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Malaria Transmission in the Vicinity of Impounded Water: Evidence from the Koka Reservoir, Ethiopia

Solomon Kibret, Matthew McCartney, Jonathan Lautze and Gayathree Jayasinghe

International Water Management Institute

CGIAR Challenge Program on WATER & FOOD

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Kibret, S.; McCartney, M.; Lautze, J.; Jayasinghe, G. 2009. *Malaria transmission in the vicinity of impounded water: Evidence from the Koka Reservoir, Ethiopia.* Colombo, Sri Lanka: International Water Management Institute. 47p. (IWMI Research Report 132)

/ malaria / waterborne diseases / disease vectors / disease control methods / dams / epidemiology / entomology / surveys / case studies / reservoirs / Ethiopia /

ISSN 1026-0862
ISBN 978-92-9090-706-0

Cover photograph by Jonathan Lautze shows the shoreline of the Koka Reservoir, Ethiopia.

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Acknowledgements

The authors would like to thank Beyene Petros, Paul Kirshen, Richard Pollack and Eline Boelee for their advice; and Tesfaye Abebe, Lemma Regassa and Asegid Taye for considerable assistance with the fieldwork and in the laboratory. They are also grateful to the late Andrew Spielman for the role he played during the early stages of this study. They thank the Ethiopian Federal Ministry of Health, the Oromia Health Bureau, the Ethiopian Electric Power Corporation and the National Meteorological Agency for the provision of data.

Project

CGIAR Challenge Program on WATER & FOOD

This report presents findings from project number 36 entitled "Improved Planning of Large Dam Operation: Using Decision Support Systems to Optimize Livelihood Benefits, Safeguard Health and Protect the Environment" of the CGIAR Challenge Program on Water and Food (CPWF).

Partners

The following organizations collaborated in the research conducted for this report:

International Water Management Institute (IWMI), Addis Ababa, Ethiopia

Addis Ababa University, Addis Ababa, Ethiopia

About the CPWF

Water scarcity is one of the most pressing issues facing humanity today. The Challenge Program on Water and Food (CPWF), an initiative of the Consultative Group on International Agricultural Research (CGIAR), contributes to efforts of the inter-national community to ensure global diversions of water to agriculture are maintained at the level of the year 2000. It is a multi-institutional research initiative that aims to increase water productivity for agriculture-that is, to change the way water is managed and used to meet international food security and poverty eradication goals-and to leave more water for other users and the environment.

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Contents

Abbreviations and Acronyms

CDC	Center for Disease Control and Prevention
CI	Confidence Interval
CSA	Central Statistics Authority, Ethiopia
CSP	Circumsporozoite protein
DDT	Dichlorodiphenyl trichloroethane
EEPCO	Ethiopian Electric Power Corporation
EIR	Entomological Inoculation Rate
ELISA	Enzyme-Linked Immunosorbent Assay
GIS	Geographical Information System
GPS	Geographical Positioning System
HBI	Human Blood Index
IRS	Indoor Residual Spraying
ITN	Insecticide Treated Nets
MoH	Ministry of Health, Ethiopia
NEPAD	New Partnership for African Development
NMA	National Meteorological Agency, Ethiopia
RBM	Roll Back Malaria
WCD	World Commission on Dams
WHO	World Health Organization

Summary

The construction of dams in Africa is often associated with adverse malaria impacts in surrounding communities. However, the degree and nature of these impacts are rarely quantified and the feasibility of environmental control measures (e.g., manipulation of reservoir water levels) to mitigate malaria impacts has not been previously investigated in Africa. This report describes entomological and epidemiological research conducted in the vicinity of the Koka Dam and Reservoir in Ethiopia. Key findings of the study include: a) substantially higher malaria case rates observed in communities close to the reservoir; b) greater abundance of malaria vectors found in community dwellings close to the reservoir as a consequence of breeding habitats created along the reservoir shoreline; and c) the association of faster falling water levels with lower mosquito larval abundance in shoreline puddles. These findings confirm the role of the reservoir in increasing malaria transmission and suggest there may be potential to use dam operation as a tool in integrated malaria-control strategies.

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Introduction

Investment in hydraulic infrastructure, including large dams, is widely advocated as crucial for sustainable economic growth and poverty reduction in many parts of sub-Saharan Africa (World Bank 2004; NEPAD 2003). However, the cost these structures impose is much more than financial. Inadequate consideration of both environmental and public health impacts can undermine the benefits to be gained from such investments (McCartney et al. 2007). Key among the potential negative effects of large dams is intensified malaria transmission, resulting from changes engendered by environmental and socioeconomic transformations accompanying water resources development (Hunter et al. 1993; Jobin 1999; Keiser et al. 2005; Birley 1995).

Although the potential health impacts of large dams are broadly understood, there is relatively little systematic research into these impacts and almost no quantitative information on the impact of dams on malaria case rates and vector density in communities at different distances from the dam, particularly in sub-Saharan Africa. The need for more research into the connections between dams and health, whose results can be used to assist with health assessment when planning and constructing dams, has been highlighted (e.g., Jobin 1999; Sleigh and Jackson 2001; WHO 2008).

This report describes a study undertaken to investigate the effect of the Koka Reservoir, located in Central Ethiopia, on malaria transmission and to evaluate the possibility of dam operation being used as a malaria-control measure. Specifically, entomological and epidemiological surveys were conducted to:

- Compare malaria case rates in villages at different distances from the reservoir (i.e., 0-9 km).
- Compare mosquito breeding habitats in villages close to (< 1 km) the reservoir with those further away (> 7 km) and characterize breeding habitats associated with the dam and reservoir shore.
- Compare vector density in villages close to the reservoir with that in villages further away.
- Explore the degree to which rates of change in reservoir water levels correlate with the abundance of *Anopheles* sp. larvae in shoreline sites and malaria case rates in the vicinity (within 9 km) of the Koka Reservoir.

Mosquitoes and Malaria in Africa

Globally, about half the world population (3.3 billion) are at risk of malaria infection and around 250 million cases occur annually, leading to approximately 1 million deaths each year (WHO 2008). Over 86% of the global burden and 90% of the global deaths occur in sub-Saharan Africa. The disease is the leading cause of the death of Africa's children, causing approximately 20% of all child deaths under five (WHO 2006). Malaria causes great economic loss in many African countries and is considered a major barrier to the socioeconomic development of the continent (Malaney et al. 2004; Kouyaté et al. 2007).

Malaria transmission involves complex interactions between *Plasmodium* parasites (i.e., the causative agent of malaria),[1] female *Anopheles* mosquitoes and people. In sub-Saharan Africa, there are 140 *Anopheles* species of which approximately 20 are known to transmit malaria to human beings under natural conditions (Fontenille and Lochouam 1999). Of these, *Anopheles gambiae* sensu stricto Giles, *An. arabiensis* Patton and *An. funestus* Giles are the most widely distributed and the most efficient malaria vector species in tropical Africa. *An. pharoensis* is also a major transmitter in arid and semiarid regions with permanent water bodies (Gillies and De Meillon 1968; Gillies and Coetzee 1987).

Generally, mosquitoes breed in non- or slow-flowing, shallow water bodies, unaffected by waves. Both *An. gambiae* s.s. and *An. arabiensis* prefer to breed in temporary sunlit puddles, including those produced by rain and irrigation, as well as in shallow shoreline puddles adjacent to rivers and lakes. *An. funestus* and *An. pharoensis* prefer shaded and permanent freshwater bodies (Table 1). The stability of malaria transmission is a function of many environmental factors. Many studies have shown that climatic variables, such as temperature, rainfall and humidity, profoundly affect key determinants of malaria transmission (Macdonald 1956; Martens 1995; Lindsay and Birley 1996; Kiszewski et al. 2004; Teklehaimanot et al. 2004; Zhou et al. 2004).

In Ethiopia, about 52 million people (i.e., 68% of the total population) live in malaria-risk areas (Figure 1). Typically, 5-6 million clinical malaria cases and over 600,000 confirmed cases are reported from health facilities each year (MoH 2004). The disease is a major cause of morbidity and mortality. In epidemic years mortality levels of up to 100,000 children are not uncommon. In the last major epidemic in Ethiopia, in 2003, there were up to 16 million cases of malaria (MoH 2008). Until recently, malaria accounted for approximately 20% of all hospital admissions and 27% of hospital deaths (MoH 2004). However, in the past few years, the rapid scaling up of interventions to control malaria (i.e., the distribution of more than 20 million bed nets to 10 million households in 2005 and doubling of DDT spraying between 2007 and 2008) appears to have resulted in an appreciable decline in the overall malaria burden of the country (MoH 2008). Nevertheless, malaria remains a major cause of mortality and is a severe economic loss to the country. Peak malaria transmission occurs at the end of the rainy season, generally lasting from mid-September to mid-November (Ghebreyesus et al. 2006). This coincides with the major growing season and harvest time and so malaria diminishes agricultural productivity.

Dams and Their Link to Malaria

Construction of dams and irrigation schemes has long been associated with the creation of breeding habitats for malaria vector mosquitoes (Keiser et al. 2005). Throughout much of Ethiopia, unstable malaria transmission and very low entomological inoculation rates (i.e., less than one infective bite per person per night during the main transmission season) mean immunity is relatively low and thus all age groups in the population are likely to suffer from the disease (MoH 2008). Lower levels of natural immunity resulting from lack of year-round

[1] Four species of malaria parasites are reported from humans. Of these *P. falciparum* is known to cause the most severe forms of the disease. Other species are *P. vivax, P. ovale* and *P. malariae.*

sustained malaria transmission in zones of unstable transmission often result in severe malaria epidemics when environmental conditions shift to favor malaria transmission (Kiszewski and Teklehaimanot 2004). In such areas, impounded water holds great potential to increase malaria transmission so long as daily temperatures are warm enough (i.e., typically higher than 20 °C) to support the development of the aquatic stages (i.e., egg, larva, pupa) of mosquitoes.

Although rarely quantifiably documented in Africa, a few studies have shown a link between the presence of impounded water and elevated malaria transmission in nearby communities (e.g., Atangana et al. 1979; Oomen 1981; Roggeri 1985; King 1996). Recent studies in northern Ethiopia have demonstrated that malaria incidence among children living in communities close to irrigation micro-dams was seven times higher than amongst those living further away (Ghebreyesus et al. 1999). Entomological surveys in the same area confirmed that increased malaria incidence associated with dams resulted from a rise in mosquito abundance, particularly *An. arabiensis* (Yohannes et al. 2005). A recent study in southwestern Ethiopia also showed a higher prevalence of malaria in villages closer to the Gilgel-Gibe Reservoir than in control villages (Yewhalaw et al. 2009).

TABLE 1. Geographical distribution, breeding sites, feeding behavior and resting sites of major malaria vectors in Africa (Gilles and Warell 1993).

Anopheles species	Geographical distribution	Breeding site	Feeding behavior	Resting site
An. gambiae s.s.	Sub-Saharan Africa (especially in more humid areas of tropical and equatorial Africa)	Sunlit puddles such as rain pools, riverbed and shoreline puddles, irrigated field puddles, etc.	Primarily feeds indoors and highly anthropophilic	Endophilic
An. arabiensis	Sub-Saharan Africa (especially in drier regions of West, East and Central Africa)	Sunlit puddles such as rain pools, riverbed and shoreline puddles, irrigated field puddles, etc.	Partially outdoor-feeder with some zoophilic tendency	Partially exophilic
An. funestus	Equatorial and tropical Africa	Permanent water bodies particularly those with emergent vegetation, irrigation canals, deep rain pools and irrigated fields with partial coverage with plant (especially rice fields)	Primarily feeds indoors and highly anthropophilic	Endophilic
An. pharoensis	Mainly in West and East Africa	Permanent water bodies with emergent vegetation, irrigated fields, irrigation canals and rain pools	Primarily feeds outdoors with some zoophilic characteristics	Exophilic with some postprandial endophilic tendency

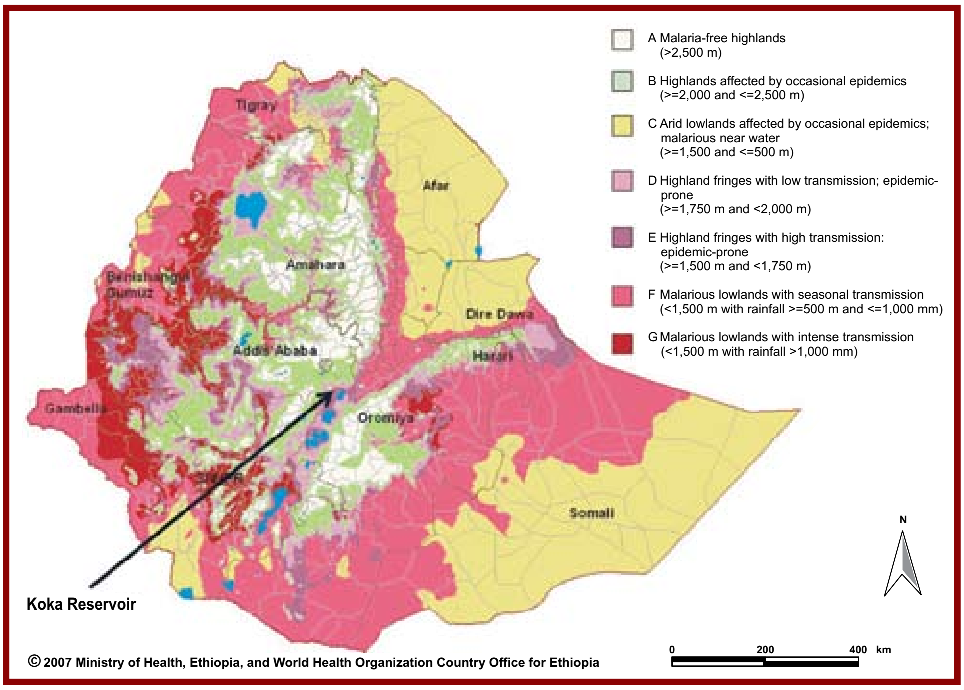


FIGURE 1. Distribution of endemic malaria in Ethiopia (*source*: Ethiopian Ministry of Health and World Health Organization 2007). This map was derived by combining data on rainfall and altitude.

