect size” which indicates the result of a single unit increase in this variable on malaria incidence.

magnitude of water level changes, were found to be the most important variables contributing to malaria incidence in nearby villages.

4.5 Discussion

This study revealed that dam associated environmental factors and local meteorological drivers influence malaria transmission around large dams in Ethiopia. The importance of these factors, however, varied across lowland, midland and highland dam sites. Interestingly, a village's distance from the nearest reservoir shoreline was the most important variable at all three dams, explaining 47%, 40% and 32% of the monthly variation in malaria incidence at the lowland, midland and highland dams, respectively. This indicates the role of dam reservoirs in malaria transmission by providing favorable breeding habitats for malaria mosquitoes. A previous study found that *An. arabiensis*, the primary malaria vector mosquito in Ethiopia, breeds in reservoir shorelines around dams (Chapter 3).

Monthly reservoir water level (lagged by 2 months) was also positively correlated with monthly malaria incidence at the lowland and midland dams. This suggests that during periods of high water level, reservoir shorelines get closer to villages (as shown by distance) and contribute to increased mosquito abundance as the result of mosquito breeding in reservoir shoreline habitats. The present study results also indicate that the shorter the distance between villages and reservoir shoreline the higher the malaria incidence. This is in agreement with the findings of a recent study that documented enhanced larval abundance of *An. arabiensis* and *An. pharoensis*, the major malaria vectors in Ethiopia, in lowland and midland dam areas (Chapter 3). Similar observations were also made around Lake Victoria in Kenya where the abundance of *An. gambiae* complex (of which *An. arabiensis* is a member) substantially increased during high water levels (Minakawa *et al*. 2008). In southwest Ethiopia, Sena *et al*. (2014) found that elevation and distance from reservoir were important factors determining malaria transmission around Gilgel-Gibe Dam in southwest Ethiopia.

Generally, the significant association between village distance from reservoir shoreline and malaria incidence confirms the role of dams in malaria transmission at all three dam settings.

Whilst precipitation was the most important meteorological driver associated with malaria incidence at the lowland and midland dams, minimum temperature appeared to be a significant driver associated with malaria incidence around the highland dam. In fact, precipitation is strongly correlated with reservoir water level as periods of high water level follow heavy rains between June-August. Teklehaimanot *et al*. (2004) indicated that precipitation is the most important factor for malaria transmission in the lowlands of Ethiopia as mosquito breeding is largely limited by water availability. This is also why peak malaria transmission often follows the main rainy season in Ethiopia (Ministry of Health, 2012). Rainfall may also have a role in filling ephemeral/semi-permanent mosquito breeding habitats at the shoreline of the dam. Conversely, heavy rainfall could wash away larval mosquitoes at the shoreline. Overall, precipitation has a direct and indirect effect on malaria transmission around dams: it increases reservoir water level which creates potential mosquito breeding habitats along the shorelines closer to reservoir villages, and forms rain pools in and around villages for mosquito breeding.

The effect of minimum temperature on malaria transmission in the highlands has long been recognized (Lindsay and Martens, 1998; Craig *et al*. 1999; Blanford *et al*. 2013; Mordecai *et al*. 2013). Temperature is a key determinant of the length of mosquito and malaria parasite life cycle (Blanford *et al*. 2013; Lyon *et al*. 2013). For instance, at 16 °C, larval development may take more than 45 days (reducing the number of mosquito generations and putting the larvae at increased risk of predators), compared to only 10 days at 30 °C (Teklehaimanot *et al*. 2004). However, temperature increases above 30 ^{o}C have been regarded as detrimental to parasite and mosquito development (Lyon *et al*. 2013). Generally, by affecting the duration of the aquatic stage of the mosquito life cycle, temperature determines the timing and abundance of mosquitoes following adequate rainfall. The feeding frequency of mosquitoes is also affected by temperature – an increase in temperature leads to increased proportions of infective mosquitoes (Paaijmans *et al*. 2010). However, the effect of temperature largely depends on elevation; as elevation increases temperature decreases which affects both mosquito and malaria parasite development (Bødker *et al*. 2003). The minimum temperature required for the development of *P. falciparum* and *P. vivax* is approximately 18 °C and 15 °C, respectively, limiting the spread of malaria at higher altitudes (Lindsay and Martens, 1998). There is also a relationship between increasing altitude and decreasing mosquito abundance in African highlands (Bødker *et al*. 2003). In light of future climate change, higher temperatures could also facilitate faster desiccation of breeding habitats, compromising larval development. These effects of minimum temperature might explain the significance of minimum temperature in determining malaria transmission around the highland dam in the present study.

Monthly NDVI (lagged by 1 and 2 months) was significantly correlated with malaria incidence, particularly around the lowland dam. Several studies have shown a positive significant correlation between NDVI in the preceding month and malaria in West, Central and East Africa (Hay *et al*. 1998; Gosoniu *et al*. 2006; Gemperli *et al*. 2006; Gomez-Elipe *et al*. 2007). However, it should also be noted that temporal variation in NDVI is often highly correlated with rainfall particularly in semiarid lowlands as shown in the present study and others (Graves *et al*. 2008; Gaudart *et al*. 2009). In Eritrea, Graves *et al*. (2008) found that NDVI is a better predictor of malaria incidence than rainfall. In the Sudanese Savannah region of Mali, Gaudart *et al*. (2009) reported NDVI is important predictor of the total surface area of breeding sites as NDVI values increase with soil moisture. In the absence of rainfall data, NDVI can thus be used to predict malaria risk in lowlands. Vegetation cover around the shorelines of the lowland and midland dams was particularly extensive, and mostly related to the presence of low-lying areas (personal observations). *Anopheles pharoensis* is a particularly important mosquito vector in such settings (Chapter 3).

Monthly change in reservoir water level (lagged by 2 months) was one of the most important determinants of monthly malaria incidence around the lowland and midland dams. The rate of water level change has been previously shown to determine availability of shoreline habitats for mosquito breeding around (Kibret *et al*. 2012; Chapter 3). Faster water level drawdown rates, determined by the magnitude in water level change between consecutive months, were associated with low larval mosquito abundance and reduced numbers of shoreline puddles. Similarly, the present study showed that a rapidly receding reservoir shoreline was associated with lower malaria incidence rates (Figure 4.6). Increasing water levels, which also shortens the distance from villages to shorelines, were positively correlated with increasing malaria incidence. This also explains the seasonality of malaria around dam villages that peaks immediately after the rainy season when reservoirs fill up. Reservoir water level is thus important factor that determine the production of mosquito breeding shoreline habitats. Previous study (Chapter 3) supports this finding, as larvae of *An. arabiensis* and *An. pharoensis* were predominantly found in the shoreline puddles of these three dam reservoirs.

Understanding the various factors that contribute to malaria transmission is crucial in order to forecast malaria risk and devise disease control tools. Although evidence for the general impact of dams on malaria has long been established in sub-Saharan Africa (Jobin, 1999; Keiser *et al*. 2005), establishing which specific factors are responsible for increased malaria around dams has been less clear. The present study for the first time has identified environmental and meteorological factors associated with increased malaria transmission around dams at different ecological settings. These findings underscore the role of reservoir water levels in malaria transmission nearby. It also brings an opportunity to assess the potential of using reservoir water level management for malaria vector control. Reservoir water level management was effectively implemented to disrupt malaria vector breeding in habitats in the Tennessee Valley, United States (Hess and Kiker, 1944). However, the efficacy of this approach has not been investigated in African settings. Future research should investigate the potential of using water level management around large dams in Africa.

In conclusion, dams intensify malaria transmission in Ethiopia. The rate of reservoir water level change and distance from reservoir shorelines were both found to be key malaria determinants. As a number of dams are currently planned in sub-Saharan Africa, understanding the factors underlying increased malaria transmission is crucial to inform where to locate dams and communities at higher risk of the disease. Health authorities and dam operators should explore mechanisms to optimize dam operation to suppress nearby malaria transmission. Effective water level management, augmented with the existing vector control approaches, could help curb the malaria risk around large dams in Africa.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Chapter 5

Can water level management reduce malaria mosquito abundance around large dams? – an experimental study at Koka Dam in Central Ethiopia

Kibret S, Wilson GG, Ryder D, Tekie H, Petros B. Can water level management reduce malaria mosquito abundance around large dams? – an experimental study at Koka Dam in Central Ethiopia.

5.1 Abstract

Background: Water level management has been suggested as a potential tool to reduce malaria around large dams. However, the effect of water level manipulation on mosquito larval abundance has not been tested experimentally in African settings. The objective of the present study was to evaluate the impact of different water level drawdown rates on mosquito larval abundance in experimental ponds on the Koka Dam shoreline, central Ethiopia.

Methods: Twelve experimental dams were constructed on the foreshore of Koka Dam in central Ethiopia. These were grouped into four daily water drawdown treatments each with three replicates: Group 1 (control, no water level change), Group 2 (10 mm.day^{-1}), Group 3 (15 mm.day^{-1}) and Group 4 (20 mm.day^{-1}). Larval sampling was conducted weekly for a period of 6 weeks during the main malaria transmission season (October to November 2013) and the subsequent dry season (February to March 2014). Larval density was compared between the control and the other treatment groups using repeated measures Analysis of Variance (ANOVA).

Results: A total of 284 anopheline larvae were collected from the 12 experimental dams during the two study periods. Most (63.4%; n=180) were collected during the main malaria transmission season, while the remaining 36.6% (n=104) were collected during the dry season. Larvae comprised four *Anopheles* species, dominated by *Anopheles arabiensis* (48.1%; n=136 of the total larval samples) and *An. pharoensis* (33.2%; n=94). Mean weekly larval density was highest in control experimental dams throughout the study, and decreased significantly with increasing water drawdown rates in both seasons. During the main transmission season, anopheline larval density was generally lower by 30%, 70% and 84% in Groups 2, 3 and 4, respectively, compared with the control dams. In the dry season, larval density was reduced by 45%, 70% and 84% in Groups 2, Group 3 and Group 4, respectively, when compared to the control group.

Conclusion: Higher water drawdown rates were associated with lower mosquito larval abundance. Water level management could thus serve as a potential control measure for malaria vectors around dams by regulating the persistence of shallow shoreline breeding habitats. Dam operators and water resource managers should consider incorporating water level management as a malaria control mechanism into routine dam operation practices to reduce the risk of malaria transmission to human populations around reservoirs.

5.2 Introduction

The construction of dams has been widely advocated to help ensure food security and promote economic development in Africa (World Bank, 2004; Eguavoen and Mccartney, 2013). In response, the Program for Infrastructure Development in Africa (PIDA), endorsed in 2012 by the continent's heads of state and government, laid out an ambitious, long-term plan for closing Africa's infrastructure gap (African Union, 2015). PIDA called for an expansion of hydroelectric power generation capacity by more than 54,000 megawatts (MW) and by 20,000 km^3 in water storage capacity. To meet these goals, Africa has entered a new era of dam building and over 200 large dams are currently under construction or planned in the near future (Zarfl *et al*. 2015). The potential effect of large dams on malaria transmission, however, could potentially disrupt the intended benefits of these infrastructure projects in Africa (Keiser *et al*. 2005; Kibret *et al*. 2015a; Kibret *et al*. 2015b).

A recent study quantified the impact of existing dams on malaria transmission in sub-Saharan Africa and found that dams contribute to over 1 million cases each year in the region (Kibret *et al*. 2015b). Dams particularly intensify malaria transmission in areas where the availability of mosquito breeding habitats is limiting (Kibret *et al*. 2015a) by providing ideal breeding sites for malaria vector species (Njunwa *et al*. 2000; Yohannes *et al*. 2005; Kibret *et al*. 2012). The long shallow shorelines created by large impoundments often create areas of mosquito breeding habitat and it is difficult to control larvae using conventional methods. Such areas have been shown to attract the two most competent malaria vector mosquito species in Africa – *An. funestus* and *An. arabiensis* (Kibret *et al*. 2012; Samb *et al*. 2012). Dam-associated mosquito breeding habitats have thus challenged the malaria control effort in tropical Africa (Keiser *et al*. 2005a), as they are generally inaccessible for conventional larval management techniques using chemical or biological agents.

