Do local environmental changes resulting from the construction of microdams lead to increased malaria transmission in Tigray, Ethiopia?

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Do Local Environmental Changes Resulting From The Construction Of Microdams Lead To Increased Malaria Transmission In Tigray, Ethiopia?

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By

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Abstract

To investigate the impact of microdams on local microclimate and malaria transmission and in order to develop appropriate methods for the control of this disease, a longitudinal microclimatic, entomological, and clinical study was conducted. The study took place in two topographically similar villages: Deba, near a microdam and Maisheru, 3-4km away, in Tigray, northern Ethiopia, where an extensive dam construction is in progress in epidemic prone areas. The weather was recorded in both villages, on the dam embankment and at different mosquito habitats. A community-led larval intervention study followed the impact assessment phase in the dam village. There was a 3.1 times greater prevalence of an enlarged spleen and 2-5.5 times higher incidence of falciparum malaria in children under 10 years of age in the dam village compared to the remote village, indicating a greater level of exposure experienced in the dam village. *Anopheles arabiensis*, which was highly anthropophilic, partially exophilic, and showed early biting peak (19:00-20:00hr), was 6.5-8 times more abundant in the dam village compared to the remote village and this was even higher during the dry season (x16) when a second peak in density was observed in the former. This corresponded to when the fields were irrigated indicating that transmission of malaria was no longer restricted to the rainy season in the dam village compared to the remote village. Despite DDT spraying and prompt treatment of clinical cases with Fansidar at a community level, the findings demonstrated that dams have the potential to increase transmission of malaria parasites. The dam not only created abundant mosquito breeding sites throughout the year, but also resulted in significant microclimate changes; notably elevated minimum atmospheric temperature, the influence weakening with distance from the dam. The dam site was 1.5 °C warmer than the dam village and that of the dam village was 1.3 °C higher than the remote village and was especially pronounced (>3.5 °C) in the cool/dry season. Mean air temperature recorded under vegetation was 1.7 °C lower than outside and the dam provided numerous cool and humid microhabitats elsewhere by raising the water table, increasing water seepage, saturating the soil and promoting abundant growth of vegetation. Indoor temperature was relatively stable with higher minima and lower maxima than outdoors and on the average 2.8-3.4 °C warmer than outdoors. The warming effect of the dam, together with profuse breeding sites, suitable indoor and outdoor resting microhabitats may have contributed to the extended and dramatic increased risk of malaria observed in near dam communities in the Ethiopian highlands in Tigray. Most importantly the larval intervention study, which involved minimal community participation, showed a 49% relative reduction in *An. arabiensis* abundance in the dam village compared with the pre-intervention period. Thus, if dams could be constructed further away from settlements and if serious and sustainable community-led environmental management measures could be introduced as a package, it would be possible to mitigate the impact of microdams to an appreciable extent and calls for an integrated approach to malaria control, in fringe areas of malaria, such as the Tigray highlands, particularly near microdams.

Key words: Dams, microclimate, mosquito ecology, Ethiopia, Tigray, malaria, *Anopheles arabiensis*, highland fringes.

Dedication

This work is dedicated to the direct victims of the Ethio-Eritrean war and its aftermath; the Agame-Irob-Zalambessa-Adiabo people and other communities at the border area, the cluster-bombed school children at Ayder in Mekelle, and to all those who sacrificed their precious lives defending their country.

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Mekonnen Yohannes Fisiha

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Abbreviations used

AWS	Automatic weather station
^{o}C	Degree Celsius
CI	Confidence Interval
cm	Centimetre
CS	Circumsporozoite proteins
CSA	Central Statistical Authority
EIP	Extrinsic incubation period
EIR	Entomological Inoculation rate
ELISA	Enzyme Linked Immuno-sorbent Assay
EM	Environmental Management
ETC	Exit trap collection
F	Fed
G	Gravid
GM	Geometric Mean
GIS	Geographical Information System
GPS	Global Positioning System
HG	Half Gravid
hr	Hour
IgG	Immunoglobulin G
IPCC	United Nations Intergovernmental Panel on Climate Change
HBI	Human Blood Index
HLC	Human landing collection
HLTC	Hourly light trap collection
HRP	Horse radish peroxidase
Km	kilometre
LTC	Light trap collection
L	litre
MARA/ARMA	Mapping Malaria Risk in Africa / Atlas du Risque de la Malaria en Afrique
m	metre
min	Minutes

ml	Millilitre
MoA	Ministry of Agriculture
MoH	Ministry of Health
MOVBDCU	Malaria and Other Vector Borne Diseases Control Unit
PBS	Phosphate buffered saline
PBST	Phosphate buffered saline with Tween 20
PCR	Polymerase chain reaction
RH	Relative humidity
SAERT	Sustainable Agriculture & Environmental Rehabilitation in Tigray
SSC	Space spray collection
RBM	Roll back malaria
TDR	Tropical Diseases Research
Tmax	Maximum temperature
Tmin	Minimum temperature
Tmean	Mean temperature
µl	Microlitre
UNDP	United Nations Development Program
UNICEF	United Nations Children's Fund (formerly United Nations International Children's Emergency Fund)
UF	Unfed
USAID	United States Agency for International Development
W	Wilcoxon's Signed Ranks Test
WHO	World Health Organization

Plate 1. Partial view of Meskebet microdam and Deba village below it.

Plate 2. Partial view of a microdam near a settlement about 10km northwest of the town of Axum in central Tigray, Ethiopia.

Chapter 1: Introduction

General Background

The term “malaria” is derived from the Latin, *mala aria* or “bad air” and indicates the disease’s association with stagnant water, a favourite breeding site of the mosquitoes that transmit the malaria parasite. Although the term does not reflect the true causation of the disease, it is the term in common use since the scientifically more appropriate term-Plasmodiosis- has never come to wider use (Wernsdorfer, 1980). Human malaria has been known to humanity from the dawn of civilization. The writings of Sumerians and ancient Chinese, Homer, Aristotle, Plato and Shakespeare all described the intermittent fevers characteristic of malaria. The exact descriptions of malarial fever were given by the Greek physician, Hippocrates in 400 BC and linked it to the proximity of stagnant waters (Garnham, 1966).

Nowadays, over 100 species of malaria causative agents, members of the genus *Plasmodium,* are know. They infect a wide range of vertebrates and exhibit narrowly defined host specificity (WHO, 1987). Human malaria is caused by four *Plasmodium* species, namely, *Plasmodium falciparum*, *P. vivax, P. malariae* and *P. ovale.* They have essentially the same and complex life cycle with *Anopheles* species as the arthropod host and man as the only natural vertebrate host, with the exception of *P. malariae* where higher non-human primates may be involved occasionally (Garnham, 1966).

Although the genus *Anopheles* was first identified by Meigen in 1818, its vectorial role was not known until Ronald Ross isolated the characteristic pigmented oocysts of the malaria parasite from the gut of the mosquito in 1897 (Dutta and Dutt, 1978). Currently, over 400 species of anopheline mosquitoes are known all over the world (WHO, 1987). Of these, around 67 were found to harbour sporozoites originating from natural infection. However, only about 27 of these anophelines are reported as potent vectors of human malaria under natural conditions, due to their biting and other habits (Wernsdorfer, 1980). Even then, in each geographical area there are usually not more than three or four anopheline species that can be regarded as important vectors (Gilles and Warrell, 1993).

The immature (egg-larva-pupa) stages of anophelines, like other mosquitoes, are passed in an aquatic environment. The physical and chemical characteristics of a particular type of water body- whether it is running, standing, clean or polluted, sweet or brackish, shaded or sunlit- determines which species of mosquito breeds in it. In some species breeding is restricted to a narrow range of habitats while others breed in a wide range of water types. Generally, eggs are deposited singly on the surface of pools of water or on the wet mud at the edges very close to the water. Each egg possesses lateral air floats to keep it afloat. The eggs cannot survive desiccation and die quickly if dry. A female *Anopheles* may deposit more than a thousand eggs during its lifetime. The eggs generally hatch after 2-3 days in contact with water depending upon temperature (WHO, 1982; Gilles and Warrell, 1993). The newly hatched larva grows by casting its skin four times before it reaches the pupal stage, the stages between successive moults being known as instars. The larvae of *Anopheles* spend most of their time horizontally at the water surface breathing and filter feeding upon organic material and microorganisms. It takes about 7 or more days for the larvae to change into the pupal stage depending on temperature and other factors. The pupa is very active but a non-feeding stage, of several days duration, and the major morphological and physiological changes required for transformation of the larva to the adult occur at this stage. After emergence the adult mosquito rests for a few minutes on the discarded pupal skin for its wings to expand and harden prior to flight. The time needed for development from egg to adult in *Anopheles* varies between species due to temperature and other factors. Generally it may take about 14 days or more in tropical species (WHO, 1982; Gilles and Warrell, 1993)

The adults of both sexes feed on plant juices but only the female feeds on blood, which is required for egg development. Mating, which occurs only once in life, usually occurs within 24-48 hours after emergence. The males of some species form a swarm at twilight and females fly into theses swarms and are mated (Charlwood and Jones, 1980). After insemination, the spermatozoa are stored in an organ in her body, termed spermatheca, and are drawn on for fertilization of all the eggs produced throughout the remainder of its life. Usually after mating the female *Anopheles* seeks a host to feed. Dispersal from breeding sites to feeding areas depends on the local topography and availability of host. In the open and sparsely populated areas flight range is grater than in well-vegetated and densely populated areas. The prevailing wind also influences the flight range. In general, the flight range of most tropical species is within a range of 1-3km, under normal atmospheric conditions (Gillies and De Meillon, 1968). The males are much weaker flyers than the females and, not taking account of the prevailing wind, their presence in large numbers indicates the proximity of breeding places of that particular species (WHO, 1982; Gilles and Warrell, 1993).

Female anophelines exhibit differing feeding preferences due to genetic and environmental factors such as the availability of hosts. Some feed only on humans (anthropophilic) or animals (zoophilic) or they may be indiscriminate biters. In the absence of the preferred host, some species like *An. gambiae s.l.* feed readily on another host and are termed as facultative feeders. Mosquitoes may feed on humans inside houses or outdoors. After a blood meal, the mosquito should rest somewhere outdoors or indoors for some time until the blood has been digested and the ovaries contain mature eggs, i.e., they are gravid. In the tropics it may take 24-48 hours for the females to be gravid depending on temperature. Anopheline species that feed and rest inside houses are described as endophagic and endophilic, as compared with exophagic and exophilic mosquitoes, which feed and rest outdoors. Others could be endophagic and exophilic or vice versa. These behaviours are very important in the epidemiology of malaria since an anthropophilic species is likely to be a better vector of malaria than a zoophilic one. Similarly, it is easier to control indoor resting mosquitoes by residual insecticides than outdoor resting ones. The gravid mosquito typically leaves the house at dusk in search of a suitable aquatic site for egg laying. After laying eggs, the mosquito again flies from the breeding sites in search of another blood meal and the cycle goes on until death interferes (WHO, 1982; Gilles and Warrell, 1993).

The chain of transmission of the malaria parasite involves the human carrier, the mosquito vector and the human victim or recipient. In the complex life cycle of the parasite in female mosquitoes, a process termed sporogony, the mosquito derives the infection by ingesting immature sex cells or gametocytes with the blood of a malaria patient or asymptomatic parasite carrier. Once drawn into the mosquito, the gametocytes are transformed into mature sex cells inside the gut of the mosquito mainly in response to the relatively lower temperature than in the human host. Female gametocytes transform into macrogametes. In a process called exflagellation, the nucleus of the male gametocyte divides up into several elongate protoplasmic processes that radiate from the surface of the male gametocyte. Each of these processes becomes a male gamete termed microgamete, which is equivalent to a mammalian spermatozoon (WHO, 1987; Gilles and Warrell, 1993).

A microgamete fertilizes a macrogamete to form a zygote, which is transformed to an elongated and motile ookinete. The ookinete bores into the gut wall and becomes a non-motile oocyst, which grows and its contents divide producing thousands of spindle-shaped sporozoites. This process is temperature dependent and does not occur at temperatures below 16 °C. The oocyst ruptures and releases sporozoites that invade the salivary glands of the mosquito. When the mosquito feeds on another host they are transmitted with the saliva, which is injected into the human body to ensure a steady flow of bloodmeal as it contains anticoagulant (WHO, 1987; Gilles and Warrell, 1993). *In vitro* transmission studies using experimentally infected mosquitoes have shown that most infected mosquitoes transmit less than 25 sporozoites, but up to 5% of the infected mosquitoes can transmit hundreds of sporozoites (Ponnudurai *et al.*, 1991; Beier, 1998). The sporozoites in the host blood stream then head straight for the victim's liver and penetrate hepatocytes. There they hide out for a week or two, depending on the species, and each sporozoite grows and develops into a schizont, a form that undergoes multiple divisions, termed exo-erythrocytic schizogony. This process of schizogony in the liver cell produces 2000-40000 separate ring-shaped tiny individuals known as merozoites. At the end of the incubation period, the infected liver cells rupture and release the vastly increased number of parasites into the bloodstream, where they invade the circulating red blood cells. (Russel *et al.*, 1963; Wernsdorfer and McGregor, 1988; Gilles and Warrell, 1993).

Once inside the red blood cell, the merozoite feeds on the contents of the cell and is transformed into a schizont that undergoes repeated divisions to produce many merozoites. This multiplicative phase in the red blood cells is called erythrocytic schizogony and the infected red cells explode, at regular intervals, unleashing a new generation of parasites into the bloodstream. Erythrocytic schizonts rupture with a periodicity of 24-72 hours, characteristic for individual species, and each liberates 10-20 merozoites that attach to specific receptors on red cell membranes to initiate invasion. Upon invading new red blood cells, the merozoites can either initiate renewed blood schizogony or develop into sexual forms. The erythrocytic cycle is associated with clinical manifestations of malaria, which depend on the presence of a definite quantum of parasites in the blood. The duration of the cycle is the duration between the successive fever episodes in the victim, each episode correlating with the simultaneous release of the merozoites from the cells. This is because the release of the merozoites stimulates the immune system to release cytokines, which cause fever. The remains of the killed red blood cells are broken down in the spleen, a reason why the spleen is enlarged in people with malaria. In general, clinical symptoms develop within 8 to 30 days of inoculation of infective sporozoites. They consist typically of sequential chills, fever and sweating, which may be preceded with a premonitory stage- headache, nausea, and malaise (Russel *et al.*, 1963; Wernsdorfer and McGregor, 1988; Gilles and Warrell, 1993).

The clinical symptoms of periodicity are not adequate to definitely establish a malaria infection, since they can resemble that of many other diseases and variations in the classical clinical course are common, especially in children. This is particularly common in infections with *P. vivax* and *P. falciparum*, where superinfection can occur with subsequent establishment of two or more broods of parasites and quotidian fever pattern. When one generation of the parasite prevails in the blood, fever typically has a regular intermittent pattern with the occurrence of paroxysms every 48 hours in cases of vivax and ovale (*simple or benign tertian*) malaria and every 72 hours with malariae (*quartan*) malaria. *P. falciparum* is invariably irregular in its pattern, due to the occurrence of two or more broods of parasites, and the protean symptoms of falciparum malaria are misleading and may appear with dramatic suddenness and severity. A child infected with a virulent strain can die within hours of the first symptoms, as ravaged blood cells clog capillaries and deprive the brain of oxygen (Russel *et al.*, 1963; Wernsdorfer and McGregor, 1988; Gilles and Warrell, 1993).

Malaria was considered as one of the main health problems in the world and its control was actively undertaken after the Second World War. Impressive success has been obtained in a number of countries, mostly in the most developed ones. Nevertheless, humanity's dream to control malaria to a reasonable level, let alone to eradicate it, appears to be shattered. In spite of global efforts to develop new antimalarials, new insecticides and new applications to combat malaria the disease still remains a major threat around the world and the situation is getting worse. Recent estimates from the

World Health Organization (WHO) indicate that malaria infects over 300-500 million and kills 1.5 to 2.7 million people each year, 90% of them in tropical Africa (WHO, 1998). Approximately 1 million deaths among children under 5 years of age are attributed to malaria alone or in combination with other diseases, especially in developing countries (UNICEF, 2000). WHO estimates that 2400 million people live in malarious regions and the disease is endemic in 100 countries (UNICEF, 2000). In 1994 malaria transmission included *P. falciparum* in 92 countries and territories, while in 8 countries only *P. vivax* transmission occurred (WHO, 1997).

In Africa, up to 20-30% of all admissions and about 30-50% of outpatient consultations are malaria-related (UNICEF, 2000), and children under five years of age as well as pregnant women are the worst affected by malaria. Over 500,000 children die each year in Africa alone (Snow *et al.*, 1999) and the major causes of death include anaemia in infants and cerebral malaria in those aged 1-5 years. The effects can be particularly severe during pregnancy, especially in primigravidae (first-time mothers), for anaemia can both slow the growth of the foetus and cause premature delivery. Malaria during pregnancy causes severe maternal illness and anaemia, and is also associated with low birth weight among newborn infants, a leading risk factor for infant mortality (UNICEF, 2000).

Apart from being a major cause of child mortality in highly endemic area of falciparum malaria, the disease is also insidious. Although malaria bestows immunity after repeated attacks, it continues to sap the energy and undermine the health of those who survive its miseries. Malaria causes chronic sufferings, results in an increased number of deaths from other causes, lowers life expectancy, and brings impaired growth in children. Over the centuries it has had a profound impact in curbing socio-economic development by reducing the productive potential of mankind wherever it persisted. The cost, beyond human suffering, amounts to billions of dollars a year in health care and lost productivity, usually in countries that can ill afford it. The economic loss from malaria was estimated at US $2 billion in Africa alone in 1997(UNICEF, 2000). Malaria is a major cause of poverty, and poverty exacerbates the malaria situation. Taken together, the effects of malaria on lives and livelihoods are devastating for economic progress in hard-hit countries. According to the WHO and the World Bank, malaria is the largest single component of the disease burden in Africa, causing an annual loss of 35 million future life-years from disability and premature mortality. Malaria is also a major public health problem in parts of Asia, Latin America, the Middle East, Eastern Europe and the Pacific (UNICEF, 2000).

Locally contracted malaria has been recorded in places over a wider latitudinal and altitudinal limits. It has been reported as far north as 64° N latitude and as far south as 32° S latitude. The altitudinal limits covered were as low as 400m below sea level in the Dead Sea area and at 2600m above sea level at Londiani (Kenya) or at 2800m in Cochabamba (Bolivia). Within these limits of latitude and altitude there are large areas free of malaria reflecting the focal nature of the disease, its transmission governed greatly by local environmental and other conditions (Gilles and Warrell, 1993). Of the four main forms of malaria, vivax malaria is the most prevalent-covering many temperate, tropical and subtropical regions. Falciparum malaria is the most frequently occurring form throughout the tropics and subtropics, although its range is restricted compared to *P. vivax* in terms of geographical distribution (Loban and Polozok, 1983). Regardless of its comparatively limited geographical area of incidence, however, *P. falciparum* is responsible for most cases of malaria and for the most severe and often fatal forms of the disease (TDR, 1988). This includes imported falciparum malaria in European countries and the USSR (Bruce-Chwatt, 1987), but the epidemiological danger associated with it is insignificant because the subspecies of anopheline mosquitoes prevalent in these areas are not susceptible to the tropical strains of *P. falciparum* from Africa (Loban and Polozok, 1983). Malariae malaria is patchily present over the same range as falciparum malaria but much less common than falciparum or vivax malaria (TDR, 1988). Ovale malaria is least prevalent of the four forms of human malaria and the geographical distribution of the parasite is quite peculiar. It occurs chiefly in tropical Africa, but also occasionally in the West Pacific (Wernsdorfer, 1980; WHO, 1987).

Within each of the four species of human *Plasmodia*, there are a number of strains that have different epidemiological and other features, although they are indistinguishable morphologically. Thus, the tropical strains of *P. falciparum* cannot readily infect the anopheline species present in Europe (Loban and Polozok, 1983). The pattern of relapses in temperate areas, particularly the West Pacific, strains of *P. vivax* is different from the relapse pattern of vivax malaria occurring in other parts of the world. There are also considerable differences between the long incubation period of the disease caused by some North European strains of *P. vivax*, and the short incubation period seen in infections by other strains of this plasmodial species. This explains the adaptability of *P. vivax* to life in colder climates, which is made possible by the capacity of the parasite to survive for a long time in the liver of the host in a dormant state in the form of hypnozoites. For example, in the northern latitudes, where the transmission period is short and seasonal, strains of *P. vivax* remain in the host in the latent form for about 6-9 months, until the next transmission period (Wernsdorfer, 1980; Loban and Polozok, 1983). In the tropical and subtropical zones, however, *P. vivax* populations are represented by sporozoites causing the development of the disease after a short incubation period. Thus, the natural populations of *P. vivax* (and *P. ovale*) seem to consist of sporozoites comprising a mixture of immediately developing and hypnozoite-destined ones (Garnham, 1987). This also explains the relapse phenomenon observed in *P. vivax* and *P. ovale* and the variations in incubation period and relapse patterns of *P. vivax* that occurs as a result of selection imposed by the local variations in transmission (WHO, 1987). It is also known that ethnic genetic differences in the susceptibility to particular species play an important role in the distribution of *P. vivax*.

Major Environmental Determinants of Malaria

Disease transmission is influenced by a complex interplay of varied factors such as local climate, altitude, vegetation density and species composition, nature of soil and land-use patterns, as well as other socio-economic factors such as the stability, immunity, mobility and behaviour of local populations. With respect to malaria one of the most important factors influencing its transmission is the local climate.

Climate

Climate is one of the major components of the physical environment and is usually defined as the average weather (i.e., short-term-day to day, hour to hour-fluctuations) over a period of years and in a particular geographical region. Climate is a composite of such factors as temperature, relative humidity, precipitation, light and wind. Climatic factors play an important part in species distribution, behaviour, survival and vectorial status and in general regulate the biology of development of both the mosquito and the parasites they transmit. The most important climatic elements in this regard are temperature, humidity and rainfall. Climate can be divided into macroclimate, meaning the average weather conditions of an area, and the microclimate, or modifications in restricted areas within the overall macroclimatic zone (WHO, 1987).

Temperature

As insect vectors and the parasites they transmit are cold-blooded, all metabolic processes and therefore the entire life processes depend on the environmental temperature. Hence, certain biological events such as the rate at which mosquitoes develop into adults, the speed of blood digestion and maturation of the ovaries and consequently the frequency of feeding, vary according to temperature. Temperature also determines the rate with which parasites are acquired and the incubation time of the parasite within the mosquito (the extrinsic incubation period or EIP) (Lindsay and Birley, 1996). *Anopheles* mosquitoes have known temperature thresholds for survival and biting rates also depend upon ambient temperatures. Provided sufficient moisture, warmer temperatures within the survivable ranges increase mosquito populations, decrease the EIP and increases biting rates (blood meals) and mosquito activity (Lindsay and Birley, 1996; Patz *et al.*, 1996).

The optimum range of temperatures allowing the maturation of the aquatic stages and gonotrophic maturation in the adult varies between vector species (WHO, 1982). In general, the aquatic stages of anopheline mosquitoes in the tropics do not breed or develop below approximately 16 °C. For most malaria vectors 20-30 °C represents an optimal range (Molineaux *et al.*, 1988). Within these optimal ranges, however, there is largely a direct relationship between temperature and growth. In general, mosquitoes breeding in the tropical zone, in water at 23 – 27 °C, usually complete their aquatic growth within two weeks (WHO, 1982). For example, under laboratory conditions over 70% of *An. gambiae s.s.* immature stages kept between 23-28 °C were observed to complete their growth into the adult stage within two weeks (9.8-14 days) (Bayoh, 2001). The lower limit for complete development to adult occurred between 16°-18 °C, and the upper threshold was 32-34 °C. At 18 °C, 42% of the immatures emerged as adults in 23.3 days whereas at 32 °C, 34.7% of them completed their development in 10 days. All in all, the rate of development from each instar to the next increased with increase in temperature up to an optimum of 28 °C and then declined. The rate of larval development, i.e. from 1st to 4th stage, was greatest between 28-32 °C, although the proportion of larvae that developed into adults was highest between 22-26 °C. Most deaths (>80%) at these temperatures occurred at the 4th instar and the pupal stages (Bayoh, 2001).

In general, provided sufficient moisture, a rising temperature tends to increase the growth rate of the vector populations by shortening the aquatic life cycle of the mosquitoes, the time between emergence and oviposition, as well as the time between successive ovipositions. Hence, rising temperatures within the range shorten the minimum generation time of the vectors, which is the sum of the intervals from oviposition to emergence and from emergence to oviposition. In fast developing species such as *An. gambiae s.l.*, the generation time may be as short as 10-11 days at high temperatures, while at lower temperatures it may take a fortnight or more depending on the prevailing temperature (Gillies and De Meillon, 1968). The rate of aquatic development at a given temperature varies between species, and the high rates attained by certain vectors, such as *An. Arabiensis* and *An. gambiae s.s.*, allow them to breed in temporary pools and to get ahead of vegetation, pollution, competitors and predators (Molineaux *et al.*, 1988).

The interval between the mosquito host's first blood meal and its first feed transmitting the infection, known as the extrinsic incubation period, is determined by the species of the parasite (i.e. by genetic factors) and by the ambient temperature. At a given temperature, the duration of sporogony increases in the following order: *P. vivax, P. falciparum, P. ovale* and *P. malariae* (Molineaux *et al.*, 1988). The parasites will develop in the vector only within a certain range of temperature. At the lower end, the parasites cease to develop in the mosquito and fail to complete their life cycle and hence further propagate the disease when the temperature is below 16 °C (Gilles and Warrell, 1993), although there is no consensus as to what that minimum temperature actually is: according to Macdonald (Macdonald, 1957) it is 15 °C for *P. vivax*, 19 °C for *P. falciparum*; according to Detinova (Detinova, 1962), it is 14.5 °C for *P. vivax*, 16 °C for other species of malaria parasites; according to Coatney and colleagues (1971: cited by (Molineaux *et al.*, 1988), it is 15 °C for *P. vivax* and *P. malariae*. Above the minimum temperature the incubation period decreases with increasing temperature (Molineaux *et al.*, 1988). Generally relatively higher temperatures facilitate the developmental cycle. For example, in *P. falciparum*, the incubation period is completed in 10 days at 30 °C and about 23-24 days at 20 °C (Macdonald, 1957). This gives a difference of about 14 days over a range of 10 °C. In general, all species have the shortest developmental cycle at the highest survivable temperature -around 27-31 °C, from a minimum of 8 days for *P. vivax* to a maximum of 15-21 days for *P. malariae* (Macdonald, 1957; Dutta and Dutt, 1978; Gilles and Warrell, 1993).

The influence of temperature on the longevity of adult mosquitoes is also very strong. Tropical species will not withstand temperatures near freezing point. Permanent high temperatures over 27-30 °C will reduce the average life of a mosquito population (WHO, 1975), thus, reducing population growth and density. Moreover, extreme temperatures tend to affect, negatively, the biting and flight activity of adult vectors, although it is not known definitely at what point high temperatures become lethal to developing parasites (Lindsay and Birley, 1996). But it is generally believed that the upper limit of temperature suitability for the parasite is largely determined by vector survival (Craig *et al.*, 1999). Temperatures of above 32 °C have been reported to cause high vector population turnover, weak individuals and high mortality (Craig *et al.*, 1999) with the daily survival approaching zero at 40 °C (Martens *et al.*, 1997). Thermal death for mosquitoes has also been reported around 40-42 °C (Haddow, 1943; Jepson *et al.*, 1947), although mosquitoes may avoid these restrictions by seeking microhabitats such as by resting in houses or shaded areas in nature. The influence of temperature on the life history of the vector species and the development of the parasite within the vector should, however, not be taken separately. Because, there are several other environmental parameters that change with increasing temperature, chief of which is relative humidity (Lindsay and Birley, 1996).

Relative humidity

Humidity of the air is most commonly expressed as relative humidity, but the crucial factor for the vector's physiology may be the absolute saturation deficit (Molineaux *et al.*, 1988). Although the relationship between mosquito survival and humidity is not straightforward (Lindsay and Birley, 1996), it is widely accepted that, humidity can also act as a limiting factor in the distribution and longevity of the vector species. Owing to their small size (hence large surface area to volume ratio) and the tracheal system of respiration insects, in general, are particularly susceptible to desiccation, as they tend to lose water to the environment at a relatively faster rate than other organisms. Forest species are more susceptible to humidity changes than those living in areas with a dry climate (WHO, 1975). Within limits, the longevity of adult vectors increases with the relative humidity of the air. Relative humidities over 50% or 55% (Dutta and Dutt, 1978), or 60% ensure the normal life span of the vector (Dutta and Dutt, 1978; Molineaux *et al.*, 1988). Some large epidemics have been attributed to unusual longevity of the vector due to abnormally high humidity of the air, but the real role of this single factor is difficult to assess as ambient humidity is regulated by the interactions between rainfall, evaporation, runoff or availability of breeding places, and temperature (Molineaux *et al.*, 1988). Except at extremely low humidities, when mosquitoes are unable to regulate their water loss, longevity is in general greater at the higher ranges of humidity and lower ranges of temperature. *An. Culicifacies*, for example, was found to survive about 10 days at a 60-65% RH and at 30-35 °C, compared with 30 days at 80-90% RH and 27-30 °C (WHO, 1982).

Rainfall

Rainfall is generally associated with greater breeding activity of mosquitoes although its effect varies according to its amount and the physical features of the terrain (WHO, 1975). The association of malaria with rainfall in parts of the world where the latter is seasonal is due not only to new opportunistic breeding places, but also to the rise in relative humidity which prolongs the life of the vectors and intensifies their biting cycle. As a result, profuse breeding and population build up as well as intensification of the biting cycle occurs during the later parts of the rainy season and immediately afterwards. Consequently, the greatest incidence of human malaria occurs at the end of the rainy months and a few weeks afterwards (Dutta and Dutt, 1978). Rainfall, which normally increases the amount of surface water, may have, at times, a negative effect on the amount of transmission of malaria, especially at its peak of occurrence. Excessive rainfall can change breeding pools into streams, resulting in temporary flushing out of the breeding places. On the other hand, exceptional drought conditions can also result in rivers drying out, producing enumerable small pools of water along the riverbed in which certain *Anopheles* would breed in profusion. The appearance of such opportunistic mosquito breeding sites sometimes precedes epidemics (Gilles and Warrell, 1993).

Apart from temperature, relative humidity and rainfall, the other climatic variable, which could influence mosquitoes, is wind. Strong winds affect the flight of vectors, hence their biting activity, and may hamper their egg laying. In other cases they may extend their flight range well beyond the normal limits (Gilles and Warrell, 1993). Under normal circumstances, most tropical species, such as *An. arabiensis,* could fly within a range of 1-3km, although there are records of few species or occasional individual mosquitoes flying much further (Gillies and De Meillon, 1968). Certain Temperate Zone species travel 4-5km and there are records of those that travelled up to 10km. Dispersal is largely down wind and strong winds can carry mosquitoes for great distances. For instance, in Egypt windborne *An. pharoensis* were reportedly recovered up to 250km from the nearest breeding sites (Garrett-Jones, 1962).

From all that has been mentioned above, it appears that data on climatic factors, especially temperature, humidity, rainfall, and wind, as well as other ecological factors, are of considerable importance for the study of the dynamics of vector populations. The monitoring and analysis of such meteorological indicators had received renewed attention in the past decade due to the concern arisen about the possible impact of global warming and climate change on the transmission and spread of vector borne diseases. For example, based on the ratio of precipitation to potential evapo-transpiration, it was possible to model and map the relative distribution of the important vectorial system of Africa and measure the transmission risk under changing climate scenarios (Lindsay *et al.*, 1998b). Nevertheless, climate acts at a coarse spatial scale and then other factors become important at a finer spatial resolution. Hence, such information should not only be collected at the macro-level but also at a local level at the time and place of observations. The macroclimate varies according to the latitude and altitude and the prevailing meteorological factors. Whereas, the microclimate varies with the presence and absence of different types of vegetation, exposure, aspect, colour, and other peculiarities of the site which produce a difference in the conditions of temperature and humidity, when compared with the macroclimate (WHO, 1975).

The microclimatic aspects of the adult environment are extremely important both from the point of view of adult survival and as regards the length of the sporogony in the infected mosquito. Insects are able to withstand the effects of normal climatic variations and can seek out microclimates that offer protection against extremes of climate. For instance, mosquitoes may evade dry weather, by concentrating in those houses or other indoor resting-places where the microclimate offers a favourable humidity and temperature. Outdoor-resting mosquitoes will rest in the vegetation near the ground or in other cool and humid holes and crevices during dry periods. During day and night, there is a daily rhythm of temperature and humidity, characteristic for each area, and insects can adapt their behaviour to the most favourable part of the diurnal cycle Many anopheline vectors, such as *An. arabiensis*, bite at night when relatively lower temperature and higher relative humidities prevail (WHO, 1975; Muir, 1988; Lindsay and Birley, 1996). Under very harsh dry and cold conditions different mechanisms are employed for survival by different mosquito species.

Many temperature mosquito species, including anophelines and culicines, may survive the harsh winters in a state of diapause as eggs, larvae or adults. For example, in Japan, some anophelines and *Culex* species were reported to diapause as adults while most *Aedes* species do so as eggs or larvae (Mogi, 1996). The survival strategy of *An. arabiensis* during the long dry and hot periods as in the sub-Saharan Sahel or northern savannah areas of tropical Africa remains puzzling. Omer and cloudsley-Thompson (Omer and Cloudsley-Thompson, 1968; Omer, 1970) found that in the Sudan desert west of Omdurman *An. gambiae s.l.* (probably *An. arabiensis*) survived the 9 months dry season as adults, taking small blood meals and not developing eggs, thus undergoing a period of quiescence. All the female specimens collected during the dry season were nulliparous, and although artificial breeding places were provided, no oviposition occurred. 77% of these females contained blood in their gut indicating that *An. arabiensis* must exhibit a degree of arrested ovarian development and that the nulliparous females complete only one gonotrophic cycle during the long dry season. The speed with which biting females reappear with the onset of the rains and the almost immediate resurgence of malaria appears to support this view. Nonetheless, recent investigations in a dry savannah zone of east Africa have failed to show any evidence of aestivation or related arrested development among the 3 main malaria vectors *An. funestus*, *An. gambiae* and *An. arabiensis* (Charlwood *et al.*, 2000). Other works in western Kenya (Beier *et al.*, 1990; Minakawa *et al.*, 2001) have pointed to the possibility of egg aestivation in the dry season representing a significant short-term survival strategy for the species. The authors reported the recovery of viable eggs in dried breeding sites along the margins of Lake Victoria. However, they did not report the moisture content of the soil, for how long the breeding sites were dry and did not exclude the possibility of contamination from the nearby breeding sites or the water they used from the lake shore. Hence much more research is required in this area to substantiate the notion that *An. gambiae* survives dry conditions as eggs.

Many ecological models consider only air temperature as an input parameter. Nevertheless, in organisms, such as mosquitoes, that pass part of their life cycle in water, the immature stages are exposed to temperatures, which differ considerably from air or bulk of water temperature (Jacobs *et al.*, 1997). Simulation studies conducted on malaria vectors indicate that mortality and development of the aquatic stages due to surface water temperature are the most important factors to determine the number of emerging adult mosquitoes (Jetten and Takken, 1994). Hence, monitoring the temperature of breeding sites is also very crucial in the elucidation of the life history vector species.

Physical landscape

The nature of the physical landscape, particularly altitude and topography, affects malarial incidence negatively or positively. The impact of altitude in the distribution and transmission of malaria had been known for a long time. European colonizers of Africa (Lindsay and Martens, 1998a) and the natives were well aware of the benefits afforded by living at higher altitudes. Ethiopians sought refuge from the scourges of malaria in the cool highlands for centuries and even today many of those who live in the lowlands seek out the highlands during the transmission season (Gebremariam, 1988). The extent and severity of malaria generally diminishes in proportion with increasing altitude above sea level although the upper limit may vary in different places depending on the latitude. On or near the equator, because the sun's rays are more direct, higher altitudes are susceptible to malaria compared to temperate regions (Dutta and Dutt, 1978). In countries such as Burundi, Ethiopia, Kenya, Morocco and Rwanda, the upper limit of malaria is about 2000m. In other countries, such as Zimbabwe, this boundary is about 1200m (Lindsay and Martens, 1998a). In the temperate zones optimum temperature for vector breeding and effective transmission of parasite can be reached at much lower elevations (Dutta and Dutt, 1978). The impact of altitude on the distribution of malaria is mediated by temperature; the average temperature decrease with height is 100m in free atmosphere (Barry, 1992).

The influence of topography or terrain on malaria transmission depends largely on its potential to hold water and create pools for the breeding of *Anopheles*. As a result, valleys with flat bottoms are usually more malarious than those without. In more sloppy terrain breeding sites are unlikely to be created due to runoff and erosion. Temporary water pools created in the downhill watercourses also tend be flushed easily. Even in flat terrain, the type of soil could affect the type of surface water available (clear or muddy, its salinity and other physicochemical characteristics) and its persistence. Clay soil is generally considered to be most conducive to mosquito breeding because of its relative impermeability. Porous limestone or sandy soils are less favourable (Dutta and Dutt, 1978) as they soak in water quickly and pools of water wouldn't persist for long. The suitability of the available surface water for breeding of different species may further be affected by many factors such as light and shade, emerging vegetation, competitors, predators and parasites (Molineaux *et al.*, 1988).

As indicated earlier, climate and the physical feature of the environment are very important in determining the distribution and transmission of malaria. Nevertheless, it is not enough to consider and note climatic elements and topography alone in order to elucidate the complex cycle of malaria transmission and classify or characterize the condition of the disease in a given area. The chain of transmission from humans to mosquitoes and back to humans may also be modified by various factors such as biogeographical factors, land use, dams and man made lakes, population movements and the like, all contribute to the distribution of disease and outbreaks.

Cultural impact

Cultural differences and changes in the environment brought about by humans result in ecological settings, which often encourage or discourage the malarial cycle. One of the essential preconditions for malaria transmission is man – vector contact. Thus, on the first place, human habits greatly influence their accessibility to vector feeding and, thus, the degree to which they are exposed to malaria infection. For example, if one's activities are more outdoor-oriented, or one sleeps without a mosquito net, or house windows do not have screen, the possibility of being bitten by an infective vector is greater. In general, the position and design of housing in relation to mosquito breeding sites and vector habits, night travels, outdoor sleeping, nomadism, immigration and local mobility of populations (Greenwood, 1989; Mouchet *et al.*, 1998), will all influence the extent to which humans are exposed to infection. Conversely, the incidence of malaria could be reduced greatly in areas with a physical potential for malaria. For example, in Europe, changes in agricultural practices leading to improved rural housing and the construction of separate stables for cattle and pigs is believed to have diverted malaria vectors away from humans and led them to feed on domestic animals (Dutta and Dutt, 1978).

Human environmental activities, such as agricultural and engineering developments, cultural attitudes toward mosquito and to treatment (as well as cooperation in control programs), and the effect of the quartet - poverty, ignorance, and illiteracy, social deprivation-often referred to as the "vicious cycle of malaria" are no less important (Greenwood, 1989; Mouchet *et al.*, 1998; Ijumba and Lindsay, 2001). In recent years, particularly if one looks at the third world, considerable environmental changes have taken place in many countries. Many of the changes occurred as a result of the creation of man-made lakes, the development of agricultural projects, deforestation, urbanization, and other economic activities involving land and water use. Each environmental change, natural phenomenon or through human intervention, alters the ecological setting affecting the mix of vectors, their biodiversity, breeding habits and abundance, vector competence and human biting behaviour as well as other aspects of their bionomics (Patz *et al.*, 2000). In vector-borne diseases such as malaria, even small variations in local microclimate can affect an insect vector's chance of survival, and therefore, the disease transmission potential within a given area. The nature and magnitude of change in the incidence of malaria due to land use can come as a result of change in settlement pattern, changes in type of soil and its degree of water absorption or retention, changes in vegetation composition and abundance, changes in the types and amounts of bodies of water, their size, shape, temperature, pH, flow, sedimentation and proximity to vegetation and, changes in climate. Hence, understanding and forecasting the consequences of changes in environmental management on tropical diseases is crucial for their control.

Genetic factors

Certain genetic factors encourage or discourage malarial infection and limit the distribution of the parasites. For example, ethnic genetic differences in the susceptibility to particular species play an important role in the distribution of *P. vivax.* This is reflected by the highest incidence of vivax malaria in Asia and its virtual absence from Central and West Africa, predominantly inhabited by people of Negroid descent (Wernsdorfer, 1980). The Central and West African populations have a high frequency of the Duffy negative genotype (FyFy) - the resistance factor to *P. vivax* in blacks (Miller and Carter, 1976) both in their country of origin and after generations of residence in the USA. In Africa, *P. vivax* is common in North Africa, but in tropical Africa its distribution is limited to eastern and southern regions, with Hamito-Semitic and Caucasian population groups (Wernsdorfer, 1980; Loban and Polozok, 1983).