In Africa, there are fewer than 1,500 large dams to date.[2] This compares to a global total of more than 45,000. Currently, Africa has by far the lowest per capita storage of any continent (WCD 2000). Responding to this shortfall, the World Bank, the African Development Bank, the European Union and China, as well as many other governments, are now investing heavily in the development of hydraulic infrastructure. As a result, many dams are under construction and many more are planned (McCartney 2007). In Ethiopia, dams are widely perceived to be essential for effective water resources development and crucial for sustainable economic growth and poverty reduction (World Bank 2006). Consequently, several large dams are currently being built for hydropower and irrigation, and feasibility studies have been undertaken for others, including several in the Awash, Omo/Gibe and Nile basins (Hathaway 2008). The degree of impact of existing dams and the likely impact of planned dams on malaria transmission are limited to speculation. Research is required to understand the relative impact of reservoirs on malaria transmission under different hydro-climatic conditions.

Reservoir Management for Malaria Control

Studies demonstrating the efficacy of conventional malaria-control strategies (e.g., use of bed nets, indoor residual spraying [IRS] with DDT and new drug cocktails) are abundant (Curtis et al. 1990;

[2] Large dams are defined as those higher than 15 m from base to crest, or those with a storage capacity exceeding 3 million cubic meters (Mm^3) for heights between 5 and 15 m (ICOLD 2003).

Coosemans and Carnevale 1995; Lengeler and Sharp 2003). However, there are also examples highlighting their limitations. Indeed, there is a growing body of literature (Abose et al. 1998; Guyatt et al. 2002; Shililu et al. 2004) documenting that bed nets may not be as effective as originally anticipated because of human behavior (e.g., child movement at night, outdoor sleeping) and/or mosquito feeding behaviors (e.g., early evening, outdoor feeding preferences). Lack of financial resources for available medical and chemical control measures is a major constraint in many countries in sub-Saharan Africa. Their efficacy is further reduced as a consequence of resistance of *Plasmodium* to drugs and of mosquitoes to DDT (Hargreaves et al. 2000; Mittal 2003). Biological control methods, such as the introduction of larvivorous fish (Howard et al. 2007), are also limited and are not always feasible, particularly in shallow, ephemeral puddles. The shortcomings of strategies relying solely on single methods of control indicate the need for approaches employing multiple tools to suppress transmission of the disease (Mutero et al. 2004).

Recent research (e.g., Mutero et al. 2000; Utzinger et al. 2001; Klinkenberg et al. 2002; Konradsen et al. 2004; Keiser et al. 2005) has devoted increasing attention to environmental management, particularly water management, to reduce malaria incidence. This body of research generally reexamines methods employed in the first half of the twentieth century, which sought to manipulate the environment to create conditions less conducive to vector reproduction. Historical studies have found that appropriate management of mosquito larval habitats, in areas with low vectorial capacity, can help suppress malaria transmission in such areas (Macdonald 1956). Examples are cited from the USA (Hackett et al. 1938; Tennessee Valley Authority 1947) and India (Henderson 1955) that demonstrate how reservoir water levels can be manipulated to render habitats less favorable for mosquito breeding. In the south of the USA, such measures helped eradicate malaria from the area, and are still used for “nuisance” mosquito control (Gartrell et al. 1972).

The Study Area

The Koka Dam is located 1,551 masl in the Ethiopian Rift Valley in the Awash River Basin, approximately 100 km southeast of Addis Ababa (Figure 2). Commissioned in 1960, it is a concrete gravity dam with a total capacity of 1,850 Mm^3 and a mean annual regulated flow of 42.3 m^3s^{-1} (Table 2). The dam was constructed primarily for hydropower generation with an installed capacity of 43.2 MW from three turbines (i.e., approximately 6% of the current total grid-based generating capacity of the country). The dam is operated by the Ethiopian Electric Power Corporation (EEPCO). Today, the Wonji sugarcane irrigation scheme (6,000 ha), located approximately 12 km downstream of the dam, is also dependent on releases from it. In addition, the dam is also used for flood control. More than 40% of the reservoir storage capacity has been lost to date as a result of sedimentation (Tate and Lyle Technical Services Ltd. 1984). Consequently, the flow to the Wonji irrigation scheme is reduced, especially during May and June.

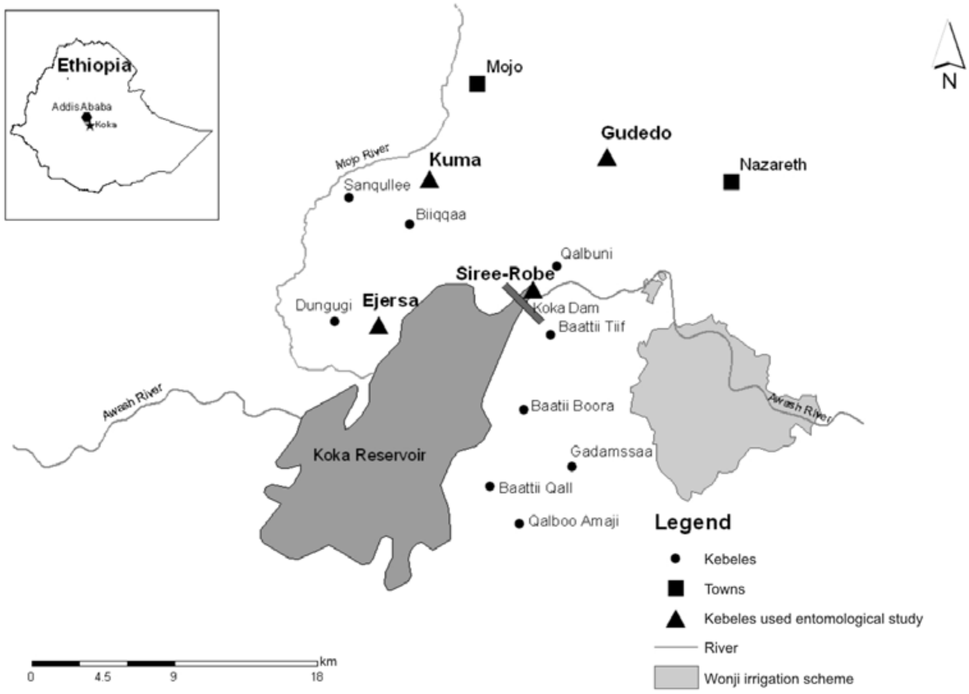


FIGURE 2. Location of the Koka area in central Ethiopia. The triangular points represent each of the study villages.

TABLE 2. Design characteristics of the Koka Dam and Reservoir.

Dam	
Location	8°28'N 39°9' E
Altitude	1,551 masl
Crest elevation	1,593 masl
Maximum height	42 m
Crest length	426 m
Hydrology	
Catchment area	11,500 km^2
Annual runoff	1,610 Mm^3
Reservoir	
Maximum normal water level (FSL)	1,590.7 masl
Minimum normal water level	1,580.7 masl
Total storage at FSL*	1,850 Mm^3
Live storage	1,670 Mm^3
Dead storage	180 Mm^3
Surface area of lake at FSL	236 km^2

* Reduced to 1,188 Mm^3 by 1999 as a consequence of sedimentation.
Notes: FSL=Full supply level.
Source: Water Works Design and Supervision Enterprise 2006.

In many places the reservoir shoreline is pitted with shallow puddles, caused by the gentle slope and often created partly by the trampling of cattle. The reservoir shoreline serves as a major livestock watering area. Pools of seepage water in the otherwise normally dry riverbed, immediately downstream of the dam, also provide mosquito breeding habitats (Figure 3a, b).

(a)

(b)

FIGURE 3. (a) Reservoir shoreline upstream of the dam; and (b) Seepage pools immediately downstream of the dam (*Photo credits:* Jonathan Lautze).

The average annual rainfall is 880 mm, but with considerable variation from year to year. Typically, most rain falls from June to September, but "short rains" usually occur between March and May (Figure 5). The mean annual temperature is 24 °C while May is the hottest month of the year (Figure 4).

In common with the whole of Ethiopia, for administrative purposes, people in the area are grouped in *kebeles* (groups of small villages, typically with 1,000–15,000 inhabitants). Most households in the area are extremely poor, surviving primarily through subsistence rain-fed agriculture and livestock-herding (cattle, sheep, goats). Typical annual income is approximately ETB 5,000 (US$525) per household (Gebremeskel 2006). Most people live in traditional mud huts, some with corrugated iron roofs, known as *tukuls.*

In central Ethiopia, malaria is seasonally demarcated, with peak transmission following the long wet season, generally lasting from mid-September to mid-November. Because it is seasonal, transmission in the region is considered unstable (Ghebreyesus et al. 2006) and most of the population lacks immunity against the disease. The regional (Oromia) health authority attempts to reduce malaria through indoor residual spraying (i.e., with DDT or malathion) in villages with higher risk of the disease and by case management (i.e., treatment of diagnosed cases with antimalarial drugs).

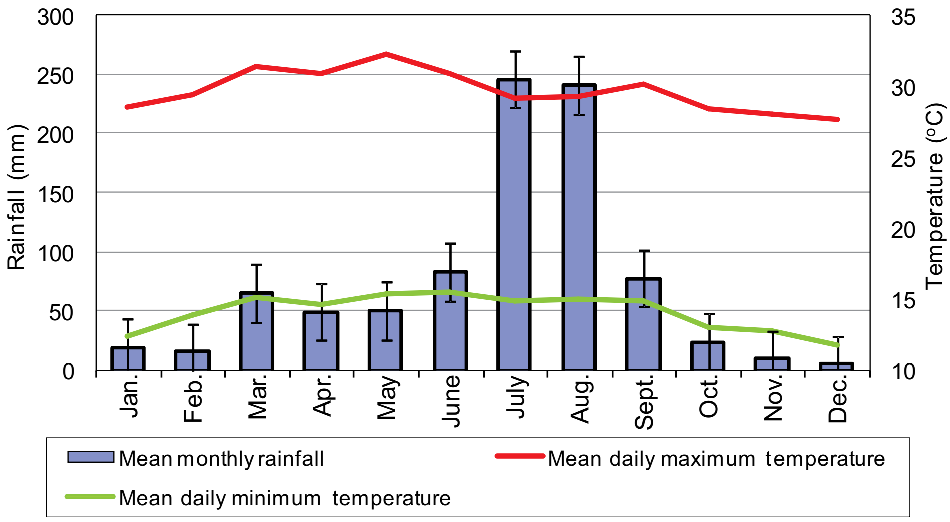


FIGURE 4. Summary of meteorological data (rainfall and temperature) from the meteorological station located at the Koka Dam (1994 to 2007). The vertical bars indicate the standard deviation in the mean monthly rainfall.

Materials and Methods

This study comprised both epidemiological and entomological surveys. The epidemiological survey utilized secondary data and combined long-term malaria case data with information on reservoir operation and climate. The entomological surveys collected primary data on both adult mosquitoes and larval breeding habitats in selected villages located at different distances from the reservoir.