Current malaria intervention strategies rely heavily on insecticide-treated bed nets and indoor residual insecticide spraying (WHO, 2015). Whilst these control tools have made a significant contribution to a 60% decline in the global malaria mortality rates between 2000 and 2015, averting an estimated 6.1 million deaths (Bhatt *et al*. 2015), the increasing cost of these intervention tools remains a challenge for high-burden developing countries. Furthermore, resistance of mosquitoes to available insecticides and parasites to drugs is also adding to the need for new control measures. With a tightening of global funds for malaria control in recent years (RBM, 2015), the need for supplementary, cost-effective vector control measures has emerged as a priority.

In Africa, malaria transmission is unevenly distributed, often clustering around water bodies (Carter *et al*. 2000; Staedke *et al*. 2003; Gemperli *et al*. 2006). The association of malaria transmission with specific locations is attributable to the presence of breeding sites of the anopheline vectors, with water body characteristics playing an important role in determining the risk of malaria. Households located nearest to larval sites are often at greater risk of the disease (Ribeiro *et al*. 1996), as *Anopheles* mosquitoes have a limited dispersal distance – rarely exceeding 5 km in African settings (Kauffman and Briegel, 2004). Indeed, it is important to understand the site specific characteristics relevant to malaria transmission. A recent research found that distance to reservoir shoreline is the most important environmental factor that explained 47% of the malaria incidence in villages within 5 km of the dam (Chapter 4). This highlights the need to explore reservoir management interventions that could feasibly reduce local rates of malaria transmission.

Utzinger *et al*. (2001) identified that environmental management is the most cost-effective malaria control measure to substantially roll back malaria transmission in Africa. Strategies such as reservoir management through the optimization of dam operation regimes have been used in the Western world to mitigate malaria around large dams (Hess and Kiker, 1944; Kitron and Spielman, 1989). For example, the Tennessee Valley Authority in the United States effectively managed mosquito breeding associated with reservoirs by optimizing water level drawdown rates during the peak malaria transmission season (Hess and Kiker, 1944). However, there is no documented record of applying reservoir water level management for malaria control in African settings. With the current dam construction boom in Africa (Zarfl *et al*. 2015), it is timely to explore additional cost-effective tools such as reservoir management in order to supplement existing conventional malaria control measures.

The present study assessed water level management as a mechanism to reduce malaria vector abundance around reservoirs. Previous desktop-modeling indicated that water levels falling at a rate of 10 mm.day^{-1} were associated with larval abundances approximately five-times lower than when water levels were reduced by 20 mm.day^{-1} (Kibret *et al*. 2009). However, these data were not tested in a field setting. Here, a field experiment was carried out to evaluate the effectiveness of four different rates of water drawdown on anopheline mosquito larval abundance in reservoir shorelines.

5.3 Methods

Study site

This study was conducted on the foreshore of Koka Dam, about 100 km southeast of the capital Addis Ababa, in Central Ethiopia (see Figure 3.1). The detail of the characteristics of the study area is presented in Chapter 3.

Anopheles arabiensis and *An. pharoensis* are the most common malaria vector species in the study area, which breed mainly in shoreline puddles and rain pools (Kibret *et al*. 2012; Chapter 3). *Plasmodium falciparum* is responsible for 60% of malaria infections, while the remaining malaria illnesses are due to *P. vivax* (Kibret *et al*. 2012).

Field experiment design

Ejersa is a small rural town located on the western shore of Koka Dam. Twelve half-cone shaped experimental dams were built in shoreline habitats near Ejersa in October 2013 during the main malaria transmission season. Each experimental dam was 2 m in depth at the deep end, with a 1 m radius (Figure 5.1; Plate 5.1). To create a natural environment, the dams were kept at full for one month before larval sampling commences. The experimental dams were 10 m apart from each other. To increase the shoreline surface area for mosquito breeding, the experimental dams were constructed with a bed slope of 70^o.

The experiment was run for six weeks each in October to November 2013 (the main malaria transmission season) and February to March 2014 (the subsequent dry season). At the beginning of the first of these experimental periods, the 12 experimental dams were allocated to one of four drawdown treatments (each with three replicates): no water-level drawdown (Control; Group 1), 10 $mm.day^{-1}$ (Group 2), 15 $mm.day^{-1}$ (Group 3) and 20 $mm.day^{-1}$ (Group 4). These drawdown rates were adopted from a previous study on the Koka Dam that observed a significant reduction in mosquito larval abundance with a drawdown rate of 20 $mm.day^{-1}$ during the main transmission season (Kibret *et al*. 2009).

The experimental dams were completely filled with unfiltered water from the adjacent Koka shoreline and drawdowns were commenced the following day. During drawdowns, all water was filtered and any mosquito larvae and other invertebrates returned to the experimental dam. Water levels in the control dams were kept constant by adding filtered water daily as required. Daily water depth was recorded from each experimental dam using a height gauge, to confirm each drawdown rate and allow calculation of dam surface area.

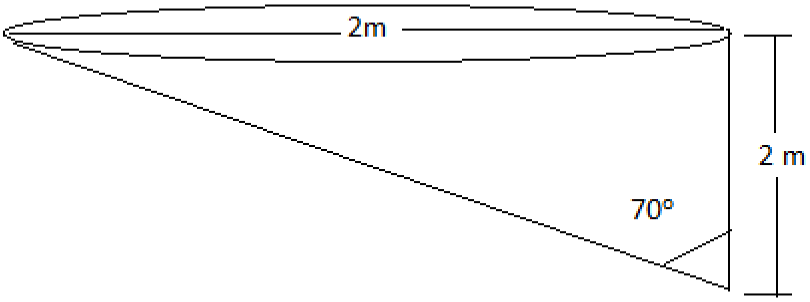

Figure 5.1. Schematic of the experimental dam

Plate 5.1. Experimental dam set-up

Larval mosquito sampling

Weekly larval mosquito sampling was undertaken using a 350 mL standard dipper (Silver, 2007). At each sampling, a total of six independent dips were taken around the edge of each of the experimental dams between 11:00 and 12:00 hours. Larvae were counted and all non-anophelines were discarded. Anopheline larvae in each sample were preserved in 70% alcohol for later species identification. In the laboratory, anopheline larvae were sorted to species based on morphological characteristics (Verrone, 1962) and counted.

Statistical analysis

Anopheline larval density was expressed as the number of larvae per m^2 of experimental dam wetted surface area. Log-transformed larval density was compared among groups as well as seasons using repeated measures Analysis of Variance (ANOVA), followed by post hoc Tukey's Honestly Significant Difference (HSD) tests. The same analyses were used to compare differences between weekly water drawdown rate and larval density for the two major malaria vector species (*An. arabiensis* and *An. pharoensis*). To determine changes in larval density relative to water drawdown rate, Odds Ratio (OR) was calculated for each treatment group by using the control group as reference. All analyses were carried out using SPSS statistical software version 22 (SPSS Inc, Chicago, IL, USA) and Microsoft Excel 2010.

5.4 Results

A total of 284 anopheline larvae were collected from the 12 experimental dams during the study period (Table 5.1). Of these, 63.4% (n=180) were collected during the main malaria transmission season while the remaining 36.6% (n=104) were collected during the dry season. Among the four treatment groups, weekly anopheline larval density was the highest in Group 1 (repeated measures ANOVA, F = 6.58; $P < 0.001$), and declined significantly with increasing drawdown rate in Group 2-4 (Tukey's HSD test, $P < 0.001$). Higher weekly larval density in all experimental dam groups was found during the main transmission season (ANOVA; $P < 0.01$) compared with the dry season (Figure 5.2). Larval anophelines appeared in the second week and increased throughout sampling weeks in both seasons.

During the main malaria transmission season, 43% (n=78) of all anopheline larvae were collected from control dams, while 31% (n=56), 16% (n=28) and 10% (n=18) were collected from experimental dams with 10 mm.day^{-1}, 15 mm.day^{-1} and 20 mm.day^{-1} water drawdown rates, respectively. Similarly, almost half (49%; n=51) of the anopheline larvae collected during the dry season were from control dams while 28% (n=29), 15% (n=16) and 8% (n=8) were collected from the experimental dams in Group 2, 3 and 4, respectively.

Compared with the control (Group 1), weekly larval density was generally reduced by 30% (OR = 0.70; $P < 0.05$), 70% (OR = 0.30; $P < 0.05$) and 84% (OR = 0.16; $P < 0.05$) in Group 2, 3 and 4, respectively, during the main transmission season (Table 5.2). Similarly, in the dry season, weekly larval density was reduced by 45%, 70% and 84% in Group 2, Group 3 and Group 4 when compared with the control (Group 1). Overall, weekly larval abundance in control dams was 1.4-1.8 times higher than Group 2, 3.3 times higher than Group 3 and 6.1 times higher than Group 4 (Figure 5.3).

Four *Anopheles* species were found breeding in the experimental dams during the study period (Table 5.3). *Anopheles arabiensis* was the predominant species, constituting 48.1% (n=136) of the total larval samples, followed by *An. pharoensis* (33.2%; n=94), *An. coustani*

Table 5.1. Summary of weekly anopheline larval sampling from 12 experimental dams in Koka area, Central Ethiopia, during the main malaria transmission (October-November 2013) and dry (February-March 2014) seasons.

	Group 1 (control)	Group 2 (10 mm.day^{-1})	Group 3 (15 mm.day^{-1})	Group 4 (20 mm.day^{-1})	Total
Main malaria transmission season (%)	78 (43)	56 (31)	28 (16)	18 (10)	180 (100)
Dry season (%)	51 (49)	29 (28)	16 (15)	8 (8)	104 (100)
Total (%)	129 (45)	85 (30)	44 (15)	26 (9)	284 (100)

* % calculated from total collection in each season.

Table 5.2. Comparison of mean weekly larval density between treatment and control groups with different water drawdown rate. [SE refers to standard error]

	Total no. larvae	Mean weekly larval density (±SE)	Odds Ratio	*P*
Main transmission season				
Group 1 (0 mm.day^{-1})	78	6.1 (±2.2)	1	-
Group 2 (10 mm.day^{-1})	56	4.3 (±1.7)	0.70	<0.05
Group 3 (15 mm.day^{-1})	28	1.8 (±0.5)	0.30	<0.05
Group 4 (20 mm.day^{-1})	18	1.0 (±0.3)	0.16	<0.05
Dry season				
Group 1 (0 mm.day^{-1})	51	4.3 (±1.1)	1	-
Group 2 (10 mm.day^{-1})	29	2.4 (±0.6)	0.56	<0.05
Group 3 (15 mm.day^{-1})	16	1.3 (±0.4)	0.30	<0.05
Group 4 (20 mm.day^{-1})	8	0.7 (±0.2)	0.16	<0.05

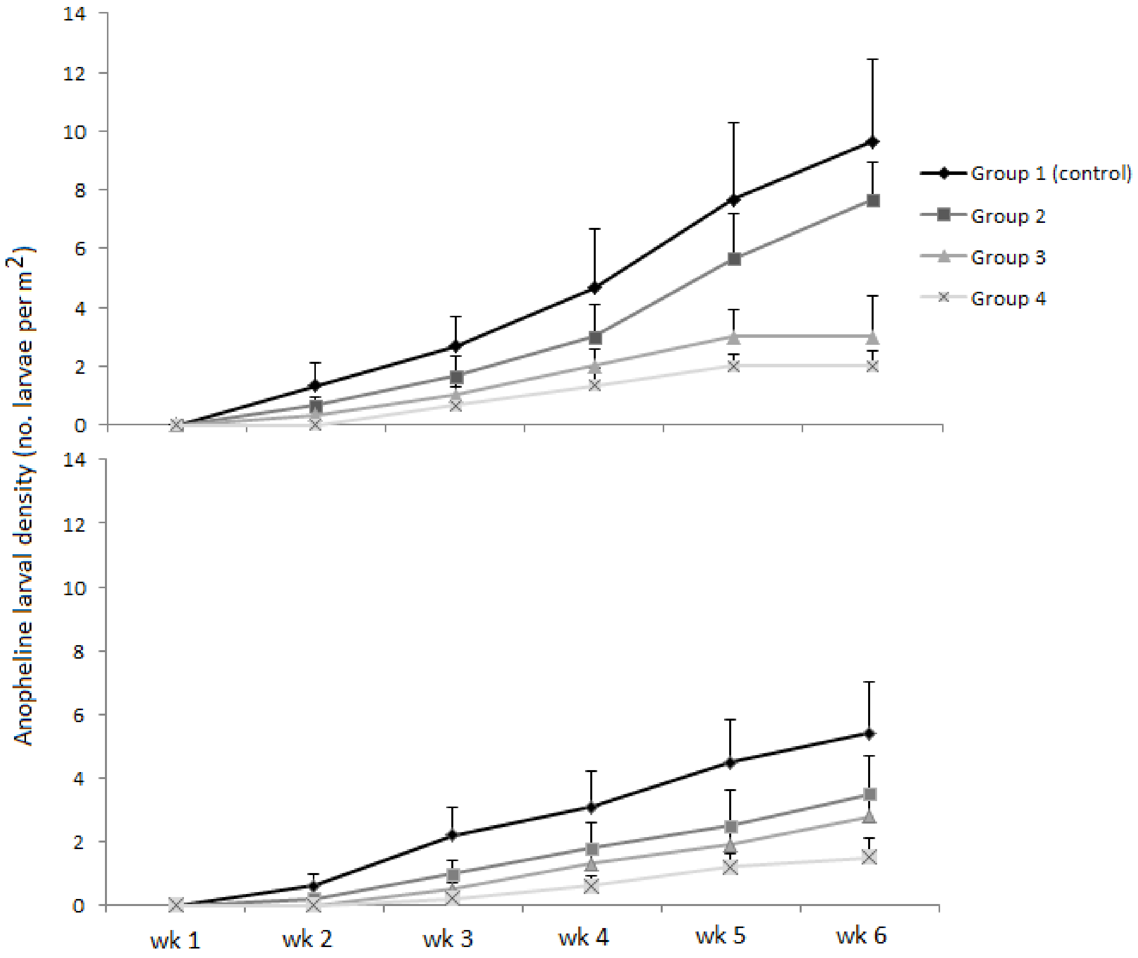

Figure 5.2. Mean weekly anopheline larval density in the four groups of experimental dams with different water drawdown rates (0, 10, 15, 20 mm.day^{-1}) during the dry and main transmission season. (A) main transmission season (October-November 2013); (B) dry season (February-March 2014). Please note, Y-axis scale varies between the two plots.