In addition to ethnic genetic differences described earlier there are many epidemiological variables in the response of the human victim to the infection, although their importance in the distribution of malaria is not known. For example, there is some evidence of the protective action of haemoglobin S and the genetic deficiency of an enzyme (Glucose-6-phosphate dehydrogenase), which is normally present in the erythrocytes (Gilles and Warrell, 1993). There is also some evidence from studies carried in Sardinia that human leukocyte antigens (HLA), a polymorphic family of proteins, play critical roles in the stimulation of immune responses against malaria parasites. Selection for particular HLA types has been observed in populations historically exposed to malaria when compared with populations of the same ancestral stock living at a higher altitude, where malaria has been endemic. There is also some evidence of associations between a few HLA antigens common in African populations and protection from severe disease (Gilles and Warrell, 1993).

Gender and age are also important factors with regard to the malaria infection and children have generally a higher degree of susceptibility than adults. Generally speaking, populations exposed continually to intense malaria in highly endemic areas develop a degree of immunity to the infection. The relationship between the prevalence of gametocytes in the population and transmission is also of paramount epidemiological significance (WHO, 1987). When malaria is endemic a proportion of the population is usually a carrier of gametocytes and this may be particularly the case amongst young children; the prevalence of gametocytaemia decreases with rising age, until it reaches low levels in adults.

The comprehensive study of Muirhead-Thomson (Muirhead-Thompson, 1957) of *P. falciparum* in Liberia has indicated that adults and adolescents form a reservoir of infection as did children aged 5 to 14 years and that both groups are only slightly less infective than the age-group 0 to 4 years. Githeko and colleagues (Githeko *et al.*, 1992), working in an area of holoendemic malaria in western Kenya, reported similar findings. They showed that children under 10 years of age were responsible for 72% of mosquito infections, individuals between 10 and 21 years of age contributing 12%, and those over 21 years of age accounted for 16%. Mosquitoes were directly fed on falciparum malaria infected volunteers and the infection rate in the mosquitoes was determined by ELISA procedure. No infection was detected in mosquitoes fed on infants less than 1 year. Asymptomatic, low-density gametocyte carrying adults were also implicated as a serious problem by acting as the main reservoir of *P. falciparum* in endemic areas (WHO, 1987; Burkot, 1988). Likewise, the longer period of infections occurred at low gametocyte densities in the absence of clinical symptoms in non-immune subjects (WHO, 1987). Parasite carriers in endemic areas may serve as source of infection for a long time because malaria in such individuals is rarely identified and they receive no treatment (Loban and Polozok, 1983). Having escaped detection, they may also enter receptive areas, trigger subsequent transmission and thus be the cause of the introduction of malaria (Wernsdorfer, 1980).

The infectivity of a malaria patient or asymptomatic parasite carrier for mosquitoes is influenced by several factors that include age, number, sex, distribution and quality of gametocytes in his/her blood (WHO, 1975). In all species of parasites there are inexplicable variations in infectivity that are sometimes attributed to varying maturity of gametocytes. While viable gametocytes are usually present in the blood at the time when the first clinical manifestations of malaria due to *P. vivax, P. malariae* and *P. ovale* appear, this is not the case with *P. falciparum.* Falciparum infections differ in the delay of gametocytes after the first appearance of parasitaemia, as they require relatively longer period (10-14 days) to reach maturity (Loban and Polozok, 1983; WHO, 1987). Thus, in some seasonal epidemics where *P. vivax* and *P. falciparum* are both involved, the former starts earlier and reaches a peak, to be followed by a seasonal peak of *P. falciparum* infections (Gilles and Warrell, 1993).

Malaria Surveys

Whatever or wherever a malaria problem may be, each factor and aspect has to be considered in the light of local characteristics. In malariological practice a number of parameters are used to classify the condition of malaria in a given area and thereby describe its epidemiological situation. For this purpose, cross-sectional surveys may be enough in some cases, but in the majority of areas only longitudinal observations may yield the basis for such classifications (Wernsdorfer, 1980). The malaria survey proper involves investigations relating to the human host and the mosquito vector, as well as collection of existing environmental and epidemiological data of a particular place (Gilles and Warrell, 1993).

The principal classical method relating to the human host is that of malariometric survey, which establishes spleen and parasite rates on the basis of screening the population for the presence of plasmodia in the blood and spleen enlargement (WHO, 1963). Early malaria surveys focused on determining the level of parasitaemia in a community of interest in a randomly selected group of subjects. Soon it was appreciated that the number of subjects with splenomegaly also gave a useful indication of the level of malaria endemicity in a population, and both parasitaemia and splenomegaly were included in the classical definition of malaria endemicity. In the 1950s and 1960s, longitudinal surveys were introduced and a number of studies of malaria were undertaken in a number of villages in Africa (Gilles and Warrell, 1993). These studies demonstrated that, in areas of high malaria endemicity, the prevalence of parasitaemia and of splenomegaly declines with age, indicating the gradual acquisition of partial immunity to malaria as a result of repeated infections.

Investigations relating to the *Anopheles* vectors are based on the collection of four groups of data: estimation of mosquito density, natural infection, biting habits and longevity. Various classical entomological techniques are used for this purpose (WHO, 1975). Dissection of mosquitoes for sporozoites has been a priority for vector incrimination and field evaluations of malaria parasite transmission. More recently, immunological tests, such as enzyme-linked immunosorbent assays (ELISA) and DNA probes, are also being used to assess the susceptibility of a given *Anopheles* strain to infection under natural conditions, and these provide the two important indices- the "oocyst" and "sporozoite" indices. In the past investigations were hampered by the difficulty in determining sporozoite rates by dissecting the salivary glands of individual mosquitoes and the lack of morphological criteria to distinguish different species of sporozoites. ELISA techniques have been developed to detect and distinguish specific circumsporozoite (CS) proteins of the main malaria parasites *P. falciparum* and *P. vivax* in malaria infected mosquitoes (Zavala *et al.*, 1982; Burkot *et al.*, 1984; Wirtz *et al.*, 1987a; Wirtz *et al.*, 1987b; Wirtz *et al.*, 1992). The development of ELISA methods for the detection, identification and quantification of sporozoites in mosquitoes has facilitated large-scale investigations (Wirtz *et al.*, 1987b; Londner *et al.*, 1988; Adugna and Petros, 1996). Most field programmes now use the ELISA methods, now available for all four human plasmodia, routinely for determining sporozoite infection rates (Beier, 1998). The ELISA test has also been applied to detect and identify blood meals in mosquitoes and proved to be both sensitive and specific (Burkot *et al.*, 1981; Service *et al.*, 1986; Beier *et al.*, 1988). However, ELISA procedures are relatively slow and impractical for field use, as they require careful operation of equipment needing electric power supply, refrigerated storage of reagents and specialized personnel. To circumvent this, Ryan and colleagues (Ryan *et al.*, 2001) developed rapid wicking assays that identify the presence or absence of specific peptide epitopes of CS protein of the most important *P. falciparum* and two strains (variants 210 and 247) of the more widespread *P. vivax*. The resulting assay is a rapid, one-step procedure using a 'dipstick' wicking test strip.

Malaria transmission is a complex process and the various factors affecting transmission do not act independently. It is the interaction of the factors that shapes the epidemiological situation and the significance of a malaria vector in a given area (WHO, 1975). Thus numerical values need to be given to factors relating to the human population, the parasites, and the vectors in order to obtain quantitative data to establish the importance of each component part of the epidemiological puzzle. With respect to the human population, fore example, factors such as the parasite rates in the population (especially in non-immune children), recovery rates from the infection, and the immune status of the population should be noted. The relative virulence of the parasites and any tendency to relapse in humans should also be taken into account. Regarding the mosquito vectors, one should be able to ask and answer the following questions: Do the mosquitoes have suitable breeding conditions (water, temperature), how long do they live, how effective are they as vectors (biting rates and preference for human blood), and are people readily available as donors and recipients of parasites? In many parts of Africa south of the Sahara the answers to these questions are affirmative and so highly favourable to the spread of malaria. The important African vectors are highly anthropophilic and the temperature and humidity conditions are favourable for vector longevity and thus maintain increased transmission of malaria (MacCormack, 1984).

There is no other tropical communicable disease to which a mathematical approach has been applied more widely and thoroughly (Gilles and Warrell, 1993). The first and most inspired attempt at formulating the quantitative laws of epidemiology of malaria and its transmission and control was made by Ronald Ross in 1911 (Rogers, 1988). In the decades following Ross' earlier work, Macdonald (Macdonald, 1950; Macdonald, 1952; MacDonald, 1953; Macdonald, 1956) developed a model that brought together for consideration all the main quantitative factors - entomological, parasitological and immunological - that constitute or limit malaria transmission. This was followed by several reports of epidemiological observations (Garrett-Jones and Shidrawi, 1969; Dietz *et al.*, 1974; Bekessy *et al.*, 1976; Krafsur and Armstrong, 1978; Aron and May, 1982; Rogers, 1988), that have confirmed the usefulness of Macdonald's formulae and which provided in-depth knowledge of the bionomics of the local vectors and transmission mechanisms.

One application of the Ross-Macdonald malaria models to malaria epidemiology is the evaluation of the vectorial capacity which attempts to measure the daily rate at which future cases arise from a currently infective case (Rogers, 1988). From measurements of epidemiological variables, in particular, the vectorial capacity, it was possible to specify the risk of malaria and to predict the impact of the various modes of intervention (Vercruysse *et al.*, 1983). The various parameters have also been used alone or in various combinations in order to characterize the endemicity in a given country or focus leading to a proposal of a number of classifications.

The endemicity of malaria is usually described in broad terms characterized by spleen and parasite rates in children. According to the WHO (WHO, 1963) classification, there are four levels of malaria endemicity, namely, **hypo-**, **meso-**, **hyper-**, and **holoendemic** malaria. The spleen index in children aged 2-9 years is a major criterion on which the classification is based. That is, about 10% in hypoendemic, varies from 11 to 50% in meso-, and is constantly over 50% in hyperendemic settings. In the hyperendemic type, adults also have high spleen index. In holoendemic conditions, the spleen and parasite indexes in age-matched children are always over 75%. The disadvantage of this classification is that it is too broad; much of Africa satisfies the criteria for hyperendemic malaria and yet the pattern of malaria varies widely throughout the continent (Greenwood, 1997). Therefore, many workers argue that the only useful system is the distinction between stable and unstable malaria, as proposed by Macdonald (Janssens and Wery, 1987). On close examination, the degree of stability is found to give a more valuable means of classification than does the severity of incidence. This is because all grades of malaria severity are experienced in both stable and unstable malaria settings. The distinction between the stable and unstable malaria lies in the regularity with which transmission is maintained over the years, rather than in the degree attained at any particular time (Macdonald, 1956).

In stable malaria, transmission occurs every year at high levels and can be either perennial or seasonal and there is very little variation from season to season. Epidemics would be very unlikely to occur and the community acquires a stable immunity during the first few years of life at the price of a high infantile-juvenile mortality. Stable malaria is dependent on transmission by a vector highly susceptible to infection by the local parasites, with a frequent man-biting habit, a moderate to high longevity at favourable temperatures. The density of mosquitoes is of lesser importance and an anopheline density resulting in an average of as few as 0.025 bites per person each night is sufficient to maintain stable transmission. In contrast, unstable malaria transmission is lower and irregular from year to year and as a consequence the human population acquires less immunity and epidemics are likely to occur affecting all age groups. Between these two situations of stable and unstable malaria, all intermediates occur, in particular in Sahel and East Africa (Mouchet *et al.*, 1998). The entomological 'Stability Index' can be used to estimate these intermediate stages (Macdonald, 1957).

On the other hand, based on ecological and socio-economic conditions, the malaria situation in the world has been stratified into eight prototypes which are: African Savannah, Plains and valleys outside Africa (traditional agricultural), Forest and forest fringes, Desert fringe and Highland fringe, Coastal and marshland, Urban slums, Agricultural developments, and Sociopolitical disturbances. Similarly, based largely on climate, landscape, socio-cultural structures and human behaviour, some workers have investigated the malaria situation in Africa and delimited the eco-epidemiological diversity of malaria into various strata. These have distinguished nine strata based on transmission contingencies, i.e. 1) perennial, 2) seasonal, 3) sporadic, 4) exceptional, 5) nomadic pastoralists, 6) modern irrigation schemes, 7) temporary development projects, 8) urban and suburban areas, and 9) non-immune visitors or temporary residents (Janssens and Wery, 1987).

In general, throughout tropical Africa south of the Sahara, malaria shows a high endemicity, but has a low epidemic potential. Thus, stable malaria covers most of west and central Africa, the eastern coast of Africa, Madagascar coasts, and the Comoros Islands (Mouchet *et al.*, 1998). In the centre of the continental area, transmission is nearly perennial, although there is seasonal exacerbation, and very high endemicities are common in the coastlands and other places at low altitude. Unstable malaria includes the southern border of the Sahara, the mountainous areas of Central Africa, countries south of the Zambezi River, and the highlands of Madagascar (Mouchet *et al.*, 1998). Epidemics are well known on the slopes of mountains in Kenya, at the periphery of the distribution of malaria in Zimbabwe and the republic of South Africa, and formerly in Mauritius. Endemicity is reduced, though still high, on the plateau of East Africa, which is at an average altitude of 1400m; the disease occurs up to a height of 2500m on some mountains, although rather as occasional outbreaks than as a continuous endemicity (Gilles and Warrell, 1993). Despite the importance of these facts, a continental perspective of where (distribution), how much (transmission intensity), when (seasonality), why (environmental determinants) and who is affected (populations at risk) does not currently exist. More recently, the Mapping Malaria Risk in Africa /Atlas du Risque de la Malaria en Afrique (MARA/ARMA) collaboration was initiated to provide an atlas of malaria risk for Africa, i.e., a continental data base of the spatial epidemiology of malaria, through the use of a personal computer-based Geographic Information System (GIS), by integrating different malaria, geographical and environmental data sets (MARA, 1998).

The main vectors of the Afro-tropical region include members of the *Anopheles gambiae* complex, the composite *An. funestus,* having a wider geographical distribution, and *An. nili* as well as *An. moucheti* having a distribution limited to more restricted areas. On the other hand, *An. phaeroensis, An. zeimanni, An. rufipes* and others constitute vectors of secondary importance (Janssens and Wery, 1987). The *An. gambiae* complex includes at present 7 species - six named ones (Gillies and Coetzee, 1987) one unnamed species (Hunt *et al.*, 1998) and several incipient species (Coluzzi *et al.*, 1979; Coetzee *et al.*, 2000) that vary in their ability to transmit falciparum malaria in Africa (White, 1974; Coluzzi *et al.*, 1979; Coluzzi, 1984). These are *An. gambiae sensu stricto*, *An. arabiensis*, *An. melas, An. merus*, *An. Bwambe* and *An. quadriannulatus* species A. The 7th member reported from southwestern Ethiopia in 1998 is temporarily designated as *An. quadriannulatus* species B, and is yet to be named (Hunt *et al.*, 1998). The two principal vectors in the complex are *An. gambiae s.s.*, which is the most efficient vector, and *An. arabiensis.*

The distribution of malaria vector mosquitoes, especially those belonging to species complexes that contain non-vector species, is important for strategic planning of malaria control programmes. *An. gambiae s.s.* and *An. arabiensis*, the two most anthropophilic members of the complex, have the widest distribution and can occur together over extensive areas (Coluzzi, 1984) - perhaps existing in about 70 percent of Sub-Saharan Africa (White, 1974). These two members of the complex show differences in behaviour, levels of vectorial efficiency, variations in seasonal prevalence (Coluzzi, 1984), differential response to DDT and have specific distribution patterns that seem to be differentially determined by climatic factors (White, 1974; Lindsay *et al.*, 1998b).

Geographic information systems have allowed researchers to visualize distribution data on maps together with environmental parameters, such as rainfall and temperature. Accordingly, using a spatial environmental database for Africa, operating within a geographical information system, Lindsay and colleagues (Lindsay *et al.*, 1998b) have shown that the range and relative abundance of these two species are correlated with climate at a regional level. Most importantly, they have found that the relative abundance of these two species was related to an index of saturation (i.e., five-monthly maximum precipitation / five-monthly maximum potential evapo-transpiration). Where this ratio exceeded a value of 1.0, and the air was moist, *An. gambiae s.s.* predominated, whereas in areas where this value was below 1.0, the air was dry and *An. arabiensis* was more common. Distribution maps based on records of identified samples are also available (Coetzee *et al.*, 2000).

In general, *An. gambiae s.s.* predominates in the equatorial forest and humid situations where annual rainfall is usually > 1000 mm (Coetzee *et al.*, 2000), though, it also occurs in the Guinea and Sudan Savanna, and even in the Sahel Savannah, with a density related to rainfall. *An. arabiensis* is more successful in the drier zones, where annual rainfall is < 1000 mm (Coetzee *et al.*, 2000), such as the Sudan Savanna and further north to the Egyptian boarder, but also in the inland areas of East Africa during the dry season (White, 1974; Janssens and Wery, 1987). *An. gambiae s.s.* and *An. arabiensis* were also reported to have differences in the Human Blood Index (HBI), the former was found to be more anthropophagic (Molineaux and Gramiccia, 1980).

An. quadriannulatus has little or no direct medical interest, owing to its marked zoophily (White, 1974). Nevertheless, since it can coexist with *An. arabiensis,* the operational value of differentiating them is obvious in relation to the evaluation of vectorial capacity, of the effect of residual spraying and the spreading of insecticide resistance (Coluzzi, 1984). *An. quadriannulatus* shares similar larval ecology with *An. arabiensis* and *An. gambiae s.s.*, breeding in shallow, open sunlit freshwater pools (Coluzzi, 1984). Although, *An. melas* and *An. merus* larvae are able to develop in freshwater (White, 1974), both species thrive in brackish marshes and lagoons (Stevens, 1984) on the west and east African Coasts, respectively.

An. funestus has been shown to be an important malaria vector in Africa (Gillies and De Meillon, 1968; Gillies and Coetzee, 1987), in some cases playing a more important role than *An. gambiae s.s.* or *An. arabiensis* (Fontenille *et al.*, 1997). *An. funestus* has a somewhat restricted distribution and is a member of a species complex comprising at least nine members, the adults of which are not easily distinguished on the basis of morphological characteristics (Gillies and De Meillon, 1968; Gillies and Coetzee, 1987). It feeds almost exclusively on humans and rests indoors making it particularly susceptible to residual house spraying. Although it readily feeds on man and does go indoors, it usually has a low sporozoite index. It breeds in permanent vegetated waters including swamps, ponds, lake margins, streams, ditches, and the like (Gillies and De Meillon, 1968; Stevens, 1984).

However useful the stratification systems might be, the outstanding feature of malaria in most cases, is essentially that it is a localized problem - governed by local conditions (Janssens and Wery, 1987).

Malaria In Ethiopia

General Background

The existence of terms for malaria in many Ethiopian languages, including in Amharic (*Weba*), Oromigna (*Bussa*), Tigrigna (*Asso*), and many others, strongly indicates that malaria has been a vexation in the country for a long time. Most of the terms coined for malaria refer to the burning fevers (Tulu, 1993) and others directly or indirectly link the disease to the proximity of stagnant water and something in the atmosphere near by. Furthermore, the distribution of malaria is believed to have partly imposed the pattern and trend of human settlement in the country, particularly of the sedentary type. Due to the wide spread occurrence of malaria in the lowlands, mountains and elevated areas have been recognized as a natural shelter against malaria for centuries. As a result, malaria has remained a bottleneck for socio-economic development (Covell, 1957; Chang, 1962; Chand, 1965). It has curbed the exploitation of the fertile and productive lowlands and as a result has contributed its share to the over population and consequent over cultivation and environmental degradation of the highland plateaus. In the past 40 years, however, there has been a new trend in population distribution, including seasonal migration. This is partly due to changes in economic policy, which resulted in the development of commercial farming and urbanization in the Rift Valley and other lowland areas (Schaller and Kuls, 1972; Gebremariam, 1988; Kloos *et al.*, 1988) and the extension of malaria control activities in the lowlands (Gebremariam, 1984). This trend intensified, in the 1980s, as a result of civil war and large-scale resettlement programs of drought victims from the highlands in the eastern and northern parts of the country into the malarious southwestern lowlands.

Most of the early literature relating to malaria in Ethiopia is available from Italian (Corradetti, 1938; Corradetti, 1939; Giaquinto-Mara, 1950; Verrone, 1962a; Verrone, 1962b), British (Melville *et al.*, 1945; Covell, 1957) and Japanese (Chang, 1962; Chand, 1965) sources and is based on investigations carried out during the Italian occupation of the country (1936-1941) and shortly afterwards. Most of these and later studies have been reviewed by Chand (Chand, 1965), Schaller and Kuls (Schaller and Kuls, 1972), and bibliographies of most studies undertaken before 1989 are compiled by Yayehyriad (Yayehyirad *et al.*, 1989). These and other unpublished documents reveal that malaria has remained a major disease of public health importance and a barrier to economic development in the country. It leads the list of the top diseases for outpatient morbidity and is the principal cause of hospitalisation and hospital death (MoH, 1999). Nearly 75% of the country, lying below 2000m in altitude, is generally suited for transmission and over 64% of the total population inhabiting these regions is at risk (MoH, 1999). Of the almost 60 million people in Ethiopia, 40 million are living in malaria-prone areas (Yemisrach, 1999). Annually, an average of 400,000-600,000 cases with positive blood film for malaria are treated. However, this is an underestimation and the actual number of malaria cases that occur annually is estimated to be between 4 - 5 million (MoH, 1999).

Distribution of malaria

Although malaria is widely distributed, the areas of transmission are often discontinuous and the country experiences a complete spectrum of malaria epidemiology ranging from intense perennial transmission to unstable, epidemic prone areas. It is generally believed that major variations in landscape and climate and complex human social forms create a wide range of macro-and microclimatic conditions and result in spatially varied incidence and distribution of malaria in the country (Covell, 1957; Chand, 1965; Gebremariam, 1988; MoH, 1999). Located in the middle of the horn of Africa, Ethiopia lies between 3° 24' and 14° 53' North and 32° 42' and 48° 12' East (Figure 1.1). It is bordered by Somalia on the east and southeast, on the south by Kenya, on the west and north- west by the vast lowlands of Sudan, on the north by Eritrea and on the northeast by Djibouti. The country is characterized by a massive plateau and mountain ranges, which comprise most of the central and northern part of the country. Ethiopia's central plateau varies in height between 2,000 and 3,000 metres. In the north and centre of the country there are some 25 mountains whose peaks rise over 4,000m. Surrounding the highlands, in the eastern, southern and western parts of the country, are extensive, sparsely inhabited, savannas, semi-arid planes, and deserts (MoA, 1998). To the west of the chain the land drops to the grasslands of Sudan, to the east to the deserts of the Afar. South of Addis Ababa, the capital, the land is dominated by the Rift Valley Lakes.

Figure 1.1. Relief map of Ethiopia (produced by Oxford Cartographers for Ethiopian Airlines).

The great East African Rift Valley, which extends in a southwesterly direction from the Red Sea to Lake Rudolf, bisects the plateau into two unequal parts forming the smaller eastern and the massive western highland plateau. The undulating plateau surface is dissected in an irregular pattern by numerous canyons, river valleys and escarpments whose contours follow the course of the natural watershed between the Blue Nile drainage to the north and west, and the Awash to the south and east (Chand, 1965). The varied topographic features thus formed represent diverse elevations and slopes with the lowest point at the Danakil depression at about 126m below sea level and the highest on the top of Ras Dashen Mountain, which is about 4620m above sea level. In between, a variety of landforms are found. There are mountain ranges rising well above 4000m, rolling grassy plains, broad fertile valleys, and deep canyons formed by the major river systems and their tributaries (MoA, 1998). The most famous Ethiopian river, the Blue Nile (or Abbay), runs a distance of 1,540km from its source in Lake Tana, to join the White Nile at Khartoum. Other main rivers include the Tekezze (which joins the Nile in the Sudan), the Awash, the Wabe Shabele, the Omo, the Baro and Birbir.

Ethiopia is a vast country and covers an area of 1.12 million km^2. Most of the land lies above 1000m elevation, and the heaviest concentration of its estimated 60 million inhabitants (1994 Census) lives above this elevation. Over 80% of the country's population are rural and are engaged in subsistence agriculture (i.e. crop and livestock production). Its economy is totally dependent on agriculture but the country's current agricultural production does not meet the food requirements of the population. This is, due largely to its high population growth rate and the consequent environmental degradation. Old traditional farming systems and miss-utilization and mismanagement of the land resources caused ecological degradation in the country. The annual population growth rate is about 3.09 percent, and the economically active segment, between ages 14 and 60 years, is about 50% of the total population (CSA, 1995; MoA, 1998).

Although the character of lowland Ethiopia is tropical, because of the high altitude of much of the country, the environment and food production systems in the highland region are similar to those in countries with more temperate climates. About 50% of all the land above 2000m altitude in Africa is in Ethiopia and more than half of the country lies above 1500m. A more tropical flora and fauna characterize the hot semi-arid lowlands surrounding the highlands (Kloos *et al.*, 1988).

There are three major agro-climatic zones in Ethiopia recognized by farmers, mainly based on the relation between elevation and temperature. The temperature difference within the zones not only enabled them to recognize broad vegetation communities adapted to environmental conditions, select crops and livestock best suited for these temperature regimes (MoA, 1998), but also select settlement areas as safe havens from the scourges of malaria. The traditional agro-climatic zones of the country are known as *Kola (<1500m), Woinadega (1500-2500m)*, and *Dega (>2500m)*, although there is no clear distinction of their boundary limits. As population pressure increased and accordingly agricultural activities expanded, two additional zones at the higher and lower temperature extremities were also recognized, namely, *bereha* and *wurch* respectively (Table 1.1).

Table 1.1. Traditional climatic zones of Ethiopia and their physical characteristics (MoA, 1998).

Traditional zone	Climate	Altitude (m)	Average annual temperature °C	Average annual rainfall (mm)
Bereha	Hot arid	< 500	> 27.5	< 200
Kola	Warm semiarid	500 – 1500/1800	27.5 – 20.0	200 – 800
Woinadega	Cool sub-humid	1500/1800 – 2300/2400	20.0 – 17.5/16.0	800 – 1200
Dega	Cool and humid	2300/2400 – 3200	17.5/16.0 – 11.5	1200 – 2200
wurch	Cold and moist	> 3200	< 11.5	> 2200

In general, the 3 agro-climatic zones (Bereha and Wurch included in Kola and Dega, respectively) have characteristic malaria endemicities (WHO, 1991). The 'Kolla' or the hot zone, lying below 1500m (mean annual temperature 20-30 °C) and which roughly constitutes 46% of the territory, has seasonal or perennial malaria transmission depending on local conditions with moderate to high endemicity. In the Danakil Depression and the Ogaden, anopheline mosquitoes and other water-based vectors cannot survive away from the rivers, swamps and lakes, except in the irrigation systems, dams and water cisterns made for livestock and human use (Prothero, 1977). In the proximity of permanent bodies of water malaria transmission is perennial and graded as **meso**-and **hyperendemic**. **Holoendemic** settings occur primarily in the southwest around 1300m, where rainfall is present throughout most part of the year (Schaller and Kuls, 1972). About 46% of the country falls within the cool sub-humid zone or 'Woinadega' (1500-2500m). It has an average temperature of 20 °C and malaria transmission occurs but most often in areas below 2000m. It is characterized by sporadic outbreaks of unstable malaria (Covell, 1957; Chand, 1965; Schaller and Kuls, 1972; Gebremariam, 1988; MoH, 1999). The 'Dega' or colder zone (about 8% of the territory) lying above 2500m and characterized by mean annual temperature of <15 °C and is free of malaria. There are no records of indigenous transmission in this zone. In general, thermal zones have strong correlation with altitude. When altitude increases temperature and evapo-transpiration decreases and rainfall increases. In the Ethiopian context studies have shown that for every 100m rise in elevation the air temperature falls within the range of 0.6-0.7 °C (MoA, 1998). Thus, climatic changes could not only easily contribute to general changes in vegetation community and soil characteristics which in turn influence the land use and crop/livestock patterns but also result in altered disease distribution and transmission patterns such as malaria.

At higher altitudes, the temperate nature of the climate ensures that the development of the parasite, man-biting densities and longevity of the vectors, under naturally prevailing conditions, are insufficient for stability of the disease (Krafsur, 1977). Where the microclimate supports vector life, as when *An. gambiae s.l.* populations shelter in warm huts in certain Ethiopian highlands (Turner, 1972), short-lived transmission occurs even at altitudes of 2400m (Abose *et al.*, 1998). Inhabited houses are not only warm enough to support vector life and allow the parasite to develop, but also the relative humidity may stabilize at about 60%, favouring mosquito survival; outside relative humidities may vary considerably (12-80 %) (Lindsay and Martens, 1998a). Where there is standing water or the flow of streams and rivers is retarded in flat areas at these higher altitudes, transmission may also have a prolonged seasonal character. In general, in most highland areas of Ethiopia, the low exposure of people to malaria parasites, due to the brevity of the transmission season, precludes the development of immunity and favours the incidence of periodic regional epidemics. These are often attended by a high morbidity and mortality both in children and adults, as illustrated by the outbreaks experienced at different times (Covell, 1957; Schaller and Kuls, 1972; Tulu, 1993), including the 1958 epidemic which claimed over 150,000 lives (Fontain *et al.*, 1961). The causes for such major extensive epidemics, including the 1965, 1973 and

1981-82 epidemics (Tulu, 1993), which occurred at intervals of 7 to 8 years, are considered to be climatological changes-such as exceptionally warm weather, prolonged rainfall or drought (Fontain *et al.*, 1961; Gebremariam, 1984).

Overall, except in relatively few low-lying localities along the course of permanent rivers or water bodies, malaria is markedly seasonal in incidence and of very low prevalence throughout the most densely inhabited regions of Ethiopia (Krafsur, 1977). The peak periods occur at the end of the "big" rains of June-September, when the inter-tropical convergence zone brings southerly and southeasterly maritime air, and around the short-lived showers of March-April (Schaller and Kuls, 1972; Kloos *et al.*, 1988).

Vectors

The major mosquito vector responsible for the transmission of most malaria cases including the occasional seasonal outbreaks and the major periodic cyclical epidemics in Ethiopia is *Anopheles arabiensis.* It is also an important vector of Bancroftain filariasis (McConnel and Schmidt, 1973; McConnell *et al.*, 1976) and Tataguine virus (Ota *et al.*, 1976) in the country. Notorious for the rapidity of its population build-up even in short seasons, it is present at some or all times of the year over the whole of the country (O'Connor, 1967). The *An. gambiae* complex hitherto represented in Ethiopia only by two forms, as identified by cytogenetic techniques (White, 1974; White *et al.*, 1981; Mekuria *et al.*, 1982; Abose, 1991), appears to be represented by three forms currently with the finding of a new species from Jimma zone in south-western Ethiopia (Hunt *et al.*, 1998). These are *An. arabiensis* and the medically unimportant forms, *An. quadriannulatus* species A and the newly identified *An. quadriannulatus* species *B.*

The occurrence of *An. arabiensis* and *An. quadriannulatus* together has been reported from the mid-western part of Ethiopia (White, 1974; White *et al.*, 1981). Mekuria and colleagues (Mekuria *et al.*, 1982) and Abose (Abose, 1991) have shown the presence of only *An. arabiensis* in the Rift Valley-the Awash and the Arba Minch valleys, respectively. The polymorphic inversions identified were 2Rb and 3Ra, although the frequencies of these inversions were variable in different localities. As in other parts of Africa (Gillies and De Meillon, 1968), *An. arabiensis* breeds in small, temporary pools exposed to sunlight, some times with emergent vegetation. *An. arabiensis* is generally considered to be endophilic and anthropophilic (Krafsur, 1971; White *et al.*, 1981;

Tekie, 1991; Adugna and Petros, 1996), although an incipient tendency to feed indoors and rest elsewhere has been reported (Krafsur, 1977; Gebremariam, 1984; Abose, 1991; Ameneshewa and Service, 1996). In certain localities it has been observed to feed equally both outdoors and indoors (White *et al.*, 1981; Gebremariam, 1984; Abose, 1991), sometimes favouring the former behaviour in some parts of country (Rishikesh, 1966; Tulu, 1993). Such inconsistent feeding behaviour of *An. arabiensis* might be attributed to varied factors including the availability and location of the host of choice at night (Tekie, 1991) and/or in response to DDT (and other insecticides) that has been in use for over 40 years in the country.

The host preference studies of *An. arabiensis* mosquitoes made in different parts of Ethiopia show a high degree of anthropophily in this species as long as the host is available. The highest proportions of human feeds were reported from human dwellings, ranging from 91.5 (Hadis *et al.*, 1997) to 100 % (Krafsur, 1971; Krafsur, 1977; White *et al.*, 1981) followed by mixed dwellings- from 20.2% (Hadis *et al.*, 1997) to 88% (range 26-92%) (Adugna and Petros, 1996). As would be expected, the lowest proportion of blood meals positive for human blood were reported from outdoors and animal sheds. The highest reported was 43% (range 9-48%) by Adugna & Petros (Adugna and Petros, 1996) in animal sheds followed by 3.5% (Hadis *et al.*, 1997) and nil by White and colleagues (White *et al.*, 1981).

Salivary gland dissections conducted at different times in several parts of the country indicated a rather low sporozoite rate in *An. arabiensis* populations, despite their high human blood index. For example, in dissections made by the WHO pre-eradication project team the proportion found positive for sporozoites were only 0.2% in the Lakes region of the Rift Valley and 3% in Kobo Chercher area in northern Ethiopia (Rishikesh, 1966). However, Krafsur (Krafsur, 1971) observed a relatively higher rate (5.4%) in southwestern Ethiopia (the Gambella area) during the period December 1967 through November 1968 (range, 0% in March/April – 5.4% in November). Two of the most important reasons for the relatively higher sporozoite rates in this area are that the vector is highly anthropophilic due to the absence of alternative hosts and the environment provides for long term survival. The inhabitants, in this part of the country, keep very few domestic animals to divert the attention of the mosquitoes and the area is known for its perennial rivers and high rainfall for most part of the year. A higher probability of survival through one day (0.9) was reported for *An. arabiensis* in the same area in both the dry and wet seasons (Krafsur, 1971).

Immunological methods used to determine the sporozoite infection load in *An. arabiensis* in different parts of the country also showed low sporozoite rates. Sporozoite rates of 0.77% *(P. falciparum)* for *An. gambiae s.l.* and 0.47% (*P. vivax*) for *An. pharoensis* were determined among the endophilic mosquitoes assayed by the ELISA method in the holoendemic Gambella region of southwestern Ethiopia (Nigatu *et al.*, 1992). Similarly, using a dot blot hybridization method, Lulu and colleagues (Lulu *et al.*, 1997) detected *P. falciparum* sporozoite rates of 2% in *An. arabiensis* populations. The assay was evaluated on 198 indoor resting blood fed female *An. gambiae s.l.* mosquitoes collected from three malaria hypo- and meso-endemic areas in the Rift Valley–near the towns of Metehara, Zeway and Arbaminch located in the eastern and southern parts of the country.

The *An. funestus* group is widely distributed and is known to be the second important vector of malaria in the country (Gebremariam, 1984). Sometimes, it even dominates *An. arabiensis* in certain endemic areas where large, rather more shaded and permanent bodies of water predominate (O'Connor, 1967; Krafsur, 1971; Turner, 1972). These are the most favoured type of breeding sites of the species (O'Connor, 1967). *An. funestus* is predominantly endophagic and endophilic and exhibits a relatively higher probability of daily survival rate. In southwestern Ethiopia, Krafsur (Krafsur, 1970) reported a lower daily mortality rate of 9-12% for this species. Of the 42 or 43 anopheline species recorded in Ethiopia (Gebremariam, 1988; Hunt *et al.*, 1998), *An. nili* and *An. pharoensis* are considered to have secondary importance in malaria transmission. *An. nili*, found localized in certain western and south-western lowlands of the country (O'Connor, 1967), has been found to be a potent vector of malaria in Gambella area, where it is known to exhibit endophagic and exophilic pattern of behaviour (Krafsur, 1977). Nevertheless, due to changed ecological conditions, its vectorial role is reported to have decreased in some of its former area of dominance such as in the Gambella region-south western Ethiopia (Nigatu *et al.*, 1995; Abose *et al.*, 1998).

An. pharoensis which is widely distributed in Ethiopia and having similar breeding habits as *An. funestus* (O'Connor, 1967) was claimed to have been found naturally infected in the country at one time or another (Rishikesh, 1966). Recent findings of naturally infected specimens with *P. vivax* in the Gambella region of southwestern Ethiopia (Seulu *et al.*, 1989; Nigatu *et al.*, 1994; Abose *et al.*, 1998), appears to have awakened a renewed interest in *An. pharoensis* in the country. Other anopheline species categorized as incidental vectors, at one time or another, include, *An. coustani, An. zeimanni, An. paludis* and *An. d'thali* (Gebremariam, 1988).

Malaria parasites

All four species of human malaria parasites occur in Ethiopia- *P. falciparum P. vivax, P. malariae* and *P. ovale*, in that order of importance. *P. falciparum* and *P. vivax,* being the two dominant species, are distributed in all malaria-endemic parts of the country and roughly account for 60% and 40% of all malaria cases, respectively (MoH, 1999). *P malariae,* restricted in distribution, comprises less than 1% of all cases and is most frequently reported from the Arba Minch area in southern Ethiopia (Tulu, 1993). *P. ovale* is rarely mentioned after its first report in 1938 which was later confirmed in 1969 (Armstrong, 1969). However, the relative frequency of the first three species varies from place to place and from season to season.

P. falciparum is the most deadly and dominant species responsible for the most, if not all, epidemics in Ethiopia while that caused by *P. vivax* are very rare (Gebremariam, 1988). *P. falciparum* is the cause of severe and complicated malaria in which the case fatality rate is about 10% in hospitalized adults and about 33% in children under 12 years old (Tulu, 1993). Little is known about the distribution and protective role of glucose-6-phosphate dehydrogenase (GPD) deficiency and sickle cell trait in Ethiopia except that reported by Perine and Tesfamichael (Perine and Tesfa Michael, 1974). Their study, which involved 1261 people from 8 different Ethiopian ethnic groups, revealed the presence of GPD deficiency in the Anuak (1.4%) and Neur (6.7%) ethnic groups of the southwestern lowlands, as well as in the Afaris (6.3%) in the Danakil Depression. They also reported one case of sickle cell trait (Hb As) in their study (Perine and Tesfa Michael, 1974).

Very limited studies of drug sensitivity tests have been made in the country. The first search for chloroquine resistance in Ethiopia, made in 1972 in the western lowlands near Gambella (Dennis *et al.*, 1974), and subsequent ones conducted at 11 locations in 8 administrative regions of Ethiopia, during 1984-88, failed to detect this trait (Gebremariam and Telehaimanot, 1986). Chloroquine, given at a dose of 25 mg/kg body weight (administered over 3 days), has been the first-line drug for the treatment of uncomplicated malaria over the last forty years (MoH, 1999). But, the first report of chloroquine-resistant strains of falciparum malaria came from southern and western lowlands bordering Kenya, Somalia and Sudan in 1986 (Teklehaimanot, 1986). Imported cases have been implicated for the development of resistance. Ever since, reports began to trickle in that chloroquine was no longer proving effective against malaria caused by *P. falciparum* (Alene and Bennett, 1996; Tulu *et al.*, 1996). The investigations have shown that chloroquine resistance was no longer confined to border areas and has become widely spread in the country. It was argued that the large-scale migration of laborers, settlers, refugees, and troops in the country appeared to have exacerbated the problem (Kloos, 1990).

Alarmed by the situation, the Ethiopian Ministry of Health (MoH) has conducted a countrywide evaluation of the therapeutic efficacy of chloroquine for the treatment of uncomplicated falciparum malaria in the country in 1996–1998. The evaluation was based on a new system by WHO that enabled evaluation of both clinical and parasitological efficacy. The study, which involved a total of 527 children aged 5-49 months and 298 older children and adults in 18 different sites, revealed the failure of chloroquine to bring acceptable clinical improvement in a majority of falciparum malaria patients in most parts of the country. The mean treatment failure rate observed in the under five year old children was 73.3% (range 0-100%) while that of adults was 63.7% (range 12.5-88.2%) (MoH, 1999).