Epidemiological Survey

Records of malaria diagnoses were obtained for a total of 13 kebeles located within 9 km of the reservoir[3] for the period October 1994 to December 2007 (i.e., 13 complete years). These data were obtained from three malaria control centers located in the towns closest to the reservoir: Adama (formerly Nazareth), Mojo and Alem Tena (Figure 2). The malaria control centers are government-run clinics, providing free diagnoses and treatment. At the centers, malaria is diagnosed by microscopically examining a giemsa[4]-stained blood-smear taken from each patient. In each case, the names of the patient's kebele and village are recorded, using a unique identification number, along with the diagnosis. For positive diagnoses, the type of malaria (i.e., *P. falciparum, P. vivax* or *P. malariae*) is also recorded. In this study, the data were obtained from the original data sheets archived at the malaria control centers, aggregated from weeks to months and keyed into excel spreadsheets. With the exception of one month with no information at Siree-Robe (October 1995) complete data sets were obtained for all the kebeles.

The limitations of clinical records (so-called passive case-detection) as opposed to active detection (such as house-to-house surveys) for computing malaria incidence are well recorded (Snow et al. 2005). In this case, the clinical records cannot capture the full level of malaria transmission in the region because some people do not report to the formal clinics, but rather use traditional healers or self-diagnose and purchase their own drugs. Nevertheless, because treatment is free, it is believed the majority do report to the control centers. Furthermore, because the region is economically and socially homogeneous it is unlikely that using clinical data will have significantly biased the analyses related to proximity to the reservoir Hence, although active case-detection would have been ideal, we are confident that the study findings, reported below, are valid.

Time series of meteorological data (i.e., rainfall, air-temperature and relative humidity) were obtained from the National Meteorological Agency (NMA) for stations operated in the vicinity of the reservoir, namely, Koka Dam, Mojo and Nazareth (Adama) (Table 3). Only monthly data were available. Data on daily reservoir water levels were collected from EEPCO from October 1994 to December 2007.

The coordinates of the center of each kebele and the three malaria control centers were determined using a Geographical Positioning System (GPS). The distances between each geo-referenced kebele and the nearest point on the margin of the Koka Reservoir, calculated at average reservoir capacity, were determined. The distances between each kebele and the nearest malaria control center and between each kebele and the nearest point on the margin of the Wonji irrigation project were also ascertained. Although it might be anticipated that the irrigation scheme would affect malaria in the kebeles located closest to it, none of the villages near the reservoir lie within the flight range of mosquitoes that might originate in the irrigation scheme. Furthermore, a line of hills separates the reservoir villages from the scheme making it even less likely that it would have affected malaria transmission in them. Accordingly, the irrigation scheme is not thought to have influenced the study results. Finally, the distances between each kebele and the meteorological stations were determined. The climate in a particular kebele was assumed to be similar to that of the closest meteorological station. If particular meteorological data points were missing, data were taken from the next nearest station for which data were available.

[3] The approximate flight range of the vector mosquitoes is 3 km (Ribeiro et al. 1996). Hence, the distance 9 km represents three-times the flight range.

[4] Giemsa stain, named after Gustav Giemsa, is used for the histopathological diagnosis of malaria.

TABLE 3. Meteorological stations for which data were obtained.

Meteorological station	Location	Altitude (masl) provided by NMA*	Mean annual rainfall (mm)	Length of record
Koka Dam	8°25'N 39°01' E	1,595	880	1994-2007
Mojo	8°37'N 39°07' E	1,870	896	1994-2007
Nazareth	8°33'N 39°17' E	1,622	882	1994-2007

*NMA – National Meteorological Agency.

Population data from the Ethiopian Central Statistics Authority (CSA) were used to generate malaria case rates (confirmed malaria diagnoses per 1,000 persons) for each kebele. Changes in population between census dates were assumed to be linear, with a single population estimated for each year of record. Cohort analyses were undertaken to determine the impact of proximity to the reservoir on malaria case rates. For this, kebeles were divided into four groups, based primarily on the number and geographical spread of villages from which data had been obtained:

- those located within 1 km of the reservoir,
- those between 1 and 2 km from the reservoir,
- those between 2 and 5 km from the reservoir, and
- those between 5 and 9 km from the reservoir.

These data were analyzed by means of the Kruskal-Wallis test, a nonparametric test for ascertaining significance among more than two groups. This test assigns a rank to each value and determines the mean rank and 95% confidence interval for all ranks of data points in each group (Ott and Longnecker 2001). The potential significance of differences among the groups' mean ranks was then determined.

Multiple linear regression techniques were used to explore the association between number of malaria cases and potential explanatory variables. To simplify the development of the statistical models, annual malaria case rates for each kebele were determined by summing individual months of data. Stepwise linear regression in statistical softwave, SPSS, was used to identify significant explanatory variables (Draper and Smith 1998). Variables were added one at a time. If the added variable explained sufficiently more of the observed variance, it was included in the model. If it did not, it was excluded. In all analyses the model identified was simply the regression equation that explained the most variance with the fewest variables.

Entomological Survey

Four villages called, Ejersa, Siree-Robe, Kuma and Gudedo, were selected for the entomological study. These villages were selected based on their proximity to the Koka Reservoir (Figure 2). Ejersa and Siree-Robe, referred to hereafter as "reservoir villages," are located close to the reservoir (i.e., within 1 km). Siree-Robe is located very close to the dam, a short distance upslope from the hydropower station. Kuma and Gudedo, referred to hereafter as "control villages," are located further away from the reservoir, well beyond the 3 km average flying range of the local malaria mosquito (Table 4).

The population of each village was determined from the CSA and changes in population over time were obtained from the kebele administrators (Table 4). Although socioeconomic conditions in the four villages are broadly similar, there are some differences which may affect area to area comparisons. Many of the inhabitants of Ejersa work in an Ethiopian leather factory (tannery) located close to the village. Some of those in Siree-Robe are employed at the hydropower plant. In both locations some households practice informal agricultural activities along the reservoir shore. In Kuma and Gudedo, most households are entirely dependent on subsistence rain-fed agriculture and livestock-herding. This may influence exposure to mosquitoes and hence risk diseases as farmers may be outdoors late in the day (Kibret et al. 2008).

The entomological surveys comprised the collection of both larval and adult mosquitoes. Surveys were conducted fortnightly in the four study villages for 17 months, between August 2006 and December 2007. Larval surveys were carried out in water bodies within a radius of 1 km of each village. In each survey, all types of available potential mosquito breeding habitats were inspected for the presence of mosquito larvae using a standard dipper (350 ml) (Figure 5a). Potential mosquito breeding habitats in the study area included seepage at the base of the dam, reservoir shoreline puddles, man-made pools, agricultural field puddles and rain puddles (Table 5). Rainwater harvesting was not practiced in any of the villages.

TABLE 4. Summary details of the villages selected for the entomological study (population data obtained from the Ethiopian Central Statistics Authority).

Name of village	Location	Altitude	Distance from the reservoir (km)	Shoreline slope	Estimated population in 1994	Estimated population in 2007
Reservoir villages						
Ejersa	8°17'N 39°13' E	1721	0.4	1.3°	4,000	7,489
Siree-Robe	08°28'N;39°09'E	1710	0.8	4.5°	1,503	2,626
Control villages						
Kuma	8°19'N 39°12' E	1786	6.5	na	1,287	5,270 *
Gudedo	08°33'N;39°10'E	1863	10	na	11,007	19,250

*Some immigration into this village. na=data not applicable.

TABLE 5. Typology of puddles investigated in the study.

Type	Description
Rain puddles	Formed during the wet season by rain falling directly into depressions.
Agricultural field puddles	Formed in fields as a consequence of seepage or spill of irrigation water on low permeable or compacted soil, mixed with rainwater in the wet season.
Man-made pools	Shallow unprotected hand-dug wells created for domestic supply and/or irrigation water. Water originates as groundwater, but with inflow of surface water in some cases.
Reservoir shoreline puddles	Formed along the shore of the reservoir in natural depressions and as a consequence of cattle trampling. Water in these originates from the reservoir, from rain and from shallow groundwater.
Seepage at the base of the dam	Formed in the riverbed immediately downstream of the dam as a consequence of leakage from the dam and water flowing under pressure beneath it. Washed out when the dam spillway gates are open.

(a)

(b)

FIGURE 5. (a) Dipping in a pool providing a mosquito-breeding habitat (*photo credit:* Amelework Tesfaye); and (b) CDC light trap, installed outside a house (*photo credit:* Jonathan Lautze).

The surface area of each water body was estimated and sampling was conducted with 6 dips per m^2 according to Amerasinghe et al. (2001). One "sample" was defined as a maximum of 30 dips taken over a surface area of 5 m^2. For sites in the range of 5-10 m^2, one sample was taken, whereas two samples were taken from sites in the range of 11-20 m^2 and so forth. An upper limit of six samples was set for all sites with a water surface area exceeding 50 m^2 (Herrel et al. 2001). Larval anophelines sampled from each type of breeding habitat were transferred to separate vials by direct pipetting. Larvae were killed by gently heating and preserved in 70% alcohol for later species identification.

Adult mosquitoes were sampled using light traps of the Center for Disease Control and Prevention (CDC) (Model 512; J. W. Hock Co., Atlanta, USA) (Figure 5b). In each village, altogether six light traps were operated from 18:00 to 06:30 throughout each sampling night. In each case, four light traps were installed in occupied houses. Each indoor light trap was hung on a wall with the bulb about 45 cm above the head of a person sleeping under an untreated bed net (Lines et al. 1991). In each village two light traps were hung outside on trees close to (about 100 m) occupied houses. Mosquitoes caught in each light trap were counted and kept in separate paper cups for later identification and laboratory analyses.

Larval and adult mosquitoes were transported to the Biomedical Science Laboratory of Addis Ababa University for species identification. Larvae were counted and third and fourth larval instars were individually mounted on microscope slides using gum chloral for species identification, based on morphological characteristics (Verrone 1962b). Adult mosquitoes were sorted by genus, of which two were identified (i.e., *Anopheles* and *Culex* mosquitoes). All anophelines were further sorted into species, based on morphological characteristics (Verron 1962a). Female *Anopheles* mosquitoes were kept in separate vials inside a glass jar containing a silica-gel desiccator for later processing to determine the presence or absence of *Plasmodium* sporozoites and the Human Blood Index (HBI; see below).

Daily larval and adult mosquito collections were log-transformed ($\log_{10}$ [n+1]), and tested for normality before analysis. Throughout the remainder of this report the term "abundance" is used to express the total number of either larvae or adult mosquitoes in specific situations. Larval density is expressed as the number of anopheline larvae per m^2 of surface area, and adult density is expressed as the mean number of mosquitoes collected per light trap per night. Comparisons of larval and adult mosquito densities between the reservoir and control villages and between seasons were done using nonparametric Wilcoxon Signed Ranks Test. Stepwise linear regression in SPSS (Draper and Smith 1998) was used to investigate the association between larval density and larvae abundance and potential explanatory variables, including shoreline puddles and changes in reservoir water levels.

The presence of malaria parasite sporozoites inside dried female *Anopheles* mosquitoes was checked by a technique known as Enzyme Linked Immunosorbent Assay (ELISA) which is a method used to detect the presence of sporozoite antigens (Wirtz et al. 1987).[5] All female anopheline mosquitoes collected in the traps were assayed. The abdominal portions of blood-fed female anophelines were individually ground for the detection of blood meals originating from humans or bovines using a direct

[5] The "head-thorax" portion of individual female anophelines was ground in an eppindorff tube containing 50 microliters (μl) of blocking buffer. Fifty microliters of the capture monoclonal antibodies (MAb) of *P. falciparum* and *P. vivax* were added to wells of separate polyvinyl chloride microtiter plates in duplicates. After 30 minutes of incubation at room temperature, well contents were aspirated and the blocking buffer was added in each well and incubated for an hour to block the remaining active binding sites. Well contents were then aspirated and 50 μl of each mosquito triturate added. Positive and negative controls were also added to specific wells at this time. The negative controls were unfed laboratory-reared uninfected *An. arabiensis.* After 2 hours of incubation, the mosquito triturates were aspirated and the wells washed twice. Fifty microliters of peroxidase-linked MAbs of *P. falciparum* and *P. vivax* were then added to respective wells of the microtiter plate and incubated for one hour. Then, the plates were washed and the substrate solution added. Absorbance values at 405 nm were recorded from the ELISA plate reader after 30 minutes. Samples were considered positive if the mean absorbance values (at 30 minutes) of the duplicate assays exceeded twice the mean of the seven negative controls as recommended by Wirtz et al. (1987).

ELISA procedure (Beier et al. 1988). This provided information to determine the HBI (i.e., the proportion of mosquitoes feeding on human rather than on animal blood).