(17.3%; n=49) and *An. funestus* (1.4%; n=4). Both *An. arabiensis* and *An. pharoensis* were significantly more abundant in control experimental dams compared to the other experimental treatments. The differences in the occurrence of *An. arabiensis* (repeated measures ANOVA, F = 14.76; $P < 0.05$) and *An. pharoensis* (F = 9.49; $P < 0.05$) were significant across the four experimental treatments: larval abundance decreased with higher

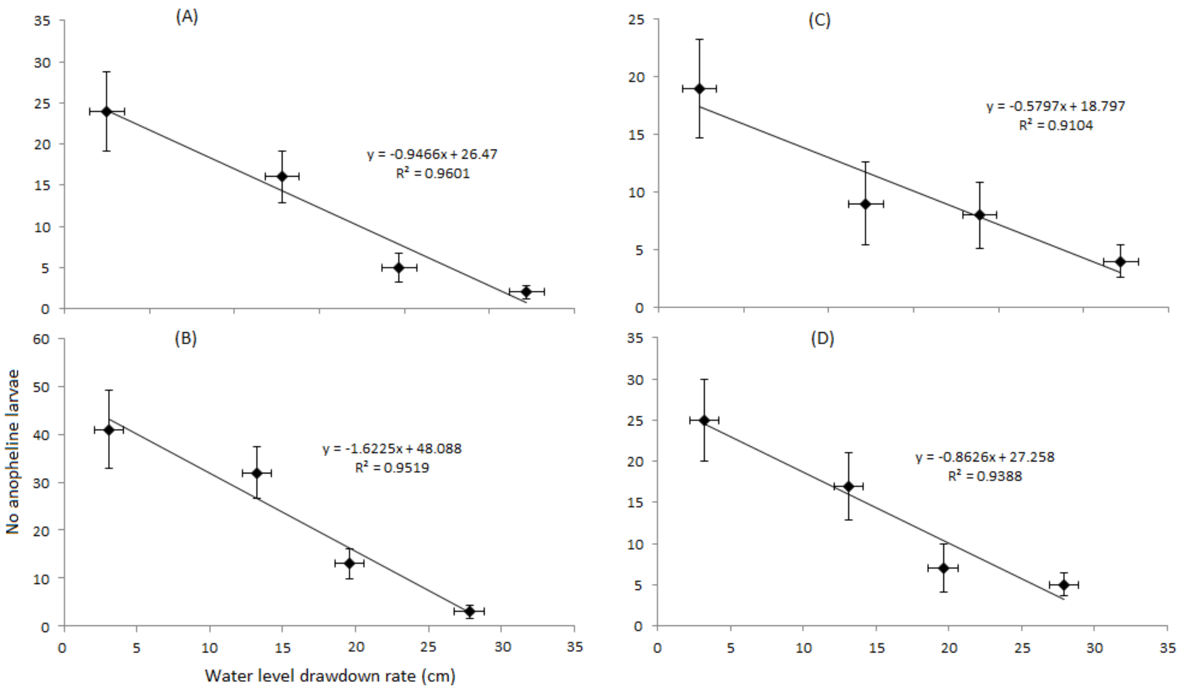

Figure 5.3. *Anopheles* vector larval abundance in experimental dams with different water drawdown rates. (A) *Anopheles arabiensis* during the main transmission season; (B) *An. arabiensis* during the dry season; (C) *An. pharoensis* during the main transmission season; (D) *An. pharoensis* during the dry season. [Please note, Y-axis scale varies across the plots.]

water drawdown rates. This trend was significant (ANOVA; $P < 0.01$) in both the dry and main transmission seasons for both of the main two vector species.

5.5 Discussion

The present study found that faster water drawdown rates were consistently associated with reduced anopheline larval abundances. Water drawdown rates of 10 mm.day^{-1}, 15 mm.day^{-1} and 20 mm.day^{-1} were associated with a 30-45%, 70% and 84% reduction in larval density, respectively, when compared to the control group – confirming that increasing drawdown rates significantly reduces larval density. Larval abundance of both *An. arabiensis* and *An.*

Table 5.3. *Anopheles* species occurrence in experimental dams with different water level drawdown rates. [Group 1 = no water level change; Group 2 = 10 mm.day^{-1}; Group 3 = 15 mm.day^{-1}; Group 4 = 20 mm.day^{-1};]

	Main malaria transmission season	Dry season	Total
Group 1 (control)			
An. arabiensis	41	24	65
An. pharoensis	22	19	41
An. funestus	3	0	3
An. coustani	12	8	20
Total	78	51	129
Group 2 (10 mm.day^{-1})			
An. arabiensis	32	16	48
An. pharoensis	17	9	26
An. funestus	0	0	0
An. coustani	7	4	11
Total	56	29	85
Group 3 (15 mm.day^{-1})			
An. arabiensis	13	5	18
An. pharoensis	6	8	14
An. funestus	1	0	1
An. coustani	8	3	11
Total	28	16	44
Group 3 (20 mm.day^{-1})			
An. arabiensis	3	2	5
An. pharoensis	9	4	13
An. funestus	0	0	0
An. coustani	6	2	8
Total	18	8	26

pharoensis, the two important malaria vector species in Ethiopia, also decreased as water drawdown rate increased.

Findings from the present study were consistent with those from previous research at Koka Dam (Kibret *et al*. 2009) that suggested larval abundances would decline with higher rates of water drawdown, while increasing and stable water levels were associated with mounting larval densities. Similarly, a recent laboratory-based study indicated that water drawdown rates affect mosquito larvae through the stranding of larvae in drying habitats (Endo *et al*. 2015). A faster receding water level results in less shoreline mosquito habitat compared to a slowly-receding water, thus suppressing mosquito productivity. The present study was the first to use an experimental field approach to identify water level manipulation as a potential tool to control malaria around reservoirs in Africa.

Reservoir water level management has been previously applied in the Tennessee Valley of the United States where mosquito breeding was significantly reduced due to desiccation of shoreline puddles that support mosquito breeding (Hess and Kiker, 1944; Gartell *et al*. 1981). This technique has been suggested for African dams (Keiser *et al*. 2005b; Lautze, 2007; Fillinger and Lindsay, 2011; Reis *et al*. 2011; Endo *et al*. 2015; Kibret *et al*. 2015b). The present study confirmed the potential efficacy of water level management as a control mechanism for malaria mosquito breeding in African settings. Results of this study also indicated that larval densities of malaria vector mosquitoes (*An. arabiensis* and *An. pharoensis*) were significantly lower under faster rates of water drawdown. This is primarily because these mosquito species prefer still and stagnant breeding habitats, and so are susceptible to stranding and desiccation when water levels recede (Tusting *et al*. 2013). In the laboratory controlled study, Endo *et al.* (2015) noted that larger proportions of *Anopheles* larvae were stranded at higher water drawdown rates. Further study is required to assess the implication of water level management on dams and its impact on reservoir’s primary purposes. Reis *et al*. (2011) investigated the water resources implications of reservoir water level management through hydrological control to reduce malaria around the Koka reservoir in Central Ethiopia and found that targeted use of hydrological control for malaria vector management would have negligible impacts on power generation and downstream irrigation industries. Nevertheless, the actual impact of reservoir management has not been determined for large dams in African settings.

With over 1 million malaria cases already associated with dams (Kibret *et al*. 2015b), the role of large dams in regulating malaria transmission should not be overlooked. Recent data indicate that Africa is planning to build approximately 200 more large dams over the next 5-10 years (Zarfl *et al*. 2015), taking the total to over 2000 dams by 2025. Tailor-made and cost-effective malaria control approaches are thus needed to curb the impact of planned and existing dams in Africa as the current conventional control tools are resource-intensive. The need to supplement the existing conventional malaria intervention tools (i.e. bednets and indoor residual spraying) has been particularly called for because these tools only target indoor biting and/or resting mosquito species (Beier *et al*. 2008; WHO, 2012). Larval management could further suppress malaria transmission by targeting the aquatic stages through reducing larval habitats, leading to a reduction of both outdoor and indoor biting vectors (Keiser *et al*. 2005b; Fillinger and Lindsay, 2011).

Larval source reduction using reservoir management also has potential as it is cost-effective and does not require a large workforce or resources to implement compared with conventional malaria controls. Keiser *et al*. (2005b) reviewed the literature to evaluate the efficacy of larval management (i.e. methods creating temporary unfavorable conditions for mosquito breeding – e.g. water or vegetation management) in reducing malaria morbidity and mortality and found that the risk of malaria was reduced by 88% in areas that applied environmental management as major malaria control tool. The World Health Organization has been encouraging countries to use integrated vector control in their rational decision-making process for the optimal use of resources for vector control (WHO, 2012).

The present study is limited in that it didn’t measure other environmental factors such as soil type, the occurrence of larval predators, vegetation cover, water temperature and other micro-ecological variables that could potentially affect mosquito breeding. For instance, vegetation cover was one of the most important environmental factors underpinning the presence of *An. arabiensis* in Kenya (Mushinzimana *et al*. 2006). The nature of the shoreline such as its slope and refuge from water wave action are also likely to have an important influence on mosquito breeding capacity around reservoirs. Future studies should include an assessment of the effectiveness of water level management for larval control at different eco-epidemiological settings. The impact of water level fluctuation on a reservoir’s primary purpose also requires investigation. At the Koka Dam, Reis *et al* (2011) indicated that hydropower generation would increase as more water was released through the turbines because losses from spill, seepage, and evaporation were reduced as a consequence of more rapid drawdown of the reservoir at the end of the wet season. Yet, further study is required to assess how best to manage the conflicting objectives of water conservation and mosquito control. The massive shoreline wetland created by dams are likely to reduce the efficacy of other malaria vector control measures such as larviciding for routine application. The overall impact of incorporating malaria control into routine dam operation regimes, thus, needs to be examined.

In conclusion, water level management has potential as a malaria mosquito control tool if applied to large reservoirs. Faster water drawdown rates are associated with lower mosquito larval abundance, which ultimately reduces the malaria risk to human populations surrounding reservoirs. Dam operators and decision makers should consider incorporating malaria control mechanisms into routine dam operation practice without scarifying the primary purpose of the water reservoir.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Chapter 6

Modelling reservoir management for malaria control in Ethiopia

Kibret S, Ryder D, Wilson GG, Kumar L. Modelling reservoir management for malaria control in Ethiopia.

6.1 Abstract

Objective: This study investigated how reservoir water level changes affect mosquito abundance and malaria transmission around three dams located in different eco-epidemiological settings in Ethiopia.