Following a critical assessment of the study results in a National Workshop on Antimalarial Drug Policy, convened in July 1998, it was recommended to revise the treatment guidelines and conduct further therapeutic efficacy studies of amodiaquine and base-line efficacy of sulfadoxine-pyrimethamine (Fansidar) be established. Accordingly, it was reported that, the study carried out on the efficacy of amodiaquine at seven sites, during the peak transmission season of 1998, revealed mean parasitological failure rate or parasite resistance level of 36% (range 12% - 75%), during a 14 day follow up period. The marginal efficacy, thus, obtained over chloroquine was considered insufficient to justify the registration of amodiaquine in the list of essential drugs and use for treatment of malaria in Ethiopia, as the drug has never been used before in the country (MoH, 1999). On the other hand, the efficacy evaluation study carried out on sulfadoxine-pyrimethamine in seven sites from 1996 to 1998, showed a mean treatment failure rate of only 5%, indicating the drug's commendable efficacy in the treatment of uncomplicated malaria, despite its wide use for over ten years in the country. Based on these findings, Fansidar replaced chloroquine as a first-line drug and guidelines for the diagnosis and treatment of malaria were produced and issued to this effect (MoH, 1999). Nevertheless, in the light of other country's experience with multiple drug-resistance, continuous monitoring and evaluation would be indispensable in the future to come, when the wider use of the drug is considered at a community level.

P. vivax is also widely distributed in Ethiopia and often precedes the transmission of *P. falciparum*. *P. vivax* is more common during the dry season, and whether this is due to active transmission or relapses has not been clearly determined (Tulu, 1993). In Ethiopia, *P. vivax* is known to show a very distinct difference in Hamito-Semitic and Nilotic populations, the latter exhibiting a high frequency of duffy-negative genotype and marked resistance to infection (Armstrong, 1978; Mathews and Armstrong, 1981). This probably explains the biphasic distribution pattern reported in the past (Garnham, 1966), with preponderance in the north and central part of the country, inhabited largely by the Semitic population as compared to the south (especially southwest) where largely Nilotic populations inhabit it.

History of malaria control

The history of organized malaria control in Ethiopia dates back to the 1950's, when three Control Pilot Projects, under the USAID/WHO, were launched at Kobo Chercher (northern Ethiopia, in 1955), Dembian Plain (western-near Bahirdar town, 1956) and Gambella (southwestern, 1957) respectively, at the recommendation of the eminent malariologist, Sir Gordon Covell. The projects were started with the aim of reducing or completely eliminating the disease from the fertile lowland areas (Chand, 1965). The projects have achieved an acceptable level of success in the interruption of transmission and also escaped the sequel of the 1958 epidemic (Fontain *et al.*, 1961). Owing to the shock generated by the outcome of the epidemics of the time and inspired by successes attained in the Pilot Project areas (Gebremariam, 1984) and elsewhere in the world, and also of the promotional activity offered by WHO and USAID (Chand, 1965), a Malaria Eradication Service was established in 1959 as a semi-autonomous organization within the Ministry of Public Health. In conjunction with this a Malaria Eradication Training Centre was set up at Nazareth to train a staff of sub-professional workers. A classical eradication programme was launched in the most populated North and Central region in 1966. Nevertheless, later changes in emphasis on Malaria Eradication Programmes by the WHO, led to a change in concept and strategy and since 1972 the name of the project has been changed to Malaria Control Programme (Gebremariam, 1984), and later to Malaria and other Vector Borne Diseases Control Programme.

The malaria service maintained its autonomy within the Ministry of Health and implemented a long-term antimalarial programme. Following the removal of the former military regime from power by the Peoples Revolutionary Democratic Front in 1991, the newly established government of Ethiopia devolved central power to the Federal states and the Ministry of Health was decentralized. At the moment the programme is totally incorporated into the Ministry of Health and regional health bureaus carry out control activities. Current control measures exercised in the country include, routine indoor application of residual insecticides, primarily with DDT and occasionally with Malathion in DDT resistant areas, of one or two spray rounds per year, depending on the endemicity of the area (MoH, 1999). Nevertheless, the effectiveness of DDT, which is believed to have been in use for over 40 years, is becoming doubtful in many parts of the country (Seulu *et al.*, 1989; TSC, 1989; Seulu, 1991).

Environmental management with community involvement is given strong emphasis, although verbally and not well implemented yet, supplemented by larviciding especially around urban perimeters, mostly with used motor oil and occasionally with Temephos. Case detection is primarily passive and active case detection is carried out during epidemics. Treatment no longer relies on chloroquine as the drug of first choice; instead sulfadoxine-pyrimethamine has become the first-line drug for treatment of uncomplicated malaria with quinine and chloroquine as second-line drugs (MoH, 1999). Some attempts have also been made in the application of biological control using the bacteria *Bacillus thuringiensis* sero-type H14 (Seyoum and Abate, 1997), and in identifying the use of larvivorous fish for malaria control (Fletcher *et al.*, 1993).

Despite the continuing intervention efforts and significant success in many areas (Gebremariam, 1988), particularly during the 1960s and early 1970s (Tulu, 1993), the situation has deteriorated in recent years. The disease has taken an epidemic form and it is believed that most of the outbreaks were attended with heavy morbidity and mortality and the malaria parasite largely responsible was *P. falciparum*. In fact owing to the urgency of the problem, aggravated by the 1972 & 1973 drought/famine and war in northern Ethiopia, a technical committee was assigned by the Ministry of Health to study the malaria situation in the country (TSC, 1989). According to the statistical records maintained by the Ministry of Health, a five-fold increase in the number of malaria cases was observed from the period 1980-1984 to 1985-1989. In terms of the annual parasite rate, the increase was from 8.9% to 33.3% during the same period (Tulu, 1993). These figures probably include cases of the extensive epidemic that occurred in most of the highlands of the country, in 1988. The epidemic covered large tracts of land and lasted from April to November 1988 (Abose *et al.*, 1998). According to Abose and colleagues (Abose *et al.*, 1998), over half a million microscopically confirmed malaria cases were recorded in 1990. Most of these were falciparum infections. More recently, in 1992, hundreds of localities were affected by a malaria epidemic in the Rift Valley (Zwai, Hosaena and Alaba areas). Over 13,000 of the estimated 700,000 inhabitants contracted the disease and 729 died from it (Abose *et al.*, 1998). In general, according to many experts, this figure may be underestimated, since most of the afflicted live in remote areas where many cases go unreported and many seek treatment from private dispensaries.

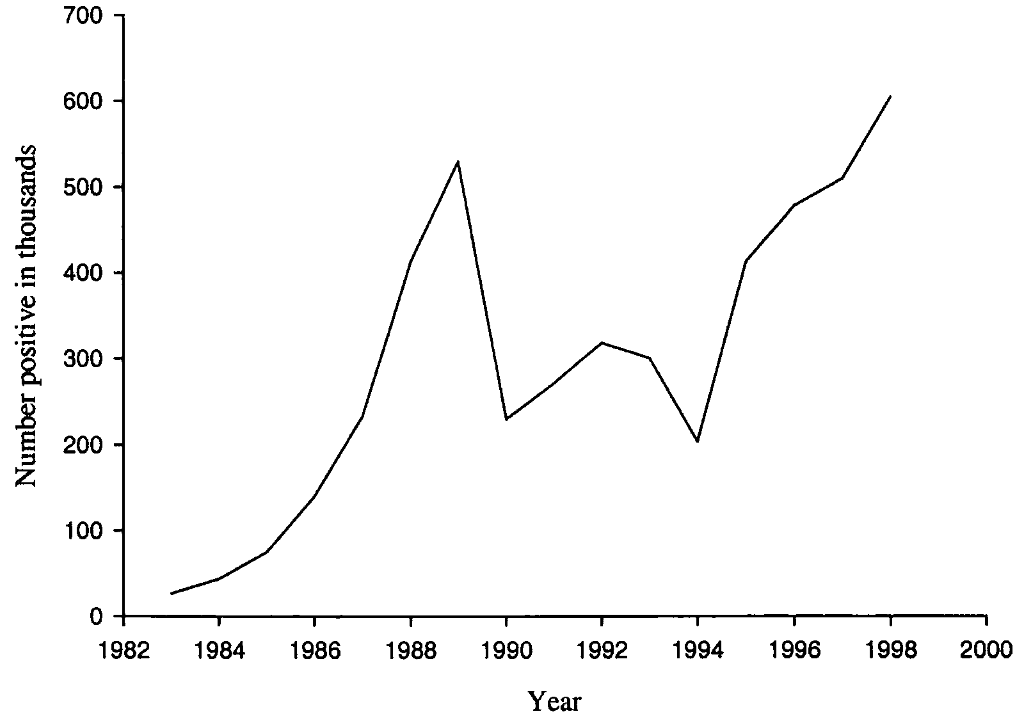


Figure 1.2. Malaria situation in Ethiopia (MoH,1983-1998). [Those diagnosed & treated on clinical grounds not included-estimated to be 3-4x > than microscopically examined].

The long established eight to ten years' cyclic trend of occurrence of epidemic malaria in Ethiopia (Gebremariam, 1988) appears to have changed into a more frequent and continuous one, although the degree and coverage may vary. Frequent press releases from the Ministry of Health in 1998-1999 reveal a worsening malaria situation in the country even in the late 1990s (Figure 1.2). Statistical records indicate that an increasing trend in malaria cases is discernible in the 1990s also- 203,242 (1994/5), 412,609 (1995/6), 478,311 (1996/7), 509,804 (1997/8), and 604,960 (1998/9) (Table 2.1(Source: MoH). Even Addis Ababa at 2400 m was not spared from malaria in recent years. According to the Ministry's report a "few" cases of malaria were reported around the Bole international airport at 2000m in 1998/99s. This is in addition to the malaria prone area of Akaki at a similar altitude, located about 20km south of Addis Ababa, where a high rate was reported in the same year. Explaining about the reported annual malaria cases in the country, the Ministry noted that "there is a gross underestimation" since there is no strong data collection system. Besides, these data do not include cases that were diagnosed and treated on clinical grounds. These are estimated to be 3 to 4 times the number of cases diagnosed by microscopic examination (MoH, 1999).

Table 1.2: Annual malaria situation in Ethiopia by region (Source MoH (Yemisrach, 1999)

Year	Region	Examined	Positive
1994/95	Afar	20,315	5113
	Amhara	149850	44679
	Benshangul Gumuz	-	-
	Gambella	21638	8356
	Oromia	232908	70729
	SNNP	168765	74365
	Tigray		
Total		593476	**203242**
1995/96)	Afar	25527	7147
	Amhara	223646	99185
	Benshangul Gumuz	91528	20637
	Gambella	25418	7953
	Oromia	387787	149330
	SNNP	222232	105356
	Tigray	63503	23001
Total		1039641	**412609**
1996/97	Afar	32558	13917
	Amhara	271156	135651
	Benshangul Gumuz	88193	32373
	Gambella	27620	10740
	Oromia	370574	150425
	SNNP	227914	102541
	Somali	5299	1207
	Tigray	87674	31457
Total	Total	1110988	**478311**
1997/98	Afar	33597	15305
	Amhara	246483	124547
	Benshangul Gumuz	31783	6739
	Gambella	27830	11820
	Oromia	397341	182963
	SNNP	270170	136354
	Somali	12293	2628
	Tigray	83623	29448
1989 Total	Total	1103120	**509840**
1998/99	Afar	47410	22414
	Amhara	244635	117535
	Benshangul Gumuz	19521	4548
	Gambella	30269	11042
	Oromia	526897	238503
	SNNP	258848	136608
	somali	11769	5947
	Tigray	166510	68363
Total		1305859	**604960**

The deteriorating malaria situation in the country and failure to contain the problem by the Ministry of Health prompted public servants and other volunteers from different walks of life from the Amhara regional state, including those residing abroad, to establish a non-governmental anti-malaria association with the aim of tackling the malaria problem in the region. The threat posed by resurgent malaria has become so critical that the Ethiopian government has also placed the problem of malaria at the top of its agenda for the last 10 years. Along with other countries of Africa, the Ethiopian government has expressed strong commitment to intensify malaria prevention and control activities in the country under the auspices of Roll Back Malaria (RBM) initiative. The RBM initiative was launched by the United Nations Agencies, WHO/UNICEF and UNDP, together with the World Bank, on 30 October 1998 to focus the world's attention and support on renewed efforts to beat this devastating disease of the young and poor. This was in response to the request by African Heads of State and government at the 1997 Organization of African Unity (OAU) Summit in Harare, when they requested support from the International community, to help them fight malaria in Africa. RBM aims at reducing overall mortality due to malaria by 50% by the year 2010. The partnership will work closely with governments to strengthen national health systems as part of health sector development (UNICEF, 2000). The government of Ethiopia planned to allocate about 10 million USD for malaria control for the year 1999/2000 which increased from the normal budget of approximately 4 million dollars. However, the malaria control unit was still concerned that if an epidemic breaks out, this amount will not be enough (Yemisrach, 1999).

Although it is difficult to present quantitative accounts of the precipitating factors, a combination of climatic, biologic, ecologic, sociological and epidemiological conditions are considered to be responsible for the deteriorating malaria situation in the country over the last 20 years. It is believed that increase in the level of chloroquine resistant falciparum malaria (Teklehaimanot, 1986; Alene and Bennett, 1996; Tulu *et al.*, 1996; MoH, 1999), DDT resistance (Seulu *et al.*, 1989; Seulu, 1991), and exophilic behaviour of vector species (Gebremariam, 1988), increasing vulnerability to disasters, and unstable political conditions that result in major altitudinal movements of the population and reduced accessibility of the health services (Tulu, 1993) and climate change have combined to raise the toll taken by malaria in Ethiopia in recent years. It is believed that these factors may continue to be major obstacles to malaria control in the near future.

Further, factors aggravating the situation are also constantly on the increase in the country in recent years.

Factors aggravating the transmission of malaria in Ethiopia

Malaria's reach is spreading

In recent years, there have been numerous reports of repeated malaria epidemics in the highland areas of Ethiopia, which were not previously vulnerable (Tulu, 1996; Abose *et al.*, 1998; UNICEF, 2000). Local transmission was reported even from the suburbs of Addis Ababa, the capital that lies at 2400m. The suburbs with reported malaria cases lie at an average altitude of 2000m. The epidemics reported from high altitude areas in the country seem to be occurring at frequent intervals in recent years, a trend deviating from the typical cyclic pattern. I have witnessed the spread of malaria into many highland areas especially in northern Ethiopia, including areas around my hometown of Adigrat (average altitude 2300m), which was hitherto, malaria free. This could partly be attributed to climate change, which has become a growing concern in recent decades, especially with regard to malaria transmission.

Analysis of 4-5 decades of meteorological and clinical data obtained from the town of Debre Zeit and surroundings, in central Ethiopia, revealed a trend of increased climatic warming in both daytime and night-time temperatures, especially since 1988, at which time a coincident peak in incidence of malaria was also observed (Tulu, 1996). Highland communities living at altitudes between 2000-2200m were affected by falciparum malaria for the first time since 1986. In contrast, a progressive decrease in both rainfall and RH was seen. Further analysis showed that each one degree centigrade rise in monthly mean night-time temperature was associated with an estimated 64% and 58% rise in the incidence of falciparum malaria two and three months later respectively.

The potential risk of the spread of malaria and other vector borne diseases to higher altitudes and latitudes due to global warming has been stressed since the past decade (Lindsay and Birley, 1996; Martens *et al.*, 1997). Although Africa, of all the major world regions, has contributed the least to potential climate change because of its low per capita fossil energy use and hence low greenhouse gas emissions, it is the most vulnerable continent to climate change because of factors such as widespread poverty, recurrent droughts, inequitable land distribution, and over dependence on rain-fed agriculture. The Highlands of Africa, notably those bordering the Great Rift Valley and stretching from the Ethiopian Highlands south nearly 6000km into South Africa, particularly represent an ecological zone of special concern in this respect (Patz and Lindsay, 1999). This is because, the distribution and density as well as the composition of the efficient vectors of Africa together with the range of *P. falciparum* dominance is predominantly linked or limited by minimal temperatures at higher altitudes (and latitudes) and is extremely susceptible to climatic changes (Coluzzi, 1994). In other words, small increases in temperature would appreciably reduce the development of *P. falciparum* in the mosquito vector and the generation time of the vector and, malaria could spread up to higher altitudes, increasing the highland populations at risk from malaria (Lindsay and Martens, 1998a). Yet it is difficult to assess the impact of this change on malaria transmission and to attribute increasing malaria in the highlands to recent global warming trends alone, without taking into account first for more local conditions (Patz and Lindsay, 1999). It should be noted that the risk of increasing endemicity and more epidemics is dependent not just on climate factors, but also upon the vulnerability of highland communities and the negative impact of human-made ecological changes.

Human Activities

If one looks at the "Third World" in general, and Ethiopia in particular, one sees changes everywhere-deliberate changes in the environment by man, geared to improve the living conditions of the population. The past decades have witnessed considerable environmental changes in many areas as a result of the development of agro-industrial projects, construction of dams, deforestation, urbanization, and other economic activities involving land and water use (Bradley, 1993; Bouma *et al.*, 1994; Coluzzi, 1994; Ghebreyesus *et al.*, 1996; Lindsay and Birley, 1996; Greenwood, 1997; Jetten and Focks, 1997; Joyce, 1997; Molyneux, 1997; Mouchet *et al.*, 1998; Lindblade *et al.*, 2000; Ijumba and Lindsay, 2001). In malaria endemic parts of the world, a change in risk of malaria can be the unintended result of economic activity or agricultural policy that changes the use of land (e.g. creation of dams, irrigation schemes, commercial tree cropping and deforestation). Even small variations in local microclimate can affect an insect vector's bionomics, and therefore, the disease transmission potential within a given area. Hence, understanding and forecasting the consequences of changes in environmental management on tropical diseases is crucial for their control.

Irrigation and dams

In the past decades many African countries, including Ethiopia, have given priority to initiating large-scale water resources development projects in order to meet the demands (particularly of food) of their ever-growing populations. These endeavours have often involved altering watercourses, and especially the construction of dams to permit the extension of irrigated agriculture. A recent review claims that over 800,000 dams have been constructed worldwide (Joyce, 1997). In Ethiopia a substantial number of socio-economic development endeavours, notably large-scale irrigated farming, are currently underway and extensive areas have been identified for development in all major river basins. Most of the agricultural development schemes, including those in the Awash, Didesa, Gode, Beles, Birr, Anger, and lower Wabe Shebele Valleys, involve diversion of rivers and lie in the highly malarious lowlands. The dams so far constructed in Ethiopia were being used mainly for hydroelectric power generation. More recently, however, an extensive microdam-based rural development programme, initiated in the Tigray Region of northern Ethiopia and now extended to other regions of Ethiopia, is in progress with the aim of obtaining self-sufficiency in food production and creating suitable conditions for rehabilitation of the land. The plan included construction of microdams for irrigation purposes and terracing the degraded mountains and hills. Most of the dam construction is going ahead in areas where malaria is endemic. Furthermore, according to recent reports (WIC, 2001), 13 big dams, which are to generate power and irrigate a 590,000-hectare development project, will be built in Ethiopia. The scheme is a component of a joint programme designed by the Nile riparian states under the Nile Basin Initiative. Around US $400 million will be needed to implement the projects under the Ethiopian component of the programme (WIC, 2001).

Irrigation is perhaps the single most effective way to increase the production of most crops through reclamation of arid and semi-arid areas, increasing yield, acreage, number of cropping cycles per year, and by reducing the risk of crop failure (Weil *et al.*, 1990). Dams have also improved the quality of human life in many instances by providing drinking water for people and their animals, and by promoting economic growth through production of hydroelectric power, improved navigation, and flood control in many parts of the world (Joyce, 1997). Nevertheless, these ecological changes brought about by development projects have frequently altered disease patterns and are well known in the dissemination of water-related and density dependent diseases such as malaria, schistosomiasis, onchocerciasis, and dracunculosis (Ward, 1977; Hunter *et al.*, 1982; Youdeowei and Service, 1986; Mouchet and Brengues, 1990). Throughout the tropical world, especially in Sub-Saharan Africa, the construction of water impoundments, both large and small, for irrigation and other purposes, in areas of endemic water-related diseases, has greatly intensified community levels of infection, and also created new areas of transmission (Hunter *et al.*, 1982). The clearest 'indicator' and one of the best-documented diseases, associated with irrigation, is malaria.

Many dams and irrigation schemes around the world and in Africa have been associated with significant, and even serious, vector-bone disease problems including malaria. The major attention of health and development planners has usually been focused on large-scale projects. Nevertheless, smaller water reservoirs, often referred to as microdams, are likely to have a much larger overall impact (Jewsbury and Imevbore, 1988). Microdams have several functions are more transitory, and develop at a faster rate; their control and control of the population who use them are less subject to management than larger schemes. In general around these dams, there is a high degree of human-water contact, a closer association of with settlements and limited, organized health facilities (Molyneux, 1997). Construction of small and medium-sized dams and over 100 small artificial lakes for aquaculture in Cameroon has been blamed for increased prevalence of endemic diseases including malaria (Ripert and Raccurt, 1987). The building of dams in the Uasin Gishu Highlands in Kenya was associated with increased malaria transmission (Khaemba *et al.*, 1994). In northern Ethiopia, seven-fold incidence of malaria was reported among children living near dams (Ghebreyesus *et al.*, 1998; Ghebreyesus *et al.*, 1999). Resurgence of malaria in once declared free dry zone forest area of Sri Lanka, has been attributed to large-scale irrigation development schemes (Ramasamy *et al.*, 1992). Substantially higher parasite prevalence rates were reported in the Ruzizi valley irrigation area, Burundi, as compared to outside the irrigation scheme (Coosemans *et al.*, 1984). In the Sudan, malaria transmission acquired a perennial pattern in irrigated areas along the River Nile (El Gaddal *et al.*, 1985).

The development of irrigation schemes almost invariably leads to an increase in those mosquitoes which transmit malaria by creating more breeding sites and extending their breeding season (Gillies and De Meillon, 1968; Surtees, 1971; White, 1974; Snow, 1983; Coluzzi, 1984). The major vectors of malaria in Africa, members of the *An. gambiae* complex, typically breed in open sunlit pools, sites that proliferate in irrigation schemes. By rendering the surrounding land swampy, the dams may also increase the diversity of habitats that could favour other anopheline species, such as *An. funestus*. This species breeds all the year round, and malaria, which was formerly a seasonal disease, may become permanent. Whilst such developments result in an increased production of mosquitoes, this does not necessarily result in increased malaria in local communities, especially in areas of high transmission. Indeed, in the majority of cases the prevalence of malaria near rice-irrigation schemes is less than the surrounding areas. This apparent paradox can be explained by the high use of bed nets and increased antimalarial consumption in irrigation communities, as well as density-dependent effects on the mosquito population reducing the risk of exposure (Ijumba and Lindsay, 2001). However, in highland communities where immunity is low, irrigation can lead to increased malaria such as in the Ruzizi Valley, Burundi (Coosemans *et al.*, 1984) and the Uasin Gishu Highlands in Kenya (Khaemba *et al.*, 1994). There is thus a need to identify the risks associated with irrigation and water-development projects in a range of ecological settings.

Urbanization

Another equally important factor involved in altering the ecology of malaria in Ethiopia, as in many parts of tropical Africa (TDR, 1988), is rapid and unplanned urbanization - which is manifested in the increasing migration of people from villages to towns (Surtees, 1971). Sub-Saharan Africa is the most rapidly urbanizing region in the world and available statistics suggest that since 1960, urbanization has developed 6-9% in Africa (Mouchet *et al.*, 1998). Urban population growth rates in Ethiopia have been consistently higher than those for the total population (Kloos *et al.*, 1988) and malaria has become a feature of many urban centers in the country (Gebremariam, 1988; Yohannes and Petros, 1996). Malaria has been known to occur in several Ethiopian towns in undetermined magnitude. It has been described mostly in the low-lying towns of the country and the urgency of the problem has been stressed in recent years (WHO, 1987; Gebremariam, 1988; Tulu, 1993; Yohannes and Petros, 1996). There are about 33 urban centers with a population of nearly a million in malarious areas (Tulu, 1993).

Ideally urbanisation does not lead to increased malaria transmission when accompanied by adequate housing and sanitation as vector breeding sites and human-vector contact are reduced. Nevertheless, rapid and unplanned urbanization, as occurs in developing countries, often leads to an increase in or resumption of malaria transmission because of poor housing and sanitation, lack of proper drainage of surface water, and use of unprotected water reservoirs that increase human-vector contact and vector breeding (Surtees, 1971; Martens and Hall, 2000). Although water pollution in urban areas usually leads to decreases in vector populations, some vectors, such as *An. arabiensis* may adapt to breeding in polluted waters as is the case in the forest belt of West Africa (Molineaux, 1988).

In Ethiopia, as elsewhere in Africa (Mouchet *et al.*, 1998), there is no specific urban vector, and the incidence of malaria decreases from the outskirts to the city center (Vercruysse *et al.*, 1983; Yohannes and Petros, 1996). *An. arabiensis* acts as the main vector both in urban centers and in the rural neighborhoods. Nevertheless, most of the breeding sites in urban areas are quite distinct from those seen in rural malarious areas as well as in settlement and agricultural developments. The commonly observed breeding sites in urban centers include burrow pits, which are dug during the rainy season for plastering of houses and for making bricks; holes dug for planting tree seedlings; discarded tires left in the open; stagnant water bodies in backyards and ditches along the sides of roads; and other human-made habitats (Yohannes, 1991).

The presence of huge populations in confined areas and migration from highly endemic or malaria free areas together with increased development activities in proximity to urban and peri-urban areas is conducive to the transmission of malaria in urban centers. Increased host availability promotes anthropophily. Inadequate immunity of the incoming people and the introduction of new strains of *P. falciparum* by those coming from endemic areas could increase the risk and raise the incidence of malaria in the area. Furthermore, a great majority of the people coming from highly endemic areas are asymptomatic reservoirs of parasites. Major development activities such as establishment of institutes of higher learning, agro-industries and military camps in and around urban centers as in the Rift Valley towns of Nazareth (or Adama) and Arbaminch further exacerbated the situation (Yohannes, 1991; Tulu, 1993; Yohannes and Petros, 1996).

Furthermore, the expansion of development activities such as irrigation schemes and extensive migrations of labour into and out of agro-industrial development areas in rural regions appeared to have contributed to the resurgence and spread of malaria in the country.

Population movement and malaria transmission

Movements of people in a variety of forms and at a variety of scales play an important role in the transmission cycle of malaria. Increase in malaria risk may occur as a result of a combination of different forms of mobility, as well as other factors unrelated to population movements. In general, human population movements contribute to the transmission of malaria by spreading drug-resistant *P. falciparum* infection and exposing non-immune people to risk of infection in endemic areas or by introducing infected people and mosquitoes into malaria free receptive regions, and they complicate measures for the control of malaria (Prothero, 1994; Martens and Hall, 2000; Prothero, 2001). Also the living conditions of migrants differ markedly from those of settled populations, resulting in increased exposure to infected mosquitoes. Population movements in Africa, in general, are manifested in a variety of ways- urbanization, colonization, labour related to agro-industrial projects and mining, nomadic and semi-nomadic movements, natural disasters and conflict.

Nomadic and semi-nomadic population movements are common in certain parts of Ethiopia-especially in the eastern (Afaris), southeastern (Somalis), and southern low lands. The movements are rather irregular, some of them being between countries, on the borders of the Sudan, Somalia and Kenya, and from highlands to lowlands, within the country. These kinds of movements together with seasonal downhill movements from a malaria-free periphery into malarious valley areas, mainly for pastoral activities and for the care of crops, pose serious problems for malaria control programmes and the spread of the disease. Individual farmers also tend to move to work as daily labourers in other household level farmsteads after tending their own farms during the harvesting season. In some parts of northern (Tigray) and southern Ethiopia, people/farmers flock to areas along perennial rivers to harvest incense or mine gold, only to contract malaria there. Since most of these movements coincide with the malaria season, this too affects the transmission of malaria and poses serious problem to its control. Gold miners and incense collectors are continuously exposed to infection, as malaria is perennial along the river courses.

Massive settlement of non-immune highlanders in the lowlands (without adequate study and necessary preparations) and deterioration of the health services during the last phase of the civil war in the early 1980s were believed to be particularly instrumental in the increased morbidity and mortality from malaria observed in the 1980s in Ethiopia (Kloos *et al.*, 1991; Tulu, 1993). The forced resettlement schemes of non-immune highlanders from the drought and famine-stricken regions of Shewa, Gojjam and regions of northern Ethiopia to the fertile lowlands, was carried out in the 1984-85. It involved the settlement of people in uninhabited lowland regions and into existing peasant associations and villages, mostly at elevations above 1500m. Nearly all the settlement areas were located in previously well known malarious areas of moderate to high endemicity. It appears that the settlement of non-immune highlanders into lowland malarious areas in the presence of semi-immune indigenous reservoirs of infection, coupled with a highly efficient vector, *An. arabiensis*, in the area, brought about a disturbance in the long established equilibrium and resulted in explosive epidemics. With the larger aggregation of human host and reservoirs of infection, there is increased parasite transmission and, the newly arrivals not only became ill, but also further increased the parasite reservoirs. The occurrence of malaria was more pronounced in the former group largely due to their location at relatively lower altitudes (Tulu, 1993). If these active transmitters return to their initial place of residence in a malaria-free but highly receptive area, they can reintroduce the parasite and initiate an outbreak of malaria. For example, in 1985, Tigrian settlers from southwest Ethiopia, having escaped from their settlement sites returned to their former villages in Tigray (specifically to Adi Gudem area-south of Mekelle), initiated malaria outbreaks (Ghebreyesus, personal communication).

This increase in malaria is illustrated by the Pawie Settlement Scheme, which comprised 44 newly established villages with an estimated 80,000 relocated population of highlanders in western Ethiopia. Located, as it is in the Metekel district in western Ethiopia at an altitude range of 1000 to 1700 meters, the area has 7 months rainfall, and is highly suitable for high malaria transmission. According to Nega and Hailmeskel (Nega and Fisseha, 1991), despite intensive and comprehensive control efforts made by the Malaria Control Programme in the area, during 1985 to 1989, a disappointing and progressive rise was experienced in the parasite rate, annual parasite index, and number of episodes. Over 150,000 slide-confirmed cases were recorded during the indicated period. In general, the colonization of unpopulated or sparsely populated areas by non-immune people tends to be accompanied by an increase in malaria through the interaction of a number of factors. These include poor housing often located in proximity to rivers or lakes to facilitate water collection, increasing the exposure of humans to mosquitoes. Activities to develop an area, such as deforestation and irrigation, can increase the number of vector breeding sites, contributing to an increase in malaria (Martens and Hall, 2000).

Malaria in disaster-stricken areas such as refugee camps and areas of famine, flood and war also needs special emphasis since, refugees and displaced people as a result of civil war and natural disasters are particularly vulnerable to epidemics of malaria. If refugees and displaced people are moving from areas with endemic malaria, they can introduce the disease in areas susceptible to transmission, or serve as reservoirs for more virulent and drug resistant parasite strains. If they are non-immune, they could travel through or to more endemic regions and acquire the infection and thus suffer more disease (Martens and Hall, 2000). WHO estimates that up to 30% of the 960,000 people who die of malaria every year in Africa are from countries affected by serious conflict, war or natural disaster. Indeed, malaria often kills more people in the aftermath of conflict, war or natural disaster than those killed during the actual emergency, according to the global RBM movement (MFI, 2000).

Located as it is at the centre of the horn of Africa, Ethiopia has long been known for its drought and instability. The country has been ravaged by internal conflict for decades. This and the instability in the neighbouring countries have resulted in the huge movement of populations and refugees in the region. Large numbers of the displaced people live in resettlement or refugee camps often located in lowland disease-endemic areas, and epidemics are common. The disruptive effect of war on agriculture and water management can increase vector breeding sites; the destruction of housing can increase human-vector contact; the destruction of cattle can prompt zoophilic vectors to become anthropophilic if their usual food supply is disrupted (Onori and Grab, 1980) or those with zoophilic tendencies such as *An. arabiensis* can become more anthropophagic.

Control measures can also be seriously diminished if healthcare facilities are reduced or unavailable (Martens and Hall, 2000).

Although the impact of these mass border crossings by Ethiopian, Somali, and Sudanese refugees on malaria has not been assessed in the past decade (Tulu, 1993), it would not be difficult to imagine how enormous the impact would be when coupled with the on-going Ethio-Eritrean war. The current unsettled Ethio-Eritrean war, involved and is still involving the unprecedented mass movement of people, often to malarious lowland areas of Tigray, in northern Ethiopia. This movement comprised not only over half a million soldiers and militia but also many thousands of people who assist the huge military machinery and many others who are attracted to theatres of war, including prostitutes, merchants or traders, drivers and the like, most of whom are from the highlands. To this could be added over 200,000 internally displaced people and forcefully repatriated Ethiopians from Eritrea as well as Eritrean refugees. This is not all. Voluntarily repatriated Ethiopian refugees from the Sudan, most of whom were being settled in the fertile malarious lowlands, could also be added to the list and all this in a country that is ill equipped to handle the situation. Lack of immunity, movement of migrating or fleeing populations through malaria infested areas, settlement on inappropriate land – ill equipped make shift camps, loss of livestock (which could result in changes in vector behaviour, with increased feeding on humans), crowded conditions (promoting increased human-vector contact), disruption of all government sectors including health services and the like are expected to have exacerbated the malaria situation in the region.

Malaria In Tigray Region

General background of Tigray

Tigray is the northernmost region of Ethiopia extending from 12° 15’ to 14° 50’North Latitude and from 36° 27’ to 39° 59’ East longitude. It is bounded to the north by the state of Eritrea, to the west by the Sudan and to the east and south by the Afar and Amhara Regions of Ethiopia, respectively. It covers a little more than 80,000km^2, most of which are highlands between 1500 and 3900m. Tigray consists of three distinct topographical zones: the Central highlands, Northwestern lowlands, and Eastern lowlands. The Central highlands are extensions of the Central highlands of Ethiopia.

Toward the west and northwest, the land slopes downwards to the dry lowlands of Sudan's Savannah belt. Close to the Sudanese border, elevation can be as low as 500m. The lowlands are more sparsely populated due to the prevalence of endemic and epidemic diseases such as malaria. The Northwestern lowlands have soils that are less eroded and exploited. The eastern escarpment of the central highlands falls steeply from the plateau of 2900m lowering to the Afar depression (MoA, 1998).

Climate of Tigray

Tigray region in general has a temperate climate that varies with altitude. This is part of the Ethiopian highland massif, which is bounded by a Tropical Zone to the south and west and by a Tropical Desert Zone to the north and east. The rainfall period is associated with the north and south oscillation of the Intertropical Convergence Zone. The combination of altitude, exposure to rain bearing winds and other factors produce the regional rainfall patterns (MoA, 1998). There is marked variation in rainfall distribution from east to west; especially in the eastern escarpment boundary area, where the reduction in rainfall between the upland plateau and the eastern escarpment slopes is sharp. The mean annual rainfall in Tigray region varies from less than 200mm in the extreme east bordering the Danakil Depression to over 1900mm in the southwestern part of the region. The rainy season, like in most parts of Ethiopia, is mainly between June and September and usually peaks in July. However, in the southeastern escarpment of Tigray Highlands additional rains falling in January and February, locally called "Belge", render a separate spring growing period, which lasts about 45 to 65 days. Nonetheless, recurrent failures of the "Belge" rains are common. In the northern end of the eastern escarpment, a short growing period may occur in exceptionally wet years. The mean annual rainfall and the length of the growing period increases considerably as one moves from lower to higher altitudes and from east to west. The length of the main growing period varies from more than 120 days in the west to 90 days along the eastern escarpment and eastern lowlands (MoA, 1998).

Mean annual temperature is estimated at about 18 °C in the region in general. In summer the eastern lowlands have a mean temperature in excess of 27.4 °C. At the foot of the eastern highland escarpment and in the extreme western part of the region, with altitudes below about 1000m, along the Tekeze River, mean temperatures ranging from 25-27.5 °C are common, especially during the growing period in case of the latter. Mean temperatures around 20 °C occur in large areas in the west of Tigray, in the catchment areas of the Tekeze and Mereb rivers and on the slopes of the great escarpment running north-south in central Tigray. Mean temperatures of 15 to 17.5 °C are restricted to the ridge of the highland, which runs west-east from the town of Indasilasse to Adigrat, and the upper slopes of the escarpment.

Population and livelihood of Tigray

The population of Tigray according to the 1994 census was 3.16 million of which 1.57 million were males and 1.59 million were females and the growth rate is estimated at 3% per year (CSA, 1995). June 1999 forecast puts the population at 3,532,546. The total fertility rate is 5.4 and estimated infant mortality is 123 per 1000 births for the region. The life expectancy is about 49 years (MoA, 1998). The average household size is 4.3 persons. The proportion of children under 15 is about 44.8% whereas 51.2% constitutes the age group 15-64. The proportion of 65 years and over is about 4% (CSA, 1995).

85% of the population is rural and engaged in subsistence agriculture. Population density ranges from 5/km^2 in lowlands to 120/km^2 in the highlands. Most of the population is thus concentrated in the highlands as these areas are free from malaria and most animal diseases. This has led to deforestation and the degradation of the land. Its historical role as a front-line strategic stronghold in the defence of the country against foreign invaders has also contributed to the deforestation of the area, as it had to support massive battling armies for decades. It was also repressed and impoverished by a series of rulers. After the end of the 17 years civil war (1974-1991) the situation seemed to be promising, but the region is again engulfed with war with Eritrea. The long-lasting effects of the wars, as well as of those of its antecedents, are many. Under the centralized governments' repressive policies, droughts became famines. In 1984 and 1985, during the highly publicized famine, more than a million people died of starvation in northern Ethiopia.

Administrative hierarchy of Tigray

The Tigray Regional State is one of the nine regional governments constituting Ethiopia and which are vested with authority for self-administration. The Tigray Regional State comprises five zones (provinces) including Mekelle, the capital city. Each zone is divided into Woredas (districts) and each Woreda consists of Tabias (clusters of villages). Below the Tabia level are the kushets (villages) and they have their own community administration (the local Baito). Currently, there are 36 Woredas in Tigray and about 614 Tabias, but the number is subject to revision. The number of kushets per Tabia varies, usually 3-5 and kushet population ranges from about 4000 to 8000. The number of Woredas per zone ranges from 7 to 10. There is a strong social system with agricultural agents, natural resources development agents, members of the militia, local judges, and locally elected community leaders serving the community without incentive. This type of organisation rendered periodic mass mobilisation of communities for construction of roads, schools, building micro-dams, and soil and water conservation activities-planting of trees, terracing the land, and the like. Further, as part of community-based development efforts during the civil war, social affairs committees were formed to implement activities in health, education, and broad social affairs. A primary health care system was established in which communities helped to plan for health through health committees, community health workers (CHWs) and traditional birth attendants (WHO, 1999).

The malaria situation in Tigray

Like in other parts of Ethiopia, malaria has been a disease of major public health importance in Tigray Region for a long time. Since the population is predominantly rural earning their living from subsistence agriculture and as the transmission season coincides with the growing and harvesting season, malaria as well as being a highly significant cause of morbidity and death, is also responsible for a great financial burden. This is from costs of treatment and the loss of many man-days of labour, leading to loss of agricultural output and other productive activities. Malaria has also been a major impediment for the exploitation of the fertile lowlands of northwestern Tigray.

About 75% of the region is malarious and 56% of the population are at risk of malaria, mostly due to *P. falciparum*, which accounts for 60-70% of infections. *P. vivax* constitutes the rest and predominates during the drier part of the year - from January to May. This is attributed to marked seasonal decreases in *P. falciparum* transmission due to the absence of favourable environmental conditions for continued transmission and possibly due also to relapses of *P. vivax*. In most years the seasonal variation of *P. vivax* infection is much less than that of *P. falciparum* (WHO, 1999).

The clinical pattern of malaria is related to environmental conditions, particularly altitude, which reflects temperature. At high altitudes (>2,000m), malaria is rare, but at lower altitudes it is epidemic affecting both children and adults (1,800-2,000m). At still lower altitudes transmission is seasonal (<1,800m). Generally, as in the rest of Ethiopia, malaria transmission varies greatly with the complex topography and relief. It is unstable and seasonal in nature, largely influenced by both altitude and rainfall. *An. arabiensis* is the main malaria vector in the region and population build up coincides with the rainy season with the maximum density occurring at the end of the rainy season in September-October. The major transmission period is from September through November, with peak prevalence occurring in October. In southern Tigray, a second transmission season (March/April) occurs following the small rains of January and February.