Although *P.vivax* infections are recorded at the malaria control centers, the only species of *Plasmodium* found in the mosquito blood samples collected during the entomological study was *P. falciparum*. Hence, sporozoite infection rate of each *Anopheles* species was calculated as the proportion of mosquitoes from the total samples, found to be positive for *P. falciparum* sporozoites. The HBI was calculated as the proportion of samples positive for human blood from the total blood meals of each species tested using the ELISA method. The level of significance was determined at p=0.05. All analyses were done using Microsoft Excel 2003 and version 13 of the statistical software, SPSS (SPSS Inc, Chicago, IL, USA).

Results

This chapter summarizes the principal results derived from both the entomological and epidemiological studies. These results highlight the role of the reservoir in increasing malaria transmission. They also illustrate the links between vector abundance and malaria incidence and changes in reservoir water levels.

Impact of the Reservoir on Malaria Case Rates

The epidemiological data were analyzed to determine the impact of the reservoir on malaria incidence. To simply illustrate spatial and temporal differences, Figure 6 presents time series of cases from two villages, one located close to the reservoir and the other further away. All the kebeles showed similar temporal patterns but very significant differences in the level of malaria incidence.

The annual case rate across all the 13 villages studied declined significantly (R^2 = 0.88) between 1995 and 2007 (i.e., the 13 years with complete data) (Figure 7a). This decline may be attributable not only to natural climatic variability but also partly to the increased interventions that have occurred all over the country in recent years. A similar trend was observed in the two villages located within 1 km of the reservoir (i.e., Ejersa and Siree-Robe). However, in all years the case rates in these two villages were significantly higher than the average across all 13 villages (Figure 7b).

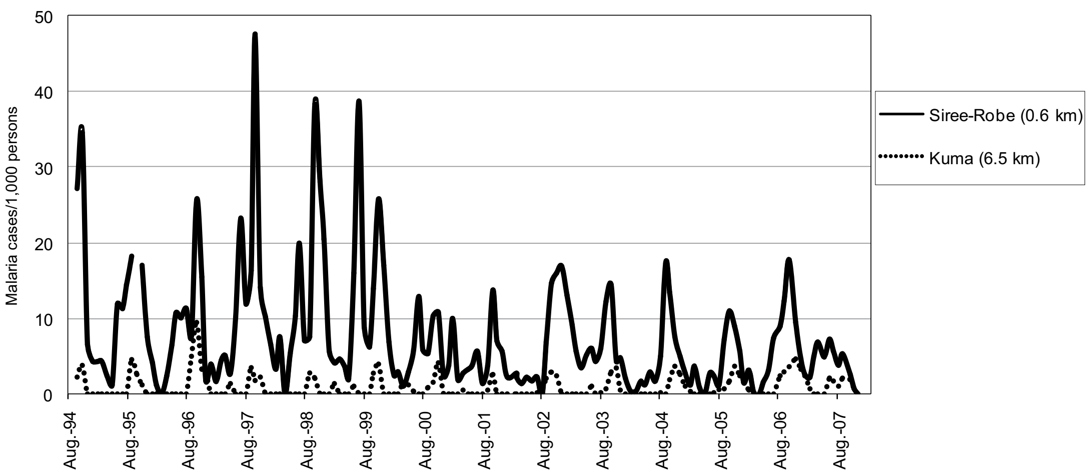
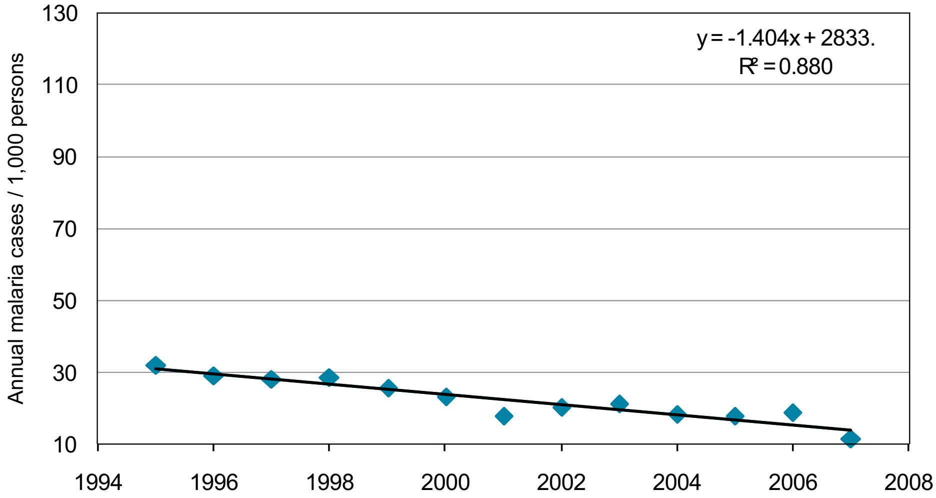


FIGURE 6. Time series of malaria case rates in two villages located at different distances from the Koka Reservoir.

(a)



(b)

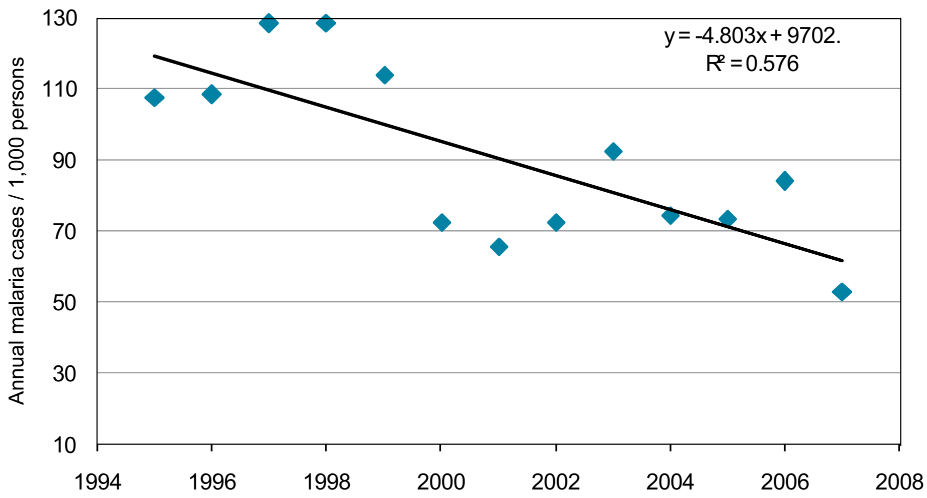


FIGURE 7. (a) Changes in annual malaria case rates (passively detected) in the 13 villages studied between 1995 and 2007; and (b) Changes in annual malaria case rates (passively detected) in the two villages located within 1 km of the reservoir (i.e., Ejersa and Siree-Robe) between 1995 and 2007.

Clinically diagnosed malaria case rates were correlated with proximity of residence to the Koka Reservoir. No potential confounding factors were considered. Although there was considerable interannual variation, the mean annual malaria case rates were highest in the kebeles located closest to the reservoir and decreased as distance to the reservoir increased (Table 6). A strong statistical relationship ($R^2 = 0.91$; $P < 0.001$) was confirmed between annual case rates and logarithmically transformed distance to the reservoir (Figure 8).

TABLE 6. Malaria cases reported (passive detection) at the health centers for 13 villages, located at different distances from the Koka Reservoir.

Cohort*	Village	Distance from reservoir (km)	Annual cases per 1,000 persons	95% CI	Average annual % *P. falciparum*†	Average annual % *P. vivax*
1	Ejersa	0.40	91.2	101.4 - 80.9	66.8	32.8
1	Siree-Robe	0.58	89.6	110.5 - 68.7	58.6	41.4
2	Qalbuni	1.30	56.5	72.9 - 40.1	66.0	33.8
2	Baatii Tiiftuu	1.72	32.7	41.4 - 24.0	72.0	26.3
2	Baatii Booraa	1.96	31.2	40.0 - 22.4	69.7	28.4
3	Baatii Qalloo	2.12	37.2	45.2 - 29.3	66.1	33.5
3	Dungugi	3.27	26.9	34.7 - 19.2	67.2	32.0
3	Qalboo Amajii	4.41	24.0	29.5 - 18.6	63.8	33.1
3	Biiqqaa	4.70	25.1	33.3 - 17.0	66.8	33.2
4	Gadamssaa	5.70	17.9	20.8 - 15.0	63.8	36.2
4	Kuma	6.50	10.4	13.0 - 7.7	64.9	35.1
4	Gudedo	7.65	2.1	2.8 - 1.4	58.0	42.0
4	Sanqullee	8.19	16.8	19.8 - 13.8	62.7	36.8

* Cohorts based on distance from the reservoir shore: 1 – located within 1 km of the reservoir; 2 – located between 1 and 2 km from the reservoir; 3 – located between 2 and 5 km from the reservoir; 4 – located between 5 and 9 km from the reservoir.

† At some locations a small percentage of cases comprised *P. malariae.* This is why the sum of *P. falciparum* and *P. vivax* is not always 100.

CI = confidence interval.

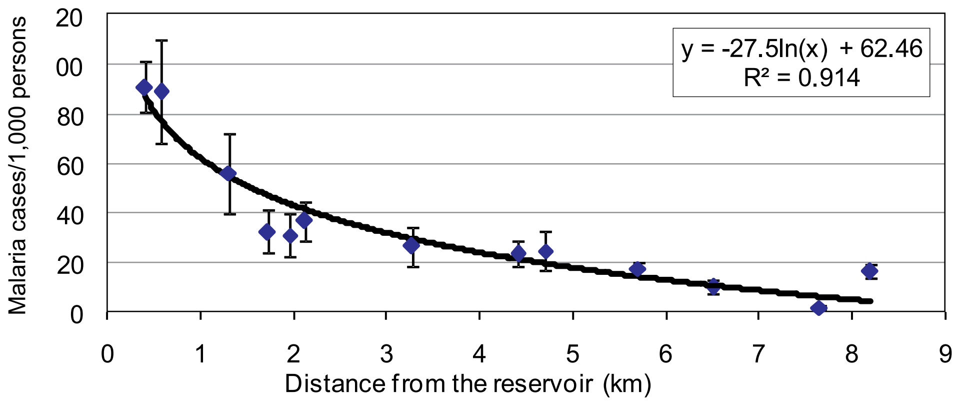


FIGURE 8. Relationship between average annual malaria case rates in 13 villages (passively reported) and proximity to the Koka Reservoir between 1995 and 2007. The bars indicate the confidence interval of the observed means.

The cohort analyses indicated that, on average, the mean annual malaria cases among people living within 1 km of the reservoir was 2.9 times greater than those living between 1 and 2 km from it, 3.7 times greater than those living 2 to 5 km from it and 19.9 times greater than those living 5 to 9 km from it (Table 7). The differences between groups were statistically significant (P < 0.001) (Table 7). These results confirm that the number of malaria cases is higher among people living close to the Koka Reservoir than among those living further away.

Multiple linear regression (stepwise) analyses were conducted to determine the relative importance of distance to the reservoir in conjunction with other factors that might affect malaria, including climatic variables and distance to the nearest malaria control center.[6] A range of climatic variables including seasonal minimum and maximum temperatures and rainfall (i.e., divided into four 3-month ranges: January to March, April to June, July to September and October to December), in some cases log-transformed, were included in these analyses. The significant variables were found to be the proximity of the village to the reservoir and the distance from the village to the nearest malaria control center. These variables explained 44.5% of the variability in annual malaria case rates observed amongst villages (Table 8). The analyses confirmed that distance to the reservoir was a highly important explanatory variable (R^2=0.406). These results indicate that, for these villages, difference in geography (i.e., distances to the reservoir and the nearest malaria control center) are more important than climatic factors in explaining differences in malaria case rates between villages. This is perhaps not surprising given the proximity of the villages to one another and hence the similarity in their climates.

TABLE 7. Results of cohort analyses – annual malaria case rates (passively reported cases per 1,000 persons) at different distances from the Koka Reservoir.

Cohort	Distance from reservoir (km)	Annual cases per 1,000 persons	95% CI	Rate ratio*	95% CI	P
1	0 - 1	90.4	77.0 - 103.8	-	-	-
2	1 - 2	37.0	28.3 - 45.6	2.9	2.2 - 3.6	<0.001
3	2 - 5	28.0	21.5 - 34.6	3.7	2.9 - 4.6	<0.001
4	5 - 9	5.3	4.3 - 6.4	19.9	14.2 -25.5	<0.001

* Rate ratio is the ratio of case rates in each cohort to cohort 1.

CI = confidence interval; p = significance test at 0.05.