Methods: Digital elevation models of three Ethiopian dams at lowland, midland and highland elevations were used to quantify water surface area and wetted shoreline at different reservoir volume (70, 75, 80, 85, 90, 95 and 100% full capacity) to estimate potential mosquito breeding habitat. Water level drawdown rates of 10, 15 and 20 mm.day^{-1} were applied as modelled water level scenarios to estimate larval abundance, entomological inoculation rate (EIR) and malaria prevalence at each dam. Malaria treatment cost and economic cost in terms of lost working days were calculated for each water level scenario and dam.

Results: At the lowland dam, modelled increased larval abundances were associated with increasing reservoir volume and wetted shoreline area. In contrast, both larval abundances and area of wetted shoreline declined with increasing reservoir volume at the midland and highland dams. Estimated EIR, malaria prevalence, malaria treatment cost and economic cost generally decreased when water level drawdown rate increased from 10 mm.day^{-1} to 15 and 20 mm.day^{-1} irrespective of reservoir volume.

Conclusion: Given the expansion of dam construction in sub-Saharan Africa, increasing the rate of water level drawdown in reservoirs may be a cost-effective and chemical-free method for reducing malaria during the main transmission season. Targeted reservoir management has the potential to address this public health challenge by reducing the malaria burden, health care costs and morbidity in communities near reservoirs.

6.2 Introduction

Water storage is crucial to improving the livelihood of rural communities and fostering economic development in sub-Saharan Africa (SSA) (Rosnes and Shkaratan, 2011). To achieve these goals, a number of dams are currently under construction across this region known for its water scarcity. However, the impact of dams on increasing rates of malaria transmission has raised concerns regarding the sustainability of these infrastructures.

Dams intensify malaria in areas of seasonal unstable malaria transmission across SSA (Kibret *et al*. 2015a). A recent study revealed that over 1 million malaria cases are associated with dams in this region (Kibret *et al*. 2015b). Several studies across SSA showed that dams increase malaria incidence by creating breeding habitats for malaria vector mosquitoes adjacent to human settlements (Oomen, 1981; Ghebreyesus *et al*. 1999; Sow *et al*. 2002; Lautze *et al*. 2007; Yewhalaw *et al*. 2009; Kibret *et al*. 2012). The two principal African malaria vector mosquitoes, *Anopheles gambiae and An. arabiensis*, thrive in shallow shoreline puddles around reservoirs (Oomen, 1981; Kibret *et al*. 2012).

Despite a significant malaria decline in recent years (Cibulskis *et al*. 2016), SSA continues to represent a disproportionately high share (174 million cases each year; 88%) of the global malaria burden (WHO, 2015). Malaria is not only a known public health challenge but also a key economic impediment for the region. The annual economic cost of malaria in Africa was estimated to be US$12 billion (RBM, 2011), including the costs of health care, working days lost due to sickness, days lost in education, decreased productivity due to hospitalization, and loss of investment and tourism. Consequently, the annual economic growth in countries with malaria transmission has historically been lower than in countries without malaria (Sachs and Malaney, 2002). Malaria is a common disease in rural farming communities and transmission generally coincides with the planting and harvesting seasons, and hence it affects agricultural productivity (Asenso-Okyere *et al*. 2011). Construction of dams for irrigation and hydroelectric generation could thus further degrade the public health as well as increase the economic impacts of malaria in Africa. Over 2000 large dams currently exist across SSA, and an additional 200 dams are under construction (Zarfl *et al*. 2015). To deal with malaria around these economically important infrastructures, Africa requires a set of malaria control interventions, tailor-made to address local circumstances.

Vector control is the major malaria intervention tool used in endemic countries (WHO, 2011). It often involves the use of long-lasting insecticide treated bednet (LLIN), indoor residual spraying (IRS) and larval source management (LSM). LLIN and IRS are the most common and widely practiced control measures and target indoor adult mosquitoes. However, the challenges of insecticide resistance and high numbers of outdoor host-seeking (Reddy *et al*. 2011; Russel *et al*. 2011; Moiroux *et al*. 2012) and resting (Govella and Ferguson, 2012) vector mosquitoes, coupled with high operational costs of LLIN and IRS (Yukich *et al*. 2007), have recently led to a renewed interest in LSM as a viable intervention.

LSM is the management of water bodies that are potential larval habitats for mosquitoes to prevent the development of immature stages (Fillinger and Lindsay, 2011). Control of immature mosquito populations is advantageous because the larvae are usually spatially concentrated, relatively immobile, and occupy confined habitats compared with adult stages that can rapidly disperse over large areas. Effective larval control minimizes the cost of adulticides, and is cost-effective and environmentally friendly (Utzinger *et al*. 2001; Worrall and Fillinger, 2011).

Around reservoirs, LSM through water level manipulation can lead to conditions unfavorable for mosquito larvae to complete their aquatic development (Christopher and Bowden, 1957; Juel, 2013). In the Tennessee Valley of the United States, reservoir water management significantly reduced the development time of mosquito larvae around the reservoirs (Gartell *et al*. 1981). During the malaria mosquito production period, cyclical fluctuations (0.3 m of vertical change per week) of reservoir water levels were applied at intervals of seven to ten days to effectively reduce mosquito populations. However, such techniques have been poorly investigated for their application in Africa, despite the potential increase of malaria transmission with the projected levels of dam development.

A recent laboratory-controlled experimental study found that faster reservoir water level drawdown rates were negatively correlated with mosquito larval abundance due to larval stranding and subsequent desiccation (Endo *et al*. 2015). Another field experimental study at Koka Dam in central Ethiopia showed that anopheline larval density was lowered by 30, 70 and 84% in experimental dams with daily water level drawdown rates of 10, 15 and 20 mm.day^{-1}, respectively, compared to the control (no drawdown) during the main malaria transmission season (Chapter 5).

Despite limited evidence from laboratory-based and experimental studies, there has been no field-based, hydrologically controlled experiment that assessed the impact of water level drawdown rates on malaria around African dams. With the current extensive dam construction in SSA, reservoirs could continue to increase malaria transmission. To mitigate this challenge, reservoir management is crucial to supplement existing malaria control tools. The present study assessed how reservoir water level changes affect mosquito breeding and malaria transmission around three dams located in different eco-epidemiological settings in Ethiopia. First, we modelled the surface areas of wetted shoreline at different reservoir volumes commonly occurring during malaria transmission season. Estimates of reservoir-scale larval productivity were used to calculate the malaria transmission intensity (i.e. entomological inoculation rate), malaria treatment cost and economic cost related to lost working days for different water level drawdown rates and reservoir capacity scenarios.

6.3 Methods

Study area

This study was conducted around three large dams in Ethiopia: the Kesem Dam (referred as lowland dam), Koka Dam (referred as midland dam) and Koga Dam (refereed as highland dam) (see Figure 3.1). A recent study classified ecological settings in Africa, using climate and elevation characteristics, as lowland (<1000 m asl), midland (1000-1700 m asl) and highland (> 1700 m asl) (IFPRI, 2010): the present study adopted the same definitions to classify the three study dams. The detail of characteristics of the study area is presented in Chapter 3.

Data sources

Digital elevation data: A high resolution (30 m x 30 m) digital elevation model (DEM) was obtained for each of the three dam sites from the Ethiopian Ministry of Water Resources.

Shapefiles for the reservoir shorelines at full supply level were created by digitizing Google Maps and importing to ArcGIS. Using the crest elevation as a reference for full capacity, each dam was modelled to show scenarios of reservoir surface area and shoreline perimeter at different reservoir water capacities. Data from previous work (2010-2014; Chapter 4) demonstrated that 56-71% of annual malaria cases around the three dams occur between September and December (Table 6.1). This period is where reservoir management has maximum potential to suppress larval development and malaria transmission. During this period, reservoir capacity averaged between 71-95% capacity across the three dams (Table 6.2). Average reservoir water level (in m above sea level, m asl) during the main malaria season (in 2010-2014) ranged from 981.4-984.4 m asl at the lowland dam, 1559.5-1563.2 m asl at the midland dam, and 1991.2-1995.5 m asl at the highland dam (Table 6.2). Thus, reservoir surface area and shoreline perimeter were modelled at 70, 75, 80, 85, 90, 95 and 100% of full capacity to quantify reservoir-scale mosquito larval abundances.

Water level drawdown rates: Four water level drawdown rates (0, 10, 15, 20 $mm.day^{-1}$) based on previous experimental work (Chapter 5) were used to model the impact of different water drawdown rates on mosquito larval and adult abundance and malaria risk.

Mosquito data: Data from previous chapter (Chapter 5) was used to estimate larval vector mosquito abundance (i.e. *An. arabiensis*) around the three study dams at each reservoir capacity scenario during the peak malaria season (September-December). Maximum adult mosquito vector travel distances of 5 km from shoreline puddles were used to estimate the risk of malaria transmission to villages within the dispersal range (Kauffman and Briegel, 2004).

Table 6.1. Annual number of malaria cases around the study dams, 2010-2014. [Data source: Chapter 3]

		Lowland dam	Midland dam	Highland dam
2010	Annual malaria cases	899	495	137
	No. cases in Sep-Dec	562	325	97
	% of annual	63%	66%	71%
2011	Annual malaria cases	1099	686	261
	No. cases in Sep-Dec	614	420	139
	% of annual	56%	61%	53%
2012	Annual malaria cases	1199	599	183
	No. cases in Sep-Dec	683	362	117
	% of annual	57%	60%	64%
2013	Annual malaria cases	1358	599	183
	No. cases in Sep-Dec	761	362	117
	% of annual	56%	60%	64%
2014	Annual malaria cases	1358	898	249
	No. cases in Sep-Dec	761	541	152
	% of annual	56%	60%	61%

Population data: Population data of villages within a 5 km radius of each reservoir at full capacity was obtained from the Ethiopian Central Statistics Agency (CSA, 2010). The villages were georeferenced and the population data imported to Microsoft Excel and ArcGIS.

Malaria treatment cost: To estimate malaria treatment costs associated with each water level scenario, we used published data from Deressa *et al.* (2007) that reported the economic costs for malaria treatment in rural Ethiopia. The same treatment costs were applied to the three study dams.

Table 6.2. Mean elevation and reservoir volume during the main malaria transmission, 2010-2014. [Data source: Chapter 3]

	Elevation* (and % reservoir volume)		
	Lowland dam	Midland dam	Highland dam
2010	984.4 (76-93%)	1560.7 (73-95%)	1995.5 (82-94%)
2011	981.4 (72-91%)	1561.2 (73-91%)	1994.3 (78-92%)
2012	980.6 (71-89%)	1562.1 (75-92%)	1992.1 (74-92%)
2013	982.3 (72-92%)	1559.5 (72-90%)	1991.8 (74-93%)
2014	981.9 (73-94%)	1563.2 (76-93%)	1991.2 (72-91%)

* Elevation is in meters above sea level

Economic cost: To estimate the employment person-days lost due to malaria, data from Deressa *et al*. (2007) was used, which found that the mean number of days lost per hospitalized patient in rural Ethiopia was 14.5 per malaria patient and 17.1 per caretaker.

Data analysis

Modelling reservoir parameters: The perimeter of the wetted shoreline (i.e. the wetted area surrounding the edge of the reservoir) for each water capacity scenario and reservoir was estimated. The wetted shoreline <0.5 m depth was considered as potential mosquito breeding habitat (Silver, 2007). Each polygon (30 m x 30 m) of the wetted shoreline, including polygons formed within the main outer dam boundaries, was counted on ArcGIS to determine area and perimeter. Then, the area of wetted shoreline for each reservoir capacity scenario that potentially supports larval breeding was calculated by multiplying the perimeter of the shoreline in each reservoir volume scenario by the estimated shoreline habitat that potentially supports mosquito breeding (i.e. shoreline puddles with < 0.5 m depth) (Silver, 2007).

Estimating malaria vector larval abundance associated with each water level scenario: Using data from previous works (Chapter 3 & 5), potential mosquito larval population was estimated for the three reservoirs at each water level scenario and reservoir capacity. The previous study (Chapter 5) found that anopheline larval density (no. larvae per m^2) declined by 30%, 70% and 84% compared to the control (i.e. no change in water level) when water level drawdown rates of 10, 15 and 20 $mm.day^{-1}$ were applied to *in situ* experimental dams. Each percentage reduction in larval density was applied to all three dam sites. For each dam, the reservoir-scale anopheline larval abundance (without optimizing the water levels) was estimated by multiplying the observed anopheline larval density (Chapter 3) by the area of potential mosquito breeding shoreline habitat in each reservoir capacity scenario (as estimated above). Anopheline larval abundance (LA) was also estimated for each of the three selected water level drawdown rates (10, 15 and 25 $mm.day^{-1}$) for each dam as: LA = LD*R*A, where LD is the anopheline larval densities obtained from previous field survey around each of the three dams (i.e. 10.8 ± 3.7 (SE), 5.1 ± 1.1 and 0.5 ± 0.2 for the lowland, midland and highland dams, respectively (Chapter 3); R is the factor by which the larval densities reduce when water level rates of 10,15 and 20 $mm.day^{-1}$ are applied (R is 0.30, 0.70 and 0.16, respectively); and A is area of potential mosquito breeding shoreline habitat in each reservoir volume scenario.