Malaria is a major public health problem in Tigray and endemicity ranges form hypo-to mesoendemic in the region, although hyperendemic pockets could not be ruled out in some places, such as along the Tekeze River. According to the limited cross-sectional parasite and spleen surveys made in Tigray, the crude parasite rates range from 3-10% during the high transmission season, and from 0-3% during low transmission months. Spleen rates in children 2-10 years range from 15 to 18% (Wezam, 1994; WHO, 1999). Owing to the unstable nature of malaria transmission, the population has little or no immunity in most parts of the region and the prevalence of the disease increases from east to west. As a result, the region is prone to epidemics and a number of such incidents have been recorded. In western Tigray, malaria epidemic in 1987 was responsible for 142,317 cases and 349 deaths. In 1990 in an epidemic in northern Tigray, 16,456 cases and 246 deaths were reported. In 1991 an outbreak in southern Tigray affected 198 localities with a population of 172,139 and 523 deaths were recorded. Prompted by these epidemics, in 1992, the government of Tigray decided to strengthen malaria control in the region (WHO, 1999).

Malaria control in Ethiopia has a history of more than 40 years, but control activities have been limited or even absent in Tigray, during the past decades, owing to the 1974-1991 civil war. The health system infrastructure of the region was severely affected by the civil war. Organized intervention efforts have started just after the overthrow of the military regime in 1992. Current malaria control activities in the region include mainly residual indoor spraying of DDT and Malathion in selected areas, epidemic control, health centre based diagnosis and treatment. Selective larviciding and environmental management for vector control was occasionally undertaken especially in certain urban areas at the end of the rainy season. In addition, community-based early diagnosis and treatment of clinical malaria was initiated in 1992, following a year of large population movements and malaria outbreaks in the region (WHO, 1999). Its approach involved training community health worker (CHW) volunteers to provide chloroquine and fansidar treatment for clinical malaria at the village level. The CHWs treat a large number of patients on a temporal pattern that coincides with a malaria transmission (an average of 489,378 patients yearly from 1994 to 1997), which represent 65-71% of patients treated for malaria in the region. Details of the programme set-up and activities and assessment of outcomes and impact could be found elsewhere (WHO, 1999).

In 1996, a pilot community-financing scheme of insecticide treated nets was also initiated in Humera area, western Tigray, which is an important area of agricultural development that is also the region's most malarious lowland. Significant success was obtained. According to the report, 78% of households in the trial area have received at least one net and 58% of the initial cost was retrieved two years after the initiation of the project. Nevertheless a very low bed net re-impregnation rate was observed for various reasons-from the initial rate of 65% in 1997 to 27% in 1998. This was attributed mainly to the Ethio-Eritrean war, which erupted in May 1998. Prices were set at USD 5.50 for a new impregnated net and USD 0.70 for re-impregnation (WHO, 1999).

Although significant success has been achieved by the ongoing intervention efforts, malaria is still a major problem in Tigray and variable levels of endemicity persist with sporadic localized outbreaks. Indicators from hospitals, health centres and malaria laboratories show a progressive increase in malaria morbidity form 1993/94 to 1997/98. Repeated mortality surveys in children under five showed a 40% reduction in the under 5 deaths from 1994 to 1996 and a 10% increase from 1996 to 1998. Mortality increased in spite of concomitant health interventions, including an increase in coverage by measles vaccination. Increases in malaria related child mortality in 1997 and 1998 was partly attributed to El-Niño related increase in transmission and possibly due the spread of chloroquine resistance in the region (WHO, 1999). Chloroquine has been the first line drug for uncomplicated malaria for over 30 years in Tigray as in the rest of

Ethiopia. Resistance was believed to have increased in the region gradually and by early 1990s high level of resistance was documented in many parts of Tigray, as in the rest of Ethiopia (Wezam, 1994; WHO, 1999). This could have worsened the deteriorating malaria situation in the region. There has also been an increase in malaria cases reported from areas previously known to be free from malaria (>2000m), and the disease is said to be encroaching into areas at higher elevations. Although the precipitating factors for such increases are not definitely known, it may be partly ascribed to the much-advocated climatological change characteristic of the century. Besides, the large-scale movement of people between the highlands and low lands due to the on going war, following the invasion of the region by the Eritrean forces, is believed to have aggravated the situation, adding new elements to the existing factors affecting the general pattern of malaria epidemiology.

Concern has also arisen about the possible effects of the increased numbers of reservoirs near human habitations on the transmission of malaria. This has lead to a comprehensive TDR/SAREC-supported survey of malaria in eight dams during 1996/8. This study demonstrated that the prevalence of malaria was seven times greater in villages situated near dams than those further away (Ghebreyesus *et al.*, 1998). In the same as well as in another study, the microdams were also found to create favourable conditions for the transmission of schistosomiasis (*Schistosoma mansoni)*, hookworm (*Ancylostoma duodenale*) and *Trichuris trichuria* (Alemayehu *et al.*, 1998).

Water-storage reservoirs have also a local effect on the surrounding climate, diminution of maximum temperature and elevating minimum temperatures (Gregory and Smith, 1967; Huntley *et al.*, 1998). Although such 'lake effects' are more pronounced with much larger water bodies, as in the temperature anomalies of +2.8 ^{O}C (January) reported adjacent to the Great Lakes (Gregory and Smith, 1967), effects of similar maginitude, a rise in temperature of +2.5 ^{O}C, were also reported for a much smaller reservoir (3.12 km^2) in the Pennines in northern England at cold temperatures (Huntley *et al.*, 1998). These small increases in temperatures can dramatically increase the risk of malaria in cool regions of the world (Lindsay and Birley, 1996; Lindsay and Martens, 1998a), like the Ethiopian highlands in Tigray.

Thus, a comprehensive study was carried out to describe the environmental changes associated with the dams and to assess the likely impact of these changes on malaria transmission. These studies have attempted to quantify which environmental changes were most important and tried to identify relatively cheaper and simple community-based targets for intervention.

Research Objectives

Study hypotheses

The construction of microdams leads to environmental changes, which increases the risk of malaria in local communities. More specifically, mosquito-breeding sites are created by human and cattle activity resulting in increased numbers of mosquitoes. In addition the water-storage reservoir results in a microclimate, which promotes mosquito production, enhances vector and parasite development and prolongs mosquito survival.

Overall Objective:

To assess the impact of microdams on the local microclimate and the dynamics of vector populations and the incidence of malaria in nearby communities.

Specific Objectives:

- Determine whether microdams result in elevated minimum atmospheric temperatures, moderate maximum temperatures, and increase in relative humidity compared with comparable sites without dams;
- Determine the extent of this 'lake effect' around a microdam;
- Identify major mosquito breeding sites around the dam;
- Develop a community-based control to reduce the number of breeding sites around the dams, and thus reduce transmission. More specifically, to test whether environmental manipulation, notably source reduction, shading of breeding sites with vegetation, and other physical methods such as filling and draining could reduce vector breeding;
- Quantify the temperature and relative humidity experienced by resting mosquitoes indoors and outdoors;
- Quantify the temperature of mosquito breeding sites

- Compare the risk of malaria (entomological inoculation rate) experienced at dam and non-dam sites.

Chapter 2. Impact of microdams on local microclimate and its relevance to malaria transmission in northern Ethiopia.

Plate 2.1. An automatic weather station on the dam embankment.

Plate 2.2. Partial view of Meskebet dam taken at the edge of the plateau separating the dam and the remote village.

Abstract

The pattern and intensity of malaria transmission is intimately related to changes in the weather. In drought-prone Tigray, microdams were introduced to provide a source of drinking water and for irrigation, but lead to a dramatic increase in malaria in local villages. It was hypothesised that part of the reason for this increase was the dams increase temperature locally, resulting in elevated rates of malaria. A longitudinal study of microclimate was carried out in two villages: Deba, situated near a microdam, and Maisheru, 3-4km away in a neighbouring valley. Both villages were situated at a similar altitude and topography. The weather was measured in both villages and on a nearby dam embankment continuously over 19 months. The yearly mean minimum temperature of the dam site was 1.5 °C warmer than the near dam village. Similarly, that of the dam village was 1.3 °C higher than the remote village and was especially pronounced (>3.5 °C) at the end of the rainy season (November to January). Along with profuse breeding sites provided by the dam, the increase in minimum temperature probably extends the transmission season. Overall the mean daily water temperature of surrogate breeding sites was 0.1-1.2 °C warmer than air temperature, suggesting that air temperatures recorded by conventional weather stations were a fairly good indicator of temperatures experienced in larval breeding sites, although the correlation was less strong during rainy days and when data were summarised as monthly averages. Increases in minimum temperature as a result of the construction of the dam may contribute to the dramatic increased risk of malaria in Ethiopian highlands in Tigray. This effect may also act as proxy for the likely impact of global warming on malaria in the African highlands.

Introduction

In malaria endemic parts of the world, a change in risk of malaria can be the unintended result of economic activity or agricultural policy (Ijumba and Lindsay, 2001). In the drought-prone region of Tigray in northern Ethiopia, partly in response to the devastating droughts experienced in 1984, an extensive program of dam construction is in progress, within a major rural development program called Sustainable Agriculture and Environmental Rehabilitation in Tigray (SAERT). These dams are largely small community-built constructions of local stone and mud, with some concrete spillways and irrigation channels. The water reservoirs vary in size from 50,000 to 4, 000,000m^3

and more than 500 dams are planned for the region (SAERT, personal communication 2000). Dams for municipality and hydroelectric power generation are also anticipated in the region, including the already completed dam of 13, 000,000m^3 capacity. Many of these are located near human settlements at an altitude range of 1700-2300m, the fringe areas of malaria transmission inhabited with people having little or no immunity. Concern has arisen about the possible effects of the increased presence of standing water around dam sites on the transmission of malaria. This lead to a comprehensive survey of malaria in eight pairs of villages, within each pair one was situated near a dam, and the other 8-10km away. This study demonstrated that the incidence of malaria was seven times greater in villages situated near dams than those further away, with this effect being most marked in communities below 2000m (Ghebreyesus *et al.*, 1999).

The dramatic increase in the incidence of malaria in near-dam villages could be due largely to increased number of breeding sites favourable for *An. arabiensis* (Chapter 5). Water-storage reservoirs also have a local effect on climate, in particular moderating climate extremes, and thus elevating minimum temperatures as in the temperature anomalies of +2.8 ^{O}C in January reported adjacent to the Great Lakes (Gregory and Smith, 1967) and a rise in temperature of +2.5 ^{O}C at cold temperatures reported for a much smaller reservoir in the Pennines in northern England (Huntley *et al.*, 1998). Such small increases in temperatures can, theoretically, dramatically increase the risk of malaria at the fringes of cool regions of the world (Lindsay and Birley, 1996; Lindsay and Martens, 1998a), like the Ethiopian highlands in Tigray.

The local microclimate of the adult environment is extremely important in vector-borne diseases such as malaria, because both the vectors and the parasites they harbour are greatly influenced by the surrounding weather elements. Changes in weather, notably in temperature, could thus be expected to increase or decrease transmission rates depending on the prevailing environmental conditions. Rises in temperature, particularly moderation of minimum temperature, speeds up the development of the malaria parasite inside the mosquito. In general, the abundance, longevity, and blood feeding frequency of the vector are all influenced by ambient temperature and this in turn influences the dynamics of malaria transmission. Given these relationships, local weather changes, natural or human induced, would be expected to influence the pattern and intensity of malaria transmission locally (Lindsay and Birley, 1996; Martens *et al.*, 1999).

In many ecological models, air temperature is used as a critical input parameter. Nevertheless, in organisms, such as mosquitoes, that spend part of their life cycle in small bodies of water (Gillies and De Meillon, 1968), the immature stages are exposed to temperatures which differ from air temperature or the temperature of large water bodies (Jacobs *et al.*, 1997). Simulation studies conducted on malaria vectors indicate that mortality and development of the aquatic stages due to surface water temperature are the most important factors to determine the number of emerging adult mosquitoes (Jetten and Takken, 1994). Hence, monitoring the temperature of breeding sites is also very crucial in the elucidation of the life history of vector species.

Thus, a comprehensive study was carried out near a microdam in the Tigray region of northern Ethiopia to describe the environmental changes associated with the dams and to assess and evaluate the part they play in producing the different distribution of the disease observed between near dam and remote from dam villages. This paper examined the range of climatic changes that could occur as a result of the construction of microdams and the temperatures experienced in surrogate mosquito breeding sites.

Materials and Methods

The Study Area

Climate and geography

The study was conducted from March 1999 to January 2001, near a microdam (capacity 2.7 million m^3), located in Lailay Adiabo Wereda (district), Western zone of Tigray Region, about 330km northwest of Mekelle, in Tigray, Ethiopia (14^0 16' - 14^0 19' N and 38^0 11' - 38^0 14' E). The microdam, known locally as Meskebet, was located 3km southeast of the district town of Adidaero, which is about 30km northwest of Inda Selassie. The longitudinal study was undertaken in Deba village near the microdam at an altitude of 1750-1790m, and Maisheru village 3-4km away in a neighbouring valley parallel to the dam at a similar altitude (1750-1790m) and topography (Figure 2.1).

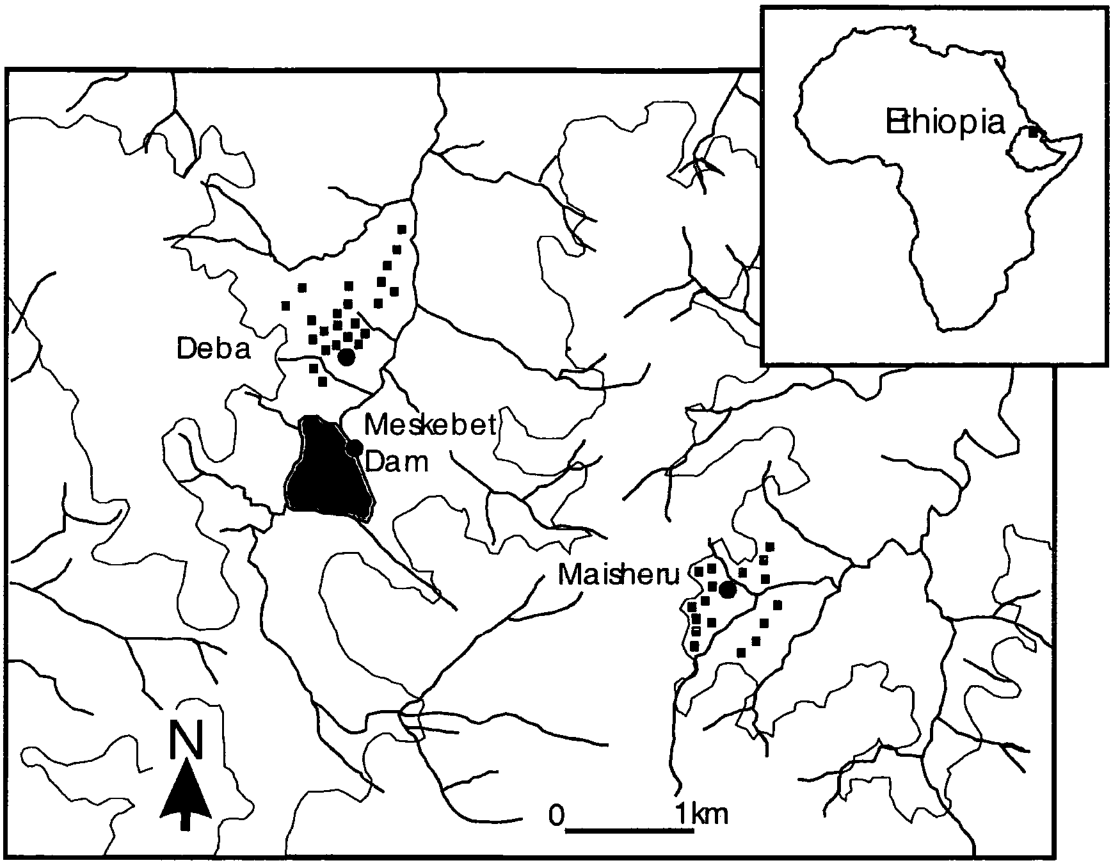


Figure 2.1. Map of study area indicating the study villages (solid squares), dam (dark grey), major streams, automatic weather stations (solid circles) and the surrounding plateau (grey) ≥ 1800m. Inset shows the position of the study site in Ethiopia [Major features of the study area were traced from a Topomap, 1: 50,000 scale, and scanned].

The study area is part of the Central Highlands of Tigray (1500-3000m altitude). The prominent feature of the surrounding topography, especially to the south of the study villages, is a massive tableland with almost a uniform altitude of 1800m above sea level. Small valleys cut into the plateau and it is topped by mountains, some of which rise to over 2000 meters.

The wet season extends from end of May to beginning of October receiving about 900-1200mm annually. The amount and duration of rainfall varies markedly from year to year. The yearly average maximum temperature of 30 °C in April immediately precedes the main rainy season. The coldest months are November through January, with a mean minimum temperature of 10.6 °C recorded in December and January over 10 years.

The predominant crops grown in the area were maize (*Zea mays*), teff (*Eragrostis abyssinica*), finger millet (*Eleusine coracan*), and Sorghum (*Sorghum bicolor*). Natural vegetation in the area was scattered and consisted predominantly of *Dodenea viscosa* and *Euclea shimperi*. In the villages, *Acacia albidia*, *A. lehay*, *Cordia africana*, *Qualia shimbri*, *Dodenia engusti*, and *Ziphus spinacle* were the predominant trees in the dam village and in the remote village, *C. africana*, *A. lehay*, *Eucalyptus* species, *Z. spinacle*, and other *Acacia* species dominated in their order of importance.

Average population density for the district based on the 1994 census with 3% growth rate (CSA, 1995), was relatively low (41.1 people per km^2). According to the latest census update (October 2000) conducted in the villages, the total population of Deba was 372 (199 females, 173 males) in 71 households. In Maisheru, the number of households and the population was 235 and 1237 (592 females, 645 males) respectively. The average number of people per household was 5.1 in both villages. The predominant occupation was subsistence farming with mainly cereal cultivation and livestock herding. People lived in clusters of " Hidumos"; rectangular, or occasionally circular, houses of stonewall with wattle and earth roofs, which are typical of rural dwellings in Tigray. The roofs were flat and made from wooden beams covered with wood, twigs and earth. The roof may occasionally be thatched or, less commonly, made of corrugated iron. Open eaves were often present between the roof and the walls for ventilation purposes. Cattle, goats, and sheep were herded for the night in open enclosures close to human habitations.

Selection of study sites

Meskebet dam, which covered about 10ha of land (about 0.9km^2) and holding about 2.7 million m^3, was selected for its large size that would make it easier to quantify its impact. Most importantly, the control village, Maisheru, located 3-4km away from Deba village was remarkably similar in topography, aspect and ecological features to the near dam village (Fig. 2.1). It was also relatively close to the dam, but far enough away that it was unlikely that any mosquitoes from the two villages could mix. The altitude range of both valleys was essentially the same (1750 - 1790m) and the surrounding plateau is uniformly 1800m in elevation.

In Deba, the nearest house was less than 170m from the dam. Irrigation extended from mid January until June. The fields were irrigated until they became saturated or flooded and pools of standing water were common throughout the study area. Fields were cultivated largely with maize, followed by vegetables such as onion, tomato, and green pepper. In 1999, 15ha was under irrigation, 9ha was cultivated mainly with maize, and 6ha with onion. Fruit, such as papaya and banana were also grown. Assisted by agricultural extension workers, farmers also grew animal fodder such as *Sesbania* species and elephant grass (*Pennisetum purpureum*) along the gullies and the perimeter of their irrigated fields. During the main cropping season, farmers grew teff and finger millet in the irrigated fields. Sowing of seeds for the rain-fed agriculture started at the end of May and extended into June, even July depending on the type of crops grown. The types of crops grown during the main rainy season were the same in both villages. In general, the predominant crops grown in the study villages, in their order of importance, were maize, teff, and finger millet. The predominant type of soil in the dam village was sandy-silt and in the remote village it was sandy. The soil type in the dam village was the type highly favoured by termites and there was substantial tunnelling under the fields resulting in the production of enumerable pools (breeding sites) and wastage of water.

After selection of the study sites, major physical features of each village and landscape was mapped using a global positioning system (GPS 38, Garmin International Inc., Olathe, Kansas). Physical characteristics including location and type of water bodies, and position of each house was mapped. Demographic and environmental information was also recorded. GPS point coordinates were taken at 10 stride intervals (about 5m) when mapping the dam, breeding sites, canals, etc. GPS counts or recordings were repeated after the Selective Availability was switched off in May 2000 improving the accuracy of GPS readings from 100m to 5m.

Monitoring the Microclimate

Three automatic weather stations (Datahog 2 -Skye Instruments Ltd., UK) were used to monitor the microclimate in the study area (Fig. 2.1). In the dam village, an automatic weather station (AWS) was placed on the embankment of the dam facing the village (14.2941° N and 38.1988° E). One station was positioned 100m from the houses nearest to the dam (14.2974° N and 38.1982° E), to minimise any windshield effect from the houses. In the remote village the station was placed at a similar position and aspect as that of the dam village (14.2832° N and 38.2259° E). Each station continuously recorded air temperature and relative humidity (RH), water temperature, rainfall, wind direction, and wind speed at 30-minute intervals from May 1999 to January 2001. All variables, except rainfall, were sampled every 30 seconds and averaged values logged every 30 minutes. The logging interval was also 30 minutes when measuring rainfall. Thermistor tips immersed into plastic buckets full of water recorded water temperature. The plastic buckets used were of the same size (diameter 17cm x 15cm deep), filled to the same level and buried to the level of the ground. From June 2000 until January 2001, earthenware containers (18cm diam x 7cm deep) replaced the plastic buckets.

The AWSs were downloaded monthly and the data inspected to ensure the proper functioning of the equipment. The AWSs were set together for one month at the beginning, midway (end of the year 1-May 2000) and end of the study (Jan.-Feb.2001) in order to detect any discrepancy in recording during the study period.

Statistical analysis

From the mean data values logged at 30-minute intervals, hourly, daily, monthly, seasonal and yearly summaries were extracted from the data recorded by each AWS. For rainfall monthly totals were determined. Paired samples t-tests were used to compare the daily, monthly, and seasonal averages of the data recorded by each AWS. Comparisons were also made between air and water temperature using scatter plots and linear regression. SPSS10 and SigmaPlot2001 software were utilized for analysis and graphing respectively. It is noteworthy to mention here that analysis of the data involved division of the study period into 2 phases: Year1 (May1999-27th April2000) and year 2 (June 2000-14th January 2001). Hence the number of days in both years is not equal.

Results

The results of the validation tests revealed insignificant differences in temperature and RH readings to warrant using correction factors. The differences in mean temperature observed between the weather stations were 0.038-0.053 °C. Similarly, insignificant differences of –0.09 to 0.13% were observed with respect to RH.

Meteorological conditions prevailing during the study period are given in Tables 2.1 & 2.2 as well as in Figures 2.2 and 2.3. Rainfall occurred largely between the end of May and October. The maximum rainfall recorded in both villages was in July and August. There was no statistically significant difference in rainfall recorded during the first year of the study period (May 1999 – April 2000) for the dam (1051mm, mean = 87.4mm) and remote villages (1063mm, mean = 87.5mm; $t = -0.03$, d.f. =11, $p = 0.97$), nor the second year (June 2000 – January 2001; $t = -0.96$, d.f. = 7, $p = 0.37$). The total amount of rainfall recorded for this part of the study was 709mm (mean = 88.6mm) in the dam village and 772mm (mean = 96.5mm) in remote village. Rainfall mostly occurred between 16:00 to 24:00hr.

Table 2.1. Comparison of the mean minimum and maximum temperatures and mean RH recorded at the dam edge, dam village, and remote village during the study period.

	Remote village		Dam village		Dam site	
	Mean	95% CIs	Mean	95% Cis***	Mean	95% CIs
Year 1 (May 1999 – April 2000)						
Tmean (°C)**	19.6	19.4 – 20.0	20.4	20.2 – 20.6	20.9	20.6 – 21.1
Tmax	26.8	26.5 – 27.1	27.1	26.8 – 27.4	26.4	26.1 – 26.7
Tmin	13.0	12.7 – 13.5	14.3	14.1 – 14.6	15.7	15.5 – 15.9
RH (%)	64.9	62.7 – 67.1	62.7	60.5 – 64.9	61.2	59.0 – 63.4
Rainfall (mm)	1063		1051		--*	
Year 2 (June 2000 – January 14, 2001)						
Tmean (°C)	19.0	19.0 – 19.4	20.1	19.9 – 20.2	20.5	20.4 – 20.7
Tmax	26.2	26.0 – 26.4	26.7	26.5 – 26.9	25.9	25.6 – 26.0
Tmin	12.8	12.4 – 13.1	14.1	13.8– 14.3	15.5	15.4 – 15.7
RH (%)	70.6	69.0 – 72.2	67.3	65.7 – 69.0	66.5	64.8 –68.1
Rainfall (mm)	772		709		--*	

* Rainfall record missing for the dam site because rodents destroyed the extension wire of the rain gauge;

**Tmean = mean temperature, Tmin = minimum temperature, Tmax = maximum temperature

***CIs = confidence intervals

The seasonal pattern of RH and rainfall in both villages is illustrated in Figure 2.2. The gap in the figure represents the month (May 2000) when the weather stations were set together to test any discrepancy in recording. RH was low during the drier months (November through June) reaching 37% in both villages in March. It increased steadily during the wet season, reaching a high value of 94% (mean monthly) in August in both villages. Mean monthly temperatures varied from about 23.7 °C in May to 16.4 °C in November (16.7 °C in December) in the remote village whereas in the dam village it varied from 23.8 in May to 18.5 °C in July and August (November = 18.7 °C). The mean temperature was 0.8 °C and 1.1 °C warmer in the dam village compared with the remote village in year 1 (z = 16.6, d.f. = 353, $p < 0.001$) and in year 2 (z = 14.8, d.f. = 226, $p < 0.001$), respectively. Overall, the mean temperature was 0.9 °C in excess in the dam village compared to the remote village throughout the study period (z = 22.0, d.f. = 580, $p < 0.001$).

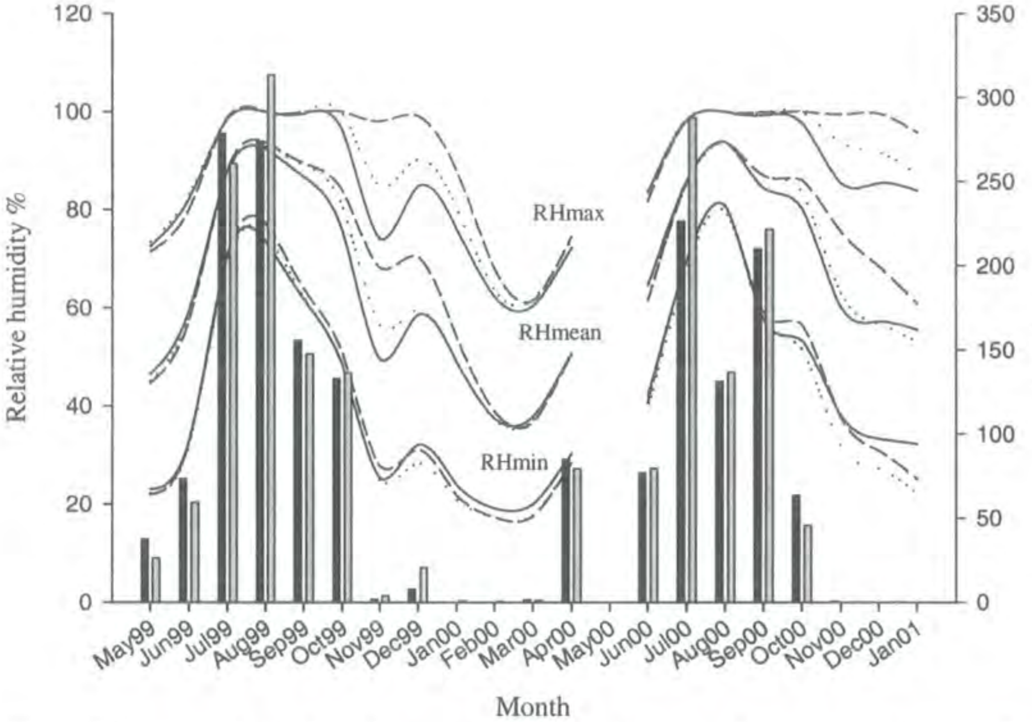


Figure 2.2. Seasonal variation of mean minimum, maximum, and average relative humidity at the dam site, dam village and remote village (May1999-Jan2001).[__ dam site, ... dam village, ----, remote village; Rainfall: black bar - dam village, grey bar-remote village]

The seasonal pattern of maximum and minimum temperatures recorded by the three AWSs for the complete one-year study period (May 1999 - April 2000) is illustrated in Table 2.2. Figure 2.3 shows the extended picture – from May 1999 – January 14th 2001. Generally, the records of the three AWSs showed a similar pattern with a sudden drop in mean monthly minimum temperatures exhibited in November. However, a relatively smooth pattern, not exhibiting a marked decrease, in minimum temperature was discernible in records by the AWS on the dam embankment, even in the coldest months of November through January. Overall, the minimum temperature was 1.3 °C warmer in the dam village compared with the remote village in year 1 ($z = 14.4$, d.f. = 353, $p < 0.001$) and throughout the study ($z = 18.6$, d.f. = 580, $p < 0.001$). The mean minimum temperature recorded at the edge of the dam was 2.6 °C higher than that recorded in the remote village in year 1($z = 23.3$, d.f. = 362, $p < 0.001$) and by 2.7 °C throughout the study ($z = 30.0$, d.f. = 589, $p < 0.001$). Similarly, the dam edge was 1.3 °C warmer than the nearby village in year 1 ($z = 24.1$, d.f. = 353, $p < 0.001$) and by 1.5 °C throughout the study ($z = 30.8$, d.f. = 580, $p < 0.001$), which was about 400 meters away from the dam, indicating the influence of the dam upon the microclimate around it, its warming effect diminishing further away from the dam.

Table 2.2. Seasonal temperature and relative humidity profile in remote village, dam village and dam site (May1999 – April 2000).

Parameter	Remote village	Dam village [a]	Dam site [b]
Dry season (November – May)			
No. days of observations	210	201	210
T_{min}	12.0 (CI 11.5-12.6)	14.0 *** (13.7-14.4)	15.5 *** (15.2-15.9)
T_{max}	28.2 (27.9-28.5)	28.6 *** (28.3-28.8)	27.7 *** (27.4-27.9)
T_{mean}	20.0 (19.6-20.4)	21.2 *** (20.9-21.5)	21.6 *** (21.3-21.8)
RH_{min}	23.7 (22.6-24.8)	22.8 *** (21.8-23.8)	24.8 *** (23.7-25.9)
RH_{max}	80.5 (77.9-83.1)	75.7 *** (73.3-78.0)	71.8 *** (69.7-73.9)
RH_{mean}	52.3 (50.1-54.5)	48.1 *** (46.3-49.8)	47.1 *** (45.4-48.8)
Rainfall (mm)	145	136	--
Wet season (June – October)			
No. days of observations	153	153	153
T_{min}	14.4 (14.0-14.7)	14.8 *** (14.5-15.3)	15.8 *** (15.6-16.1)
T_{max}	24.7 (24.3-25.1)	25.1 *** (24.7-25.5)	24.5 *** (24.1-24.9)
T_{mean}	19.0 (18.8-19.3)	19.4*** (19.1-19.6)	19.8 *** (19.5-20.0)
RH_{min}	59.2 (56.2-62.3)	57.5 *** (54.5-60.6)	57.7 * (54.6-60.8)
RH_{max}	95.8 (94.3-97.4)	96.4 ** (95.1-97.6)	95.4 *** (94.0-96.7)
RH_{mean}	82.7 (80.3-85.0)	81.9 *** (79.6-84.2)	80.6 *** (78.3-82.8)
Rainfall (mm)	918	915	--

Where a is Remote village vs. dam village; b is Dam village vs. Dam site; * is $p < 0.05$, ** $p < 0.01$, and *** $p < 0 .001$

Note that the number of days of observations does not add up to a year, because the AWSs were set together starting from 27April2000 for 1month & the AWS in the dam village started recording 10 days behind the others in May1999, hence the data of 10 days was excluded from the two other met stations when comparisons were made with the dam village.

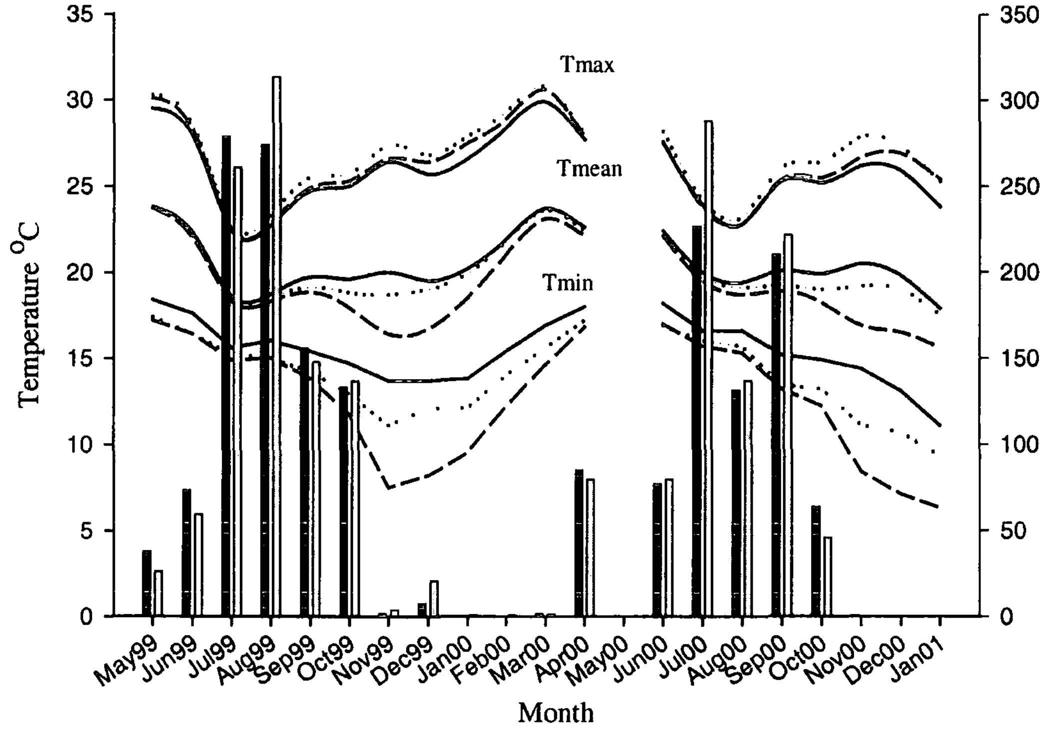


Figure 2.3. Seasonal variation of mean minimum, maximum and average temperature at dam site, dam village & remote village (May1999-Jan2001).[__ dam site, ... dam village, - - -, remote village; Rainfall: black bar - dam village, grey bar-remote village]

The difference in mean minimum temperature was more pronounced during the dry season (Table 2.2). The mean minimum temperature recorded in the dam village exceeded that of the remote village by 2.0 °C in year 1 ($z = 14.59$, d.f. = 200, $p< 0.001$) and by 2.3 °C throughout the study period ($z = 20.2$, d.f. = 274, $p <0.001$). The difference was even more pronounced when the recordings of the coldest months of the year (Nov – Jan.), following the rainy season, were considered separately. The mean minimum temperatures recorded by the three AWSs during this period were 13.4°C (95% CI: 13.2-13.7, dam embankment), 11.1 (CI: 10.7-11.4, dam village) and 7.6 °C (CI: 7.3-8.0, remote village); a 3.5 °C difference between the dam and the remote village. The statistical significance of the warming effect of the dam is exaggerated as the data was auto-correlated and this effect could not be removed from the time series analysis even when the data were averaged on a weekly basis.

The mean maximum temperature recorded during the first complete year (May1999-Apr2000) at the edge of the dam was 0.8 °C lower than that of the nearest village ($z = -31.7$, d.f. = 353, $p < 0.001$) and 0.4 °C lower than that in the remote village ($z = -14.5$, d.f. = 362, $p < 0.001$). Nevertheless, the RH values obtained in my study presented a slightly different picture. The mean RH recorded during the first year of study (May1999 – Apr2000) at the dam edge was 1% lower than that recorded at the dam village ($z = -6.6$, d.f. = 353, $p < 0.001$) and by 3.0 % lower than that in the remote village ($z = -10.5$, d.f. = 362, $p < 0.001$).

The nighttime scatter plot of wind speed and direction for the dry and wet seasons on the dam embankment is illustrated in Figures 2.4 and 2.5 respectively. The wind speed and direction records, sampled at 30 second intervals and averaged and logged at 30 minute intervals, were individually plotted to indicated the general trend of wind speed and direction. Thus, every 30-minute average of wind speed and direction is represented by one dot or point on the graph. The wind direction readings depicted in a polar graph format indicate the degree of the compass and the circular grids indicate the average speed (ms^{-1}). The length of the line at any particular point shows accumulated readings from that direction. The wind direction fluctuated and vacillations towards all directions were observed. However, on average, the nighttime wind direction during the dry season was mainly to the north (NNE, NE) carrying the warmth toward the dam village and down the valley. During the wet season the direction was predominantly to the west (WW, SW) of the dam carrying the warmth away from the study village nearby. Overall, although the direction of the wind was predominantly to the north and northeast, the wind speed was not strong for most parts of the year, especially at night. Hence, weak oscillations or eddies around the dam predominated.

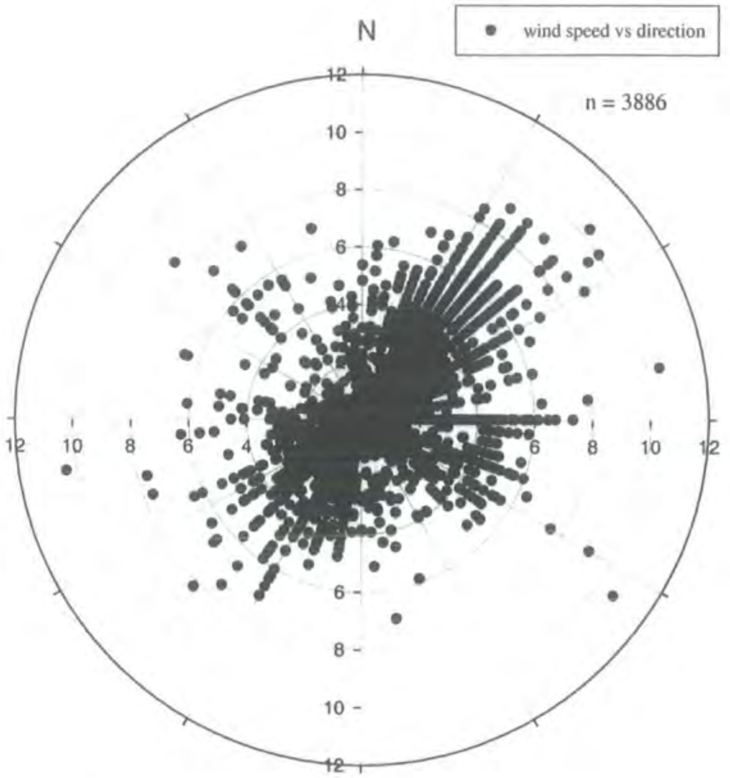


Figure 2.4. A scatter polar plot of nighttime wind speed (ms^{-1}) and direction (degrees) recorded at 30 minute intervals on the dam embankment during the dry season.

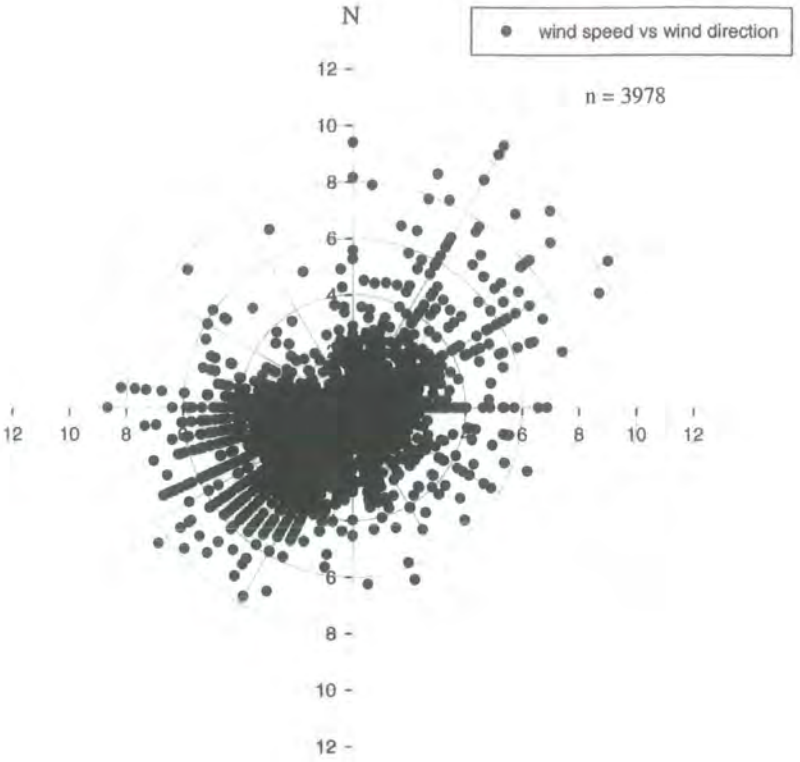


Figure 2.5. A scatter polar plot of nighttime wind speed (ms^{-1}) and direction (degrees) recorded at 30 minute intervals on the dam embankment during the wet season.