TABLE 8. Results of multiple linear regression analyses. The outcome variable is log-transformed annual malaria cases per 1,000 persons.

Model	Adjusted R^2	Change statistics				
		R^2 change	F change	df1	df2	Sig. F change
1	0.406[a]	0.406	99.152	1	145	0.000
2	0.445[b]	0.039	10.101	1	144	0.002

[a] Predictors: (Constant), Distance to the reservoir (km).

[b] Predictors: (Constant), Distance to the reservoir (km). Distance to malaria control center (km).

[6] Distance to the malaria control center was used as a surrogate for health-seeking behavior, based on the assumption that people living closer to a center were more likely to visit the center than those living further away.

Significant positive correlations were obtained between the difference of successive 12-monthly (January to December) logarithmically transformed malaria case rates, minimum temperatures and rainfall (Table 9). This result is consistent with research conducted in South Africa, where differences in malaria cases in successive years were found to be correlated with rainfall and temperature (Craig et al. 2004). Overall, these results indicate that while interannual variation in case rates is largely a function of climate, differences in transmission levels between villages are explained mainly by variation in their distance to the reservoir.

The cohort data were examined to determine the impact of proximity to the reservoir on seasonal malaria case rates. The results showed a statistically significant seasonal variation in malaria case rates in all cohorts, with the peak recorded between October and December. They also indicate that proximity to the reservoir increases malaria risk at all times of the year (Figure 9). Overall, within 1 km, the reservoir adds approximately 40 cases per 1,000 persons in the rainy season and approximately 15 cases per 1,000 persons in the dry season. These results are statistically significant ($p<0.05$). Therefore, the impact of the reservoir is both to increase malaria risk during the rainy season, when transmission is most intense, and to effectively extend the malaria transmission into the dry season.

TABLE 9. Results of multiple linear regression analyses. The outcome variable is log-transformed interannual difference in malaria cases per 1,000 persons.

Model	Adjusted R^2	Change statistics				
		R^2 change	F change	df1	Df2	Sig. F change
1	0.699[a]	0.701	337.241	1	144	.000
2	0.772[b]	0.074	47.342	1	143	.000
3	0.789[c]	0.018	12.354	1	142	.001

[a] Predictors: (Constant), interannual difference from June to December-minimum temperature.

[b] Predictors: (Constant), interannual difference from June to December-minimum temperature, log of minimum temperature from October to December.

[c] Predictors: (Constant), interannual difference from June to December-minimum temperature, log of minimum temperature from October to December, log of rainfall from October to December.

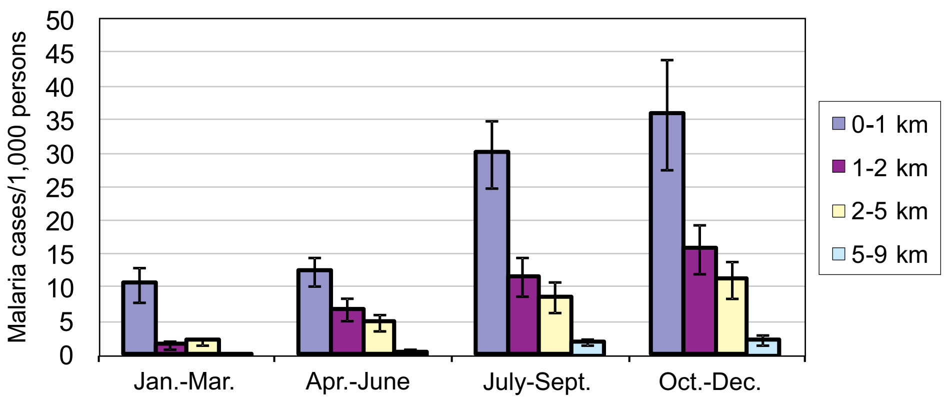


FIGURE 9. Seasonal distribution of malaria cases passively reported at different distances from the Koka Reservoir (vertical bars indicate 95% confidence intervals).

Impact of the Reservoir on Vector Abundance

The entomological data obtained from the four villages (i.e., Ejersa, Siree-Robe, Gudedo and Kuma) were analyzed to assess the impact of the reservoir on both larval and adult mosquito abundance.

The total numbers of potential and positive mosquito breeding sites of different types in the reservoir and control villages are presented in Table 10. All potential breeding sites within a radius of 1 km from the center of each village were surveyed when possible. Positive breeding sites were those where mosquito larvae occurred. In the reservoir villages, among 298 potential mosquito breeding sites surveyed, 53.6% (n=160) contained *Anopheles* larvae. By contrast, in the control villages, of 157 potential mosquito breeding sites encountered during the study period, only 29.3% (n=46) contained *Anopheles* larvae. Among the five types of habitat surveyed, shoreline puddles and seepage at the base of the dam were the major *Anopheles* breeding habitats accounting for three-quarters of the total positive larval breeding sites in the reservoir villages. In the control villages, rain pools (52.2%, n=24) and agricultural field puddles (45.6%, n=21) formed during the wet seasons were important *Anopheles* breeding sites.

Seasonal variations in the number of positive *Anopheles* larval breeding sites were evident in all study villages. In both the reservoir and control villages, the number of positive larval breeding sites increased following the onset of the main rainy season in June and peaked between August and October towards the end of this season. During the dry season, and the short wet season, fewer positive sites were found in the reservoir villages and no positive sites were found in the control villages (Figure 10). Overall, during the period of the study, the mean number of positive larval breeding sites was 6.6 times higher in reservoir villages than in the control villages (Table 11). Correspondingly, *Anopheles* larval density (i.e., number of *Anopheles* larvae per m^2 of potential breeding sites) was about 65 times higher in the reservoir villages than in the control villages throughout the study period (Table 11).

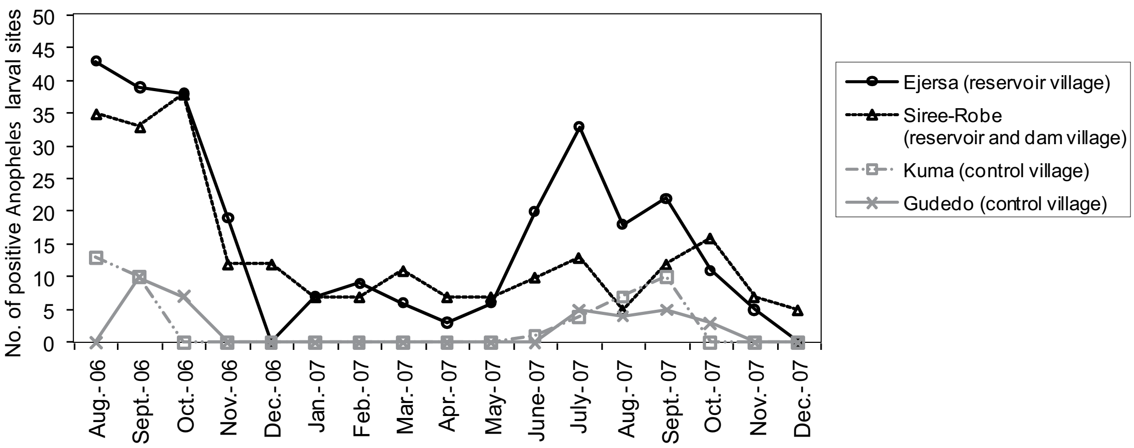


FIGURE 10. Number of positive *Anopheles* larval breeding sites in each month in the two reservoir and two control villages at different distances from the Koka Reservoir between August 2006 and December 2007.

TABLE 10. A summary of the number of breeding sites sampled and number of positive *Anopheles* larval habitats in reservoir and control villages in the vicinity of the Koka Reservoir between August 2006 and December 2007.

	Reservoir villages						Control villages					
	Ejersa		Siree-Robe		Total		Gudedo		Kuma		Total	
Type of larval habitat	No. of potential larval sites	No. of positive larval sites	No. of potential larval sites	No. of positive larval sites	No. of potential larval sites	No. of positive larval sites	No. of potential larval sites	No. of positive larval sites	No. of potential larval sites	No. of positive larval sites	No. of potential larval sites	No. of positive larval sites
Agricultural field puddles	20 (10.9)	9 (8.2)	-	-	20 (6.7)	9 (5.6)	18 (21.4)	6 (31.6)	38 (52.1)	15 (55.6)	56 (35.7)	21 (45.6)
Man-made pools	22 (12.0)	10 (9.1)	-	-	22 (7.4)	10 (6.3)	14 (16.7)	1 (5.3)	-	-	14 (8.9)	1 (2.2)
Rain pools	24 (13.0)	14 (12.7)	17 (14.9)	6 (12.0)	41 (13.8)	20 (12.5)	52 (61.9)	12 (63.2)	35 (47.9)	12 (44.4)	87 (55.4)	24 (52.2)
Seepage pools	-	-	55 (48.3)	25 (50.0)	55 (18.5)	25 (15.6)	-	-	-	-	-	-
Shoreline puddles	118 (64.1)	77 (70)	42 (36.8)	19 (38.0)	160 (53.7)	96 (60)	-	-	-	-	-	-
Total	184	110	114	50	298	160	84 (100)	19 (100)	73 (100)	27 (100)	157 (100)	46 (100)

( ) Number within brackets is the percentage of the total.

TABLE 11. A summary of the number of positive larval breeding sites and mean larval density in reservoir and control villages in the vicinity of the Koka Reservoir between August 2006 and December 2007.

	Mean number of positive larval sites	95% CI	p	Mean larval density	95% CI	p
Reservoir villages	15.2	9.3 – 21.1	<0.0001	3.52	1.02 – 6.22	< 0.0001
Control villages	2.3	0.5 – 4.1		0.05	0.00 – 0.09	

CI = confidence interval; p = significance test at 0.05; mean larval density is number of larvae per m^2.

TABLE 12. Species composition of third and fourth instar *Anopheles* larval collections in different types of habitats in reservoir and control villages in the vicinity of the Koka Reservoir between August 2006 and December 2007.

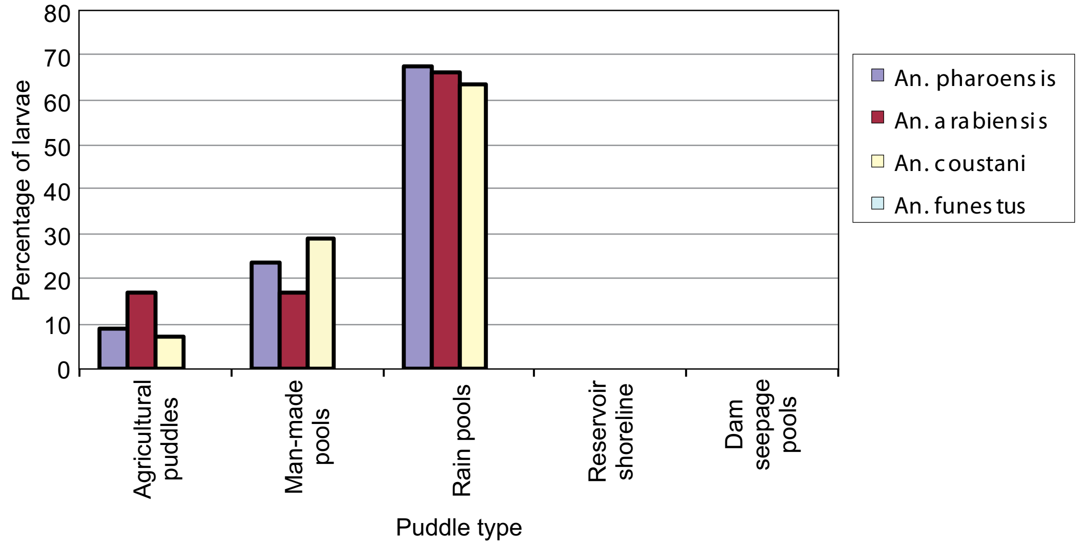
Villages	Type of larval habitat	*An. arabiensis*	*An. pharoensis*	*An. coustani*	*An. funestus*	*Total*
Reservoir	Agricultural field puddles	20 (1.5)	16 (1.9)	16 (5.1)	0 (0.0)	52
	Man-made pools	139 (10.7)	57 (6.7)	41 (13.0)	0 (0.0)	237
	Rain pools	292 (22.5)	130 (15.3)	63 (19.9)	0 (0.0)	485
	Reservoir shoreline puddles	530 (40.8)	367 (43.2)	129 (40.8)	46 (70.8)	1,072
	Seepage pools at the base of the dam	319 (24.5)	280 (32.9)	67 (21.2)	19 (29.2)	685
	Total (%)	1,300	850	316	65	2,531
Control	Agricultural field puddles	56 (17.1)	9 (8.8)	8 (7.3)	0 (0.0)	73
	Man-made pools	55 (16.8)	24 (23.5)	32 (29.1)	0 (0.0)	111
	Rain pools	216 (66.1)	69 (67.7)	70 (63.6)	0 (0.0)	355
	Total (%)	327	102	110	0	539

Number within brackets is the percentage of each species in each habitat type for reservoir and control villages.