Estimating human population around reservoir shoreline at different water level scenarios: The total human population living within a 5 km radius of the reservoir shoreline was estimated for each water level scenario by measuring the distance of each village from the shoreline in each scenario using ArcGIS.

Estimating malaria risk: Entomological Inoculation Rate (EIR) is a more direct measure of malaria transmission intensity than traditional measures of malaria prevalence or hospital-based measures of infection or disease incidence (Killeen *et al*. 2000). EIR from larval abundance was estimated using the equation derived by Gu and Novak (2005). The conventional formula for EIR (MacDonald, 1952) is the product of human-biting rate (*ma*, where *m* is the number of host-seeking mosquitoes per person and *a* is the man-biting tendency of individual mosquito species) and the proportion of sporozoite infected mosquitoes (*s*) as EIR = *mas*. Gu and Novak (2005) rearranged this formula to determine EIR from larval mosquito abundance as:

$$\mathrm{EIR} = \gamma P \mathrm{e}^{-dT} as \ ,$$

where γ is the base level of emerging female mosquitoes, *P* is larval productivity (no. larvae per m^2), *d* is daily mortality rate of adult mosquitoes, *T* is the extrinsic incubation period, *a* is man-biting habit (same as the Human Blood Index), and *s* is the proportion of sporozoite infected mosquitoes. The values γ, *d* and *T* were taken from a previous study that estimated these values from robust data in Africa (Killen *et al*, 2000). The values for *a* and *s* were adopted from previous studies in the region (Chapter 3). The difference in EIR between water level drawdown rates was compared at each dam by Analysis of Covariance (ANCOVA) using SPSS version 22.

Estimating malaria cases: To estimate the number of malaria cases that arise from the EIR, a formula derived by Smith *et al*. (2005) was adopted. The malaria prevalence rate (PR) was computed as:

$$PR = 1 - \left(1 + \frac{b\varepsilon}{rk}\right)^{-k}$$

,

where ε refers to EIR, *b* is transmission efficiency (i.e. the probability that a bite by an infectious mosquito results in an infection), 1/*r* the expected time to clear each infection, *k* is a constant that takes into account the heterogeneous infection (i.e. the fraction of all infections received by the subpopulation that is infected most). Smith *et al*. (2005) estimated that 1/*k* is 4.2 and *b/r* is 0.45 using an extensive African dataset, and these values were used in the present study. After estimating the malaria prevalence rate, the total number of malaria cases was calculated by multiplying PR by the total population around the reservoir shoreline (< 5 km) for each water level and reservoir capacity scenario at each dam.

Malaria treatment cost: The malaria treatment cost was estimated by multiplying the US dollar cost of malaria treatment at health facilities (Deressa *et al*. 2007) by the number of malaria patients in each reservoir water level drawdown and volume scenario. The dollar value between 2007 (the year where the previous study (Deressa *et al*. 2007) was conducted) and 2015 (present study) was adjusted based on the World Bank's Consumer Price Index (World bank, 2015).

Economic cost: The total number of days lost per hospitalized malaria patients around each dam for each reservoir capacity scenario and modelled rates of water level drawdown was calculated by multiplying the number of malaria patients in each scenario by the number of days lost per hospitalized malaria patient (14.5 days; based on Derressa *et al*. (2007)).

6.4 Results

Reservoir models: As reservoir capacity increases from 70 to 100%, the perimeter of wetted shoreline and area of larval habitat increased at the lowland dam, but decreased at the midland and highland dams (Figure 6.1; Table 6.3). At the lowland dam, the wetted shoreline area and perimeter was highest when the reservoir was 90% capacity. In contrast, the wetted shoreline area and perimeter decreased as reservoir capacity in the midland and highland dam approached full capacity. The midland dam generally had the highest perimeter and area of wetted shoreline, followed by the highland and lowland dams.

Larval vector abundance: The total area of potential mosquito breeding habitat around the shoreline increased at the lowland dam but decreased at the midland and highland dams as the reservoir approached full capacity (Table 6.3). At the lowland dam, the reservoir-scale area of mosquito larval habitat increased as the reservoir capacity increased, with the largest area recorded at 90% capacity. Consequently, reservoir-scale larval mosquito abundance increased as the reservoir approached 90% capacity and declined slightly

Faster rates of water level drawdown were associated with lower reservoir-scale total larval abundances at all dams (Table 6.3). At the lowland dam, water level drawdown rates of 10, 15 and 20 mm.day^{-1} were associated with a 24%, 54% and 72% reduction respectively in larval abundance compared with those in constant water level scenarios. At the midland dam, these water level drawdown rates were associated with a 48%, 78% and 88% reduction in larval abundance compared to a constant water level scenario. Similarly, a 17%, 65%, 81% reduction in larval abundance was found at the highland dam when the reservoir was simulated at water level drawdown rates of 10, 15, and 20 mm.day^{-1}.

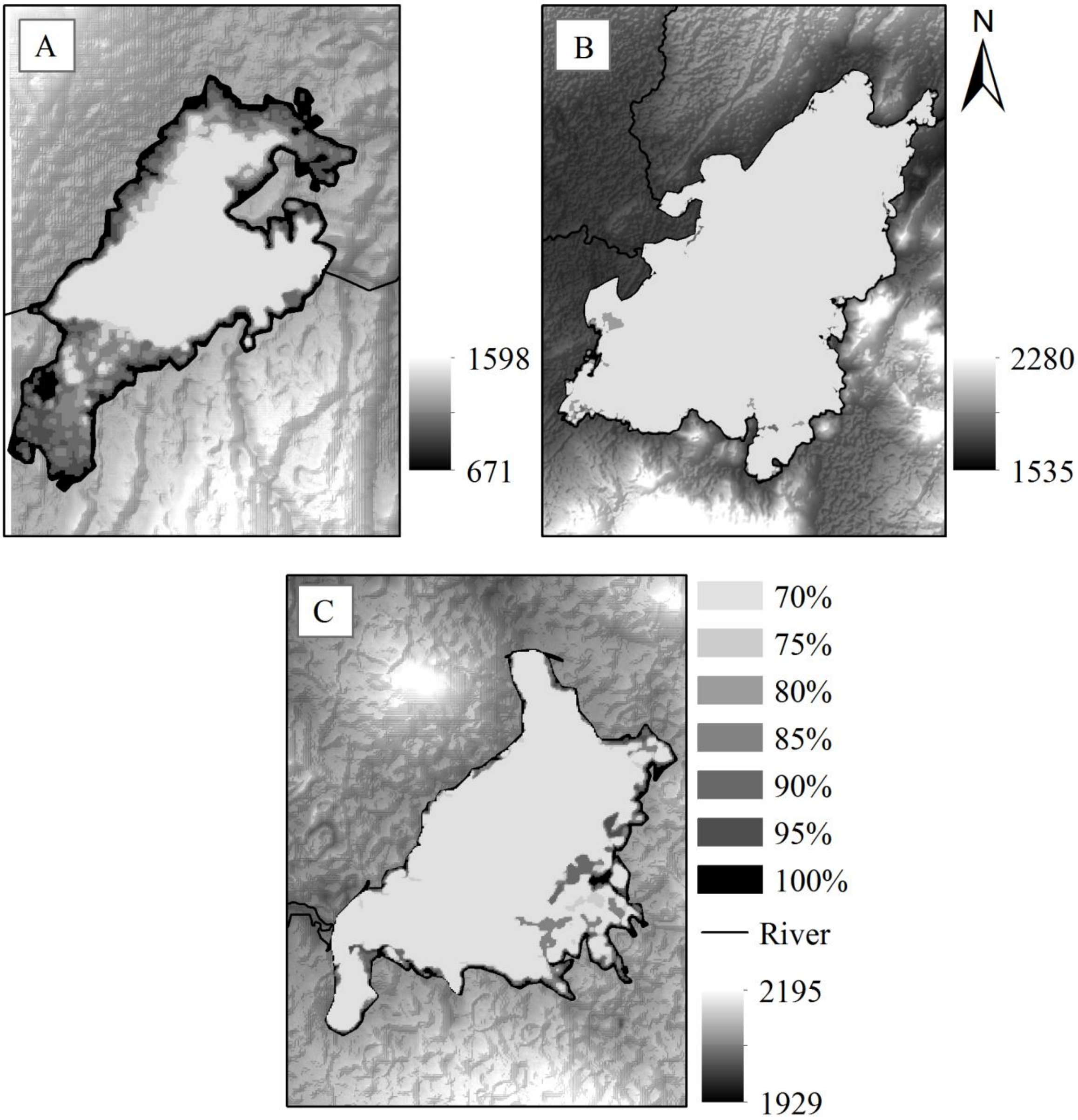

Figure 6.1. Reservoir models showing reservoir shoreline at different volume capacity. (A) lowland dam, (B) midland dam, and (C) highland dam.

Entomological Inoculation Rate (EIR): The EIR mirrored the trend in larval and adult abundances in the lowland and midland dam (Figure 6.2). EIR was not estimated for the highland dam as no sporoizoite-infected mosquitoes have been reported in this eco-

Table 6.3. Reservoir model parameters and malaria vector larval abundance

	Reservoir volume	Shoreline Perimeter (m)	Larval habitat area (m2)	Total no. larvae at reservoir scale	Larval abundance - water level drawdown rate models		
					10 mm.day-^{1}	15 mm.day-^{1}	20 mm.day-^{1}
Lowland dam	70%	35,083	17,542	190,107	133075	57032	8449
	75%	40,182	20,091	189,448	132614	56834	8420
	80%	43,581	21,791	216,983	151888	65095	9644
	85%	53,900	26,950	235,337	164736	70601	10459
	90%	61,245	30,623	291,060	203742	87318	12936
	95%	58,696	29,348	330,723	231506	99217	14699
	100%	55,417	27,709	316,958	221871	95088	14087
Midland dam	70%	1,110,842	555,421	3,379,082	2,365,357	1,013,724	540,653
	75%	1,110,842	555,421	2,832,647	1,982,853	849,794	453,224
	80%	860,383	430,192	2,832,647	1,982,853	849,794	453,224
	85%	860,383	430,192	2,193,977	1,535,784	658,193	351,036
	90%	648,901	324,451	2,193,977	1,535,784	658,193	351,036
	95%	648,901	324,451	1,654,698	1,158,288	496,409	264,752
	100%	487,926	243,963	1,654,698	1,158,288	496,409	264,752
Highland dam	70%	76,875	76,875	33,778	23,645	10,133	5,405
	75%	69,825	69,825	38,438	26,906	11,531	6,150
	80%	69,825	69,825	34,912	24,439	10,474	5,586
	85%	64,216	64,216	34,912	24,439	10,474	5,586
	90%	55,235	55,235	32,108	22,476	9,632	5,137
	95%	48,582	48,582	27,617	19,332	885	4,419
	100%	42,728	42,728	24,291	17,004	7,287	3,887

epidemiological region (see Chapter 3). The EIR was significantly higher at the lowland dam than the midland dam (F = 6.73; df = 1; *P* < 0.01), ranging from an EIR of 4.2-7.1 at the lowland dam and 0.6-1.7 at the midland dam. Water level drawdown rates of 10, 15, and 20 mm.day^{-1} were associated with a 19%, 48% and 65% reduction in EIR at the lowland dam and a 40%, 71% and 82% decline at the midland dam.

Malaria burden: The number of malaria cases dropped considerably at the lowland dam from its current 33,700 to 25,700, 15,600 and 9,400 as the water level drawdown rate increased from 10 to 15 and 20 mm.day^{-1}, respectively, (Table 6.4). Compared to the current malaria burden, these drawdown rates are associated with a 24%, 54% and 72% reduction in the number of malaria cases. At the midland dam, the number of malaria cases estimated at current, 10, 15 and 20 mm.day^{-1} water level draw down rate was 11,700, 6,100, 2,600 and 1,500, respectively, revealing a potential decrease of 47%, 78% and 87%, respectively.