The nighttime wind direction and speed for the dam village is shown in Figures 2.6 and 2.7 and for the remote village in Figures 2.8 and 2.9. As indicated in Figures 2.6 and 2.7, although the wind speed was relatively slower than at the dam embankment, the wind flow was predominantly to the north (and to the south) during the dry and to the southwest during the wet season. This is similar to that of the dam embankment indicating that the wind carries warm breath from the dam to the village. Nonetheless, compared to the dam edge, the strength of the nighttime wind at the nearby village was relatively weak. A similar picture was observed in the remote village both during the dry and wet seasons (Figures 2.8 and 2. 9).

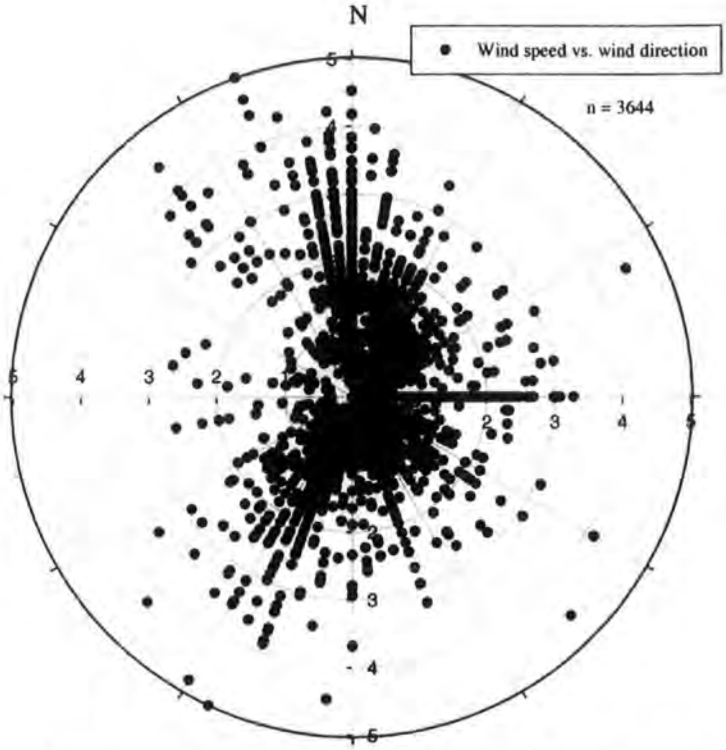


Figure 2.6. A scatter polar plot of nighttime wind speed (ms^{-1}) and direction (degrees) recorded at 30 minute intervals at the dam village during the dry seasont.

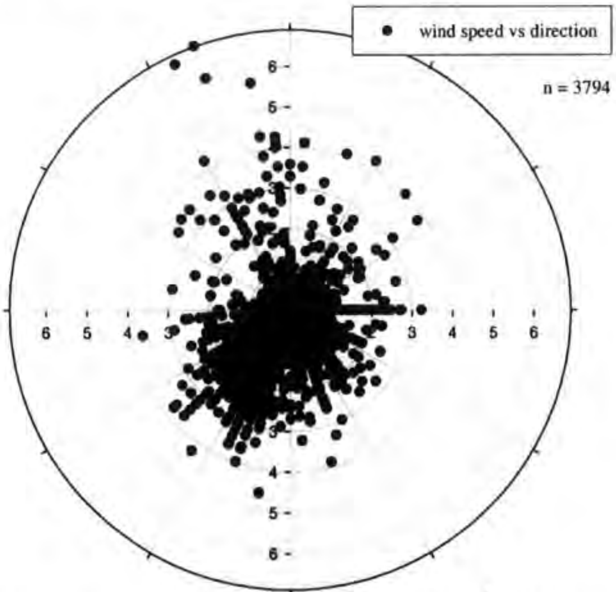


Figure 2.7. A scatter polar plot of nighttime wind speed (ms^{-1}) and direction (degrees) recorded at 30 minute intervals at the dam village during the wet season.

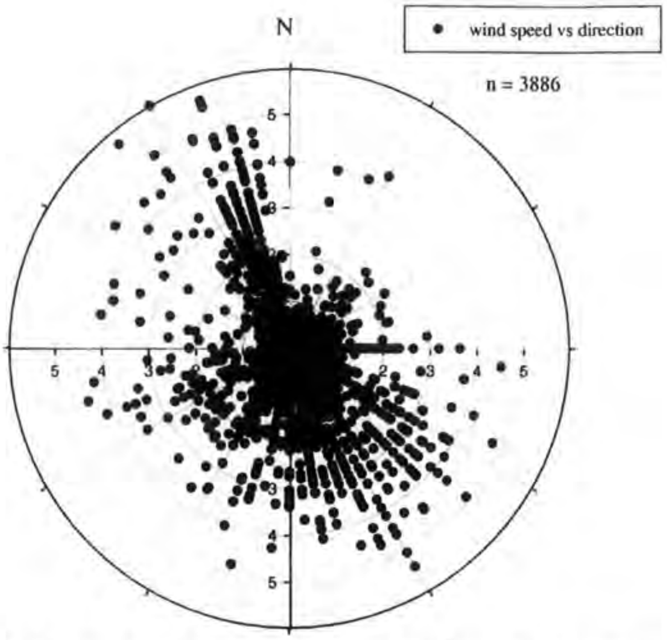


Figure 2.8. A scatter polar plot of nighttime wind speed (ms^{-1}) and direction (degrees) recorded at 30 minute intervals in the remote village during the dry season.

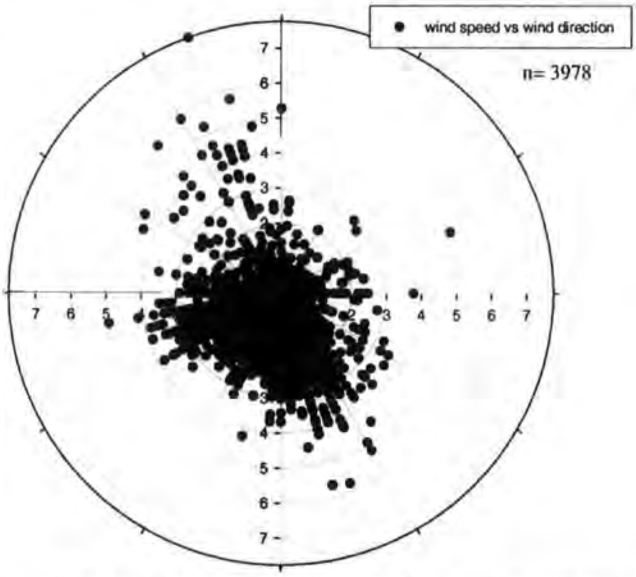


Figure 2.9. A scatter polar plot of nighttime wind speed (ms^{-1}) and direction (degrees) recorded at 30 minute intervals in the remote village during the wet season.

Comparison of mean hourly air and water temperature over a three dry months (October-December) vs. wet season (July-September) is shown in figures 2.10 and 2.11. As illustrated in figure 2.10, during the rainy days of the wet season water temperature was constantly higher than air temperature throughout the 24-hour period, the difference being more pronounced during the daytime. Air temperature approached water temperature at about 9:00hr in the morning but lagged afterwards. The maximum difference between air and water temperature was observed between 14:00 and 15:00hr (water > by 6.1 ^{o}C).

The mean hourly air and water temperature relationship during the dry season is illustrated in Figure 2.11. Water temperature was higher than air temperature throughout most of the 24-hour period. Air temperature approached water temperature at about 07:00hr in the morning and warmed up faster than water exceeding the latter slightly until about noon (12:00hr). Water temperature started to exceed air temperature at about 12:00 hours and reached its maximum between 13:00 – 14:00 hr (> by 2 ^{o}C at 14:00 hr). It remained warmer than air through the latter half of the day and night until the following morning, except at about 17:00 hrs when air approached it. Both during the dry season and the rainy days of the wet season, the hourly relationship of water and air temperature was not linear and temporal autocorrelation could not be ruled out. Hence, considering the very small standard errors associated with the means, it was thought that the graphs would give a better picture rather than a complex time-series analysis for linear regression of a non-linear relationship. The mean ± S.E are plotted as indicated in the figures (Figures 2.10 and 2.11).

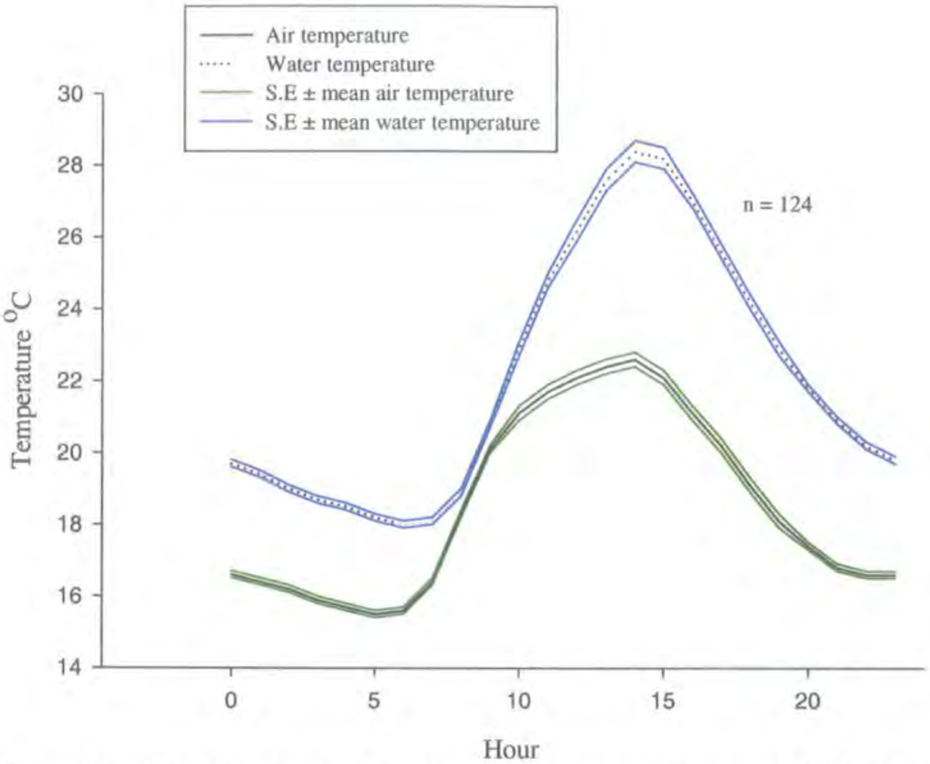


Figure 2.10. Diurnal variation of air and water temperatures determined for the rainy days of the wet season in the dam village (Jul-Sep).[mean ± S.E plotted for each curve]

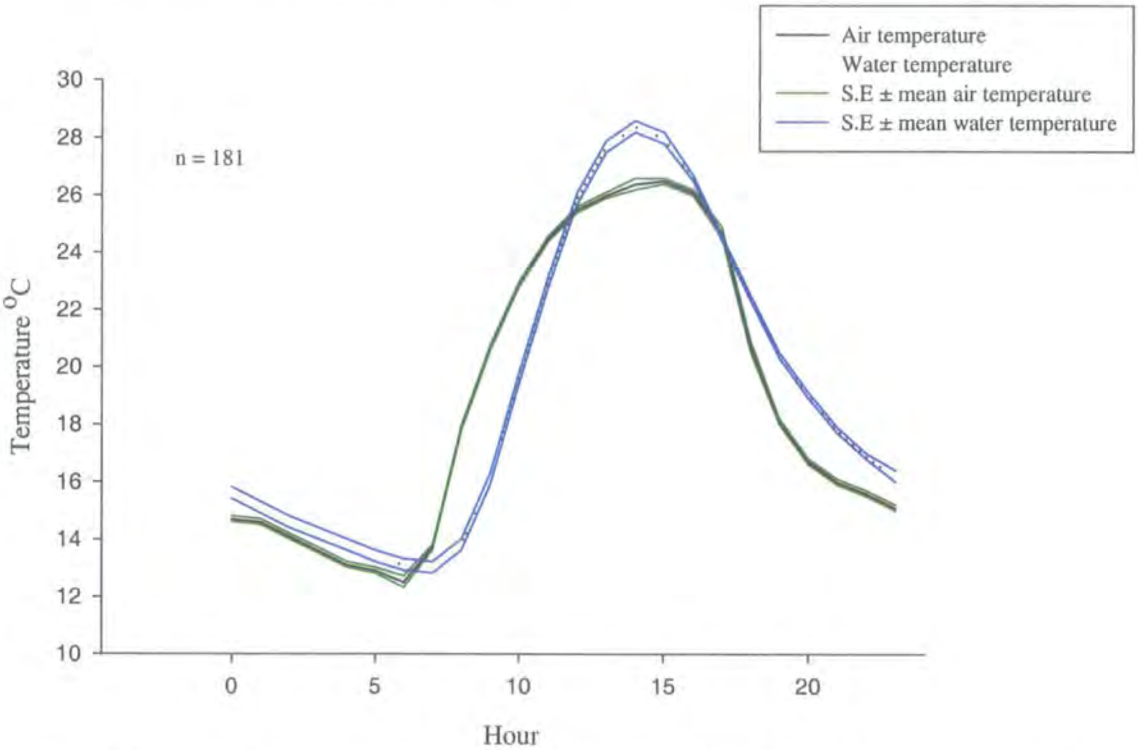


Figure 2.11. Diurnal variation of air and water temperature during the cool dry season (Oct-Dec) in the dam village [mean ±. S.E plotted for each curve]

Hourly air and water temperature recordings were also compared for the complete year dry and wet seasons without averaging (Figures 2.12 and 2.13). A strong positive correlation was obtained between the two variables both in the dry ($R = 0.903$) and wet seasons ($R = 0.75$), although relatively stronger in the former. For the wet season, the correlation was higher ($R= 0.85$) when both rainy and non-rainy days were considered together ($R^2 = 0.724$, $F = 9596.102$; $y = 3.433 + 0.973$, $t_a = 17.474$, $t_b = 97.96$, $p < 0.001$).

As daily mean air temperature records are widely available from most conventional meteorological stations, comparison of the daily mean air and water temperatures of both the dry and wet seasons were made in the dam village as indicated in the scatter plots of Figures 2.14-2.15. In general, a positive correlation was noted in both the dry ($R = 0.8$) and wet season ($R = 0.6$), although relatively weak in the latter. A similar correlation was noted between air and water temperatures at the dam site both during the dry ($R^2 = 0.599$, $R= 0.8$, $y = 3.393 + 0.753x$, $p < 0.001$) and rainy season (Dry days: $R^2=0.236$, $R= 0.49$, $y=16.433 + 0.235x$, $p < 0.001$; Rainy days: $R^2=0.220$, $R= 0.47$, $y= 15.201 + 0.293x$, $p < 0.001$). The correlation, however, was relatively stronger during the dry season.

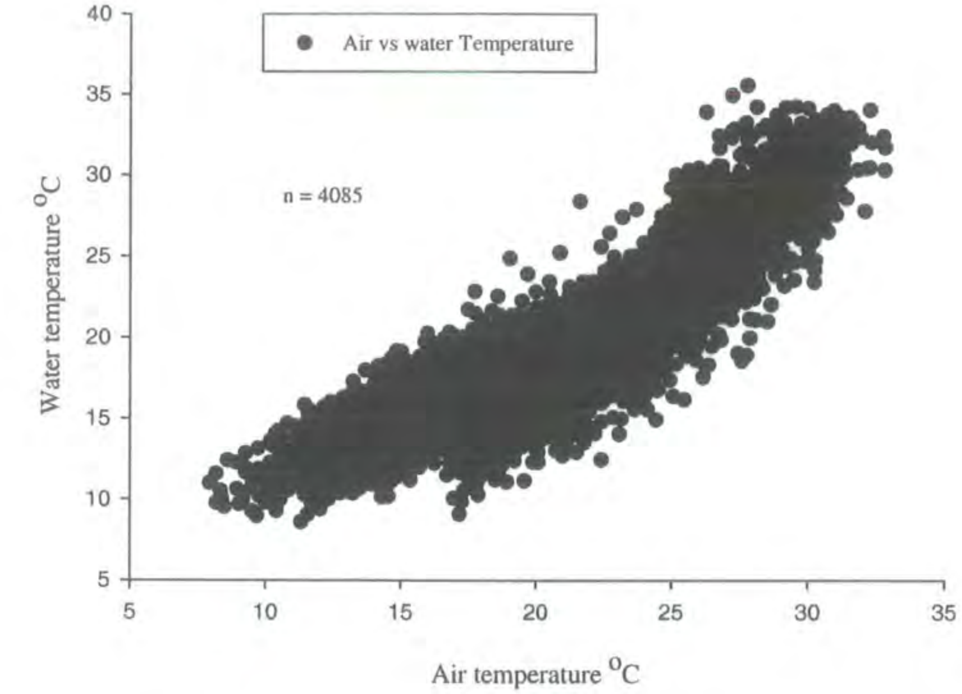


Figure 2.12. Dry season hourly air and water temperature scatter plot in the dam village [$R^2 = 0.815$, $F = 18013.42$, $y = 0.08377 + 0.943x$, $t_a = 0.548$, $t_b = 134.214$, $p<0.001$]

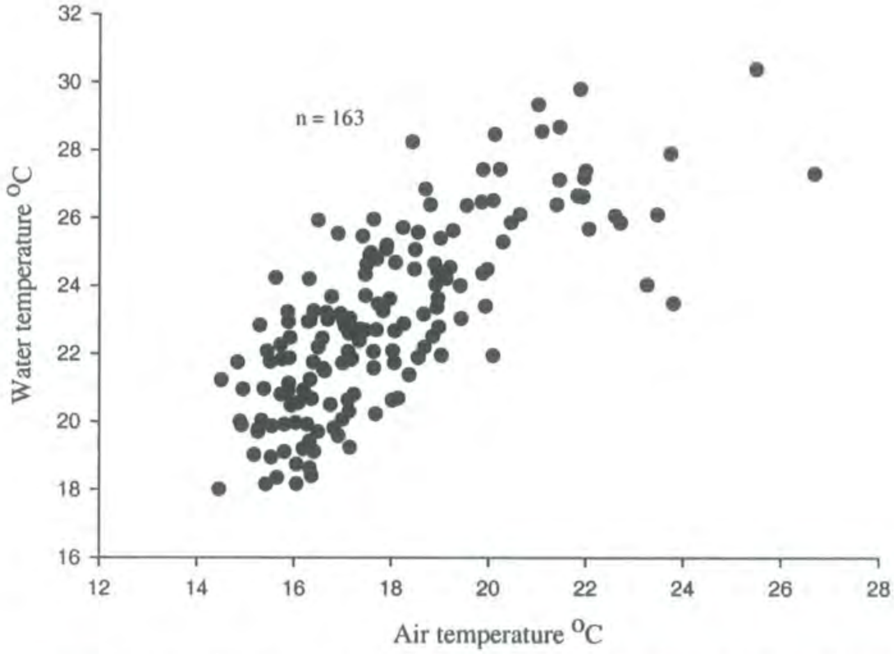


Figure 2.13. Hourly air and water temperature scatter plot during the rainy days of the wet season in the dam village.[$R^2 = 0.561$, $F = 208.02$, $y = 6.856 + 0.903x$, $t_a = 6.07$, $t_b = 14.423$, $p<0.001$]

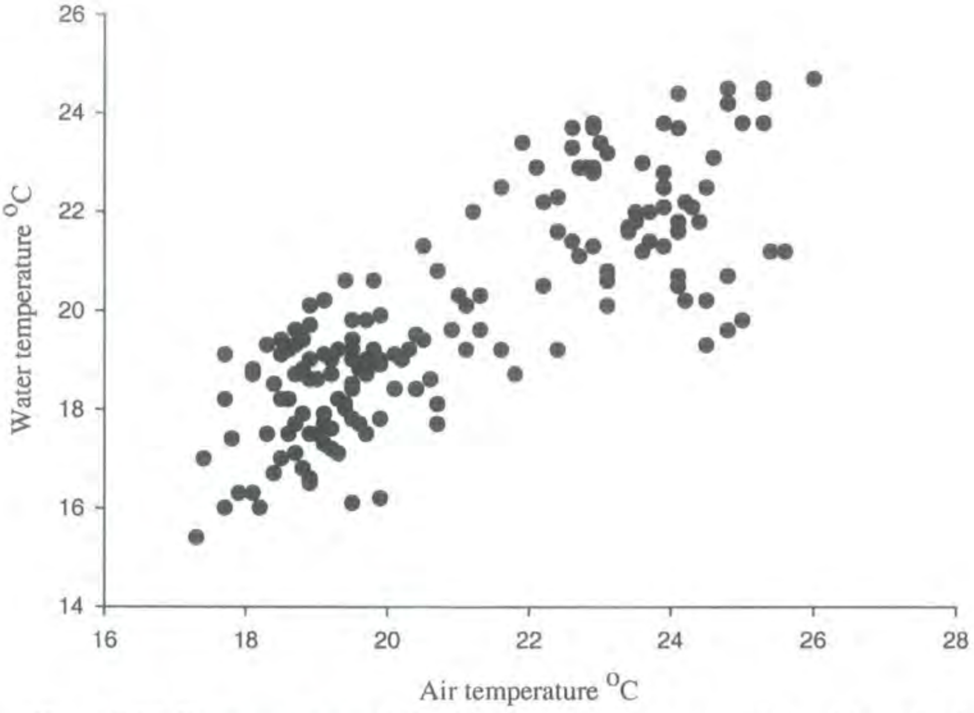


Figure 2.14. Dry season mean daily air and water temperature relationship in the dam village (May1999-Mar2000)

[R^2=0.661,F=330.734, y=3.3835+0.765x, t_a=0.305, t_b=18.186, p<0.001]

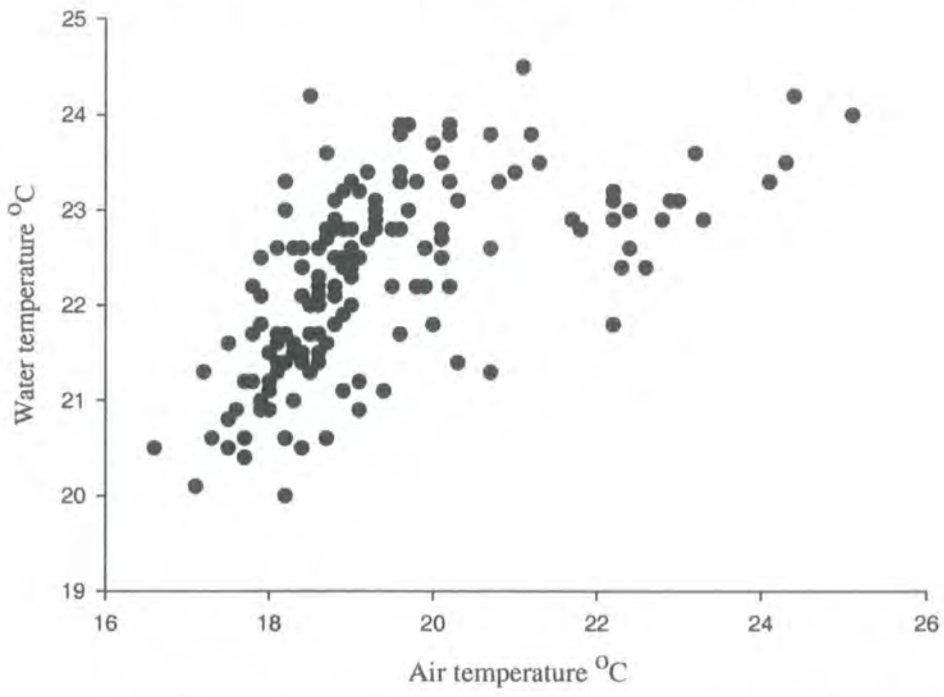


Figure 2.15. Wet season mean daily air and water temperature relationship (June1999-October2000).

[R^2=0.346, F= 81.494, y =15.379+0.357x, t_a=20.007,t_b=9.027, p<0.001]

The monthly mean air and water temperature relationship for the weather stations at the dam edge, dam village and remote villages is indicated in Table 2.3. The correlation was poor compared to continuous hourly and daily recordings, but during the dry months it was relatively strong.

Table 2.3. Relationships between monthly air and water temperatures at the dam site, dam village and remote village (R^2 and regression line).

Site	All months	Seasonal	
		Dry months	Rainy months
Remote village	0.349 (R= 0.59)* 8.091+0.646x	0.775 (R=0.88)* 5.991+0.680x	-0.329 (R=0.57) 22.66+-0.023x
Dam village	0.071 (R=0.27) 13.721+0.376x	0.81 (R= 0.9)** 4.587+0.743x	-0.092 (R=0.33) 20.82+0.099x
Dam site	0.053 (R= 0.23) 13.775+0.334x	0.737 (R= 0.86)** 4.401+0.718x	0.033 (R= 0.18) 16.279+0.275x

Where * refers to $p<0.05$, **$p < 0.01$, those without asterisks are insignificant

Discussion

The results of the study showed that the microclimate in the village situated near a microdam differed from that of a control village 3-4km away from the dam. Overall, the air temperature in the dam village was warmer than the remote village by 0.8 °C and 1.1 °C in the first and second years of the study respectively, and by 0.9 °C throughout the study period. The greatest differences in temperature were seen with minimum temperature that was 2 °C higher in the dam village during the dry season (November – May), 0.4 °C higher in the wet season (June-October) and 3.5 °C higher at the end of the rainy season (November-January), the relatively coldest months of the year in the region. The relatively low difference in minimum temperature during the wet season indicated the cooling effect of rainfall on the impact of the dam. During the rainy season not only is minimum temperature relatively higher but also the dam warms up relatively slowly due to the attenuation of solar radiation by cloud cover.

With ecological studies such as this, it is not possible to say conclusively that the higher minimum temperatures experienced in the village near the dam were due to the presence of the dam, since it is possible that these inherent differences also occurred before the dam was constructed. However, I think this is unlikely since the two villages were extremely similar in altitude, aspect and topography. The two adjacent valleys, where the villages are located, are parallel and separated only by a thin extension of the overlying plateau that drains in both directions. Both villages are situated on the western side of their valleys facing the east and the houses are distributed similarly from the fringes of the escarpment downwards and along the length of the valleys. The valleys thus formed had very similar features including topography and aspect. The altitude (1750 - 1790m) range and average slope (~1%) of both valleys was also the same. Breeding sites persisted throughout the year in both villages, although relatively restricted in the remote village. The same amount of rainfall and RH, together with similar wind patterns, experienced in both study villages also explains their similarity.

The most plausible explanation for the differences in local climate between the two villages, therefore, is due to a "lake effect" of the dam. In fact, the significantly higher minimum temperature observed at the edge of the dam (by >1.3 – 1.5 °C) as compared to the nearby village clearly reflects the 'lake effect' of the dam. This effect results from the large thermal mass of the water body that accumulates heat relatively slowly during the daytime compared to the surrounding air. Hence, the surrounding air remains warmer than the water for most of the day. During the latter half of the day temperature stratification may occur in the water due differential warming of the upper water column by insolation. As most of the incoming solar radiation is absorbed at the surface, warm and less dense water forms a layer over cold and denser water below. At night this energy store becomes the source of energy, which sustains an upward flow of heat to the atmosphere throughout the period. As the upper layer loses heat to the surrounding, mixing may occur (Macan and Maudsley, 1966; Martin, 1972; Young, 1975; Oke, 1987; Jacobs *et al.*, 1997).

The water body thus acts as energy sink by day and a major heat source at night. In general, during the day time and during the rainy season, the lake warms relatively slowly and can have a cooling influence; by the dry or sunny season, the lake is warmer than the air, especially on cold nights, and so will have a warming influence upon adjacent areas (Oke, 1987; Huntley *et al.*, 1998). This influence is likely to be more pronounced in valleys than in a vast and flat terrain and also likely to be extended downwind. The wind direction on the dam embankment, especially during the months when higher difference in minimum temperature was observed between the two villages, was predominantly to the north (NNE), carrying the warm air towards the village and down along the valley. At night, katabatic sinking of the denser cold air from the surrounding elevated area to the valley floor replaces the warm air. Such type of draining of cold air to a low lying area under the influence of gravity may occur even at height differences of less than one meter, as in hollows and basins (Oke, 1987). The flow of cold air from all directions merges at the valley floor and continues down the valley away from the dam, creating a valley wind. As one goes from the valley floor up the slope, the temperature increases with height until the top of the pool of cold air is reached. Most settlements occur above this thermal belt, as it is the warmest part of the valley.

The temperature lag characteristic of large water bodies, especially during the daytime, appeared to be slightly different from those small water pools or surrogate breeding sites studied. Unlike large water bodies, small pools in this study appeared to heat up more quickly and remain slightly higher than air throughout most of the 24-hour period. Air temperature approached water temperature early in the morning at about 09:00hr. Thereafter water temperature exceeded air temperature until the following morning both decreasing proportionally from about 14:00hr onwards. During the wet season, water temperature was not only constantly higher than air temperature over a 24hr period but also the difference between the two measurements was greater than in the dry season. This is because, as the minimum air temperature is relatively higher at night during the rainy season, water probably looses heat to the surrounding relatively slowly at night. Hence, it heats up quickly the following morning, exceeding air temperature, and remains relatively warm throughout the afternoon and night. Besides, air temperature tends to come down quickly in the afternoons, as the cloud cover increases and rain sets in. This, along with higher humidity and more breeding sites, probably explains the rapid build up of mosquito populations especially towards the end of the rainy season. During the following cool dry season, not only are nights very cold, the daytime is chilly and windy, typical of the harvesting season in the country. This facilitates mixing and radiative cooling of the water body.

In general, the temperature profile exhibited by small surrogated breeding sites in the study is in line with the limited earlier studies made on water pools of similar size (Haddow, 1943) and the heat dynamics of shallow waters (Jacobs *et al.*, 1997; Wallace and Merritt, 1999). In shallow water bodies, the incoming radiation can penetrate to the floor. This warms the lower boundary of the system and the water is warmed from below as well as from above. Border effects may also occur at the sides of the water body, and the smaller the width the greater these influences become. They arise because of heat conduction between the water body and the surrounding ground (Oke, 1987). Thus, water pools tend to show relatively lower diurnal fluctuation than air temperature. However, air and water temperature appeared to fluctuate closely together. In fact, a relatively weak positive correlation was observed between air and water temperature on hourly, daily, and monthly basis, in decreasing order.

The correlation between air and water temperature was relatively strong during the dry season. During the rainy season the correlation was better during the rainy days than non-rainy days. The lower correlation observed during the wet season was probably due to the influence of cloud cover and rain. Because as the cloud cover becomes thick and followed by rain, air temperature tends to drop more quickly than does water temperature. The characteristic rapid heating during the daytime and the maintenance of the warmth throughout the night observed in small breeding sites, could facilitate the rapid development of the aquatic stages of mosquitoes. Unlike adult malaria vectors, which actively seek warm indoor microclimates or cool and humid habitats outdoors during the day, the aquatic stages are confined to these small pools. Hence the observed inherent characteristic of small water pools could be an advantage in the rapid turn over of mosquito populations. Since natural breeding sites varied in size, shape and other characteristics, however, the observed thermal dynamics may be a simplification of the natural phenomena. Nevertheless the positive relationship described between air and water temperature in my study may help others to cautiously extrapolate from data collected from meteorological stations to conditions experienced in larval sites.

Although the effect of proximity to oceans and seas upon temperature and humidity on a wider scale is well established, few studies have investigated such influences on lakes and smaller water bodies, particularly in the tropics. However limited they may be, they clearly indicated influences of similar magnitude, although they were associated with much larger lakes and water bodies as compared to microdams in Tigray, Ethiopia. Gregory and Smith (Gregory and Smith, 1967) reported temperature anomalies of + 2.8 °C (in January) adjacent to the North American lakes. In the Pennines in northern England, a reservoir, 3.12km^2 in area, resulted in a rise in temperature of +2.5 °C at cold temperatures (Huntley *et al.*, 1998). A two month study in a much smaller water body at Selset Reservoir (1.11km^2), reported an air temperature differential of >0.5 °C between leeward and windward shores for 43% of the study period (Gregory and Smith, 1967). Nonetheless, as in the present study, the influence of large water bodies on the surrounding RH was not very pronounced. Summaries of earlier studies conducted during the first half of the 20th century have been reviewed by Gregory and Smith (Gregory and Smith, 1967). Although fragmentary and of short duration, most of these studies emphasized the influence of lakes and water bodies on local microclimate. For instance, at Lake Balaton, five stations established along a line normal to the shore, up to a distance of 700m inland, revealed that the lake caused a diminution of the daily maximum by up to 3 °C and an increase in atmospheric humidity, these influences weakening with distance from the lake. Most of the changes took place within 300m of the lake edge. But the limitation of this study was that the observations were made only during the daytime. Another study that included night time temperature recording around the Susser Sea, revealed day time cooling and nocturnal warming where the magnitude of such influences amounted to 1 to 2 °C (Gregory and Smith, 1967). Influences of comparable magnitude were also reported from Lake Baikal and Kuibyshev reservoirs in the former USSR, the down wind influence extending to a greater distance. Mention was also made of unpublished reports indicating of higher minima of 2 to 4 °C recorded near a reservoir located in a valley than in adjacent valleys at similar altitude without reservoirs and which were in other respects more or less similar (Gregory and Smith, 1967).. It is noteworthy to mention here that the warming effect of reservoirs or man-made lakes is likely to be greater in small valleys, such as the study site, than on exposed and flat terrain.

From the foregoing, it is clear that water bodies have the potential to alter the microclimate around them although the magnitude of the influence may vary depending on the size. The effect of this change on the ecology of the surrounding may be varied, ranging from major vegetation changes (Huntley *et al.*, 1998) to altered patterns in water related vector-borne diseases such as malaria. In general, along with profuse breeding sites provided by the dam, the moderation of the night-time temperature in the dam village, particularly during the coldest months of the year (November – January) following the main transmission season, coupled with the relatively warmer indoor environments would be expected to favour vector abundance and parasite development thereby extending the transmission season. In the potentially epidemic prone areas of higher altitudes, such as in Tigray, this would entail exposure of the non-immune population to increased risk of malaria. In relatively higher altitudes of northern Pakistan, an increase in mean November and December minimum temperatures by 2 °C and 1.5 °C, respectively, resulted in an increase of the incidence of falciparum malaria (Bouma *et al.*, 1996). Since the present study area, and many others where microdams are already constructed or planned, is situated at the current geographical fringe of the distribution of *P. falciparum*, the introduction of microdams may greatly extend the malaria transmission season both by providing continuous breeding sites and elevating minimum temperatures.

The potentially epidemic fringe areas in Ethiopia lie within the traditional climatic zone known as Woinadega, encompassing areas lying between 1500 – 2300m above see level and characterised by mean annual temperature of 20.0 –16.0 °C and 800 – 1200mm of rainfall. According to the widely held view, the greatest effect of increased temperature on transmission is likely to be observed at fringe areas, which lie in the range 14-18 °C (Githeko *et al.*, 2000). This range encompasses the lowest temperature threshold for the development of the malaria parasites in the mosquito. For *P. vivax* this threshold is approximately 14 °C. For *P. falciparum*, the lowest of the various estimations is 16 °C (Detinova, 1962). Below this level, the extrinsic incubation period cannot be completed. That is why the distribution of falciparum malaria is restricted mainly to the sub tropical and tropical climates. Nevertheless, rises in temperature in the lower range has a significant and non-linear impact on the extrinsic incubation period and consequently on disease transmission (Lindsay and Birley, 1996). Similarly, if water temperature rises the aquatic stages take a shorter time to mature to adult stages and as a result there is greater capacity to produce more mosquito population (Clements, 1992). Increase in temperature also means adult female mosquitoes digest blood faster and feed more frequently and consequently increased transmission intensity (Lindsay and Birley, 1996). Generally, given that higher temperatures result in decreased number of days for the development of the parasite in the mosquito, this coupled with faster rates of blood digestion as well as development of the aquatic stages and therefore shorter generation times of the mosquitoes will lead to increased man-vector contact hence increased transmission of malaria.

Thus, the presence of human made lakes and water impoundments, especially at the fringes of higher altitudes, generally implies providing suitable breeding sites all the year round and favourable microclimate both for the proliferation of the vectors and the development of the parasite. In the past, although artificial and natural lakes of variable sizes have also been associated with water related and vector-bone diseases (Birley, 1989), the association was solely attributed to the creation of abundant breeding sites and humid strips in proximity to the water bodies. But, particularly at higher altitudes, change in microclimate might have also contributed to the abundance and increase in malaria transmission. For example, Khaemba and colleagues (Khaemba *et al.*, 1994) associated the increased incidence of malaria due to *P. falciparum* and abundance of *An. gambiae* around a newly developed highland urban area (2080m) and its environs in Kenya to the presence of dams in the vicinity. Mill dams together with other factors were also reported to have increased the incidence of malaria in highland regions of Kenya by Garnham as far back in the 1940s (Garnham, 1948). In many cases, this has led not only to an increase in vector density, but also to a prolonged period of vector activity extending beyond the rainy season (Coluzzi, 1994). The results of my study, however, suggest that the incidence of malaria in dam villages, particularly at higher altitudes in Tigray, also may have increased due to increases in minimum temperature. My findings also suggest that the wet season is suitable for malaria transmission not only because of the presence of breeding sites but also due to the relatively elevated minimum temperature characteristic of the rainy season. During the wet season, the influence of the dam was minimal and the mean minimum temperature recorded in the dam village was higher than the remote village only by 0.4 °C.

Although the influence of lakes and major water impoundments on local microclimate may be stronger, smaller impoundments are likely to have a much larger overall impact. This is because microdams not only have several functions, and develop at a rapid rate, they also are often closely associated with settlements. If many microdams are built close to each other, as in Tigray, the cumulative effect on the microclimate could be very high. Besides, with small water impoundments, their control and the control of the population who use them are less subject to management than larger schemes (Jewsbury and Imevbore, 1988). In general around these dams, there is a high degree of human-water contact, a closer association with settlements and limited, organized health facilities (Molyneux, 1997).

In conclusion, the construction of dams near human settlements can increase local minimum temperatures in addition to the provision of abundant breeding sites for *An. arabiensis* throughout the dry season. Increases in minimum temperature would be especially crucial during the coldest months of the year when malaria transmission comes to a halt mainly due to low temperatures for the sporogonic development of the parasites within the mosquito and low generation time of the vector population. Thus, the pronounced increase in minimum temperature observed during this period, together with abundant breeding sites, would be expected to extend the transmission season in settlements near microdams located in the fringe areas of malaria transmission in the highlands of Tigray, Ethiopia. This phenomenon can have serious consequences on malaria transmission in the African highlands such as Tigray, for non-immune populations inhabiting these areas. The results of this study may also have wider implications with respect to the assessment of potential climate change impacts upon malaria transmission patterns especially in sub-Saharan Africa such as the highlands of East Africa.

Chapter 3. The microclimate of mosquito resting and breeding habitats near a microdam and its relevance to malaria transmission in Tigray, northern Ethiopia.