During the study, about five times more mature *Anopheles* larvae were collected in reservoir villages (n=2,531) than in the control villages (n = 539) (Table 12). Four *Anopheles* species were morphologically identified: *An. arabiensis*, *An. pharoensis*, *An. coustani*[7] and *An. funestus*. Across both the reservoir and the control villages, *An. arabiensis* and *An. pharoensis* were the major species, comprising 53% and 31.3%, respectively, of the total. In reservoir villages, a large proportion of larval *An. arabiensis* (65.3%) and *An. pharoensis* (76.1%) was obtained from the reservoir shoreline puddles and the seepage pools at the base of the dam. In the control villages, these species were mainly found in temporary pools (i.e., rain pools and agricultural field puddles) formed during the main wet season (Figure 11). Overall, the two malaria vectors (i.e., *An. arabiensis* and *An. pharoensis*) utilized reservoir-associated pools for breeding throughout the year, with peak larval densities during, and immediately after, the main rainy season (Figure 12).

[7] The role of *An. coustani* (also known as *An, ziemanni*) in malaria transmission in East Africa is unclear (Kamau et al. 2006).

(a)



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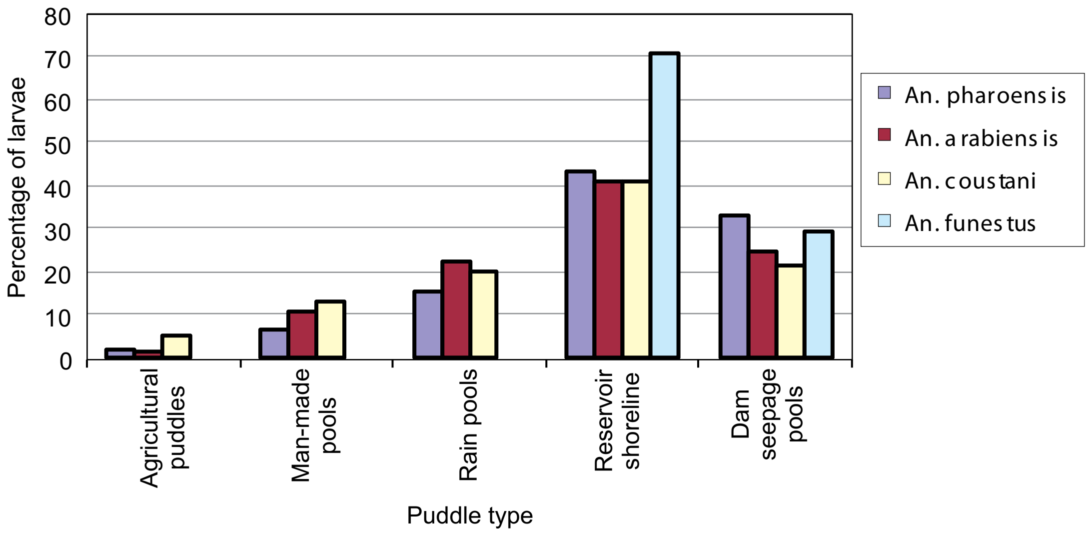

FIGURE 11. (a) Seasonal *Anopheles* larval density (mean number of larvae per m^2); and (b) Percentage occurrence of *Anopheles* larvae in different breeding habitats for control villages; in the reservoir and control villages.

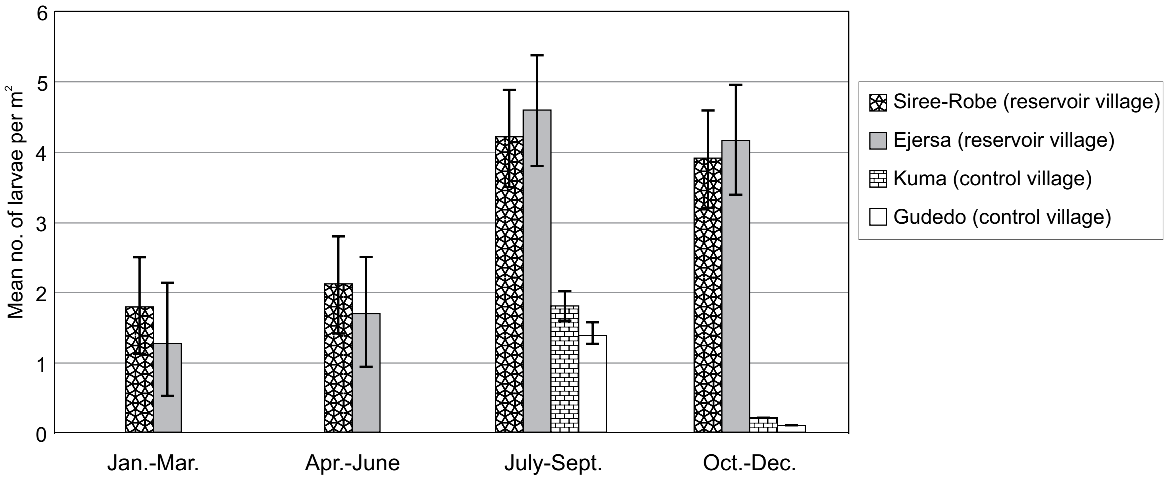

FIGURE 12. Density of *An. arabiensis* and *An. pharoensis* in the reservoir and control villages around the Koka Reservoir between August 2006 and December 2007. The bars indicate the confidence interval.

Over the study period, altogether 2,952 adult *Anopheles* mosquitoes were collected from the four study villages (Table 13). Of these 85.2% were from the two reservoir villages. *An. arabiensis* and *An. pharoensis* were the major species, comprising 55.3 and 29.8%, respectively, of the total adult collections (Table 13). The density (i.e., mean number of mosquitoes per light trap per night) of *Anopheles* mosquitoes was significantly higher (mean ratio = 5.77, $P < 0.001$) in the reservoir villages than in the control villages throughout the study period. Overall, adult densities of *An. arabiensis* and *An. pharoensis* in the reservoir villages were respectively fivefold and eightfold higher than those in the control villages, (Table 14). In both reservoir and control villages, adult mosquito densities peaked during the main rainy season (Figure 13).

TABLE 13. Summary of adult *Anopheles* mosquitoes captured by CDC light traps from indoors and outdoors in the reservoir and the control villages in the vicinity of the Koka Reservoir between August 2006 and December 2007.

Village	*An. arabiensis*	*An. pharoensis*	*An. coustani*	*An. funestus*	Total
Ejersa	824 (49.3)*	574 (34.4)	252 (15.1)	20 (1.2)	1,670
Siree-Robe	532 (63.0)	213 (25.2)	90 (10.7)	9 (1.1)	844
Reservoir villages (total)	1,356 (53.9)	787 (31.3)	342 (13.6)	29 (1.2)	2,514
Gudedo	161 (64.9)	42 (16.9)	45 (18.2)	0 (0.0)	248
Kuma	117 (61.6)	50 (26.3)	23 (12.1)	0 (0.0)	190
Control villages (total)	278 (63.5)	92 (21.0)	68 (15.5)	0 (0.0)	438
Grand total	1,634 (55.3)	879 (29.8)	410 (13.9)	29 (1.0)	2,952 (100)

*Number within brackets is the percentage of the total.

TABLE 14. Density of *Anopheles* mosquitoes (indoors and outdoors) found in the reservoir and control villages in the vicinity of the Koka Reservoir between August 2006 and December 2007.

Species	Reservoir villages			Control villages		
	Indoor (95% CI)	Outdoor (95% CI)	Mean (95% CI)	Indoor (95% CI)	Outdoor (95% CI)	Mean (95% CI)
An. arabiensis	2.6 (1.2-4.0)	2.5 (1.4-3.6)	2.6 (1.3-3.8)	0.5 (0.1-0.9)	0.4 (0.1-0.7)	0.5 (0.1-0.9)
An. pharoensis	1.2 (0.4-1.8)	1.8 (0.6-3.0)	1.5 (0.6-2.4)	0.2 (0.1-0.4)	0.3 (0.1-0.5)	0.2 (0.0-0.4)
An. coustani	0.5 (0.2-0.8)	1.1 (0.6-1.6)	0.8 (0.5-1.3)	0.1 (0.0-0.2)	0.2 (0.0-0.4)	0.2 (0.0-0.4)
An. funestus	0.0 (0.0-0.0)	0.2 (0.0-0.3)	0.1 (0.0-0.2)	0.1 (0.0-0.2)	0.00	0.00

CI = confidence interval. p = significance test at 0.05.
Density = Mean no. of female anophelines collected per light trap per night.

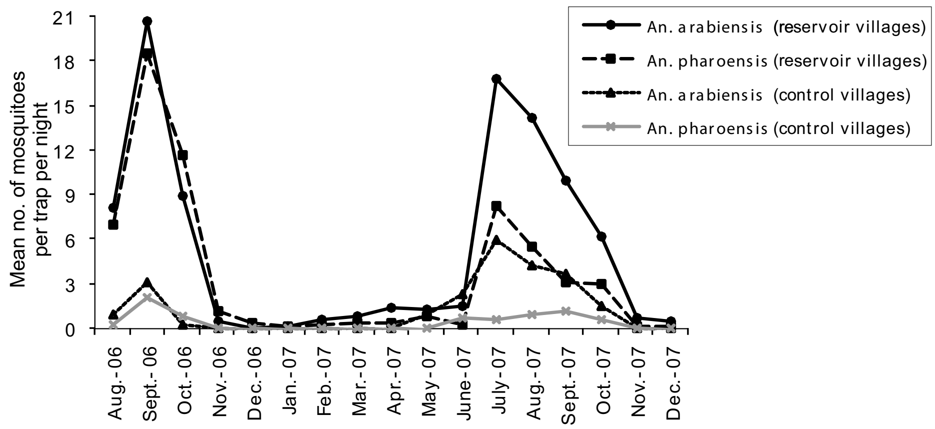

FIGURE 13. Graph showing a potential relationship between total larval abundance in shoreline puddles at Ejersa and Siree-Robe and the rate of falling reservoir water levels.

An. arabiensis showed no significant difference ($p > 0.05$) in its density indoors and outdoors, suggesting that the species is equally exophagic (i.e., outdoor feeding) and endophagic (i.e., indoor feeding) during the night. The other *Anopheles* species were found primarily outside in all study villages, suggesting an exophagic feeding behavior (Table 14).

Among female *An. arabiensis, An. pharoensis* and *An. coustani* caught in the reservoir villages with blood in their guts, 74.6%, 62.3% and 42.7%, respectively, had fed on humans and 21.6%, 28.8% and 62.1%, respectively, on cattle (Table 15). Overall, *An. arabiensis* was the most anthropophagic (i.e., human-feeding) species, followed by *An. pharoensis*. In contrast, both *An. coustani* and *An. funestus* appeared to be predominantly zoophagic (i.e., with a preference for animal feeding) although in both reservoir and control villages some proportions were found to have fed on humans.

TABLE 15. Blood-meal sources of *Anopheles* mosquitoes in the reservoir and control villages in the vicinity of the Koka Reservoir between August 2006 and December 2007.

Village	Species	No. tested	No. positive for human blood	No. positive for bovine blood	Unidentified
Reservoir	*An. arabiensis*	319	238 (74.6)	69 (21.6)	31 (9.7)
	An. pharoensis	385	240 (62.3)	111 (28.8)	72 (18.7)
	An. coustani	103	44 (42.7)	63 (61.2)	16 (15.5)
	An. funestus	8	2 (25.0)	4 (50.0)	3 (37.5)
Control	*An. arabiensis*	136	85 (62.5)	41 (30.1)	29 (21.3)
	An. pharoensis	45	26 (57.8)	15 (33.3)	8 (17.8)
	An. coustani	23	5 (21.7)	13 (56.5)	6 (26.1)
	An. funestus	0	0	0	0

Number within brackets is the percentage of the total.

Note: Some samples were positive for both human and bovine blood and were included in both categories. "Unidentified" means that the blood was neither from humans nor from cattle. *An. funestus* was not found in the control villages, so no samples to test.