Malaria treatment cost: Like the number of malaria cases, the cost of malaria treatment was generally higher at lower rates of water level drawdown (Table 6.5). At the lowland dam, the cost of malaria treatment was USD 46,000, 41,000, 25,000 and 15,000 at current, 10 mm.day^{-1}, 15 mm.day^{-1} and 20 mm.day^{-1} water level scenarios, respectively. Compared to the current, costs declined by 11%, 46% and 67% when 10, 15 and 20 mm.day^{-1} water level rates were applied. At the midland dam, the total cost of malaria treatment in reservoir communities was estimated to be USD 15,000. The cost declined by 47% (USD 7,900), 77% (USD 3,400) and 87% (USD 1,963) at water level drawdown rates of 10, 15 and 20 mm.day^{-1}, respectively.

Economic cost of malaria at different water level drawdown rate scenario: The economic cost of malaria, estimated from lost working days, was estimated to decrease with increasing rates of water level drawdown in both the lowland and midland dams (Table 6.6). At the lowland dam, the current total annual economic cost was estimated to be 444,000 lost working days. This was predicted to drop by 24, 54 and 72% as the water level drawdown rate increased from 10, 15 to 20 mm.day^{-1}, respectively. At the midland dam, the current economic cost of malaria around the dam was estimated to be 137,951 which reduced by 47, 77 and 87% when water level drawdown rate increased from 10 to 15 and 20 mm.day^{-1}, respectively.

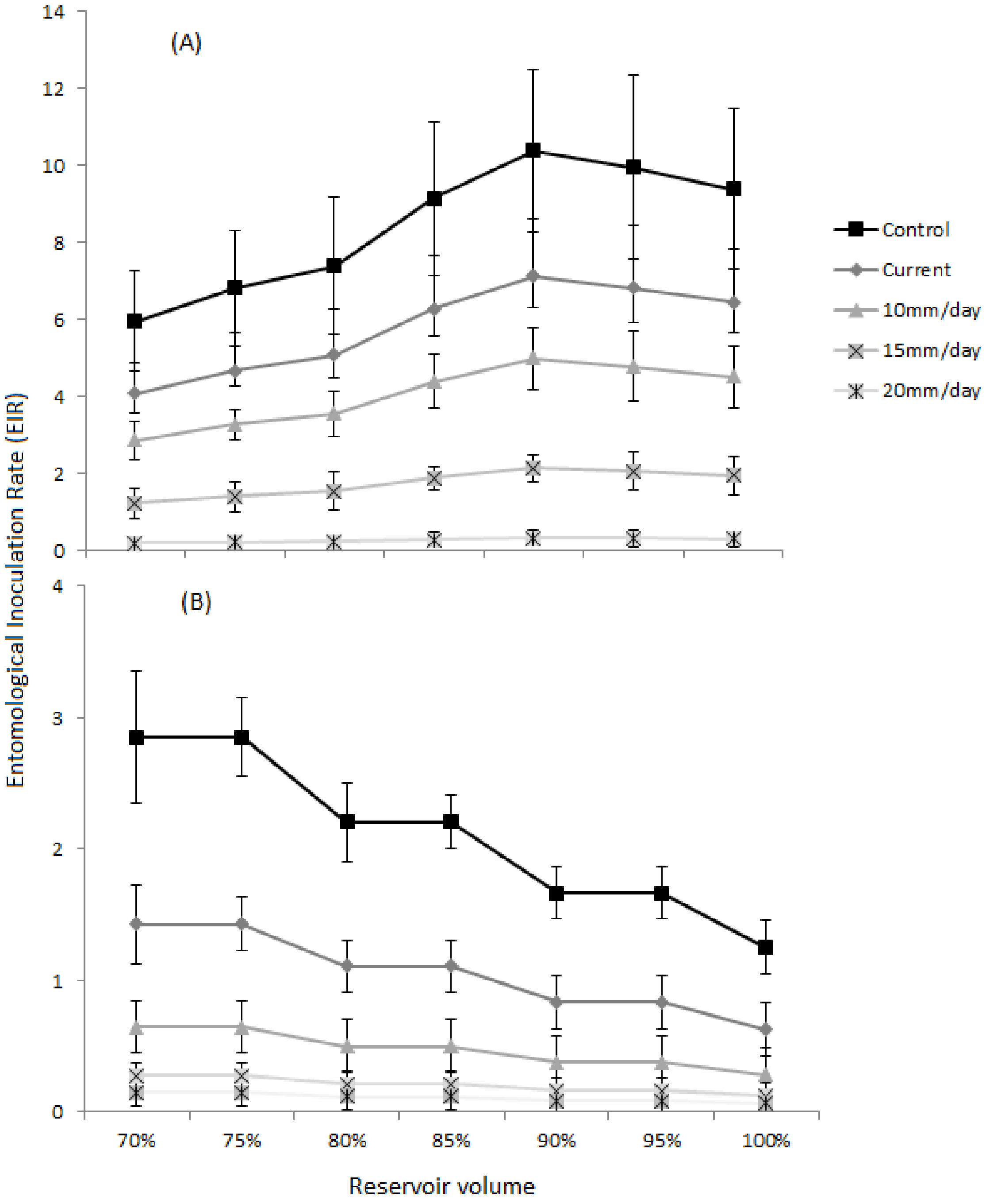

Figure 6.2. Estimates of Entomological Inoculation Rate (EIR) at the (A) lowland and (B) midland dams for different reservoir volume scenarios and water level drawdown rates.

Table 6.4. Estimated number of malaria cases at different water level drawdown rate scenarios

		Malaria cases - Water level drawdown rates				% Change from current		
	Reservoir volume	Current	10 mm.day^{-1}	15 mm.day^{-1}	20 mm.day^{-1}	10 mm.day^{-1}	15 mm.day^{-1}	20 mm.day^{-1}
Lowland	70%	3,092	2,365	1,439	868	24	53	72
	75%	3,539	2,707	1,646	993	24	53	72
	80%	3,837	2,934	1,784	1,076	24	54	72
	85%	4,742	3,626	2,203	1,327	24	54	72
	90%	5,387	4,118	2,501	1,506	24	54	72
	95%	5,163	3,947	2,398	1,444	24	54	72
	100%	4,876	3,728	2,264	1,364	24	54	72
	Total	33,738	25,798	15,677	9,450	24	54	72
Midland	70%	1,841	965	411	234	48	78	87
	75%	1,841	965	411	234	48	78	87
	80%	1,428	750	321	184	47	78	87
	85%	1,428	750	321	184	47	78	87
	90%	1,080	569	245	141	47	77	87
	95%	1,080	569	245	141	47	77	87
	100%	815	431	187	109	47	77	87
	Total	11,707	6,148	2,629	1,503	47	78	87

6.5 Discussion

This study is the first of its kind to model reservoir-scale responses of malaria transmission to water level drawdown, and demonstrate their application to reservoir management in sub-Saharan Africa. It demonstrated that increasing rates of reservoir water level drawdown during the main malaria season when the reservoir capacity is between 70 and 100% will decrease mosquito vector abundance and malaria prevalence around dams in sub-Saharan Africa. As a consequence, the EIR, malaria prevalence, cost of malaria treatment and economic cost due to malaria also declined with increased rates of water level drawdown in lowland and midland regions. These findings reaffirm previous laboratory-based (Endo *et al.*

Table 6.5. Estimated cost of malaria treatment ($USD) at the lowland and midland dam at different water level drawdown rates.

			Cost ($US) - Water level drawdown rates			% change from current		
	Reservoir volume	Current	10 mm.day^{-1}	15 mm.day^{-1}	20 mm.day^{-1}	10 mm.day^{-1}	15 mm.day^{-1}	20 mm.day^{-1}
Lowland	70%	4,963.6	3,783.6	2,301.6	1,389.6	24	54	72
	75%	4,946.5	4,330.4	2,633.0	1,588.4	12	47	68
	80%	5,662.3	4,694.9	2,853.9	1,721.0	17	50	70
	85%	6,139.4	5,801.5	3,524.5	2,123.3	6	43	65
	90%	7,588.0	6,589.1	4,001.9	2,409.8	13	47	68
	95%	8,619.1	6,315.8	3,836.2	2,310.4	27	55	73
	100%	8,261.2	5,964.1	3,623.1	2,182.5	28	56	74
	Total	46,180	41,276	25,084	15,119	11	46	67
Midland	70%	2,945.1	1,544.2	657.6	373.9	48	78	87
	75%	2,945.1	1,544.2	657.6	373.9	48	78	87
	80%	2,285.4	1,200.4	513.7	293.9	46	78	87
	85%	2,285.4	1,200.4	513.7	293.9	47	78	87
	90%	1,728.4	910.1	392.1	226.4	47	77	87
	95%	1,728.4	910.1	392.1	226.4	47	77	87
	100%	1,304.4	689.1	299.6	175.0	47	77	87
	Total	15,222	7,998	3,426	1,963	47	77	87

2015) and experimental (Chapter 5) studies that found rapid rates of water level drawdown significantly reduce mosquito larval abundance and malaria transmission.

The present study showed that the area of larval habitat increased with reservoir capacity at the lowland dam, but not at the midland and highland dams. The maximum area of wetted shoreline was achieved when the lowland, midland and highland dams were at 90%, 50% and 70% full capacity, respectively (Appendix 2). These differences are explained by differences in topography of these dams: the slope of the lowland dam reservoir (2%) is much lower than the midland (6%) and highland (5-8%) dams (Berhanu *et al*. 2014), meaning that an increase in volume does not necessarily translate into increased surface area. Similarly, lower

Table 6.6. Estimated seasonal economic costs during the main malaria transmission season in terms of lost working days

		Cost ($US) Water level drawdown rates				% change from current		
	Reservoir volume	Current	10 mm.day^{-1}	15 mm.day^{-1}	20 mm.day^{-1}	10 mm.day^{-1}	15 mm.day^{-1}	20 mm.day^{-1}
Lowland	70%	44,827.4	34,289.3	20,858.3	12,593.2	24%	53%	72%
	75%	51,314.2	39,244.5	23,861.5	14,395.1	24%	53%	72%
	80%	55,638.4	42,547.7	25,863.4	15,596.2	24%	54%	72%
	85%	68,766.0	52,575.7	31,941.1	19,242.8	24%	54%	72%
	90%	78,110.2	59,713.7	36,267.1	21,838.4	24%	54%	72%
	95%	74,867.4	57,236.5	34,765.8	20,937.6	24%	54%	72%
	100%	70,695.9	54,050.0	32,834.5	19,778.9	24%	54%	72%
	Total	444,219.6	339,657.4	206,391.7	124,382.1	24%	54%	72%
Midland	70%	26,690.2	13,994.6	5,959.4	3,388.2	48%	78%	87%
	75%	26,690.2	13,994.6	5,959.4	3,388.2	48%	78%	87%
	80%	20,711.6	10,878.5	4,655.0	2,663.5	47%	78%	87%
	85%	20,711.6	10,878.5	4,655.0	2,663.5	47%	78%	87%
	90%	15,663.5	8,247.4	3,553.6	2,051.6	47%	77%	87%
	95%	15,663.5	8,247.4	3,553.6	2,051.6	47%	77%	87%
	100%	11,821.0	6,244.6	2,715.2	1,585.8	47%	77%	87%
	Total	137,951.6	72,485.5	31,051.3	17,792.3	47%	77%	87%

reservoir capacities revealed small-scale topographic features (islands) that increased shoreline perimeter with decreased reservoir capacity.

Previous research reported that shoreline puddles < 0.5 m depth contribute 70-90% of larval vector habitats around reservoir villages at the three study dam sites (Chapter 3). If dam water levels are managed in a way that suppresses mosquito development, a significant proportion of these breeding habitats will be minimized. The present study indicated that a 10, 15 and 20 $\mathrm{mm.day^{-1}}$ water level drawdown rates was associated with a 24, 54 and 72% reduction in larval abundance at the lowland dam and a 48, 78 and 88% reduction at the midland dam during the main malaria transmission season, respectively. These reductions translated to a 19, 48 and 65% drop in EIR in the lowland dam and a 40, 71, 82% decline in EIR at the midland dam, respectively. In line with our findings, Gu and Novak (2005) found that a 30% coverage of targeted larval management could reduce the EIR by 70% at low transmission areas. In Zimbabwe, Geissbuhler *et al*. (2009) showed that larval management decreased EIR from 1.06 (0.64-1.77) to 0.56 (0.43-0.77) following larval reductions. The present study highlights the potential role of dam management in controlling larval abundance and malaria transmission in Africa settings. Indeed, water management was effectively used for malaria control in rice irrigation schemes in Kenya (Mutero 2000; Mwangangi *et al*. 2010).