Plate 3.1. A miniature Stevenson screen for placing data loggers

Abstract

Changes in land use are often accompanied by altered patterns of malaria transmission in endemic areas. In drought-prone Tigray, introduction of microdams, mainly for irrigation purposes, resulted in dramatic increases of malaria in local villages. Part of the reason for this increase was that the dams raised minimum air and water temperatures, resulting in elevated rates of malaria. In order to study the impact of the microdam on local microclimate a longitudinal study was carried out in two topographically similar villages; Deba, situated near a microdam, and Maisheru, 3-4km away in a neighbouring valley. The weather on the dam embankment and further away from the dam as well as in different types of mosquito habitats was recorded over 19 months. Minimum temperature on the dam embankment was 1.3 °C higher compared with the edge of the dam village and 3.5-3.9 °C in excess of that recorded on a transect along the field below the dam. There was no gradient in temperature and relative humidity (RH) along the irrigated fields, parallel to the village. However, the minimum, maximum and mean temperatures increased from breeding sites toward the village by 2.4, 1.3, and 1.8 °C respectively during the whole study period, with a greatest difference observed during the dry season (by 4.9, 1.8, & 3.7 °C). RH at the edge of the village was correspondingly lower than near the breeding sites by 22 %, 3%, and 10 % during the dry season, wet season, and the whole study period respectively. Mean air temperature recorded under vegetation was 1.7 °C lower than that recorded in the shade outside, although there was no appreciable difference in RH under vegetation and outside. Indoor temperature was 3.4 °C warmer than the outdoor environment during the dry season and 2.8 °C in excess during the wet season. RH outdoors consistently exceeded the indoor environment by 15-16% and 12-18 % during the dry and wet seasons respectively. It was 0.3 °C warmer at 2m than 1m. No difference in RH was observed at 1 and 2m indoors. During the wet season mean water temperature was constantly higher than air temperature whereas during the cool dry months of the year following the rainy season, the reverse was true. Longer larval duration due to low water temperature may partly explain the dramatic drop in mosquito density and malaria incidence during the cool dry months at the end of the transmission season (November-January). Near microdams, the moderation of the weather extremes by the dam along with favourable microhabitats outdoors and indoors would be expected to extend the

transmission season, especially in areas of fringe transmission, like the Tigray Highlands.

Introduction

Malaria transmission is mainly governed by local environmental factors. Land use change, such as the construction of dams and large-scale water development projects, has long been associated with altering the risk of water and vector-borne diseases in many endemic parts of the world (Hunter *et al.*, 1982; Coluzzi, 1994; Ijumba and Lindsay, 2001). Indeed in the drought prone Tigray region in northern Ethiopia, where an extensive microdam based irrigation scheme is in progress, a 7 fold higher incidence of malaria was observed in villages near reservoirs than those 8-10km away (Ghebreyesus *et al.*, 1999). The study involved 8 of the 60 microdams so far constructed. These microdams range in size from 50,000 to 4,000,000 m^3 and constitute only 12% of the total envisaged for the region (SAERT, personal communication).

The higher incidence of malaria in near-dam villages could partly be ascribed to the elevation of the minimum temperature around dam sites as a result of the warming effect of the reservoirs. As described elsewhere (Chapter 2), the yearly mean minimum temperature recorded in the dam village was 1.3 °C higher than that of the remote village and was especially pronounced (3.5 °C) at the end of the rainy season. Along with profuse breeding sites provided by the dam, the increase in minimum temperature would be expected to extend the transmission season, by reducing the incubation period of the parasite within the vector and increasing the development rate of the aquatic stages, thus increasing the mosquito population. Water storage reservoirs are also expected to raise the water table and create favourable conditions for abundant growth of vegetation in the area. This, together with presence of abundant water pools and saturated soil conditions, would create favourable microclimatic conditions for mosquitoes.

The microclimate of the adult environment is extremely important, not only from the point of view of adult survival but also epidemiologically as regards the length of the sporogony in the infected mosquito. Insects are able to withstand the effects of normal climatic variations and can seek out microclimates that offer protection against extremes of climate. For instance, mosquitoes may evade dry weather, by concentrating in those houses or other indoor resting-places where the microclimate offers a favourable humidity and temperature. Outdoor-resting mosquitoes will rest in the vegetation near the ground during dry periods. During day and night, there is a daily rhythm of temperature and humidity, characteristic for each area, and insects can adapt their behaviour to the most favourable part of the diurnal cycle (WHO, 1975; Lindsay and Birley, 1996).

Indoor resting mosquitoes must seek oviposition sites after the blood meal is digested and their ovaries matured. This involves, first orientating themselves toward the location of breeding sites and afterwards selecting specific sites to lay their eggs (Muirhead-Thomson, 1951). To do so, they must follow certain behavioral cues and this probably involves relative humidity and temperature, as well as other factors. It is, therefore, important to investigate a temperature and RH gradient between the breeding sites and the village periphery. As the development and survival of the immature stages of vectors, hence the output of adults, is largely influenced by surface water temperature (Jetten and Takken, 1994), monitoring the temperature of natural breeding sites is also very important to understand the life history of vector species. Nevertheless, information on thermal changes in small water bodies in tropical regions is limited (Haddow, 1943; De Meillon, 1947; Young, 1975).

Thus, a comprehensive study was carried out near a microdam in the Tigray region of northern Ethiopia to determine the extent of the influence of the dam and describe the microclimate of mosquito habitats outdoors under vegetation, indoors and in different types of breeding sites. Specifically, I tested the following hypotheses. Firstly, that the microclimate (temperature and RH) indoors and outdoors under vegetation is different from that outdoors in the open. Secondly, that the temperature and RH at different heights indoors differ. Thirdly, that owing to the influence of the dam, a RH and temperature gradient occurs as one goes further away from the dam. Fourthly, that a RH and temperature gradient occurs between breeding sites and the village nearby, and lastly, that there is a positive correlation between air and breeding site temperature.

Materials and Methods

The Study Area

Climate and geography

A detailed description of the study area is provided in chapter 2. Briefly, the longitudinal microclimatic study was undertaken near Meskebet dam in two topographically similar villages; Deba, situated near a microdam, and Maisheru, 3-4km away in a neighbouring valley at a similar altitude (1750-1790m). Located 330km northwest of Mekelle in the central highland plateau of Tigray, the study area is characterised by a massive tableland intersected with small valleys.

Air temperature tends to be highest from March to May and coldest from November to January (inclusive) with a mean minimum temperature of 11.1 °C in November and a mean maximum of 30.7 °C in March recorded in the study villages during the study period. The main rainy season extends from end of May to October receiving about 900-1200mm annually. The amount and duration of rainfall is erratic and marked inter-annual variations characterise the region. The predominant wind direction was to the east (NE) during the dry season and to the west (SW) during the wet season.

The total population of Deba was 372 in 71 households and that of Maisheru constituted about 1237 people in 235 households. Houses mainly consisted of clusters of rectangular houses of stonewall with flat roofs of wattle and earth, which are typical of rural dwellings in Tigray. Open eaves were often present between the roof and the walls for ventilation purposes. People herded their cattle, goats, sheep and pack for the night in open enclosures attached to their dwellings.

Meskebet dam, which was selected for its large size, covered about 10ha of land and was roughly 1362m long and 600m wide (about 0.9km^2). Its circumference was 4872m. The dam embankment was 570m long and 27m high at its maximum point where the outlet was located. The maximum depth of the water near the embankment was 24m but the overall average depth was about 17.5m. The water level fluctuated, being high during and after the rainy season and lower at the end of May after irrigation started. In Deba, irrigation extended from January until June, preceded by field preparations in November-December. The irrigated fields, located to the north of the dam down stream, were about 10m lower in elevation from the dam. Farmers irrigated their fields until they became saturated. Because of this and seepage water from the dam, pools of standing water were common throughout the study area. Fields were cultivated largely with maize, followed by vegetables such as onion, tomato, and green pepper. Farmers grew animal fodder, such as *Sesbania* species and elephant grass (*Pennisetum purpureum*), along the gullies and the perimeter of the irrigated fields. During the main cropping season, farmers grew short or low-lying crops such as teff (*Eragrostis abyssinica (or Eragrostis tef*) and finger millet (*Eleusine coracan*) in the irrigated fields. The rain-fed cropping season extended from end of May to November. Houses and water bodies were mapped (Figure 3.1) using a global positioning system (GPS 38, Garmin International Inc., Olathe, Kansas). A total of 1063 in the dam village and 513 in the remote village GPS coordinates were recorded. For the major waterways, the dam and irrigation canals, each coordinate were taken after every 10 strides. The readings were simply plotted on SigmaPlot graphical software.

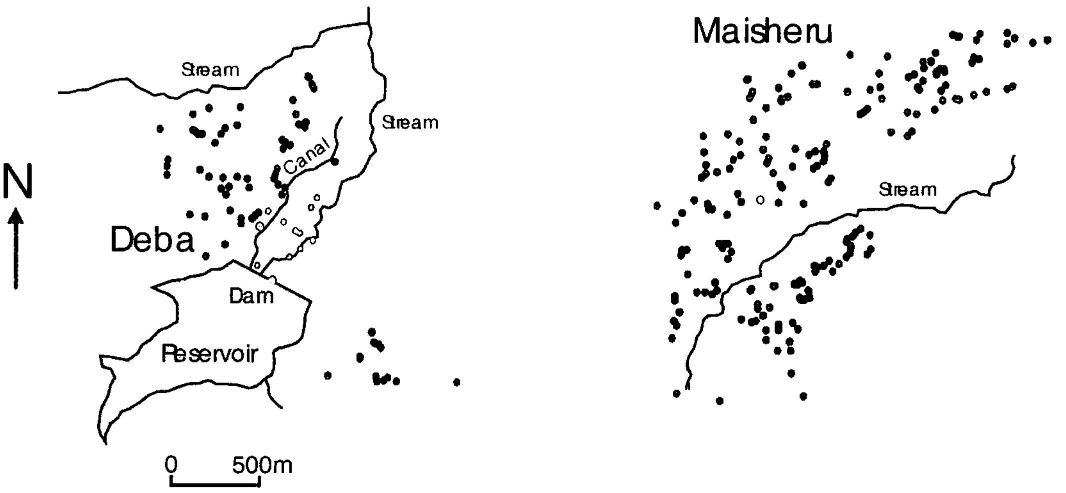


Figure 3.1. GPS point coordinates of the reservoir, major waterways, houses (**black** circles), weather stations (red circles) and data loggers (**blue**-on a transect parallel to the village, orange-on a transect from breeding site toward the village, green-temperature loggers in breeding sites). NB. For convenience, the relative position of the villages is not shown to the exact degree latitude and longitude-Maisheru village is slightly to the south.

Monitoring the microclimate

Outdoor microclimate

An automatic weather station (AWS; Datahog 2 -Skye Instruments Ltd., UK) placed on the embankment of the dam facing the village and 3 pairs of data loggers (Gemini data loggers Ltd., UK) positioned at fixed intervals (200m) along the irrigated fields parallel to the village were used to monitor temperature and RH gradient from the dam towards the other end of the village from March 1999 – April 2000 (Figure 3.1). To identify the microclimate of adult mosquito outdoor resting sites, two pairs of data loggers were located underneath dense vegetation. The data loggers positioned 1.4m from the ground in a Stevenson screen (40 x 48 x 40cm) at each site, measured temperature and RH at 30-minute intervals.

In order to investigate a temperature and RH gradient between the breeding sites and the village periphery, four pairs of Tinytag data loggers (RH and temperature) in Stevenson screens were placed on a transect between them from June 2000 to January 2001. One pair was placed at the edge of the village; another pair at the edge of the breeding sites and the remaining two pairs were positioned between the two at 130m intervals (position of loggers shown in Figure 3.1).

Temperature data loggers were also used to record water temperature in different types of breeding sites in the dam village (Figure 3.1). The three most abundant types of breeding sites selected, in order of importance, were seepage, pools in irrigated fields or nearby and human-made shallow pools in streambeds. Temperature probes lying horizontally just below the surface of the water body recorded water temperature from June 2000 until January 2001. The sensor rods (about 12cm long), fixed to submerged woody yokes at both ends, maintained their positions just below the water surface (see Plates 3.2 & 3.3). Data loggers were placed in small metal boxes (17 x 17 x 20cm) with a small hole at the side for the temperature probe extension wire to pass through. The white painted metal boxes, hoisted about 30cm above the ground, protected the data loggers from rain and intruders (see plate 3.3). Enumerators and their assistants were assigned in shifts to look after them on a daily basis.

Plate 3.2. A temperature probe (rod) lying horizontally below the water surface in a river puddle- data logger inside a box as shown below (anopheline larvae slightly visible).

Plate 3.3. A temperature probe in seepage water (data logger inside the white box)

Indoor microclimate

To determine the microclimate of indoor-resting mosquitoes, data loggers positioned 2m from the floor, continuously recorded temperature and RH in two randomly selected houses at the edge of the village from March 1999 to April 2000. Temperature was also recorded indoors at ground level and heights of 1m, 2m and > 2m to see whether the internal microclimate varied with height above ground. Readings were made in two houses starting from the ground level from March 1999 – November 2000 using thermocouples at 2-hour intervals each day (24 hours-from 06:00 – 10:00 hrs) for 3 days/month. This was done on the walls of the house far from the entrance, in the darkest interior of the house where mosquitoes are likely to rest during the day. Data loggers placed at 1 and 2m also recorded RH and temperature in 2 houses at the edge of the village from June 2000 to January 2001.

The meteorological stations and the data loggers were downloaded monthly and the data inspected to ensure the proper functioning of the equipment. All data loggers were set together for one month at the beginning of the study as well as in May 2000 and February 2001 in order to note any discrepancy in recording. The digital thermometers were tested using electronic testers at intervals at the University of Mekelle.

Statistical analysis

The temperature and RH recordings logged at 30-minute intervals by each AWS and data loggers were reduced to hourly, daily, monthly, seasonal and yearly summaries (minima, maxima and mean). Duplicate temperature and RH recordings indoors (in 2 houses) and outdoors under vegetation (2 sites/ village) were averaged to give daily readings. Data collected by thermocouples were entered into Epinfo, and exported to SPSS for analysis. Paired samples t-tests were used to compare the hourly (when appropriate), daily, monthly, and seasonal averages of the data recorded by each automatic weather station and data loggers. Regression analysis was used to examine relationships between air and water temperatures of different breeding sites. SPSS10 and SigmaPlot2001 software were utilized for analysis and graphing respectively.

Results

Outdoor and indoor air temperature and relative humidity

The results of the weather data collected along a transect further away from the dam and parallel to the nearby village on the irrigated fields are shown in Figures 3.2 and 3.3. The values for the edge of the village are included in the figures for comparative purposes. No clear-cut gradient either in RH or in temperature was observed both during the dry and wet seasons. At the dam embankment, however, minimum temperature was always higher than that recorded by data loggers by 3.5-3.9 °C, with more marked difference during the dry season (4.4 °C-5.0 °C) than the wet season (2.2-2.7 °C). The difference in minimum temperature between the dam edge and the data loggers in the field below was higher than that of between the dam edge and the nearby village, which was lower than the dam embankment by 1.3 °C only. Maximum temperature was also significantly lower at the dam edge during the dry season, indicating the cooling effect of the dam during the daytime. At the edge of the dam, slight excess in RH was also noted during the dry season, although the overall mean for the whole year did not differ appreciably.

Paired temperature and RH data loggers on a transect between breeding sites and the village, however, showed a distinct gradient (Figures 3.4 and 3.5). While minimum, maximum and mean temperatures increased from breeding sites toward the village, with RH the reverse was observed. Overall, the minimum, maximum and mean temperatures near breeding sites were lower than the edge of the village by 2.4, 1.3, and 1.8 °C during the whole study period, by 4.9, 1.8, and 3.7 °C during the dry season and by 1.1, 1.0 and 0.8 °C during the wet season, respectively. RH near breeding sites was higher than at the edge of the village by 10% during the whole study period and by 22% during the dry and by 3% during the wet seasons. During the wet season, not only was the difference in RH observed between the streambed and the edge of the village relatively small, but also there was no distinct gradient compared the dry season.

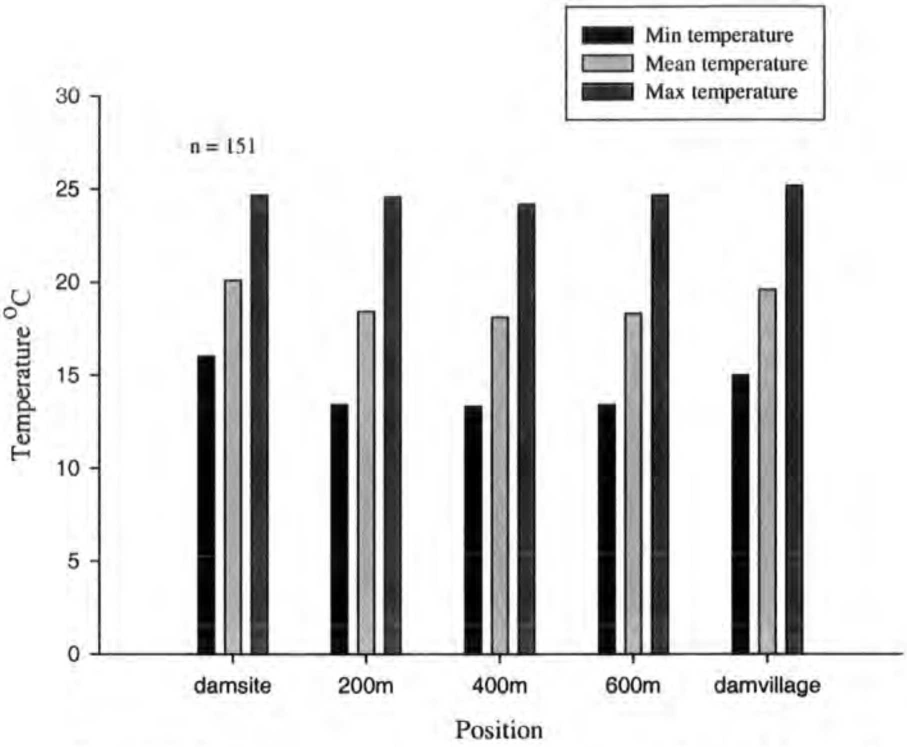


Figure 3.2. Wet season temperature profile on a transect from the dam northwards and parallel to the nearby village (June1999-October 2000).

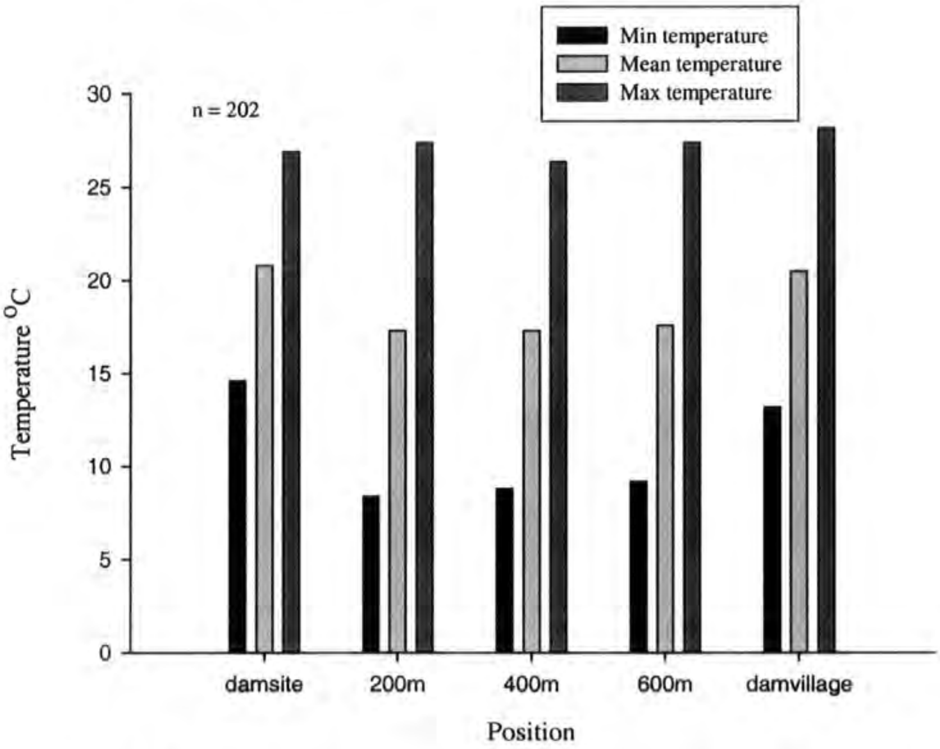


Figure 3.3. Dry season temperature profile on a transect from the dam northwards and parallel to the nearby village (May99,November 1999-April 2000).

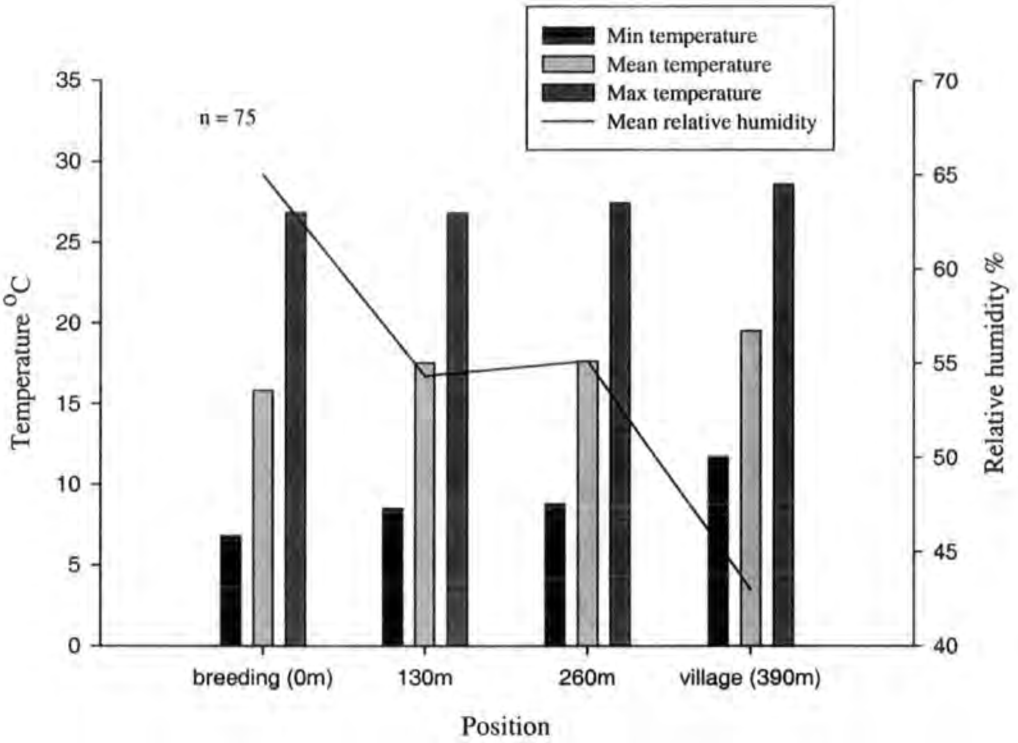


Figure 3.4. Dry season temperature and relative humidity conditions on a transect from a streambed at the valley floor towards the edge of the village (November2000-January2001).

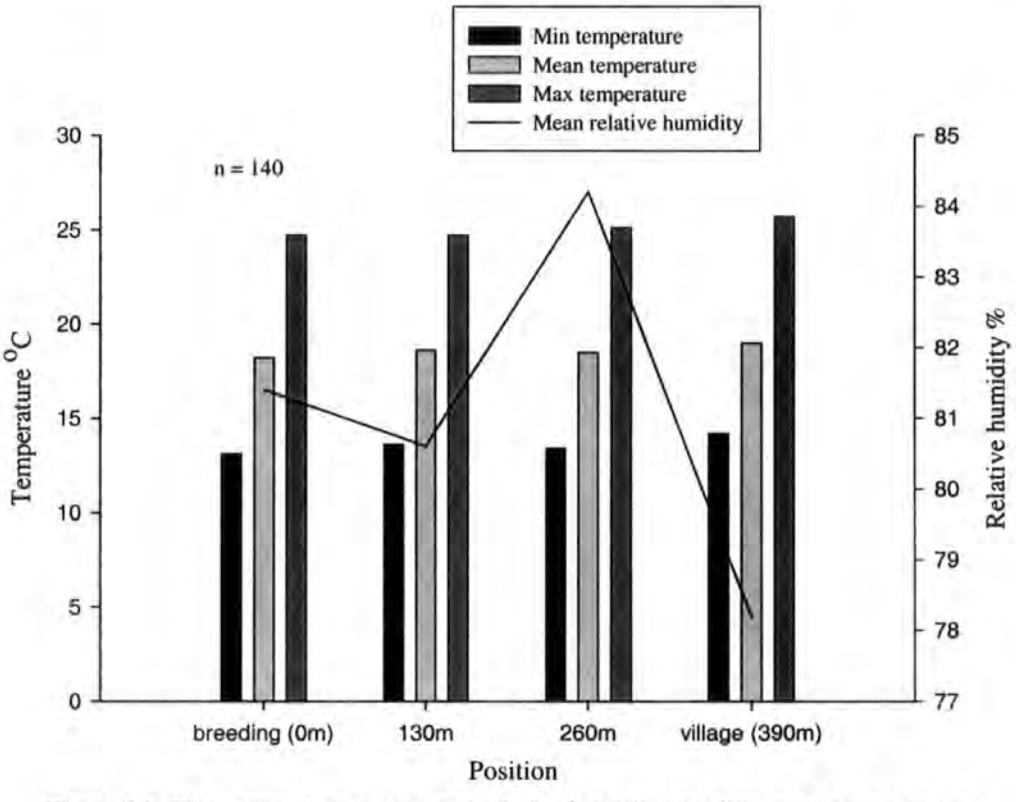


Figure 3.5. Wet season temperature and relative humidity conditions on a transect from a streambed at the valley floor towards the edge of the village (June-October2000).

Comparison of RH and temperature under vegetation and outside in a shade is shown in Table 3.1 and Figures 3.6 and 3.7. As indicated in Figure 3.6, a similar trend in RH was observed peaking during the rainy season. Overall, outside shade mean RH was higher than under vegetation by 1% during the whole study period (z= -3.1, d.f. = 350, p < 0.01) but this was within error of recording devices (± 5%). However, as indicated in Fig 3.7, there is a real difference in temperature between outside and under vegetation. Overall, the mean temperature under vegetation was lower than outside by 1.7 °C (z=29.33, d.f. = 342, p < 0.001). Whilst its minimum temperature was lower than outside by 1.7 °C (z = 18.75, d.f. = 342, p< 0.001), its maximum was lower by 2.2 °C (z = 30.22, d.f. = 342, p< 0.001). The difference in minimum and maximum temperature between outside and under vegetation was much higher during the dry season. Minimum temperature recorded under vegetation during the dry season was lower than outside by 2.3 °C and by 0.8 °C during the wet season. With maximum temperature, outside recordings exceeded that of under vegetation by 2.4 °C during the dry season and by 2.0 °C during the wet season. Overall, mean temperature under vegetation was lower than outside by 2.0 °C during the dry season and by 1.3 °C during the wet season.

Table 3.1. Seasonal comparison of temperature and relative humidity under vegetation and outside in a shade in the dam village (March 1999- April 2000).

Parameter	Dry season			Wet season		
	Under vegetation (95% CIs)	Outside	Z	Under vegetation (95% CIs)	Outside (95% CIs)	Z
No days	192	192		151	151	
Tmin	11.8 (11.4-12.2)	14.1 *** (13.7-14.5)	17.04	14.0 (13.7-14.2)	14.8*** (14.5-15.1)	14.91
Tmax	26.4 (26.2-26.7)	28.8*** (28.4-28.9)	18.45	23.1 (22.7-23.5)	25.1*** (24.7-25.6)	42.82
Tmean	19.2 (18.8-19.5)	21.2*** (20.9-21.6)	21.57	18.1 (17.8-18.3)	19.4*** (19.1-19.6)	48.20
RHmean	45.3 (43.5-47.1)	47.8** (45.9-49.6)	2.80	81.4 (79.1-83.8)	81.8* (79.5-84.1)	2.26

Where * is p < 0.05, ** is p < 0.01, and *** is p < 0.001, CIs = confidence intervals

Tmin = minimum temperature, Tmax = maximum temperature, Tmean = mean temperature

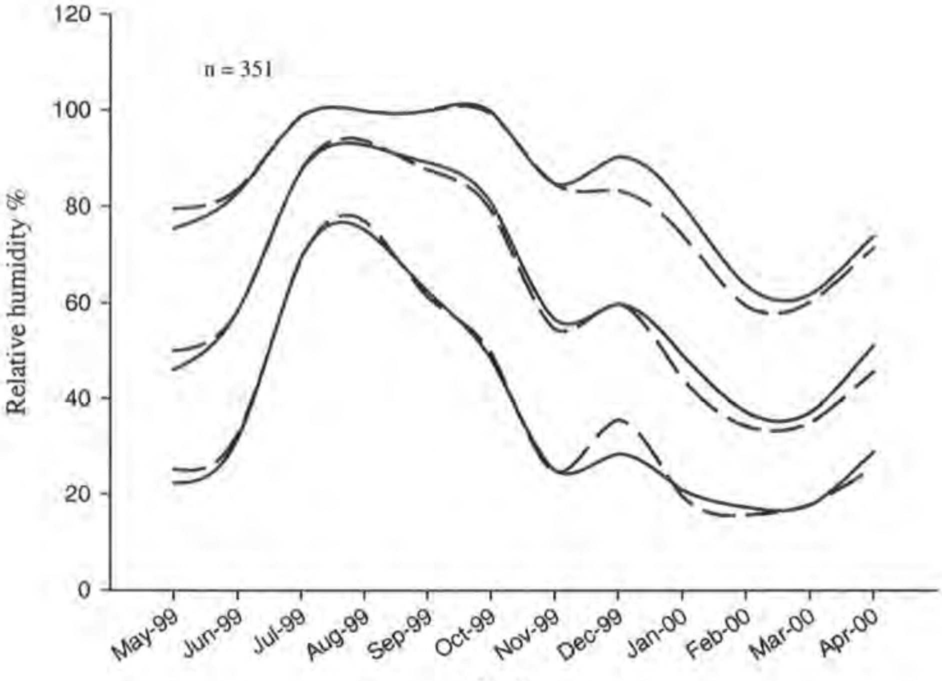


Figure 3.6. Seasonal variation of mean minimum, maximum and average RH under vegetation and outside in the fields in the dam village (May 1999 - April 2000).
[____ outside RH, - --- - under vegetation RH]

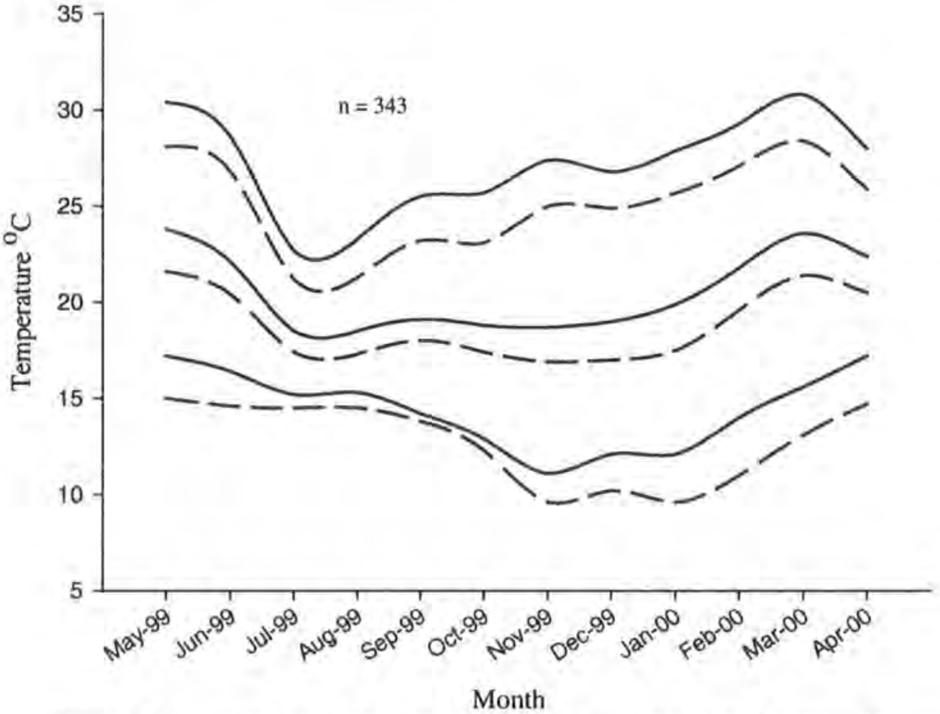


Figure 3.7. Seasonal variation of mean minimum, maximum, and average temperature under vegetation and out in the fields in the dam village (May 1999- April 2000).
[___ outside, - --- - under vegetation]

Comparison of the outdoor and indoor mean air temperature indicated that the indoor environment was 3.4 °C warmer than the outdoor environment during the dry season, and 2.8 °C in excess during the wet season (Table 3.2). The minimum indoor temperature was 7.5 °C and 5.6 °C higher than outdoors during the dry and the wet seasons respectively. Indoor temperature maximum, however, was lower than the outside by 1.5 °C during the dry season and by 1.2 °C during the wet season.

Table 3.2. Seasonal comparison of temperature and relative humidity indoors and outdoors in the dam village (March 1999- April 2000).

Parameter	Dry season			Wet season		
	Indoor (CIs)	Outdoor [a] (CIs)	z	Indoor (CIs)	Outdoor[b] (CIs)	z
No days	188	188		151	151	
Tmin	21.5 (21.2-21.8)	14.0 *** (13.6-14.4)	43.9	20.4 (20.2-20.6)	14.8 *** (14.5-15.1)	48.7
Tmax	27.2 (26.9-27.5)	28.7*** (28.4-28.9)	-10.4	23.9 (23.6-24.2)	25.1 *** (24.7-25.6)	-9.9
Tmean	24.6 (24.3-24.8)	21.2 *** (20.9-21.6)	26.4	22.2 (22.0-22.4)	19.4*** (19.1-19.6)	52.7
RHmean	32.1 (30.8-33.3)	47.3 *** (45.5-49.1)	-21.3	63.7 (61.7-65.7)	81.8*** (79.5-84.1)	-54.4

Where '**a**' is dry season indoor vs. outdoor, '**b**' is wet season indoor vs. outdoor, & *** is $p < 0.001$; CIs = confidence intervals; Tmin = minimum temperature, Tmax = maximum temperature, Tmean = mean temperature,

In general, the daily readings of maximum and minimum temperatures showed that the indoor temperature fluctuated comparatively little compared to the outdoor environment (Figures 3.8 and 3.9). The mean range of the indoor environment was lower than half that of outdoors. The daily indoor maximums were always lower than that of the screens but the minimums were higher than the outdoor minimums. Only in very few circumstances, perhaps when a fire was started indoors for cooking purposes, did the indoor maximum temperature approach, but never exceeded, that of outdoors.

In hot dry weather, there was a great difference between indoor and outdoor temperatures (Figure 3.8). The general trend of maximum and minimum temperatures indoors and outdoors during the wet season is shown in Figure 3.9. Wet weather was characterized by a fall of both maximum and a rise of minimum. With respect to RH, the indoor environment was significantly lower (by 17%) than outdoors during the whole year (z = -37.8, d.f. = 345, p <0.001). During the dry season, indoor RH was lower than outdoors by 15.4% and by 18.1 % during the wet season.

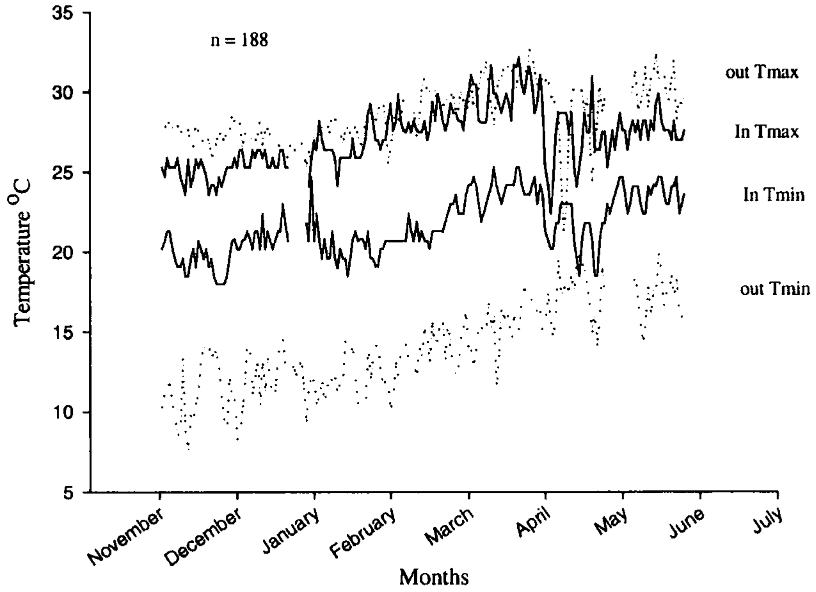


Figure 3.8. Daily indoor and outdoor minimum and maximum temperatures in the dam village during the dry season (November-May).[__ indoor, ... outdoor]

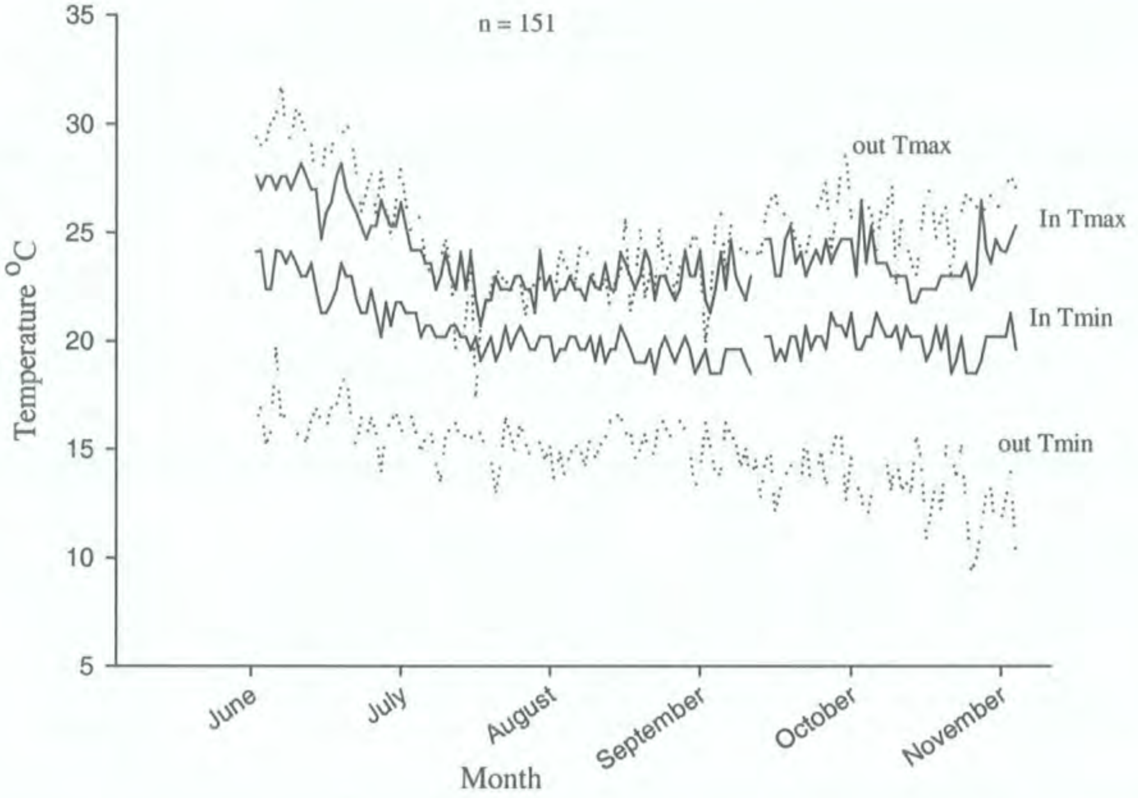


Figure 3.9. Wet season daily minimum and maximum temperatures indoors and outdoors in the dam village (June-October).[__ indoor, ... outdoor]

The results of paired temperature and RH data loggers placed indoors at 1 and 2m is shown in Table 3.3. Overall, the temperature at 2m was 0.3 °C warmer than at 1m and the difference was statistically significant (z= -39.76, d.f. = 5149, $p < 0.001$). This is consistent with the temperature recordings of thermocouples. Overall, the mean temperature recorded by thermocouples at 2m was 0.2 °C warmer than at 1m (z = -9.89, d.f. = 718, $p<0.001$) and 0.4 °C than at ground level (-12.94, d.f. = 718, $p< 0.001$). Similarly, the mean temperature at 1m was 0.2 °C higher than at the ground level (z = -7.73, d.f. = 718, $p <0.001$). With respect to RH no definite stratification was observed at 1 and 2 meters.

Table 3.3. Seasonal temperature and relative humidity profile at various heights indoors in the dam village (June 2000-January 2001).