Plasmodium falciparum-infected *An. arabiensis* and *An. pharoensis* were found in the reservoir villages while none of the adult anophelines in the control villages were positive (Table 16). In the reservoir villages, a higher *P. falciparum* sporozoite rate was recorded in *An. arabiensis* populations (0.97%–1.32%) than in *An. pharoensis* populations (0.47%–0.70%). All the malaria sporozoite-infected mosquitoes were collected during the main malaria transmission season (i.e., between August and October). None of the *An. coustani* and *An. funestus* mosquitoes were infected with *P. falciparum* sporozites (Table 16).

TABLE 16. *Plasmodium falciparum* sporozoite rates of *Anopheles* species in the reservoir and control villages around the Koka Reservoir, from collections made between August 2006 and December 2007.

	An. arabiensis		*An. pharoensis*		*An. coustani*		*An. funestus*	
Village	No. tested	No. positive (%)	No. tested	No. positive (%)	No. tested	No. positive (%)	No. tested	No. positive (%)
Ejersa	824	8 (0.97)	574	4 (0.70)	252	0 (0.00)	20	0 (0.00)
Siree-Robe	532	7 (1.32)	213	1 (0.47)	90	0 (0.00)	9	0 (0.00)
Gudedo	161	0 (0.00)	42	0 (0.00)	45	0 (0.00)	0	0
Kuma	117	0 (0.00)	50	0 (0.00)	23	0 (0.00)	0	0

Impact of Water-Level Changes on Malaria Case Rates

Data collected in the epidemiological study were used to investigate relationships between clinically diagnosed malaria case rates and changes in reservoir water levels. Multiple linear regression (stepwise) analyses were conducted to determine the relative importance of changes in the reservoir water levels (both rising and falling) over and above the absolute water level and climatic variables (i.e., rainfall and maximum and minimum temperatures). Time series plots of the environmental variables with case rates revealed the potential for leading indicators (Table 17). Cross correlation analyses were performed to identify how many months the variables could be lagged. Although the cross correlations sometimes revealed significant correlation at higher lags, this was limited to a maximum of 2 months because beyond this, biophysical explanations become difficult. All the explanatory variables, except the mean monthly water level (which showed no significant cross correlations), were lagged by 1 and 2 months generating a total of 13 potential explanatory variables.

TABLE 17. Results of stepwise linear regression of potential explanatory variables on malaria case rates.

Variables fitted	Stepwise regression of water-level change and climatic variables				Stepwise regression of climatic variables only			
	Siree-Robe	Ejersa	Gudedo	Kuma	Siree-Robe	Ejersa	Gudedo	Kuma
Mean monthly water level (m)								
Water-level change (m)*		x						
Lagged by 1 month			(x)	x				
Lagged by 2 months	(x)	(x)		(x)				
Rainfall (mm)								x
Lagged by 1 month							x	
Lagged by 2 months					x	(x)	x	(x)
Monthly minimum temperature (°C)			x				x	
Lagged by 1 month								
Lagged by 2 months	x	x	x		x	x	(x)	
Monthly maximum temperature (°C)	x				(x)			
Lagged by 1 month		x						
Lagged by 2 months						x		
Adjusted R^2 (model)	0.32	0.62	0.24	0.46	0.30	0.41	0.23	0.35
Number of variables selected	3	4	3	2	3	3	4	2
Effect size	2.16	3.66	0.08	0.69	-0.86	0.03	0.02	0.009
Total number of observations	150	151	154	154	150	151	154	154
Number of zero observations	6	4	81	89	6	4	81	89

x indicates variables selected. For each model, the variable with the largest t statistic (i.e., the most significant effect) is indicated by brackets, i.e., (x). The nonstandardized coefficient for this variable is reported here as the "effect size." This number indicates the result of a single unit increase in this variable on malaria case rates.

* Water-level change is the change between the first and the last days of the month.

The model that explained the highest proportion of variation (adjusted $R^2 = 0.62$) is for the reservoir village Ejersa (Table 17). For the other reservoir village, Siree-Robe, the best model explains a much smaller proportion of the variation (adjusted $R^2 = 0.32$). For both reservoir villages the most significant explanatory variable was found to be where water-level changes lagged by 2 months (Table 17). For the control villages (Gudedo and Kuma) explanatory models explain less than half the variation: adjusted $R^2 = 0.24$ and 0.46, respectively. In common with the reservoir villages, for both control villages the most significant explanatory variable was found to be lagged water-level changes, although the lag for Gudedo was 1 month rather than two (Table 17). Both the control villages are more than 6 km away from the reservoir (i.e., significantly more than the maximum flying distance of mosquitoes (Ribeiro et al. 1996) and so will not be colonized by mosquitoes from the reservoir. Consequently, there is no obvious biophysical explanation as to why changes in reservoir water levels would affect malaria case rates in these villages. However, there is a high correlation ($R^2 = 0.54$) between water-level changes and rainfall (i.e., broadly water levels rise as a consequence of rainfall and drop when rainfall ceases) which confounds the analyses. Furthermore, Kuma is located close to the Mojo River (Figure 2) and although we did not investigate the effect of the river, rising and falling river water levels will almost certainly follow a similar temporal pattern as the reservoir water levels. Another possible confounding factor that we did not consider is population movement between the reservoir and control villages.

To investigate further, a stepwise regression was performed using climatic variables only. In this case, the most significant variable in the model for both Ejersa and Kuma was lagged rainfall (Table 17). For all models the adjusted R^2 was lower than when lagged water level was included. Because the control villages had a large number of zero observations and skewed distributions, the above analyses were repeated using log (case rates+1). Although the total variation explained by the model was, in all cases, approximately the same or lower than previously derived, the most significant explanatory variable was always the same as before. Therefore, the results of the regression on the untransformed outcome variable were retained because the primary interest was not to develop a predictive model but rather to explore if there was an association with water-level changes over and above climatic variables, together with an easily interpretable, approximate estimate of effect size.

Impact of Water-Level Changes on Mosquito Larvae and Adults

Data collected in the entomological study between August 2006 and December 2007 were used to investigate relationships between changes in reservoir water levels and both larvae in the shoreline puddles and adult mosquitoes in the reservoir villages. The hypothesis to be tested was that rapid changes in water levels would result in desiccation of shoreline puddles and this would prevent larval production that would, in turn, cause a decline in the density of adult mosquitoes in the reservoir villages. This would seem to provide options for environmental malaria control by purposeful operation of the dam.

As in the analyses conducted with malaria case data, multiple linear regression (stepwise) analyses were conducted to determine the relative importance of changes in reservoir water levels (both rising and falling), over and above the absolute water level and climatic variables (i.e., rainfall and maximum and minimum temperatures). In this case, all the explanatory variables, including the mean monthly water level were lagged by 1 and 2 months generating a total of 15 potential explanatory variables. However, because the entomological survey was conducted over a period of just 17 months, far fewer data were available than for the analyses of malaria case data obtained over 13 years. For the non-reservoir villages, the proportion of observations with zero larvae and zero adult mosquitoes collected was high and there was insufficient variation in the nonzero observations to determine a relationship with explanatory variables. Consequently, analyses were not conducted for the control villages.

For larval density, each of the models that explained the highest proportion of variation for Siree-Robe and Ejersa contained just one variable. However, for Siree-Robe this was mean monthly water level lagged by 2 months and for Ejersa it was rainfall lagged by 1 month. In neither case was water-level change selected (Table 18).

TABLE 18. Results of stepwise linear regression of potential explanatory variables on larval density in shoreline puddles and adult mosquito density in reservoir villages.

Variables fitted	Stepwise regression of water-level change and climatic variables			
	Larval density		Adult density	
	Siree-Robe	Ejersa	Siree-Robe	Ejersa
Mean monthly water level (m)				
Lagged by 1 month				
Lagged by 2 months	(x)			
Water-level change (m)*			(x)	(x)
Lagged by 1 month				
Lagged by 2 months				x
Rainfall (mm)				
Lagged by 1 month		(x)		
Lagged by 2 months				
Monthly minimum temperature (ºC)				x
Lagged by 1 month				
Lagged by 2 months				
Monthly maximum temperature (ºC)				
Lagged by 1 month				
Lagged by 2 months				
Adjusted R^2 (model)	0.56	0.5	0.6955	0.926
P	0.002	0.002	<0.000	<0.000
Number of variables selected	1	1	1	3
Effect size	-2.5	0.02	6.7	9.1
Number of observations	12	12	12	12
Number of zero observations	6	2	1	0

x indicates variables selected. For each model, the variable with the largest t statistic (i.e., the most significant effect) is indicated within brackets, i.e., (x). The nonstandardized coefficient for this variable is reported here as the "effect size." This number indicates the result of a single unit increase in this variable on malaria case rates.

* Water-level change is the change between the first and the last days of the month.

Interestingly, for adult mosquito density water-level change was selected as the key variable for both villages (Table 18). Although for Ejersa the adjusted R^2 is very high (0.926), it is more likely a consequence of the model being over-paramaterized (i.e., four variables, including the constant, for just 12 observations). Hence, without further evidence, caution is required before generalizing this result.

The above results are likely due to the high correlation between water-level changes, mean monthly water level and rainfall. To investigate this, the specific relationship between the rate of water-level change and total larval abundance (i.e., the total number of larvae counted in the shoreline puddles of both Ejersa and Siree-Robe) was investigated. Visual inspection of scatter plots indicated a potential linear relationship with falling water levels but no relationship with rising water levels. A simple linear regression fitted only to falling water levels resulted in an R^2 of 0.44. This indicates that the faster the drop of water levels the lower the larval abundance (Figure 14). Although there is a great deal of scatter, the regression equation suggests that, broadly, water levels falling at a rate of 10 millimeters per day (mmd^{-1}) and 20 mmd^{-1}, respectively, are associated with larval abundances approximately 5x and 2.5x higher than when water levels fall at 25 mmd^{-1}.

Analyses of the correlation between water-level changes and larval density showed no notable relationship. Similarly, no relationship was found between water-level changes and changes in larval density or between water-level changes and proportion of mature to total larvae.

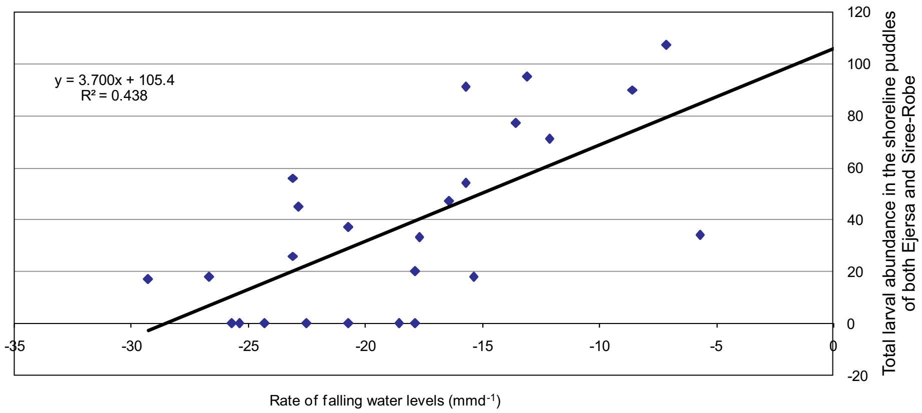

FIGURE 14. Graph showing a potential relationship between total larval abundance in shoreline puddles at Ejersa and Siree-Robe and the rate of falling reservoir water levels.

Discussion

The principal finding of this study is intensified malaria transmission in communities living close to the Koka Reservoir. This is the result of increased vector abundance due largely to breeding sites directly associated with the permanent water body. The second major finding is that changes in reservoir water levels appear to influence larval abundance in shoreline puddles. This suggests that intentional manipulation of reservoir water levels could potentially reduce larval abundance and possibly lessen malaria in communities living close to the reservoir.

Although the principal findings are the same, some results differ slightly in detail from those previously published (e.g., Lautze et al. 2007; Lautze 2008). The analyses conducted for this report are based on longer and improved data series. In the previous publications, 8 years of malaria case data were used for the epidemiological analyses and 12 months of data (i.e., one transmission season) were available for the entomological study. Analyses were conducted on three cohorts (0-3 km, 3-6 km and 6-9 km from the reservoir) and multiple variable regression models were used to explore the associations between malaria case rates and proximity to the reservoir. For this Research Report more detailed analyses have been conducted using a data set extended to 13 complete years for the epidemiological study and 17 months (i.e., two transmission seasons) for the entomological study.