Historically, successful malaria elimination programs utilizing larval management were conducted in the United States, Italy and Israel (Hess and Kiker, 1944; Kitron and Spielman, 1989; Juel, 2013). For instance, breeding habitats of *An. sacharovi* and *An. superpictus* in Palestine/Israel and of *An. labranchiae* and *An. sacharovi* in Italy were successfully reduced by the draining of wetlands (Kitron and Spielman, 1989). A number of studies in different eco-epidemiological settings (where larval habitats were distinct and accessible) in Africa

(Utzinger *et al*. 2001; Fillinger *et al*. 2004; Keiser *et al*. 2005; Walker and Lynch, 2007; Killeen *et al*. 2011; Tusting *et al*. 2013), South America (Soper and Wilson, 1943; Killeen *et al*. 2002; Martins-Campos *et al*. 2012) and Asia (Kirby *et al*. 2004; Yusuoka and Levins, 2007) have shown that larval management through environmental management can reduce the density of adult vectors and consequently malaria transmission and morbidity.

The model used for EIR estimation has some limitations. Firstly, it did not take in to account the variability in host-feeding preference of various mosquito vectors in the study area. Secondly, data generated in the present study were from mosquito traps deployed either in close proximity to people (e.g. inside houses) or adjacent to cattle. Such an approach assumes that mosquitoes freely feed indoors or outdoors, which may not always be true since some mosquitoes could be exclusively endophagic or exophagic. This could create a bias in other areas where the vectors exhibit such behavior. Therefore, caution should be taken when applying the approach used in the present study to other areas since the local prevalence of human-biting is influenced by both the mosquito species as well as availability of alternate hosts.

This study did not factor in the potential economic impacts from optimized dam management for malaria control on downstream irrigated-crop production at lowland and highland dams or hydropower generation potential of the midland dam. However, a previous study at Koka Dam in central Ethiopia (Reis *et al*. 2011) found that the application of malaria control measures using water level management would increase total average annual electricity generation from 87.6 GWh per year to 92.3.2 GWh per year (i.e. a 5.3% increase). The net increase in energy arose as more water was released through the turbines because losses from spill, seepage, and evaporation were reduced as a consequence of more rapid drawdown of the reservoir at the end of the wet season. Moreover, water level management was also predicted to have no impact on the capacity of the reservoir to meet downstream irrigation demands, yet would reduce downstream impacts of flooding from 28 days to 24 days per annum. The overall benefits of optimized dam operations and its associated cost should be examined in light of creating better health outcomes and its direct and indirect socio-economic advantages.

With over 1.1 million new annual malaria cases estimated to have originated from constructed reservoirs in SSA (Kibret *et al*. 2015b) and over 200 dams currently planned across the region, the need for additional malaria control measures is critical. Here, we have presented how the rate of water level drawdown can positively influence larval abundance at the reservoir scale. Future studies are required to investigate the economic cost of malaria around dams in sub-Saharan Africa compared with economic losses related to optimized dam operation for malaria control. Furthermore, research is needed to evaluate the actual benefits of optimized dam management by applying proposed water level drawdown scenarios.

A limitation of this study was that the resolution of the DEM (30 x30 m) used was not able to estimate reservoir parameters for a very small change in reservoir capacity. For instance, the area of wetted shoreline at the lowland dam did not change from 70 to 75% of full supply or from 80 to 85%. This could have been resolved using a higher resolution DEM (e.g. 5 x 5 m). Given the importance of shallow shoreline habitats for mosquito breeding, and the potential for error in scaling up to reservoir-scale estimates, future studies should use the highest resolution DEM available to best model the effects of water level change on shoreline larval breeding habitats and malaria risk. This study is not advocating reservoir management as the only measure to mitigate malaria around dams; instead it should be considered as an additional tool to strengthen existing vector control efforts. Thus, research is needed to illustrate the added value of reservoir management above and beyond the outcome of existing vector control measures.

This study highlighted the benefits of modifying reservoir management to incorporate mosquito control, which then translate into a reduced disease and increased economic savings. Current malaria control measures around dams are mainly composed of adult vector control using bed nets and indoor residual spraying. While these measures are important for reducing mosquito-human contact, the addition of larval management will further reduce the existing burden of malaria around large dams in Africa. The findings of this study support Fillinger *et al*. (2011) who suggested that integrated vector control (using LLIN, IRS and LSM) could bring down the EIR to near zero.

In conclusion, while dams offer vital economic opportunities for Africa, their management should incorporate cost-effective malaria control approaches. Increasing rates of water level drawdown during peak malaria transmission season could help reduce malaria transmission by suppressing the formation of stable larval habitat required to complete this life cycle stage. Thus, optimized dam operation, when coupled with currently exiting vector control measures, could help mitigate malaria around dams.

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Chapter 7

Synthesis

Despite the paramount importance of dams for economic and social development in Africa, relatively little attention has been given to the link between dams and malaria, a key public health concern in communities living around reservoirs (Kibret *et al*. 2015a). However, local entomological, environmental and climatic factors that influence malaria transmission at different eco-epidemiological settings have been unclear. Understanding such factors helps devise tailor-made approaches to tackle malaria risk around large dams in Africa. This study has looked at the association of dams with malaria and evaluated the potential for optimizing dam operation for malaria control.

Impact of dams on malaria transmission

The impact of dams on malaria transmission is not straight forward: the results of this investigation suggest that dams intensify malaria in unstable areas but not in stable areas of sub-Saharan Africa (Chapter 2 – Kibret *et al*. 2015b). This was explained by the differences in behavior and bionomics of vector species between stable and unstable areas. Epidemiological and entomological field surveys indicate that dams amplify the intensity of malaria transmission during the main transmission season (Chapter 3). The presence of malaria sporozoite-infected vector species (*An. arabiensis, An. pharoensis* and *An. funestus s.l.*) at the lowland and midland dams reaffirmed the role of these species in malaria transmission around dams. However, the intensity of malaria transmission related to dams varied significantly across elevations. Larval and adult mosquito vector abundance, entomological inoculation rate (EIR) and malaria incidence were highest at the lowland dam (Chapter 3), followed by the midland dam, and lowest at the highland dam. Furthermore, higher *P. falciparum* sporozoite infection rates were detected in *An. arabiensis* and *An. pharoensis* samples from the lowland and midland dams, while none of the female anophelines at the highland dam were found sporozoite positive. Strikingly, for the first time in 40 years, this study detected *An. funestus s.l.* infected with *P. falciparum* sporozoites at the lowland dam. This species was thought to have disappeared a long time ago from the Ethiopian lowlands (Krafsur, 1977). The reappearance of *An. funestus s.l.* at Kesem dam indicates that the ecological changes in the lowland region have created favorable breeding habitats for this vector species. Moreover, adult mosquitoes of this species were predominantly collected from outdoor traps at the lowland dam, which suggests their exophagic behavior and a challenge for control using conventional indoor-based vector control measures (i.e. bednets and IRS). The exophagic behavior of this species could also mean that people who work at night (to escape from the high humidity during the day) in sugarcane farms around the Kesem Dam (personal observation) would be highly susceptible to the infective bites from this species. Dams also attract more people – suggesting the potential for introduction of malaria parasites into areas previously non-malarious. This illustrates the critical need to re-evaluate the effectiveness of current malaria intervention measures in this region.

Shoreline puddles and irrigation canals together contributed to 96%, 70% and 62% of the total anopheline larval collections at the lowland, midland and highland dams, respectively. This reveals that dams and their associated irrigation development render favorable mosquito breeding habitats that help propagate the level of malaria transmission in nearby communities. Indeed, reservoir shorelines provide stable mosquito breeding habitats throughout the year when other habitats disappear during the dry season. Nevertheless, a complex interplay of various environmental and meteorological factors governs the dynamics of malaria transmission at different ecological settings.

Factors influencing malaria around dams

A number of environmental and meteorological factors were assessed to identify those that most explain differences in malaria incidence around three ecologically diverse study dams (Chapter 3). Village distance from the nearest reservoir shoreline was the most important factor at all three dams: the closer a village is to reservoir shoreline, the higher the risk of malaria. This is expected as mosquitoes transmitting malaria have limited flight range (Ribeiro *et al*. 1996; Kauffman and Briegel, 2004). Evidently, distance between villages and the nearest reservoir shoreline was shortest (1-2 km) during the main transmission season – indicating an elevated risk of malaria transmission as vector abundance peaked during this season. In contrast, distance of villages from reservoir shoreline was considerably higher (5-7 km) during the dry season, which consequently reduces the risk of malaria transmission as fewer young mosquitoes could travel the longer distances from the shoreline habitat to villages. This risk of increased malaria due to proximity to larval habitats is widely recognized across sub-Saharan Africa (Minakawa *et al*. 2002; Staedke *et al*. 2003; Zhou *et al*. 2004; McCann *et al*. 2014).

However, temporal change in a village's distance from the reservoir shoreline was the result of reservoir water level change: increasing water levels shorten the distance between the villages and the shoreline while receding water levels increase the distance between the shoreline and nearby villages. Monthly reservoir water level and monthly water level change when lagged by 1 and/or 2 months were also important environmental variables significantly associated with monthly malaria incidence at the three study dams (Chapter 4). Malaria incidence generally peaked following the months of high reservoir water level. High malaria incidence during this period was mainly the outcome of amplified larval and adult vector abundances as a result of shoreline puddle formation as mosquito breeding habitat (Chapter 3) – particularly when the reservoir water levels starts to fall from full capacity. Larval control using reservoir water level management would be ideal and seemingly effective if targeted during this period. The experimental and modelling work identified that faster water level drawdown rates were significantly negatively correlated with larval vector abundance (Chapter 5 and 6). If water level management is effectively applied, a significant proportion of shoreline larval habitats could be reduced (Chapter 6). A previous study indicated that targeting major larval breeding sites for larval control could result in an 86% reduction in EIR and 73% reduction in malaria incidence in low transmission areas (Gu and Novak, 2005).

Meteorological factors were also found to play a role in determining the intensity of malaria transmission around the study dams (Chapter 4). Regression models showed that while precipitation was an important factor at lowland and midland dams, minimum temperature was found to influence malaria incidence at the highland dam. Obviously, the availability of water at semi-arid lowland and midland regions is largely associated to the rainy season. Heavy rains also affect reservoir water levels since over 60% of reservoir water originates from rainfall related runoff. Teklehaimanot *et al*. (2004) reported that precipitation could be used as an early warning system for malaria epidemics in the lowlands of Ethiopia, as epidemics often follows months of heavy rainfall.

In the highlands, temperature is the major determinant of malaria transmission, as indicated in studies elsewhere (Lindsay and Martens, 1998; Craig *et al* 1999; Blanford *et al*. 2013;

Mordecai *et al*. 2013). This explains why larval abundances were significantly lower at the highland dam site compared with the lowland and midland dam sites (Chapter 3). Although reservoir shoreline and downstream irrigation canals provided ample mosquito breeding habitats during the main transmission season, low temperature (<15°C) appeared to limit larval development as it takes several days (> 47 days) to complete mosquito aquatic stages (Teklehaimanot *et al*. 2004). However, in view of future climate change scenarios, which are generally projected to increase temperatures in Eastern African highland (Caminade *et al*. 2014), the impact of highland dams on mosquito productivity may change to support higher developmental rates of mosquitoes.

Opportunities for malaria control

Analyzing the trade-off between the malaria impact and benefits of dams is required to ensure their sustainability. Although dams intensify malaria transmission, particularly in lowland and midland settings, field-based experimental (Chapter 5) and modelling (Chapter 6) work indicated that dams could also be used for larval mosquito control. When water level drawdown rates of 10, 15 and 20 mm.day^{-1} were tested in field experimental dams, significant reductions in anopheline larval abundance were observed with increasing water level drawdown rates (Chapter 5). Consequently, the risk of malaria infection (as measured by EIR), number of malaria cases and costs associated with malaria treatment and working day losses were significantly diminished with increasing drawdown rates (Chapter 6). Previous works in the United States, Israel and Italy documented that anopheline breeding habitats around reservoir shoreline can be desiccated if cyclic water level fluctuations were applied during major mosquito propagation seasons (Darrow, 1949; Juel 2013). The present study provides corroborative accounts for the opportunity of using dam management for malaria control in African settings.