Parameter	1m 95% CIs	2m 95% CIs
Dry season (November 2000 – January 2001		
No days of observations	75	75
Tmean	22.4 (22.2-22.6)	22.7*** (22.5-22.9)
RHmean	38.9 (37.4-40.4)	38.9 (37.4-40.4)
Wet season (June – October 2000)		
No of days of observations	140	140
Tmean	21.8 (21.6-22.0)	22.1*** (21.9-22.3)
RHmean	66.7 (65.1-68.4)	66.9 (65.2-68.6)

Where *** is $p < 0.001$, Cis = confidence intervals, Tmean = mean temperature

Breeding site temperature

Figure 3.10 shows the average monthly air and water temperatures of different breeding sites. Data was collected for the rainy season (June-October 2000) and the coldest months of the year (November 2000-January 2001) following the wet season. During the wet season mean water temperature of all types of breeding sites exceeded air temperature. At the end of the wet season, starting from end of October, mean water temperature gradually decreased and gave way to air temperature. This can also be seen from the daily mean readings in Figure 3.12. Although the minimum temperature of breeding sites remained higher than minimum air temperature throughout, the maximum temperature appeared to be lower than air temperature following the rainy season (Figure 3.11). As a result, the mean water temperature went below air temperature during this period.

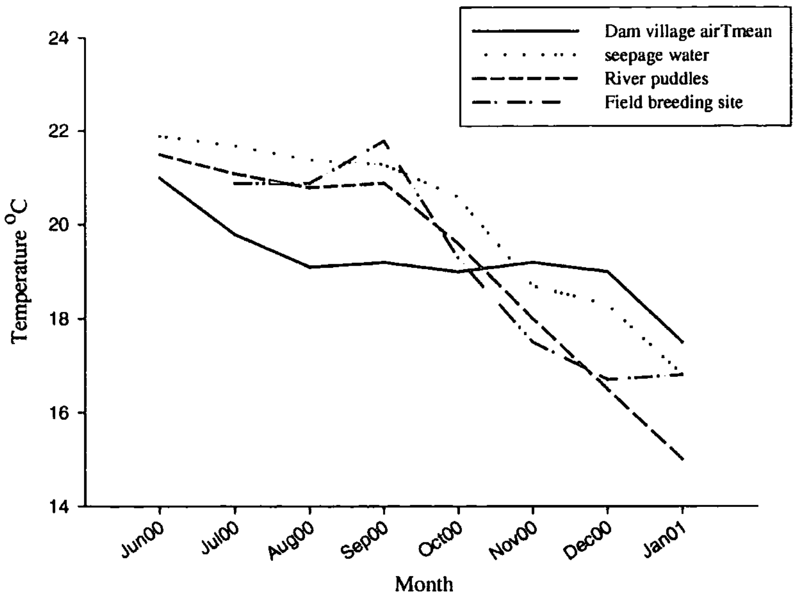


Figure 3.10. Seasonal variation of mean air and water temperatures of different breeding sites (June2000-January2001)[No data in June for field breeding site] .

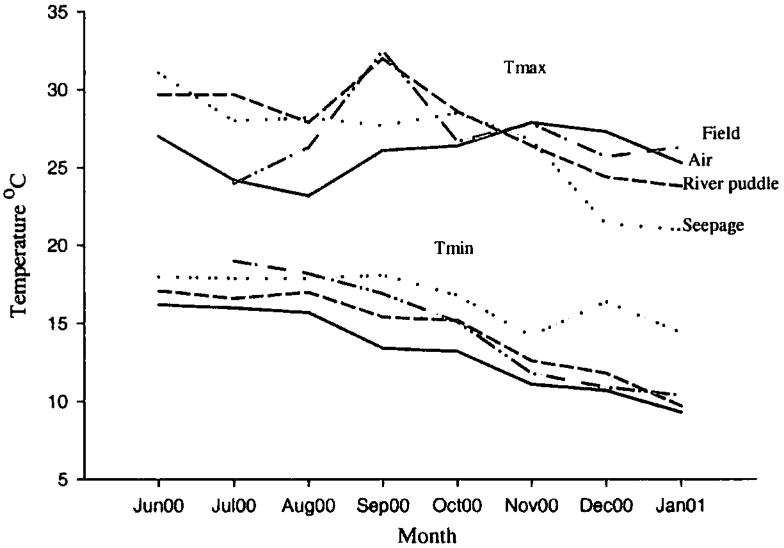


Figure 3.11. Seasonal variation of mean minimum and maximum air and water temperatures of different breeding sites.

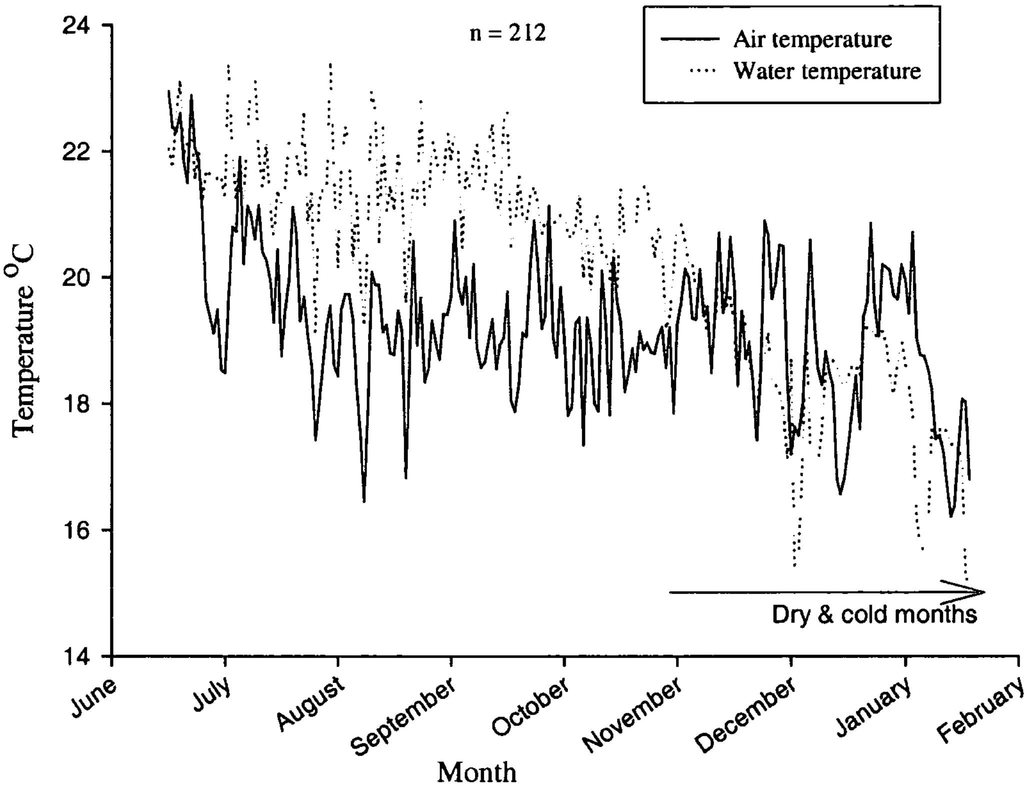


Figure 3.12. Seasonal variation of daily mean air and seepage water temperature during the study period (June2000-January2001).

Table 3.4 shows the seasonal profile of different types breeding sites, but for the dry season we have data only for the first three coldest months of the year (November-January). As already indicated in the Figure 3.10, seepage water was significantly warmer than the other breeding sites both during the dry and wet seasons. But there was no significant difference between river puddles and field breeding site in mean temperature. The maximum water temperatures recorded were 34.5 °C (seepage), 36.9 °C (field) and 38.9 °C (river puddle).

Table 3.4. Comparison of air and water temperature in natural and surrogate breeding sites during the dry and wet seasons in the dam village (Confidence intervals indicated in brackets).

Parameter	Seepage [a]	River puddle [b]	Field [c] breeding site	Dam village Air temp.	Dam village Surrogate water temp
Dry season					
No days	75	75	75	74	74
Tmin	15.1*** (14.7-15.6)	11.7 * (11.3-12.2)	11.2 *** (10.7-11.7)	10.6 (10.1-11.1)	11.7 (11.4-12.2)
Tmax	23.6 (22.7-24.3)	25.1 *** (24.7-25.5)	26.6 *** (26.1-27.1)	27.2 (26.9-27.5)	31.0 (30.7-31.3)
Tmean	18.2 *** (17.9-18.5)	16.8 (16.5-17.3)	17.0 *** (16.8-17.3)	18.8 (18.5-19.1)	19.2 (18.9-19.5)
Wet season					
No of days	139	115	115	139	139
Tmin	17.7 *** (17.4-17.9)	16.0 *** (15.7-16.3)	17.2 * (16.8-17.6)	14.8 (14.5-15.1)	16.8 (16.5-17.1)
Tmax	27.9 ** (27.3-28.5)	29.5 *** (28.9-30.0)	27.6 (26.8-28.3)	25.2 (24.8-25.5)	34.0 (33.4-34.5)
Tmean	21.2 *** (21.0-21.3)	20.5 * (20.4-20.7)	20.7 *** (20.5-20.9)	19.4 (19.2-19.6)	22.9 (22.6-23.1)

Where **a** is seepage vs river puddle, **b** is river puddle vs field, and **c** is seepage vs field; *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$; Tmin = minimum temperature, Tmax = maximum temperature, Tmean = mean temperature

The hourly mean air and water temperature for the dry and wet seasons is given in Figures 3.13 and 3.14. Generally, during the dry season (Figure 3.13), which consisted of the coldest months of the year, air temperature exceeded water temperature from about 9:00hr up to 20:00hr and then went below water temperature until the following morning. During the rainy season, however, water temperature was constantly higher than air temperature during almost all the 24hr period (Figure 3.14).

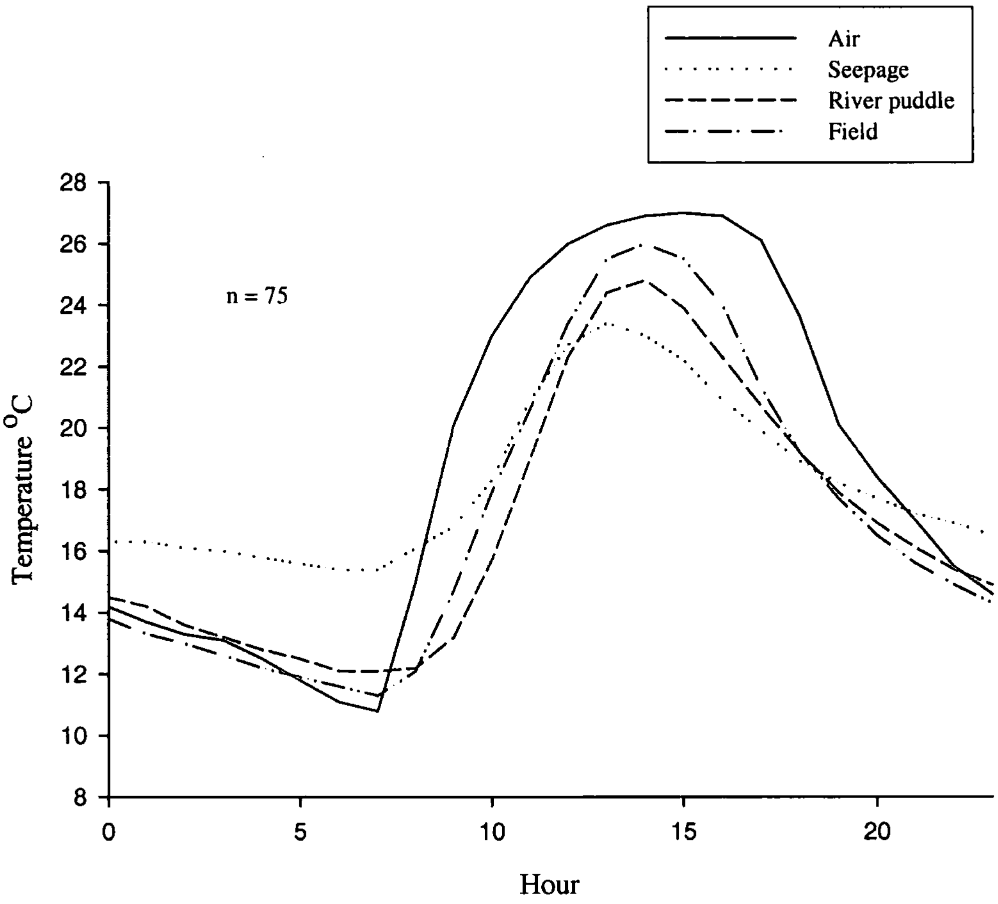


Figure 3.13. Diurnal variation of air and breeding site water temperatures during the dry season in the dam village (November2000-January2001).

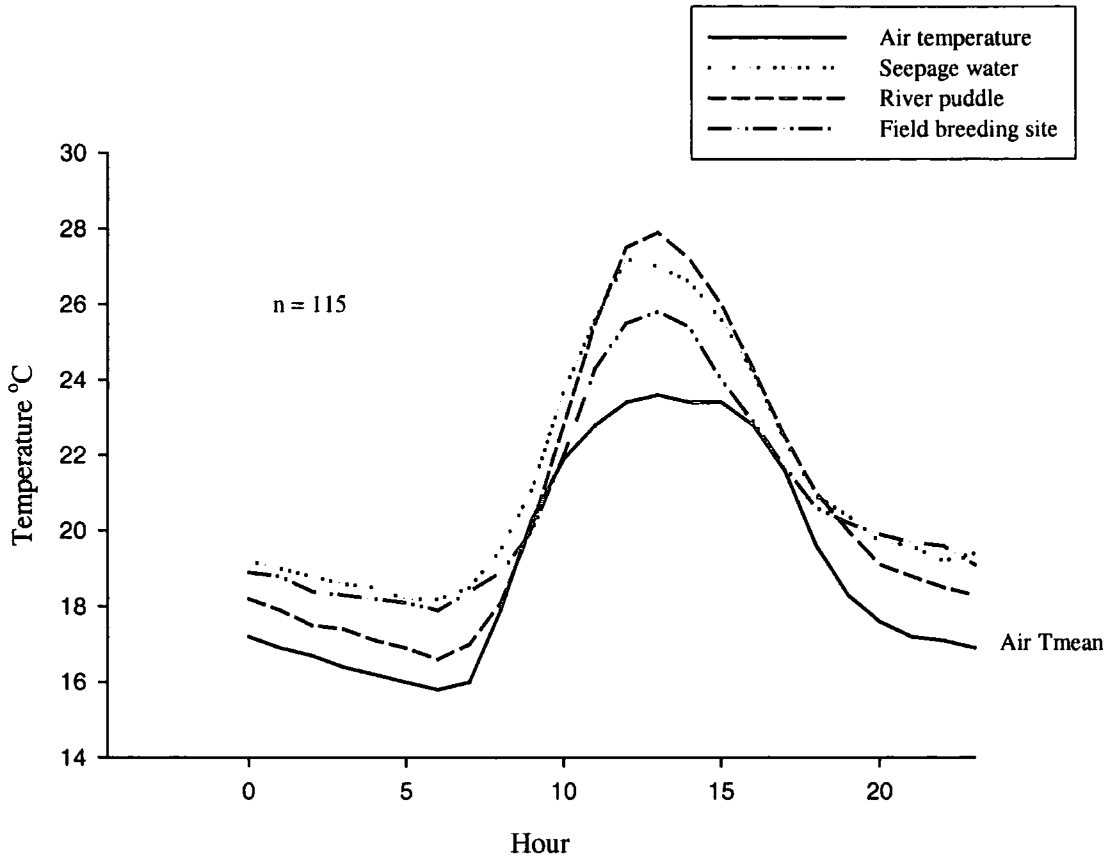


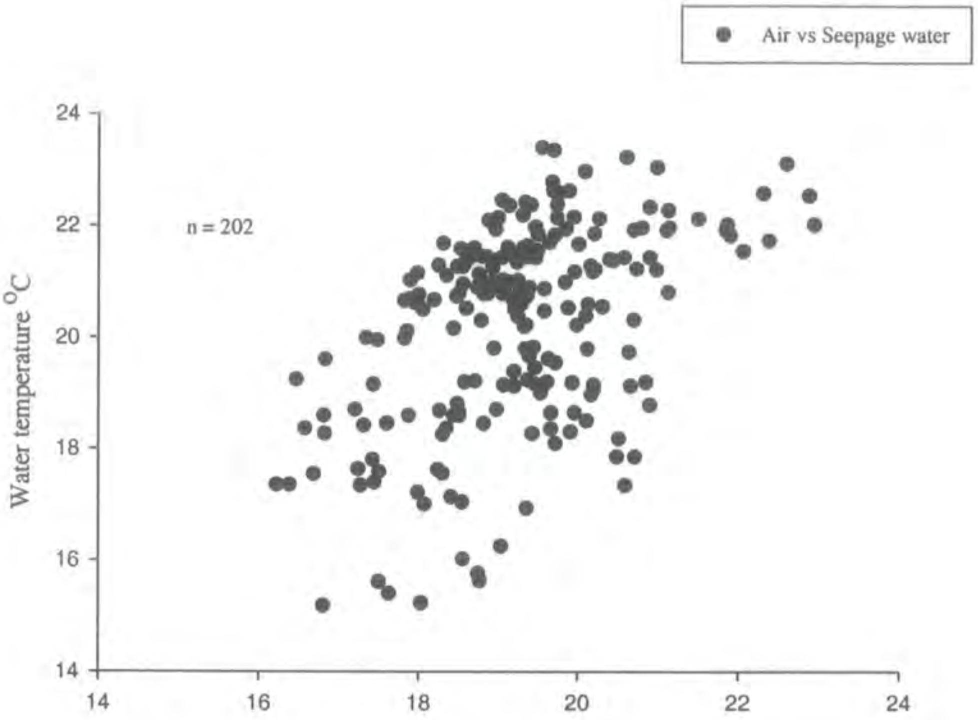
Figure 3.14. Diurnal variation of air and breeding site water temperatures during the wet season in the dam village (June-October 2000).

The relationship between daily mean air and breeding site temperatures was also examined. Table 3.5 shows the R^2 values and the regression equations for the different types of breeding sites during the dry and wet seasons. The R-values are also given in bracket to show the correlation. As indicated in the table, a weak positive correlation was noted between air and breeding site water temperatures. The correlation was relatively stronger between air temperature and riverbed puddles both during the dry and wet seasons. During the wet season the correlation was relatively higher during the rainy days than during the non-rainy days for all types of breeding sites indicating the cooling influence of rain on both air and water. The scatter plot of the relationship between air and water temperature for the whole study period is shown in Figures 3.15 and 3.16.

Table 3.5. Correlations between air and breeding site temperatures during the dry and wet seasons in the dam village (adjusted R^2 and regression line).

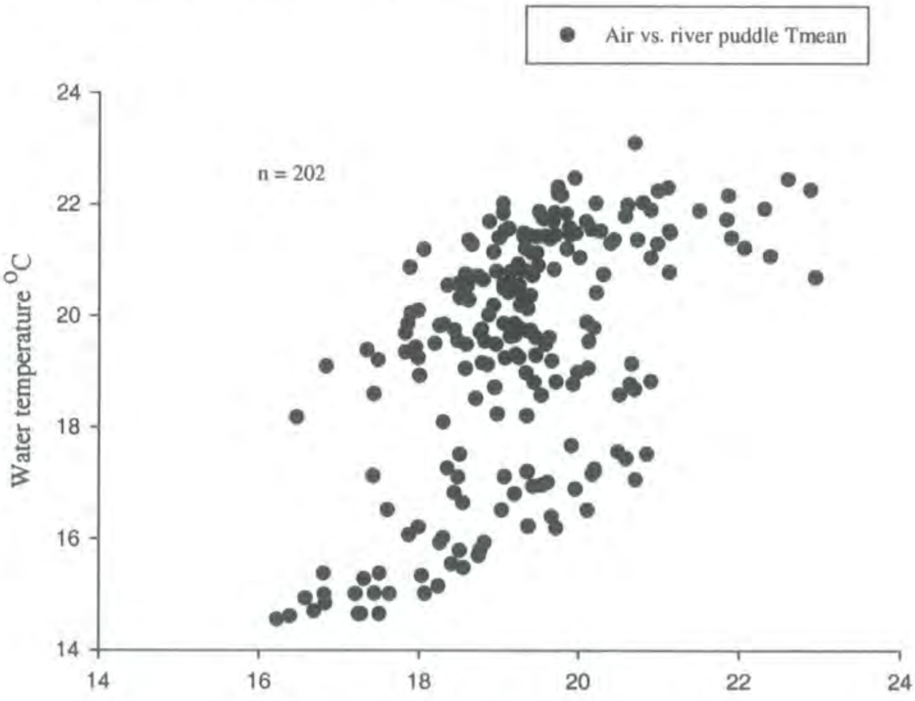
Site	Dry season R^2 (November – January)	Rainy season R^2 (June– October)	
		Dry days	Rainy days
Seepage	0.221 (R=0.5)*** 9.599 + 0.457x	0.212 (R=0.5)*** 14.378 + 0.353x	0.513 (R=0.7)*** 11.309 + -0.522x
Riverbed puddle	0.545 (R=0.7)*** -0.25 + 0.907x	0.292 (R=0.5)*** 11.31 + 0.479x	0.575 (R=0.8)*** 7.838 + 0.671x
Field	0.309 (R=0.6)*** 7.427 + 0.510x	0.159 (R=0.4)** 8.638 + 0.624x	0.223 (R=0.5)** 9.682 + 0.584x

Where, *** refers $P < 0.001$, ** $p < 0.01$,



Air temperature ^{O}C

Figure 3.15. Daily mean air and seepage breeding site temperature scatter plot for the whole study period (June 2000- 15th January 2001).



Air temperature ^{O}C

Figure 3.16. Daily mean air and river puddle water temperature scatter plot for the whole study period (June 2000- 15th January 2001).

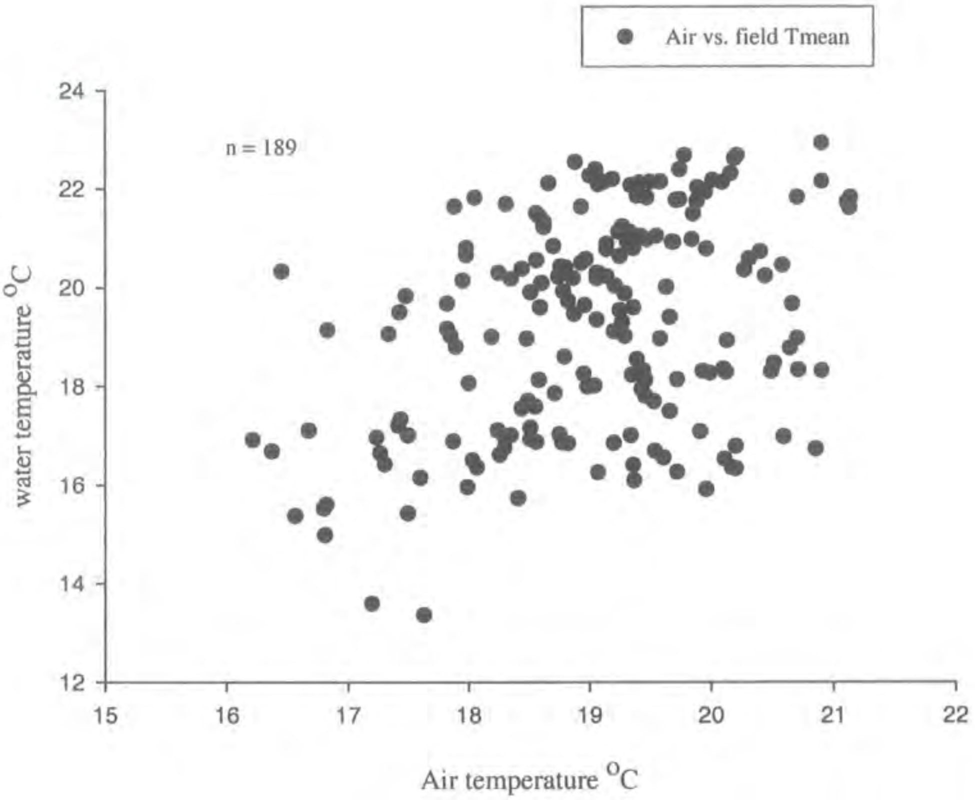


Figure 3.17. Daily mean air and field breeding site temperature scatter plot for the whole period (9th July 2000-January 2001).

Discussion

The present study showed that the microclimate near the dam differed from the nearby fields irrigated by the dam. Overall, the dam embankment was warmer than the fields below (by 1.7-2.1 °C) during the whole study period. The difference was specially reflected in minimum temperature, which was higher on the dam embankment by 3.5-3.9.°C during the whole year and by 4.4-5.0 °C during the dry and by 2.2-2.7 °C during the wet seasons. Nevertheless, no distinct gradient in temperature was noted from the dam further away to the north in the fields parallel to the village.

Part of the reason for the absence of distinct gradient along the fields at the valley floor could be the effect of wind direction and topographic drainage on minimum temperature. As the data loggers were located in the fields down stream, which is about 5-10m lower in elevation with respect to the dam and the village, one would expect a lower minimum temperature at the valley floor at night. This is due to katabatic flow of cold air from a relatively elevated area, down the slopes, towards the fields at the valley bottom under the influence of gravity at night. The flow of cold air continues down the valley, away from the dam. Height differences of even less than one meter away may allow cold air to drain to the lowest lying portions of landscape (e.g., hollows, basins, valleys) (Oke, 1987).

A progressive increase in minimum temperature noted by data loggers placed on a transect from the breeding sites (the gully/valley floor) across the fields toward the village supports the above reasoning. The breeding area sited at the valley was found to be colder than the village edge by 4.9 °C during the dry season and by 1.1 °C during the wet season. This is because, as the coldest and densest air settles to the lowest levels at night, the temperature increases with height above the valley floor until the top of the pool of cold air is reached. Thus, the most favorable location on the valley sides, for human habitation, is just above the level to which the cold pool builds up and it is known as the ''thermal belt''. Mosquitoes follow humans to this belt in search of blood meal and settle there until their blood is digested. Its height depends upon the geometry of the valley and the areas of cold air sources, which feed the cold pool (Oke, 1987).

With respect to RH, the opposite trend to temperature was noted. The breeding area exceeded the edge of the village by 22% during the dry season and only by 3.2% during the wet season. Since as a package of moist air cools it's RH will increase, the reverse gradient of RH observed would be expected. Further, compared to the dry edge of the village, evaporation from abundant standing water in the streambed coupled with evapo-transpiration from abundant vegetation nearby is expected to increase the RH of the surrounding in the valley floor. Besides, the predominantly down valley wind from the dam may partly contribute to the relatively higher relative humidity observed at the valley floor. It is interesting to speculate whether the RH gradient may be used as cues for finding a breeding site for egg-laying mosquitoes. Mosquitoes are known to seek humid places and take refuge nearby. For example, it is commonplace to find mosquitoes resting aggregated near earthenware or similar water pots and under moist bridges as well as in holes and crevices along riverbanks in tropical areas. Even laboratory-reared mosquitoes will aggregate around the moistened cotton wool or a piece of soaked sponge placed on top of the cage to maintain RH of the cage. If we hypothesize, as Muirhead-Thompson (Muirhead-Thomson, 1951) did, that some of the environmental factors that lure mosquitoes to lay eggs act at a distance, while others come into operation while the female is on the point of egg laying, it seems logical to argue that mosquitoes may make use of such gradients to locate breeding sites at night.

Once the eggs are laid the microclimate and physicochemical characteristics of the breeding sites become very crucial. Since temperature is the primary determinant of the growth and development of the aquatic stages of mosquitoes, realistic simulation of their bionomics will require information about the functional relationships between these populations and the thermal characteristics of their aquatic habitats (Collins *et al.*, 1985). In the present study, both diurnal and seasonal fluctuations in water and air temperature were present. But they varied in amplitude according to the season. During the wet season mean water temperature of all types of breeding sites exceeded air temperature. This is because in cloudy and rainy conditions air temperature goes down more rapidly than water temperature. At the end of the wet season (starting from end of October), however, water temperature gradually decreased and air temperature almost constantly exceeded water temperature. The period starting from end of October until January is the harvesting season in Ethiopia and it is windy and cold. This may have important implications as to the duration of the transmission season. Longer larval duration due to low water temperatures at this time of the year may partly explain the dramatic decrease in mosquito density as well as malaria incidence during the coldest months following the peak in October. Breeding sites are not scarce during this part of the year in most parts of the country. Nevertheless, nearer microdams, the moderation of the weather extremes by the dam along with favourable microhabitats outdoors and indoors would be expected to extend the transmission season, especially in fringe highlands areas like in Tigray.

The water temperature trend exhibited by the breeding sites during the dry months, however, is not consistent with the pattern observed with the surrogate breeding sites. As described in chapter 3, water temperature was consistently higher than air temperature both during the dry and wet seasons. The discrepancy in temperature between the surrogate and natural breeding sites during the dry-cold months was found to be due to difference in maximum temperature. The maximum and minimum temperatures of the surrogate breeding sites were always higher than the respective air temperatures; hence the mean water temperature remained higher than air temperature both during the wet and dry seasons. With the natural breeding sites, however, although the minimum temperature was higher than that of the air both during the wet and dry months, the maximum temperature was lower than air temperature during the dry cool months. As a result, the mean water temperature during this period went below air temperature. Nevertheless, even with the surrogate breeding sites the difference between air and water temperature was very narrow during the cool and dry months and both air and water temperatures were relatively low at this time of the year.

Despite the importance of water temperature for aquatic organisms, such as the immature stages of mosquitoes, very few records of temperature from small water bodies have been published. This is especially true with the transient pools favored by malaria vectors. In warm regions few prolonged studies on small water pools have been made, and results have been based on spot readings with a thermometer, rather than on continuous temperature recordings. Most studies have been concerned only either with the occurrence of thermal stratification or diurnal fluctuations, rather than on seasonal changes (Young, 1975; Jacobs *et al.*, 1997). A study conducted on a tropical pond in Kenya (Young, 1975) reported that in a tropical pond, when the average weekly air temperature was compared with the average water temperature, the water temperature was found to be warmer than the air temperature. Similar reports were made from temperate ponds, but in this case during the summer (Macan and Maudsley, 1966; Collins *et al.*, 1985). In Kisumu, Kenya, Haddow (Haddow, 1943) conducted two series of hourly measurements of temperature and light intensity, each extending over 24 hours in artificial pools (pans) about 30.5cm in diameter by 20.3cm deep, representing differing breeding conditions – e.g., clear vs. turbid water, shaded vs. open pool. Shade air temperature was recorded in a Stevenson screen. The results showed that there was no significant difference in temperature between clear and muddy water, but a slight difference was noted between the open pool and the pan with clear water with growing grass 30.5cm high. At night both pools approximated to the air temperature in the screen, but by day the temperature of the open pool rose far above that in the screen and the grassy pool, while the temperature of the latter remained below that in the screen. The temperature of the grassy pool by night was higher than that of the screen and the open pool, and the latter equal to or slightly lower than air temperature in the screen. This indicates that the breading sites of *An. gambiae* may undergo much greater diurnal fluctuations compared to shaded pools and air temperature.

Symes (Symes, 1932) reported a temperature range of 17.4-23.5 °C in water pools from a relatively higher altitude in Kenya. Measurements of midday temperature in actual breeding pools of *An. gambiae* were also made at Kisumu during May and June 1940. The highest figure obtained was 36.5 °C. Similar and higher temperatures were recorded in other tropical sites. Weir (Weir, 1969) reported a maximum temperature of 38 °C in central Africans pans and Muirhead-Thompson (Muirhead-Thomson, 1951) states that in small pools the water temperature frequently reaches over 40 °C. Holstein (Holstein, 1952) reported temperatures of 40.5-41.8 °C in pools with larvae and pupae in Mali. The maximum temperatures recorded in my study were 34.5 °C (seepage), 36.9 °C (field) and 38.9 °C (riverbed puddles).

But most of the above studies were based on relatively large water collections or ponds not on small transient water pools. Moreover, it should also be emphasized that air temperatures were recorded at nearby meteorological stations and not at the site of the ponds. Those studies conducted on relatively small water collections were either spot checks or of a couple of days duration and do not reflect seasonal trends of water and air relationship. Even then, a daily comparison of our results show that water temperature does not invariably exceed air temperature. Besides, the thermal characteristic of container water and natural habitats may inherently be different due to factors associated with heat loss and gain by conduction or other heat loss or gain mechanisms under natural conditions. Moreover, the temperature of a body of water is not influenced by its size alone, and that each breeding site has its own peculiar characteristics, for example, shape, location, and other physical traits of the substratum or surrounding may also have an influence. Hence, differences are normally expected between different water collections.

In general, as with the surrogate breeding sites, the temperature of the natural breeding sites showed a similar trend of fluctuations with air corresponding to the seasons. Normally the temperature of small pools follows air temperature closely with only a small lag in amplitude and time, whereas a large one may accumulate heat all the day and be warmest at a time when average air temperature starts to fall at night (Macan and Maudsley, 1966). In general, the courses of the two run in parallel. Significant correlations between water and air temperature suggest that air temperature records, which are widely available, can be used to predict water temperatures. The strong positive correlation observed between daily records of air and water temperature is especially noteworthy. This is because, daily heat regimens that are persistent, and therefore more predictable, might be more important than the monthly, seasonal or annual cycles of heating and cooling for aquatic populations of mosquitoes that have short generation times (Collins *et al.*, 1985).

Climatic variables as measured outdoors in Stevenson screens or by automatic weather stations may give a partial picture of the actual microclimate in which the mosquito lives. Therefore, attention has been directed to the climatic conditions inside houses, as they are most obvious resting and feeding places of the mosquitoes vectoring malaria (De Meillon, 1947; Muirhead-Thomson, 1951). The greatest diurnal range in temperature both indoors and outdoors was observed during the dry season or the warmest months of the year. Nevertheless, the house maximum was always lower and its minimum was always higher than that of the outside in the open, the difference being less pronounced during the wet season. During the dry season, when RH conditions are low and temperature remains high, the highest maximum, lowest minimum and greater temperature ranges, were observed outdoors. These observations suggest that indoor resting mosquitoes such as *An. arabiensis* are not exposed to sudden or marked changes of temperature. It also means that they are not exposed to high temperatures by day and to temperatures as low as those outside by night. This is particularly true for the dry season, as smaller ranges, relatively elevated minimum and diminution of the maximum temperatures characterize the wet season. The difference in temperature at different heights indoors also indicates that even within the indoor environment mosquitoes could select more favourable microclimates as resting sites.

Similar comparisons between indoors and screens were made by Haddow in Kisumu, Kenya (Haddow, 1942) and by Muirhead-Thomson in Assam in India (Muirhead-Thomson, 1951), although slight differences, especially in maximum temperature were encountered, reflecting inherent differences in the microclimate of differing native habitations. In Kisumu, lower average temperature maximum of about 3 °C and higher mean minimum temperature of 3 °C magnitude was reported from mud houses and thatched huts than the corresponding screen figures. In hot dry weather this difference reached as high as 6 °C, while in wet weather it was considerably reduced, with the hut maximum sometimes only 1 °C less than that of the screen. Overall, the temperature range inside houses was only about half that of the screen. In my study it was even less. In the Assam valley, in northeast India, the mean maximum temperature in a typical mud-walled and thatch roofed hut was reported to be 2 °C lower than that of the screen while the mean minimum was found to be about 2 °C higher than that of the screen during August and July, when temperature and RH conditions are high. During cool weather, the difference between houses and screen is accentuated with the hut maximum about 3 °C lower and the minimum 3-4 °C higher than the corresponding screen figures. But in houses with corrugated iron roofs, daily maxima could be very high especially below the roof (Muirhead-Thomson, 1951).

Of particular importance is that, the indoor minimum temperature always exceeded the critical temperature threshold of *P. falciparum* extrinsic incubation period of about 16 °C. Only once (1%) did the indoor temperature minimum approached 18 °C, a threshold temperature below which transmission, especially of *P. falciparum*, is unlikely because adult mosquitoes may fail to survive the longer period required for sporogony at that temperature, and because mosquito abundance is limited by long larval duration (Craig *et al.*, 1999). In contrast, outdoor minimum temperature fell below 16 °C for most part of the year -76.1% of the time (18.0 °C - 95.4%) during the whole comparison period (1 complete year). During the dry and wet seasons it fell below16.0 °C 74.9% and 77.8 % of the time respectively. Below 18 °C, it fell 92.8 % of the time during the dry season and 98.7 % during the wet season.

Similar results were reported in studies conducted in Kisumu (3720ft or 1134m) in Kenya (Haddow, 1942) where the house temperature never dropped below 16 °C. Similarly, at higher altitudes of Tanzania 2,250m (7380ft), (Garnham, 1948) reported that the minimum temperature inside small native thatched houses with no windows or ventilation and overcrowded with people and domestic animals seldom fell below 18 °C, and development of parasites was uninterrupted. With respect to RH, however, the present findings are not consistent with the relatively higher values reported (Haddow, 1943; Muirhead-Thomson, 1951; Gilles and Warrell, 1993) or expected (Lindsay and Martens, 1998a) from indoor environments as compared to outdoors. In this study indoor RH was found to be consistently lower (11 – 18%) than outdoors both during the dry and wet seasons.

Of importance in the life of many mosquitoes is the microclimatic condition of the outdoor resting-places. The data loggers placed under vegetation revealed no significant difference in RH with outside shade RH recorded in screens. In fact, slight excess in RH was observed outside and this occurred from November-January, the coldest months in the region in general. Although the difference was statistically significant, considering the inherent problem of recording RH accurately in nature, the observed difference is negligible (sensitivity of metrological instruments was ± 5%). However, the air under vegetation was cooler than in the open in Stevenson screens indicating the insulating property of vegetation for mosquitoes seeking refuge under vegetation during the daytime. However, the sites selected for accommodating the Stevenson screens may not strictly represent the variety of small daytime sorties of mosquitoes. Because it was impractical to place data loggers in the small damp and cooler holes and crevices along the riverbanks and elsewhere in the study village where we observed *An. arabiensis* resting during the daytime (see chapter 5). Although, the measurement made by De Meillon (De Meillon, 1947) in a hollow under a stone – an outdoor resting place of *An. gambiae*-in the Transvaal- suggest that the climate conditions in such shelters bear roughly the same relation to those of the standard screen as do those of typical mud-walled thatched roof houses, it seems unlikely as causal test recordings made in river banks showed much higher RHs and low temperatures during the day time.

Overall, the study has shown that the lake effect of the dam on the surrounding microclimate may not be uniform due to a number of factors operating together including topographic features of the valley. This is shown in the distinct RH and temperature gradient between breeding sites and the village nearby, and perhaps this gradient helps mosquitoes locate breeding sites at night. The present study also showed that the temperature under vegetation is lower than that of outdoors in the open and that this could provide suitable shelter for outdoor resting mosquitoes from the intense heat of the day and dryness. In this respect, dams could provide favourable microhabitats for exophilic *An. arabiensis* by raising the water table and promoting abundant growth of vegetation and creating saturated conditions in holes and crevices in the gully and elsewhere along the banks. For endophilic *An. arabiensis* populations the indoor environment provided more stable and favourable microclimate and this was especially true during the dry season, characterized by a great range of temperatures outdoors. In the presence of a stable indoor environment and suitable outdoor microclimate under vegetation and elsewhere, small increases in minimum temperature brought about by the warming effect of dams could promote transmission of malaria parasites and extend the transmission season. Besides, a strong positive correlation between daily air and water temperature means that the surrounding air influences the temperature of breeding sites, and moderation of climate extremes would create favourable aquatic environment for rapid development of the immature stages. This also means that air temperature data, which is widely available, could be used to predict water temperatures. The drop in water temperature observed during the cool dry months, following the main transmission season probably explains the drop in vector density and incidence of malaria at this time of the year in Tigray in general. Nonetheless, in proximity to dams their overall warming effect together with suitable indoor, outdoor, and breeding site microclimate would be expected to extend the transmission season of malaria in near dam villages in Tigray (esp in areas of fringe transmission) by speeding up the generation time of the vectors, the sporogonic development of the parasite and increasing the longevity of the vectors.

Chapter 4. Impact of microdams on local microclimate and its relevance to malaria transmission in Tigray, Northern Ethiopia: Pre-intervention entomological and clinical surveys.

Plate 4.1. The seepage area and the dam embankment seen from below.