Effect of the Koka Reservoir on Malaria Transmission

The finding that the Koka Reservoir enhances malaria prevalence is consistent with the results from several other African studies. The Bamendjin Dam in Cameroon was found to have increased malaria prevalence in adjacent areas (Atangana et al. 1979). Proximity to the Kamburu Dam in Kenya was found to be correlated with increased malaria case rates (Oomen 1981; Roggeri 1985). The Manantali Dam in Mali was found to have increased malaria risk (King 1996) and proximity to a micro-dam in northern Ethiopia was found to be an important risk factor for malaria (Ghebreyesus et al. 1999). Similarly, in southwestern Ethiopia a higher prevalence of malaria (due to *P. vivax*) was found in villages closer (<3 km) to the Gilgel-Gibe Dam than in control villages further away (5-8 km) (Yewhalaw et al. 2009). However, this result is inconsistent with the findings of a study on the construction of the Diama Dam in the Senegal River Basin, which found that the dam had not affected malaria incidence in the region (Sow et al. 2002). This was mainly due to the low survival rate and low anthropophilic index of the major vector there (*An. pharoensis*), which limited its role in malaria transmission (Sow et al. 2002). Clearly, local ecology and climate as well as dam design and operation all influence vector breeding and adult mosquito abundance, and local socioeconomic conditions influence vector-host contact. However, to date there have been no systematic studies to determine the relative impact of dams on malaria under different ecological, climatic and socioeconomic conditions. Very valuable, policy-relevant research needs to be undertaken to improve the understanding of factors that trigger different impacts.

The present study clearly showed that, at Koka, malaria case rates increased as distance to the reservoir decreased. This strongly indicates a higher risk of malaria to communities living closer to the reservoir than to those living further away. The entomological data support this finding, as more larval and adult Anopheles specimens were found in villages close to the reservoir than in those located further away. These results indicate that the Koka Reservoir enhances malaria risk for people living close to it by providing suitable breeding sites for mosquito vectors.

In an area with a favorable climate, the three major factors that determine the intensity of malaria transmission are mosquito densities, their propensity to feed on humans and the proportion infected with malaria parasites (Molineaux 1988). The present study indicates that, although strong seasonal variation remains, the Koka Reservoir intensifies malaria transmission in both wet and dry seasons. This finding is not only consistent with the observations on the seasonality of vector abundance but also supports the proposition of others that reservoirs facilitate perennial transmission in areas of traditionally seasonal transmission (Keiser et al. 2005; Yohannes et al. 2005). Although the intensity of malaria does not correlate directly with morbidity and mortality due to the modulating effects of immunity and other factors, in an area of hypo-endemic transmission such as this region of Ethiopia, increased malarial infection is likely to constitute a serious health risk (Brewster 1999).

Effect of the Koka Reservoir on Vector Abundance

Through the creation of larval habitats, reservoirs can promote enhanced populations of certain vectors. In the present study, shoreline puddles and seepage pools downstream of the dam were found to provide an ideal breeding habitat for Anopheles mosquitoes. A higher abundance of breeding sites, in combination with high productivity (i.e., as indicated by larval density), resulted in much greater numbers of adult mosquitoes in those villages located close to the reservoir than in those located further away.

Other than the construction of the dam, the major anthropogenic activities in the area that have affected mosquito breeding are agricultural activities and the construction of "man-made pools" (i.e., shallow hand-dug wells for domestic water supply or informal irrigation). In both cases, people's behavior is likely to affect how it influences vector abundance and malaria transmission. The role of cattle trampling in creating larval breeding habitats around the shore is unclear and requires further research. Whatever the impact, shoreline management that excludes this trampling would seem to be impractical, at least in the near future.

In all study villages larval and adult A*n. arabiensis* were found to dominate, but significant numbers of *An. pharoensis* and *An. coustani* were also present. These species are common elsewhere in the Ethiopian Rift Valley (Ameneshewa 1995; Abose et al. 1998; Taye et al. 2006; Kibret 2008). In the reservoir villages, a few *An. funestus* (not found in the control villages) were also caught. These observations are consistent with the known breeding habitat preferences of these species and with the findings of other researchers. For example, in Senegal, *An. pharoensis* became substantially more abundant following the construction of water resources infrastructure (Petrarca et al. 1987; Carrara et al. 1990; Faye et al. 1995) and in northern Ethiopia the construction of micro-dams significantly increased the number of *An. arabiensis* (Yohannes et al. 2005).

The presence of *P. falciparum* sporozites in *An. arabiensis* and *An. pharoensis* confirms that they are the principal malaria vectors in the area. This finding is consistent with those of other studies conducted in the region (e.g., Abose et al. 1998; Taye et al. 2006; Kibret et al. 2008). Although none of the *An. coustani* and *An. funestus* mosquitoes were infected with *P. falciparum* sporozoites, the partial anthropophagic behavior of *An. coustani* and the fact that in Ethiopia it tends to bite outdoors in the early part of the evening (Taye et al. 2006), mean that the possibility of this species transmitting malaria in the area cannot be ruled out. *An. funestus* is known to be the second most important malaria vector in Ethiopia and is particularly abundant in the lowlands of the country where there is permanent water (WHO 2007). Consequently, although only very few were caught and none were infected the possibility that it is transmitting malaria also cannot be ruled out.

An. pharoensis primarily feeds outdoors and, under normal circumstances, *An. arabiensis* is also a partial outdoor feeder. Hence, the most abundant anophelines in the vicinity of the Koka Reservoir tend to feed outdoors. Furthermore, it is possible that the outdoor questing tendencies of vectors around the Koka Reservoir have been enhanced by the frequent application of IRS. Evidence exists from the region that anophelines may increase outdoor feeding as a response to repeated indoor spraying with insecticides (Ameneshewa and Service 1996). In addition, some mosquitoes feed early in the evening when many people are still active outdoors (Abose et al. 1998; Yohannes et al. 2005; Kibret 2008). Certainly, of the females of both species caught with blood in their guts a large proportion (i.e., in excess of 55% at all locations) had fed on humans. These results suggest that the effectiveness of conventional malaria prevention strategies (e.g., ITNs, IRS) may be partially undermined by mosquito behavior.

Effect of Reservoir Operation on Malaria Vectors and Malaria Case Rates

Nonchemical measures were successfully used to target the larval stages of mosquitoes in many places until the middle of the twentieth century. However, since the introduction of DDT in the 1940s and the associated development of IRS the focus of malaria prevention strategies has largely shifted to the control of adult vectors (Walker and Lynch 2007). Nonetheless, it is likely that targeting larvae in the vicinity of the Koka Reservoir could help reduce malaria vector abundance in those villages located close to it.

There are various chemical, biological and environmental management approaches that can be used to control larvae (Walker and Lynch 2007). In the case of the Koka Dam, it is probable that many approaches would not be appropriate. For example, the use of chemical larvicides and oils over such a wide area is impractical. Although larvivorous fish (i.e., predatory fish that eat mosquito larvae) have been found to be effective in reducing larvae numbers in some circumstances in Ethiopia and Somalia (Fletcher et al. 1992; Mohamed 2003) it is not certain that the habitat of the Koka Reservoir would be conducive for such fish or that they would be effective in the shallow ephemeral puddles around the shore.

Against this background, a key hypothesis of this study was that manipulation of reservoir water levels at critical times would disrupt larval development by desiccating shoreline puddles and that this would, in turn, result in reduced numbers of adult vectors and hence less malaria in reservoir villages. Although not conclusive, the results broadly support this hypothesis.

Reservoir water-level changes were found to be only moderately correlated with malaria case rates in reservoir villages. Models improved when climate-related factors were used as covariates. However, despite the absence of a biophysical reason to explain the statistical relationship, water-level changes were also found to be the most significant explanatory variable for malaria case rates in the control villages. This may, in part, be a consequence of the high correlation between water-level change and rainfall which confounds the analyses. It is also possible that water-level changes are an attenuated version of rainfall (i.e., less noisy signal) that better mimics the epidemiological cycle of larvae than rainfall. Factors such as soil-moisture saturation and other environmental controls, more directly associated with specific vector-breeding habitats, also tend to be attenuated forms of rainfall.

Water-level changes were found to explain the largest proportion of variation in regression models describing adult *Anopheles* density in the reservoir villages. However, for larval density absolute water levels and rainfall rather than water-level changes were found to be the most significant explanatory variables at Siree-Robe and Ejersa, respectively. This again demonstrates the confounding nature of the link between water-level change and rainfall, making attribution difficult. Nevertheless, analysis showed a moderate correlation between total larval abundance in shoreline puddles and falling water levels. Faster rates of drawdown were associated with reduced larval abundance. This suggests that faster drawdown can create conditions that reduce the number of larvae, presumably by rendering breeding sites less suitable for their development. The fact that water-level changes did not correlate with larval density is counterintuitive and seems to be inconsistent with this finding. Further research is required to understand this apparent contradiction.

The results of the study differed in the two reservoir villages, Siree-Robe and Ejersa. In general, associations between both malaria cases and vector densities and explanatory variables were stronger at Ejersa than at Siree-Robe. This is possibly because of structural differences between the two villages. For example, the slope of the shoreline was greater, and generally homesteads are located slightly further from the shore at Siree-Robe than at Ejersa. In Ejersa, informal agricultural activities around the shoreline have created additional mosquito-breeding sites particularly towards the end of the wet season when many fields are flooded for a period of time. Furthermore, the presence of seepage downstream of the dam, which provides an additional breeding habitat, further increases the complexity of the situation at Siree-Robe.

This study was limited by a number of factors. First, to date, the dam has never been purposefully operated to affect larval habitat or malaria case rates. Hence, any associations had to be identified from within patterns of dam operation intended primarily to optimize hydropower production. Second, only a relatively short time series (just 17 months) of entomological data on a fortnightly time-step were available. Because of the complexity of factors affecting larvae and adult mosquito populations, the short time series proved insufficient to produce conclusive results of their association with reservoir water-level changes. A large number of potential confounding factors including small-scale variations in soil, vegetation type and topography, as well as differences in water quality and temperature between different puddle types were disregarded in the study. Also ignored were small-scale variations in socioeconomic conditions between kebeles that might have influenced differences in malaria transmission. Third, the fact that only light traps were used and no resting collections were obtained may have partially biased our results because we have no idea of the daytime resting habits of mosquitoes or their response to indoor residual spraying (Ameneshewa and Service 1996). Finally, in this study no allowance was made for malaria-control interventions. This variable was not taken into account because control methods and insecticides have changed over time, making it a complex covariate.

These constraints mean that the results of associations with water-level change are not definitive. Nevertheless, they do provide evidence to support the contention that management of reservoir water levels could play a role in controlling vector abundance and elevated levels of malaria in villages situated close to the reservoir shore. The evidence indicates that most anophelines around the reservoir feed mainly outdoors and early in the evenings when people are still active (Abose et al. 1998). Consequently, the impact of conventional malaria-control strategies (i.e., bed net distribution and IRS) may be undermined. Therefore, inclusion of source-reduction measures, such as management of reservoir drawdown, could possibly increase the effectiveness of an integrated malaria-control strategy in the vicinity of the reservoir. However, before this can be stated categorically, more research is required to obtain empirical evidence of cause and effect relationships and to deduce the optimum timing and rates of drawdown. Furthermore, the impact of modified reservoir management to control vectors on both electricity production and the downstream irrigation needs to be carefully assessed so it can be incorporated into the decision-making process.

Concluding Remarks

By creating numerous mosquito vector breeding sites close to the reservoir shore, the Koka Dam in Ethiopia has substantially increased the frequency of diagnosed cases of malaria. As a result, communities closest to the reservoir are at increased malaria risk. Although not conclusive, evidence from this study suggests that increased rates of drawdown could play a role in reducing larval habitat with a consequent impact on malaria transmission in the area.

In light of the likely increase in dam building in sub-Saharan Africa in the near future, methods to control malaria need to be prioritized. In conjunction with historic experiences from elsewhere in the world, results from the current study indicate that manipulation of water levels to control *Anopheles* larvae has the potential to suppress malaria and could be a useful supplement to control measures targeting adult mosquitoes. More research is required to gain insight into the processes and mechanisms operating and to be able to predict under exactly what conditions such control measures are likely to be both successful and cost-effective.

Glossary

Anthropophilic	Mosquitoes that frequently take blood from humans rather than from other animals.
Endophilic	Female mosquitoes that rest indoors after blood-feeding till the blood in their abdomens gets fully digested.
Exophilic	Female mosquitoes that rest outdoors (e.g., in vegetation) after blood-feeding till the blood in their abdomens gets fully digested.
Hypoendemic	An area with low malaria transmission.
Postprandial endophily	The behavior of female mosquitoes that rest indoors just after feeding and later return outdoors to find more humid places.
Zoophilic	The behavior of mosquitoes that feed on nonhuman hosts (i.e., domestic or wild animals).

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ISSN: 1026-0862
ISBN: 978-92-9090-706-0