Limitations of the study

This study bears a number of limitations, like any other longitudinal study. Firstly, the experimental work was only conducted at the midland dam, and the results were assumed to be consistent at all study dams. Since mosquito development is the result of the interplay between various ecological, climate and entomological parameters, the results from the experimental work should be interpreted with caution. Nevertheless, the experimental work was selectively conducted in the midland dam so that the results would represent a conservative estimate intermediate of the two extreme settings (lowland *vs* highland). Obviously, it is costly to duplicate the experimental work in all study dams with limited resources. Secondly, the modelling work that estimated larval anopheline abundance, EIR and malaria prevalence rates at wetland scale for different water level drawdown rates were based on several assumptions (i.e. larval density and productivity at different water level drawdown rates, transmission efficiency, and sporozoite rate). Thirdly, the impact of different water level drawdown rates on the primary purposes of the dams (i.e. irrigation-based crop production and hydroelectric generation) was not investigated. Moreover, proper planning is required to manage the water that would be released from the dam for malaria control purposes during the main transmission season. In fact, a previous study at Koka Dam indicated that targeted use of water level management for malaria vector larval management could be undertaken without sacrificing the key benefits of the reservoir (Reis *et al*. 2011). Nevertheless, the economic and social impacts of water level manipulations for malaria control require further investigation.

Implications for management

A recent study showed that dams contribute to over 1 million cases of malaria in sub-Saharan Africa (Kibret *et al*. 2015a). Even worse, the impact of dams is expected to worsen in light of the current extensive dam constructions in the region. This is not good news for Africa as the region is striving for malaria elimination, setting a new goal of shrinking the malaria map "towards zero" by 2030 (RBM, 2015). Various global partners such as the Roll Back Malaria Partnership, Gates Foundation, Global Fund for HIV/AIDS, TB and Malaria, and the US President's Malaria Initiative have called for new tailor-made malaria intervention tools to achieve the ambitious malaria control goal. With several reports of mosquitoes' resistance to available insecticides and widespread resistant strains of malaria parasites to first-line drugs, the world once again has turned its face to larval management (Worrall and Fillinger, 2011). Optimized dam management is thus a potential, chemical-free, and cost-effective approach to mitigate malaria around a large area of wetlands that arise due to dams.

The findings of the present study highlight that dam water levels can be manipulated to disrupt larval development by desiccating shoreline puddles. Indeed, faster drawdown rates, at least in experimental dams, were shown to lead to significantly reduced larval abundance due to a fast-drying shoreline. In view of the on-going extensive dam construction in Africa where over 200 large dams are currently planned or under construction (Zarfl *et al*. 2015) – taking the total number of large dams over 2000 – additional tailor-made malaria control tools are indeed required. Targeting larval management using reservoir water level manipulation therefore would be a relatively cost-effective additional vector control tool in Africa. The potential of using larviciding or insect growth regulator applications could also be an option to reduce larval population around reservoirs, Furthermore, since mosquito larvae, unlike adults, cannot change their habitat to avoid control, larval management targets all mosquitoes, including those exophgic and exophilic mosquito species that currently challenge the efficacy of current vector control tools, before they disperse to human habitations.

Environmental management of larval habitats (i.e. alteration of breeding habitats to create unfavorable conditions for mosquito production) has been shown to profoundly impact malaria transmission, particularly when used in combination with other proven vector control measures, such as indoor residual spraying and insecticide-treated nets (Keiser *et al*. 2005; Bier *et al*. 2008). These findings led the World Health Organization to advocate malaria prevention and control strategies that emphasize on ‘integrated vector management’ (IVM) (WHO, 2014). If Africa is serious about implementing malaria elimination strategies, IVM will be indispensable to dramatically reducing EIR to below one (Killeen *et al*. 2000; Shaukat *et al*. 2010). Beier *et al* (2008) reported that only annual EIRs less than one could reduce parasite rates to levels that could interrupt malaria transmission. The present study provides accounts of supplementing the existing vector control measures with larval management using optimized dam operation for mitigating malaria. Environmental impact assessment of dam construction should critically consider measures to fully offset adverse effects of dams on public health while designing, constructing and operating these infrastructures. The need for intersectoral collaboration between the health and water authorities is therefore required to assess possible institutional constraints of optimized dam management for operationalization.

Future research directions

This study underscores the need to optimize dam management in order to incorporate malaria vector control into reservoir management practices. Future research should assess the practicability of dam management for malaria control in diverse African settings. Analyzing the cost of optimized dam operation on crop production and hydropower generation is also required. Future studies should also explore malaria risk associated with climate change in the vicinity of dams in Africa. Future investigations need also to assess how temperature and rainfall changes will affect reservoir water levels, shoreline parameters, and hence future dam operations. Understanding such broader picture will in turn provide a more holistic understanding of impacts of water resources development on malaria transmission.

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Publication from this Thesis

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Appendix 1

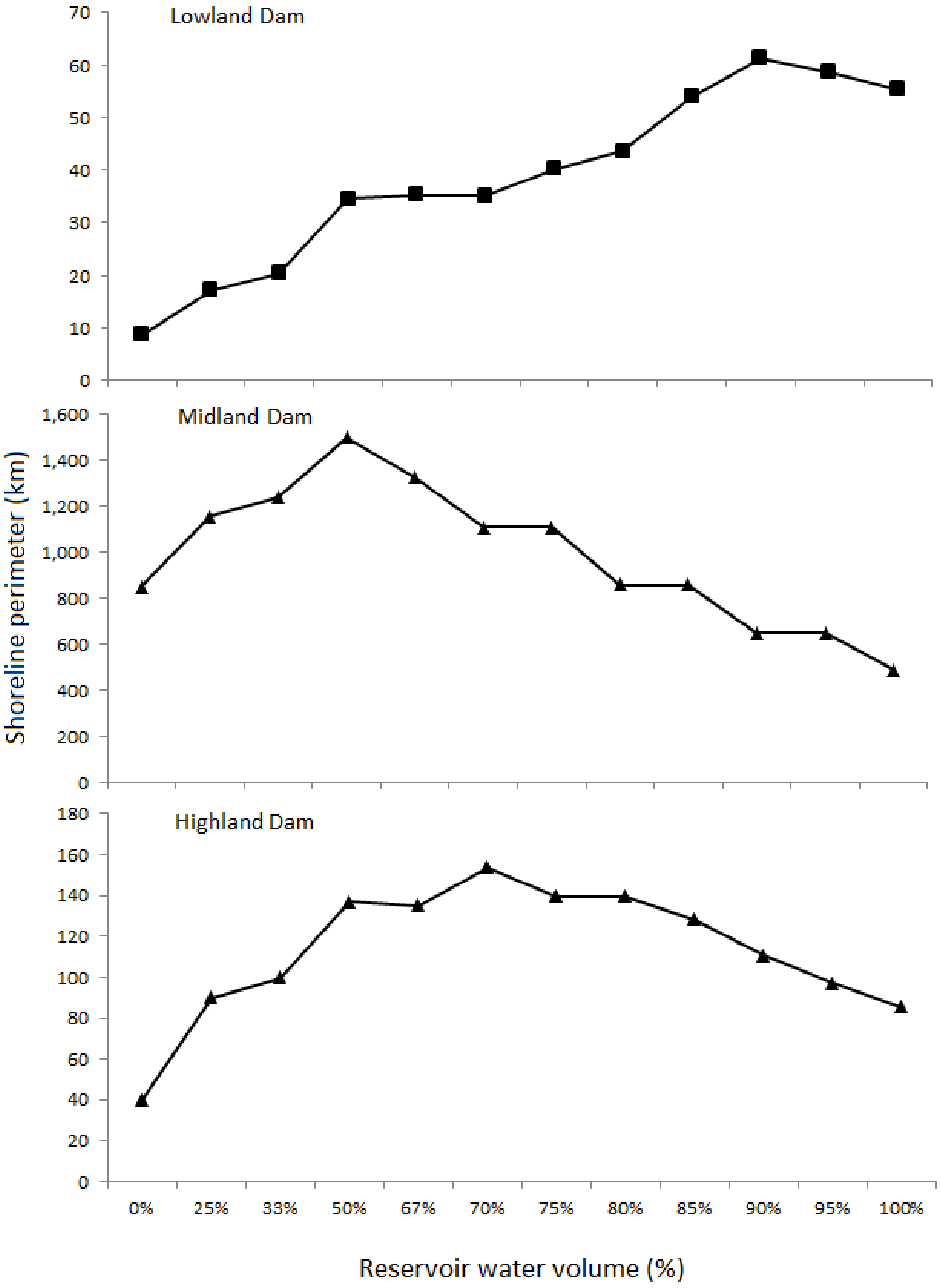
Cross-correlation among environmental factors

Variables	Monthly mean minimum temperature	Monthly mean maximum temperature	Mean monthly total precipitation	Monthly average water level	Monthly change in water level	Monthly NDVI
Monthly mean minimum temperature	1	0.744*	0.206	-0.612*	0.101	0.211
Monthly mean maximum temperature	0.744*	1	0.461*	-0.432*	0.574*	0.613*
Mean monthly total precipitation	0.206	0.461*	1	0.236	0.789*	0.561*
Monthly average water level	-0.612*	-0.432*	0.236	1	0..244	0.348*
Monthly change in water level	0.125	0.558*	0.789*	0.244	1	-0.455*
Monthly NDVI	0.211	0.613*	0.561*	0.348*	-0.455*	1

* Pearson correlation significant ($P < 0.05$)

Appendix 2

Perimeter of the wetted shoreline at different water volume capacities



Appendix 3 - Data Permission Request Letters

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27 August 2013

Metehara Woreda Health Office
West Harerghe Zonal Administration
Oromia Regional State
Ethiopia

Re: Request for retrospective clinical malaria data

Dear Sir/Madam,

Solomon Kibret Birhanie is a PhD student at the University of New England in Australia, undertaking research on malaria management around large dams in Ethiopia. The attached proposal gives further information on Solomon's research aims and proposed activities.

Solomon will be collecting mosquito and water-level data from near Koga, Koka and Kessem dams to examine the link between malaria incidence, mosquito abundance and water level fluctuation at these dams. However, he will also access water level data from each dam from the past five years to examine how dam water levels may have influenced local malaria infection rates.

One of Solomon's study sites is the area where Kessem dam is located. This letter is thus to request that you provide Solomon with access to the past five years of retrospective malaria data from health centres in the Kessem dam area, in order to investigate the link between Kessem dam water-level fluctuations and malaria incidence in the nearby community. These data will be used solely for Solomon's research, and we will send you a copy of any publications from this work.

I thank you for your cooperation in advance.

Sincerely yours,

[redacted]

Dr Glenn Wilson

Principal Supervisor

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One of Solomon's study sites is the Ejersa area where Koka dam is located. This letter is thus to request that you provide Solomon with access to the past five years of retrospective malaria data from health centres in the Ejersa area, in order to investigate the link between Koka dam water-level fluctuations and malaria incidence in the nearby community. These data will be used solely for Solomon's research, and we will send you a copy of any publications from this work.

I thank you for your cooperation in advance.

Sincerely yours,

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Ethiopian Electricity and Power Corporation

Addis Ababa, Ethiopia

Re: Permission to access Koka and Kessem dam sites and provision of water-level data

Dear Sir/Madam,

Solomon Kibret Birhanie is a PhD student at the University of New England in Australia. His research focuses on malaria management around large dams in Ethiopia. The attached proposal gives further information on Solomon's research aims and proposed activities.

Solomon wishes to collect mosquito and water-level data from Koka and Kessem dams to examine the link between malaria incidence, mosquito abundance and water level fluctuation at these dams. This letter is thus to request your permission for Solomon to have access to these two dam sites between September 2013 and May 2014. During this period, Solomon would like to meet with dam managers to inform them of his sampling activities and to learn more about the rules used to manage each dam's water levels and releases.

Solomon would also greatly benefit from you providing him with water level data from the two dams for at least the past five years, in order to match patterns in water-level fluctuation with local malaria incidence data collected by Health Department authorities over the same period. These data will be used solely for Solomon's research, and we will send you a copy of any publications from this work.

I thank you for your cooperation in advance.

Sincerely yours,

[redacted]

Dr Glenn Wilson

Principal Supervisor