Abstract

To determine the impact of microdams on malaria transmission, clinical and entomological surveys were conducted routinely in 2 topographically similar villages; one near a microdam, the other 3-4km away in Tigray, northern Ethiopia, from March 1999 to February 2000. Children under 10 years were examined for enlarged spleens (November 1999) and blood films collected in the dry season (January-February) and end of the wet season (October-November). Adult mosquitoes were collected monthly indoors using exit traps, space spraying, and CDC light traps and outdoors using hand collections. All night human landing catches and hourly light trap collections were also conducted for five months. Samples of *Anopheles gambiae s.l.* were identified and source of blood meals determined using the direct ELISA method. Samples of head-thorax specimens were examined for sporozoite infection using a dipstick test for *Plasmodium falciparum* and *P. vivax* circumsporozoite antigens. The prevalence of an enlarged spleen was 3.1% (3/93) in the dam village and none (0/413) in the remote village indicating that malaria was hypoendemic in the area and illustrating a greater level of exposure experienced in the dam village. The incidence rate in the dam village was 2-5.5 times higher than in the remote village, although it was not statistically significant. All malaria cases were infected with *P. falciparum*. *An. arabiensis*, was largely anthropophilic (HBI= 73%) but partially exophilic, and was the only vector in the area. Of the 2650 mosquitoes tested, only one (0.04%) specimen was infected with *P. falciparum* sporozoites. *An. arabiensis* showed seasonal trends in density in both villages and was 6.5-8 times more abundant in the dam village compared with the remote village. There were two annual peaks in mosquito abundance in the dam village, the first of which corresponded to when the fields were irrigated, indicating that transmission of malaria was no longer restricted to the rainy season. *An. arabiensis* was 16 times more abundant (per light trap/night) in the dam village during this period. The number of bites received/person/night was 3.6-10 times higher than the remote village during the dry season and 4-5.6 times higher during the whole study period as determined by human landing and light trap collections. An average villager was likely to get about 0.3 infective bites of *P. falciparum* per annum in the dam village and 0.08 in the remote village. Overall, despite DDT spraying and prompt treatment with Fansidar during

the study period, the entomological findings demonstrated that dams have the potential to increase transmission of malaria parasites.

Introduction

The mosquito vectors of malaria and the parasites they transmit can respond sharply to changes in the ecology of their habitats due to human disturbance to natural ecosystems (Coluzzi *et al.*, 1979; Coluzzi *et al.*, 1985). Apart from the evident economic benefits, the construction of dams, formation of human-made lakes and development of irrigation projects in tropical areas can introduce important changes in the environment resulting in a number of risks to human health (Hunter *et al.*, 1982; Ijumba and Lindsay, 2001). As hypoendemic highland regions of Ethiopia have long been known to be liable to epidemics of malaria, the extensive program of dam construction in progress in Tigray Region, northern Ethiopia, raised concerns about the possible effects of the reservoirs on the transmission of malaria. Most of these dams, ranging in size from 50,000 to 4,000,000 m^3 (personal communication, Co-SAERT), are used for irrigation and as a source of drinking water and are situated less than 2km from local communities, well within the flight range of *Anopheles arabiensis* (Gillies and De Meillon, 1968), the major vector in the country. Currently about 60 microdams are constructed and up to 500 dams are planned. Other larger dams are also envisaged for hydropower (e.g. construction underway in the Tekeze River Basin) and as a source of urban water supply. Alarmed by the increasing danger of the continued presence of standing water on malaria transmission, especially in the fringe areas, an extensive study was conducted near 8 microdams. The incidence of malaria in villages near dams was 3.18%, whereas it was only 0.54% in villages away from these sites, a 7-fold increase in near dam villages (Ghebreyesus *et al.*, 1999).

The creation of abundant breeding sites favourable for *An. arabiensis* could partly explain the higher incidence of malaria in dam villages. Apart from the small excavations, associated with the construction of the dam and feeder roads, that fill up with water and serve as breeding sites during the construction phase, dams also increase the extent of breeding sites and their seasonal duration (Birley, 1991). Nonetheless, large water bodies such as reservoirs are also known to change the microclimate of the surroundings as demonstrated in the present study site and elsewhere (Gregory and Smith, 1967; Huntley *et al.*, 1998) and this could be part of the reason for the dramatic change in the pattern of malaria transmission in near dam villages. As described in earlier chapters, higher minimum temperatures of 1.3 °C-3.5 °C were observed in the dam village compared to the remote village. Such changes in local microclimate are often associated with changes in vegetation density and diversity (Huntley *et al.*, 1998) and in the production of biotopes more favourable than before to intermediate hosts or vectors of infectious diseases (Hunter *et al.*, 1982; Hunter *et al.*, 1993) such as malaria. In the presence of numerous breeding sites, such changes in microclimate would be expected to favour vector abundance and rapid development of the parasite in the infected mosquitoes increasing the risk of malaria in communities near microdams, especially at the fringes of higher altitudes such as the highlands of Tigray, northern Ethiopia.

Environmental monitoring in these transitional zones is thus a priority for detecting any change in disease driven by the construction of dams and water impoundments as well as other human incursions in the environment such as deforestation. Here I compared the transmission and infection rates in two villages; one near a dam and the other remote from the dam in order to investigate the impact of the dam on malaria risk.

Materials and Methods

Study Area

The longitudinal study was undertaken from March 1999 to February 2000 near Meskebet microdam (14° 16' - 14° 19' N and 38° 11' - 38° 14' E), located 330km northwest of Mekelle in Tigray, northern Ethiopia. It involved one pair of topographically and ecologically similar villages – Deba (population ~ 372 in 71 households) near the microdam and Maisheru (population ~ 1237 in 235 households) 3-4km away in a neighbouring valley parallel to the dam. A detailed description of the study area is given in chapters 2 and 3. Briefly, the study villages are situated at an altitude between 1750-1790m. Rainfall (900-1200mm annually) falls mainly from the end of May to October, with a distinct peak in

July. The rainy season is immediately followed by the coldest months of November through January and March-May is the hottest period.

The inhabitants of the study villages, all of whom were farmers, lived in stone and mud-walled houses, with flat roofs of wattle and earth. These houses are typical of rural dwellings in Tigray and had open eaves between the wall and the roof as well as wide openings in the doors, which were fitted with wood and twigs. The average number of people per household was 5.1 in both villages and most of the villagers herded cattle, goat, sheep and pack animals, which were kept in open stonewalled enclosures attached to their houses.

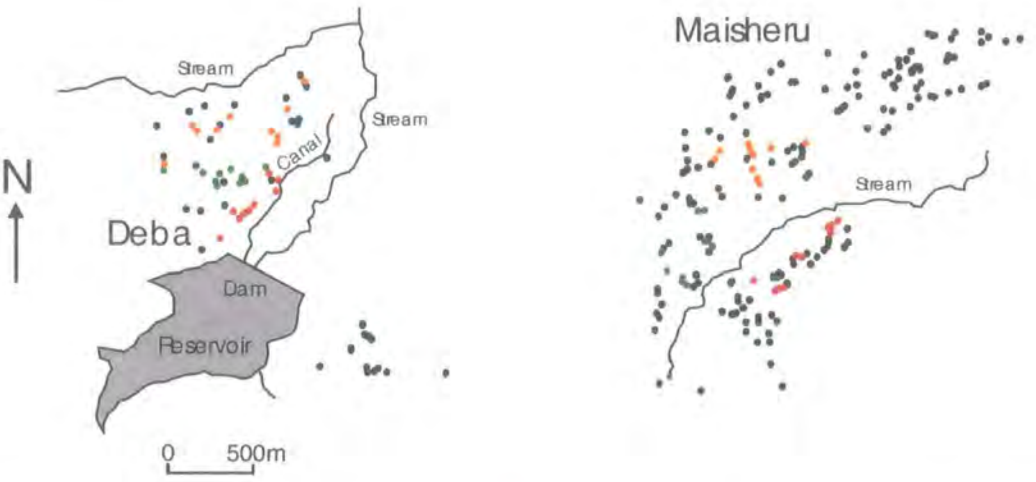


Figure 4.1. Dam and remote village GPS point coordinates of reservoir, major water ways, irrigation canals and houses (Mosquito collection houses–**red** (zone 1), **green** (zone 2) and **orange** (zone 3). [The GPS readings were plotted on SigmaPlot graphical software and the two axes (y and x-axis) removed to produce the map. A total of 1063 in the dam village and 513 in the remote village GPS coordinates were recorded].

Meskebet dam was completed at the end of 1996 and holds about 2.7 million m^3 of water. It had, a 4.9km shoreline and a 570m long dam embankment made of a pile of compacted earth, extending across a stream. The dam was used to cultivate about 15ha of land, although it was designed to provide irrigation for 65ha. The fields were situated downstream below the dam on either side of the gully, towards Deba village (Fig. 4.1).

Houses at the southern edge of the dam village were less than about 170m from the dam. The main canal followed the contour at the edge of the village, within 70–200m, all the way to the northern end of the village. The 2km long irrigation canal was not lined, except the first 200m from the outlet. Preparation of fields for irrigation and seedling plots started in December and the fields were irrigated from January until June following sowing and transplanting. The dam, irrigation canals, major waterways, and the position of each household were mapped using a global positioning system (GPS – Garmin 38, USA) after the selective availability was switched off in May 2000. Demographic and environmental information was recorded and each village roughly divided into three zones for ease of collecting parasitological and entomological data. This was based on proximity to breeding sites identified. Each household (defined by members living together) was visited and numbered, and each household member assigned a number. After collection of baseline census data, we maintained an ongoing record of births, deaths, and migration to and from the villages.

Both villages were sprayed with DDT in September 1999 by the same team of sprayers, two months after the normal spraying period (in June) in the area. Other control measures practiced in the study villages during the study period included community-based early diagnosis and treatment of clinical malaria with chloroquine, which was replaced by Fansidar in June 1999. Any sick child was encouraged to consult the project enumerators in their village for treatment. Those with clinical malaria (defined as 1 or more days of fever, chills, sweating, headache) were treated with Fansidar (a single dose equivalent to 25mg sulfadoxine and 1.25mg pyrimethamine/kg body weight). Refractory cases and those with severe malaria and other diseases were referred to the nearest health clinic located 5km from Deba and about 9km from Maisheru. The community did not practice environmental management for vector control during the study period.

Clinical Surveys

To ensure the co-operation of the inhabitants, village meetings organized by the local project guards, who were members of the local Baito (village administration), preceded the surveys. To monitor the incidence of malaria in the community all children in each village aged 10 years and below were enrolled in the study between April 1999 until February 2000, and each child assigned a survey number. Axillary temperature was recorded with a thermometer and a finger prick blood sample obtained for the preparation of thick and thin blood films in October and November 1999, December 1999 and January 2000. A second blood film was taken from each child as close to 30 days as possible after the initial film. Febrile cases or children who had clinical malaria at the time when the first blood film were taken received Fansidar (equivalent to 25mg Sulfadoxine and 1.25mg pyrimethamine/kg body weight over 1 day) and another blood film taken after 14 days. In addition, a blood film was taken from any child falling sick during the intervening period and treated with Fansidar if appropriate. Furthermore, a prevalence survey was carried out at the beginning of the rainy season (June 1999) and all children were palpated for enlarged spleens at the end of November 1999. The slides were air- dried and stained for 30 minutes in 3% Giemsa solution and examined for malaria parasites. The number of parasites found in 100 fields was recorded. Other senior microscopists re-examined all positives and 10% of the negatives. The census data were entered on a dBase-computerized system that enabled tracking of individuals and vital events throughout the study (Stephens *et al.*, 1989).

Entomological Surveys

House selection

Populations of adult mosquitoes were sampled indoors and outdoors from March 1999 to February 2000 using light traps, space spraying and exit traps, as well as by hand capture outdoors and human-landing collections. Collection of adult mosquitoes by light traps, space spraying and exit-traps was carried out in 30 houses each month (WHO, 1975). In order to obtain a representative sample of the mosquito population, the dam village was stratified into three zones: near the dam, in the middle of the village and far from the dam. Houses were numbered and 10 randomly selected from each strata (Figure 4.1). Houses that had windows, preferably facing the east, were sampled, as this was used to site the exit trap. Each day collections were made in six houses in each village, two from each zone. The same 30 houses were used throughout the study both for light trap and space spray collections.

Space spraying and exit trap collections

Exit trap and knockdown collections by space spraying were made in six houses each day for five consecutive days each month in each village. To collect house-leaving mosquitoes, window exit traps were set at 18:00hr in the evening and collected at 06:00-07:00hr in the morning. After removing the exit traps and closing the open eaves under the roof and any other wide openings in the room, using sacking and white sheets, houses were sprayed with a 300ml aerosol of pyrethroids –(Mobil: composition (% Weight): Tetramethrin 0.20; Phenothrin 0.12; Allethrin 0.25; Solvents, Propellants, and essential oils 99.43; Mobil Africa Sales Inc., Belgium). Mosquitoes knocked down on white sheets spread on the floor were collected and placed in pre-labelled petri dishes lined with moist filter paper until identified and processed the same day. Tissue paper was applied on top before sealing the petri dishes to prevent damage and loss of specimens. During entomological collections the age and number of occupants, type and number of large animals (cows, sheep, goat, horse or donkey) kept inside houses and in the immediate vicinity outside, whether or not fire was set on the previous night or early in the morning, house number, date, and village code were recorded.

Light trap collections

In order to avoid any repellent effect of the insecticide, light trap collections were made in each house five days after space spraying. CDC light traps (Model 512, John W. Hock Company, USA) were set up at 18:00hr local time and taken down at 07:00hr the following morning. One light trap was placed in each bedroom, next to the wall, with the bulb about 1m from the floor, or about 45cm above the head of a person sleeping under untreated bed net. The trap was placed about 40cm from the wall, so that the edge of the tray does not touch the wall or net. To prevent the rotating fan from drying trapped mosquitoes, the wire-meshed base of the collection bottle was covered with a plastic bag containing soaked cotton wool. In some cases, when the house occupants slept outside nearby, one trap was placed indoor and another outdoor close to the sleepers. In households with two rooms, the light trap was set in one of the rooms and all the people, including those in the adjacent room, slept under untreated bed nets. If a house had several separate rooms that were used as sleeping quarters, then the light trap was installed in the room where most people stayed during the night. Information on people and animals and whether the light trap was working or not at the time of collection was recorded. Records of light traps found not working at collection time in the morning were excluded from analysis.

Mosquitoes caught in the light traps were aspirated or, if dead, emptied on to a white sheet of paper from the collection bottle after untying it from the light trap. The specimens were then transferred into paper cups, killed, and placed in pre-labelled petri dishes until processing the same day. The house occupants, especially of those houses located at the edge of the village towards the dam, were allowed to keep the bed nets at the end of the study.

Human-landing catches

All-night human-landing catches were carried out for five months per year during the study; in March, May and September through November 1999 and 2000. Catches were conducted indoors and outdoors from 18:00 to 07:00hr. Human baits were employed locally and trained to catch mosquitoes landing on their bare legs using aspirators and hand-held torches. Each month, catches were made in eight houses on the edge of each village, closest to the dam and main crop growing area in the remote village. Two houses were used each night, in each village, for four consecutive nights. At each house one collector was stationed indoors and the other outdoors 5-10m from the house. Each team consisted of one collector and one assistant and worked in 3-hour shifts. Collections started at 18:00hr and a new team of collectors replaced each team every three hours until 07:00hr in the morning. Each night, therefore, produced 13 hourly samples from each site. Trained locals assisted by enumerators made the catches.

Mosquitoes aspirated while biting were placed in paper cups with netting. At the end of each sampling hour, mosquitoes were killed with Mobil insecticide moistened cotton wool applied to the netting of the paper cup. They were then transferred into moist paper-lined petri dishes, previously labeled as to the hour of capture and location, until the morning when they were identified and their number recorded. The collectors were interchanged on consecutive nights in order to minimize bias. The catch was supervised at all times.

Hourly light trap catches were also made concurrently in nearby similar houses indoors and outdoors and compared with night-biting collection in order to verify the biting cycle of *An. arabiensis* and estimate the catching efficiency of light traps. At the end of each hour the mosquito holding plastic bottles were replaced and the mosquitoes aspirated into labeled paper cups. Temperature, rainfall, and wind was recorded indoors and outdoors during the nights of collection.

Outdoor-resting collections

Outdoor-resting collections were made at five sites per day for three consecutive days each month. Catches were conducted in different types of vegetation and other likely outdoor mosquito resting sites including: animal burrows and termite mounds, under bridges and large tree roots, in holes and crevices along riverbanks and near human habitations. Collections were made by placing a large netted frame on the ground (2 x 2 x 3m), disturbing the vegetation and /or by spraying with a small quantity of insecticide mist and collecting adult mosquitoes from inside the net using aspirators. Suction tubes were also used to collect mosquitoes from holes and crevices where netted frames were not suitable. Mosquitoes were also collected from under a bridge by spraying the interior with an insecticide mist after hanging white sheets over the outlets. The position of collection sites was recorded using a GPS. Mosquitoes aspirated from inside the net and other sites were placed in paper cups with netting, killed, and transferred into petri dishes until processing.

DDT – Susceptibility test

Susceptibility tests were performed on mosquitoes collected from adjoining villages; using the standard test kits with 4% DDT impregnated papers (WHO, 1981). Twenty blood-fed indoor resting *An. arabiensis* were exposed to 4% DDT impregnated paper for one hour. Another group of 20 were exposed to oil impregnated paper for an equal period of time and used as controls. Each of these tests was carried out once owing to scarcity of mosquitoes as the test was carried out during the intervention phase of the study. The mortality values obtained from the exposure period of one hour were recorded. Temperature and relative humidity were recorded during the test period.

Processing of mosquitoes

All adult anopheline mosquitoes were counted and identified to the species level based on morphological descriptions (Verrone, 1962a; Gillies and Coetzee, 1987). *An. gambiae s.l.* specimens were classified by stages of abdominal appearance into unfed (UF), freshly fed (FF), half gravid (HG) and gravid (G). The number of other anophelines and culicines was also noted. Samples of adult *An. gambiae s.l.* specimens were dried, placed in the wells of microtiter plates, stored with desiccant and taken to the UK where they were identified by polymerase chain reaction (PCR) (Scott *et al.*, 1993) at the beginning of the study. The abdomen of samples of freshly fed *An. arabiensis* mosquitoes obtained from indoors and outdoors were squashed individually onto Whatman No. 3 filter paper (Evengard *et al.*, 1988) using forceps tips covered with a removable plastic tape. Blood meals were dried on filter paper and kept in a petri dish with silica gel for bloodmeal identification. The head-thorax portions of samples of *An. arabiensis* mosquitoes were also placed in the wells of microtiter plates stored in a container with desiccant and taken to the UK where they were processed for the determination of salivary gland infection.

Source of mosquito blood meal

Each bloodmeal was tested twice, and in duplicate in each case, using a direct ELISA technique adapted from Service and colleagues (Service *et al.*, 1986) for traces of human and bovine (cow, sheep & goat combined) IgG. Briefly, blood spots on filter paper were cut and eluted overnight in 1500μl of normal phosphate buffered saline (PBS) at 4 °C. The following morning, 100μl of each eluate was transferred to ELISA plates (NUNC F96 maxisorb) in duplicates, covered and incubated overnight at room temperature. In other words, on each plate the eluate of each blood sample was done in duplicate. The contents of the wells were then drained and the plates washed 4 times with PBS containing 0.05% Tween 20 (PBST). This was followed by the addition of 100μl of horse radish peroxidase (HRP) conjugated anti human IgG (Sigma, UK) diluted 1:2,000 in PBST and incubated for 1hr at room temperature. To the duplicate plate 100μl/well HRP conjugated anti bovine IgG was added and treated afterwards in the same way. After incubation, the wells were washed 5x with PBST and blocked with 150μl of PBST and incubated for 1hr in sandwich boxes over a layer of moistened tissue paper. The blocking buffer was discarded and 100µl/well of orthophenylene diamine (OPD; Sigma, UK, 100mg OPD dissolved in 50ml of citrate phosphate buffer pH 4.5 plus 20µl of hydrogen peroxide/50ml buffer) added. The reaction of enzyme-substrate was stopped with 25µl of 2.5N H_2SO_4 per well after 30 minutes and the plates read visually. Human and cow sera and PBS were used as positive and negative controls in each plate where appropriate. Mosquitoes fed both on humans and animal hosts were classified as human-fed. The human blood index (HBI) was calculated as the percentage of human-fed mosquitoes of all blood meals identified. Calculations were based on pooled samples of mosquito blood meals from both the dam and remote villages.

Sporozoite rates

The VecTest™ Malaria Sporozoite Antigen Panel Assay (Medical Analysis Systems Camarillo, CA, U.S.A.; http://www.vectest.com) was used to test the head and thorax portions of *An. arabiensis* collected for the presence of *P. falciparum* and *P. vivax* circumsporozoite protein (CS; Pf, Pv210 and Pv247) as described by Ryan and colleagues (Ryan *et al.*, 2001). Briefly, pools of 10 female *An. arabiensis* head and thorax specimens were placed in a tube containing 250µl of grinding buffer. Mosquitoes were homogenized with a plastic pestle provided with the kit. A dipstick was placed in the tube containing 250µl of the triturate solution and allowed to develop for a period of 15min. Dipsticks were examined visually for the formation of a reddish purple line on the nitrocellulose strip and compared to a template on the package insert.

Data analysis

Clinical survey

Days at risk were calculated in untreated children from the date of first film to the date of passive case detection (if treated or positive) or date of second film. Days at risk for treated children were similarly calculated from time of negative follow up film to passive case detection or second film. Children whose first blood film yielded positive results for *P. falciparum* were excluded even if results were negative on follow up (14 days), as late recrudescence could not be ruled out (Teklehaimanot, 1986). As children with *P. vivax* infection were not treated with primaquine, relapsing vivax infections could not be ruled out; thus second and subsequent *P. vivax* infections in individual children were not taken as incident cases. Incidence rates were calculated from numbers of incident cases and child months at risk, the latter being calculated on a daily basis from the data base system. Statistical analysis of incidence is based on rates of cases per child month at risk and the incidence as well as enlarged spleen rates between the villages was compared using Fisher Exact Test. The Ethiopian Science and Technology Commission and the Tigray Regional Health Bureau gave ethical approval of this study and local consent was obtained through community meetings.

Entomology

Daily counts of mosquitoes were transformed (Ln (x+1)) to normalize the data. Data were back transformed after calculations to compare the geometric mean of the relative abundance between seasons and the dam and remote villages. The relative abundance of mosquitoes by space spraying/exit traps and light traps, as well as human landing catches were compared between the two villages and seasons using Wilcoxon's Signed Ranks Test (*W*). The man – vector contact was determined from human landing catches, space spray and exit trap collections as well as from light traps and then the entomological inoculation rate (EIR) number of infective bites/person/night), was estimated for each method. Where,

$$\mathrm{EIR} = mas$$

m is the number of mosquitoes per person per night,
a is the biting habit of the mosquito and,
s is the sporozoite rate

The number of infective bites/person/night obtained above was multiplied by 365 (days) in order to get the number of infective bites/person/annum. With Human landing (HLC) and Light trap (LTC) catches the biting habit equal to 1 (or 100%) as mosquitoes coming to bite are considered. With space spray collection, m represents the proportion of blood fed (freshly fed and half gravid or late fed) mosquitoes/house occupant and a is the Human Blood Index, derived from the ELISA blood meal results. Since most mosquitoes fed early in the evening and the blood was already dark after the morning collection, these mosquitoes were classified as half gravid. In calculating the EIR from routine monthly light trap collections, only unfed mosquitoes were considered.

In calculating the man-biting rates from human-landing catches, the bed time of the inhabitants was taken into account. From observations during the study, nearly all villagers went to bed by 22:00hr, and this earlier period was used to represent the proportion of mosquitoes biting outdoors. During this period (18:00-22:00), an average villager was estimated to stay outdoors for about an hour and the remaining hours of darkness indoors. Thus, the outdoor component of the man-biting rate was represented as the total number of bites per bait/hr during the period 18:00-22:00hrs. The indoor component was determined as the number of bites/indoor bait in 3hrs between 18:00 and 22:00hrs, plus the total number in 8hrs between 22:00 and 07:00hrs. The total man-biting rate/night was then obtained by adding the two components together.

In order to determine the biting cycle of *An. arabiensis* in the villages (Figures 4.5-4.6), the percentage of mosquitoes caught in the act of biting at each hour were plotted for both indoors and outdoors separately. Hourly light trap catches were similarly treated to compare the trend of mosquito activity with hourly human landing collections. Regression analysis was also used to compare the relationship of human landing catches with concurrent light trap collections on an hourly and nightly basis. In order to quantify the efficiency of light trap catches compared with human landing catches, the ratios were calculated by dividing the daily light trap catches (Ln LTC+1) by the matched human landing catches (Ln HLC+1). The proportion of blood-fed females in exit traps and the ratio of gravid: fed plus half gravid (G:F+HG) mosquitoes caught by space spraying was used to estimate the degree of exophily. The half gravid (or late fed) specimens were included with fed ones as those mosquitoes with dark blood in their abdomen in the morning, due to early evening feeding, were classified as half gravid. The ratio of HG + G:F was also shown for comparative purposes. Comparison of F + HG vs. UF + G proportions between exit trap and space spray in each village was made using χ^2 tests to determine the composition of the exiting mosquitoes after entering houses.

Results

Demographic information

Although Maisheru (remote village) had a greater population than Deba (dam village), the average household size was similar in both villages (Table 4.1). For the analysis of entomological data, the average number of people sleeping in the house at collection time was taken. About 48% of people in the dam village were below 15 years old compared with 54% remote village. About 32% in the dam village and 40% in the remote village constituted the age group below 10 years.

Table 4.1. Demographic information of the study villages (Deba and Maisheru).

Village	October 1999			October 2000			No.of Households	Average household size
	Male	Female	Total	Male	Female	Total		
Dam village (Deba)	161	186	347	173	199	372	71	4.9(5.1)*
Remote village (Maisheru)	619	557	1176	645	592	1237	235	5.0(5.01)*

*Numbers in bracket represent October 2000 average household size

Parasite and Spleen Surveys

All parasites found in the children's blood were *P. falciparum*. The incidence rate per 100 child months in the dam village (0.6) was 2 times higher compared to the remote village (0.3), but it was not significantly different (Tables 4.2, Fisher exact test, $p = 0.46$). The malaria prevalence rate was 2.3% (2/86) in the dam village and 0.3% (1/322) in the remote village at the end of the dry season, 7.7 fold greater in the former, though not statistically significant (Fisher exact, $p = 0.11$). The spleen rate in age-matched children was significantly higher (3.1% (3/93), Fisher exact test, $p < 0.05$) in the dam village compared to the remote village (0%, 0/413).

Table 4.2. Incidence of malaria/100 child months in the dam and remote villages (1999/2000).

Survey	Malaria incidence/100 child months	
	Dam village	Remote village
October-November 1999	0	0.3 (1)
January – February 2000	1.1(1)*	0.2 (1)
Total	0.6(1)	0.3 (2)

*Number of cases inside bracket

Entomological Findings

A total of 6444 female mosquitoes were collected in the dam village and 1770 in the remote village during the study. In the dam village they comprised 82.7% (5328/6444) *An. gambiae s.l.*, 0.03% (2/6444) *An. pharoensis*, 1.8% (114/6444) other anophelines, and 15.5% (1000/6444) culicines. The corresponding figures in the remote village were 46.6% (825/1770) *An. gambiae s.l.*, 0.06%(1/1770) *An. pharoensis*, 5.6%(100/1770) other anophelines, and 47.7% (844/1770) culicines. *An. gambiae s.l.* mosquitoes were considered to be *An. arabiensis* as all 90 specimens tested by PCR study belonged to this species. *An. arabiensis* was thus the dominant species in the dam village. It formed a lower proportion in the remote village because of the relatively large number of culicines and other anophelines caught in the village. Other anopheline species mostly encountered in the area during pre- and post-intervention (chapter 5) entomological surveys included *An. squamosus, An. cinereus, An. preterionsis, An. christyi, An. demeilloni, An. natalensis, An. turkhudi, An. dancalicus, An. rivulorum,* and *An. maculipalpis.*

Seasonal abundance of An. arabiensis

The seasonal abundance of *An. arabiensis* by light trap collection is shown in Figure 4.2. Overall, there were 6.3 times more *An. arabiensis* /trap/night in the village close to the dam (Geometric mean (GM) = 4.4; 95% CI = 3.8-5.1; *w*, z = -12.641, n = 354, p <0.001) compared with the remote village (GM = 0.6; 95% CI = 0.51-0.76). There were two peaks in mosquito numbers in the dam village, one during the dry season (May) and the other at the end of the wet season in September. *An. arabiensis* was 16 times more abundant per trap per night in May in the dam village (GM= 16.1, 95% CI = 10.4-24.4, $p < 0.001$) compared to the remote village where no mosquitoes were collected. The peak abundance in the remote village was associated with the rains. A sharp decline in mosquito abundance was observed during the peak rains in July-August and after September. The drastic drop in mosquito density after September (Figure 4.2) was attributed to residual DDT spraying. Both villages were sprayed with 75% DDT during the collection period (September 1999).

The seasonal pattern of adult *An. arabiensis* abundance by knockdown (space spray and exit trap) was similar to the light trap collections. There were 8 times more mosquitoes collected from the dam village (GM = 0.4 /house/night, 95% CI = 0.31-0.43; *w*; z= -9.873, n =336, $p<0.001$) compared to the remote village (GM = 0.05 /house/night, 95% CI = 0.04-0.07). Relatively high densities of *An. arabiensis* per house per day were seen in April through the first week of June during the dry season. During the rainy season, peak indoor resting densities occurred in September. A sharp decline in numbers was noticed afterwards and this was due to DDT spraying in both villages.

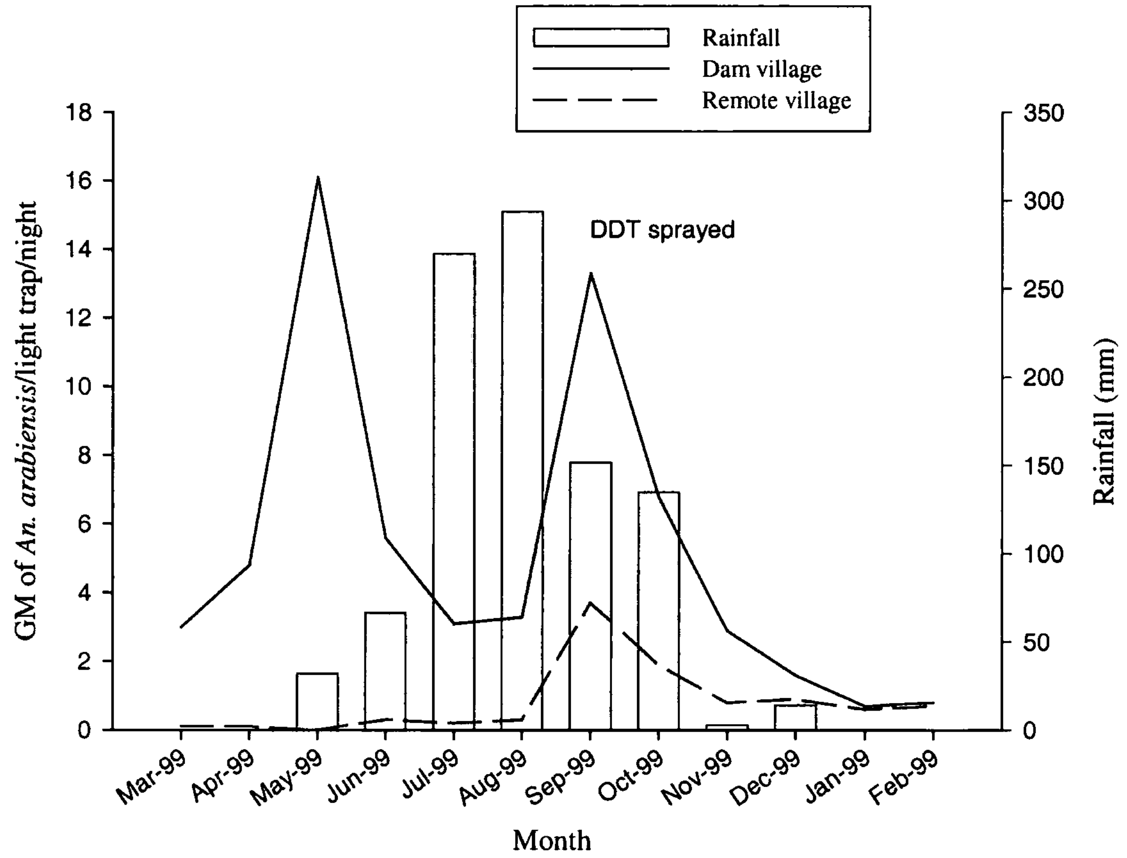


Figure 4.2. Seasonal variation of *An. arabiensis* abundance by light trap collection (Geometric mean/light trap/night) in both the dam and remote village.

Outdoor resting densities

The number of female mosquitoes collected from outdoor resting sites is shown in Table 4.3. Most were *Culex* species both in the dam (67.2%) and remote (75.5%) villages. *An. arabiensis* comprised 31.1% of mosquitoes collected in the dam village and 2.4% in the remote village. Although *An. arabiensis* were found resting under vegetation, 94 % caught outdoors in the dam village came from holes and crevices along stream banks and tree trunks, under local bridges, in termite mounds and in stone walls and fences near human habitations. The mean catch in these sites was 1.5 mosquitoes/trial. In the remote village, most were caught from under shrubs and small trees (GM = 0.06/trial). The relative abundance and seasonal distribution of *An. arabiensis* collected outdoors is shown in Figure 4.3. Overall, more mosquitoes were collected outdoors in the dam village

(GM=0.4/trial, 95% CI=0.3-0.5, *w*, z=-5.8, n=166, p<0.001) compared to the remote village (GM=0.03, 95% CI=0.008-0.06). *An. arabiensis* collections outdoors were higher at the end of the rainy season (October) and in February, when fields were irrigated.

Table 4.3. Total number of mosquitoes collected outdoors in the dam and remote villages (number of *An. arabiensis* / trial are shown in parentheses).

	Type of collection site					**Total**
	Grass	**Crops**	**Other herbs**	**Shrubs/young trees**	**Holes/crevices**	
Dam village						
No sampled	21 (8)*	10 (5)	25 (12)	47 (28)	63 (9)	166
An. arabiensis	7 (0.3)	0	17 (0.7)	13 (0.3)	94 (1.5)	131(0.8)
Other Anophelines	0	0	0	1	6	7 (0.04)
Culex	42	34	30	53	124	283
Remote village						
No sampled	40 (17)*	1	12 (7)	70 (37)	42 (15)	165
An. arabiensis l	2 (0.05)	0	0	4 (0.06)	2 (0.05)	8 (0.05
Other Anophelines	0	0	0	0	2	2
Culex	146	0	12	92	68	318

* Numbers in bracket of numbers sampled are negative samples

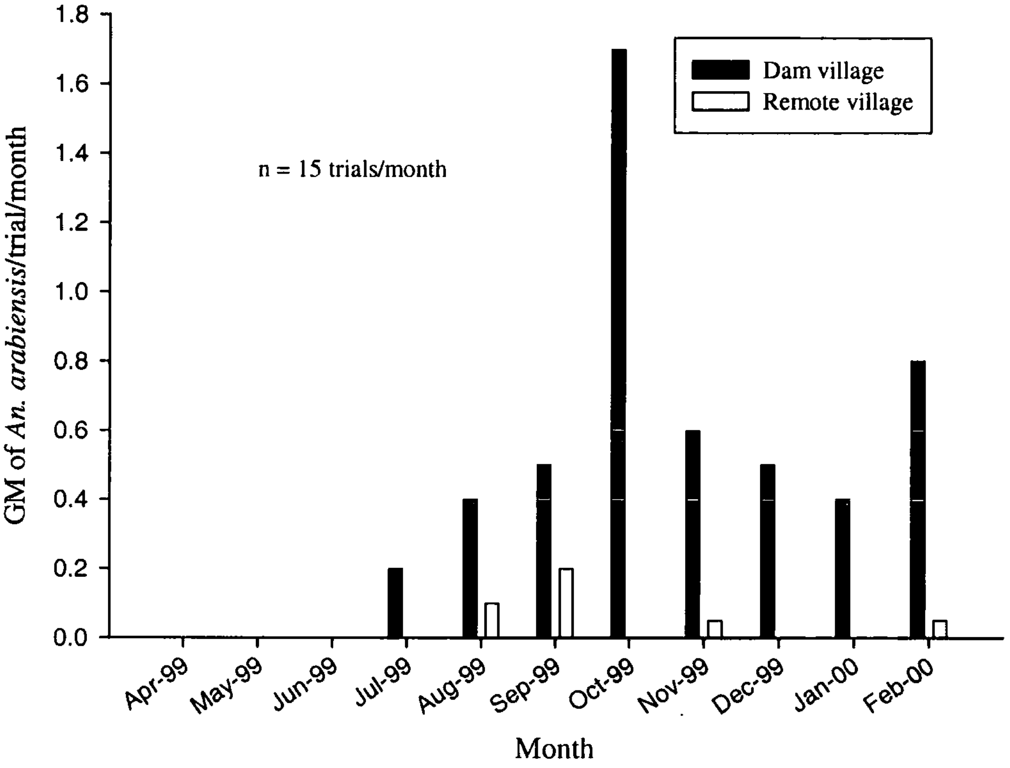


Figure 4.3. Seasonal variation in abundance of *An. arabiensis* caught at outdoor resting sites (GM/trial/month) in the dam and remote village.

Human-landing catches

A total of 424 *An. arabiensis* in the dam village and 99 in the remote village were collected off human baits during 5-month collections. As shown in Figure 4.4, two peaks of *An. arabiensis* biting humans were observed in the dam village- at the end of the dry season (May) when the fields were irrigated and end of the rainy season (September). In the remote village, they were most numerous at the end of the rainy season.

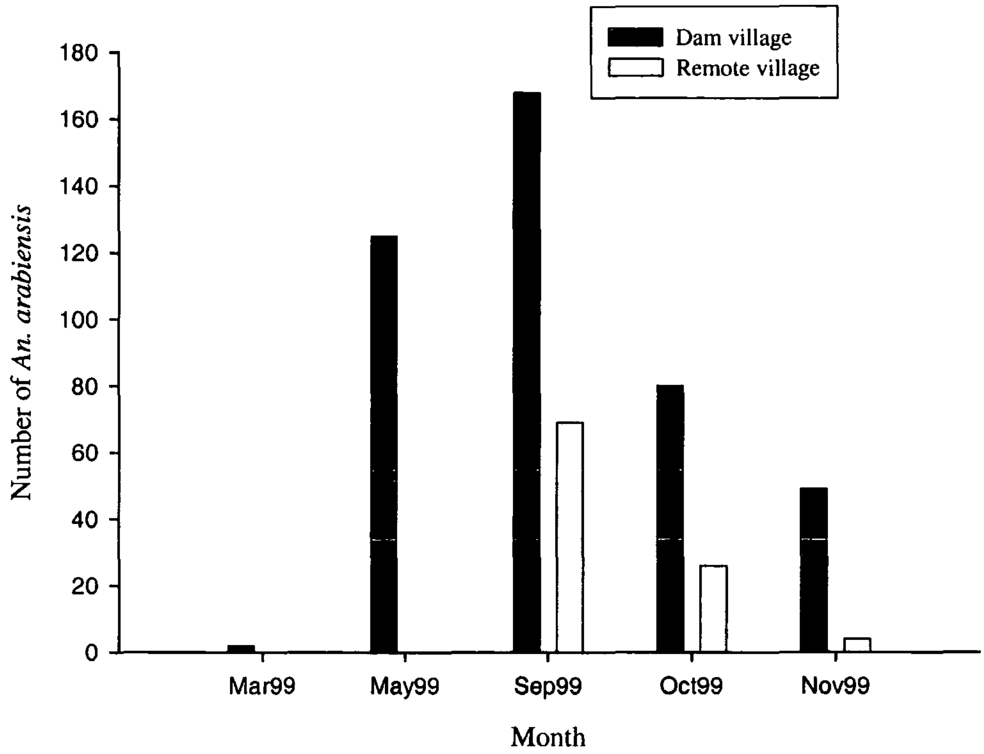


Figure 4.4. Seasonal variation of *An. arabiensis* caught biting humans in the dam and remote villages (n = 8 night catches/month/village indoors and outdoors).

The biting rhythm of *An. arabiensis* in the dam and remote villages is shown in Figures 4.5 and 4.6 respectively. Overall, an early biting peak (19:00-20:00hr) occurred followed by a general decline through the night. The nocturnal activity of *An. arabiensis* collected using light traps (Figure 4.7) was similar to that seen with human bait collections. Hourly light trap collections were positively correlated with human landing catches for both indoor (adjusted R^2=0.78, R = 0.88, F = 43.59, p <0.001, n = 64, y = -0.201 + 4.726x) and outdoor collections (adjusted R^2 = 0.65, R= 0.80, F = 23.72, p<0.001, y = 0.043+0.634x).

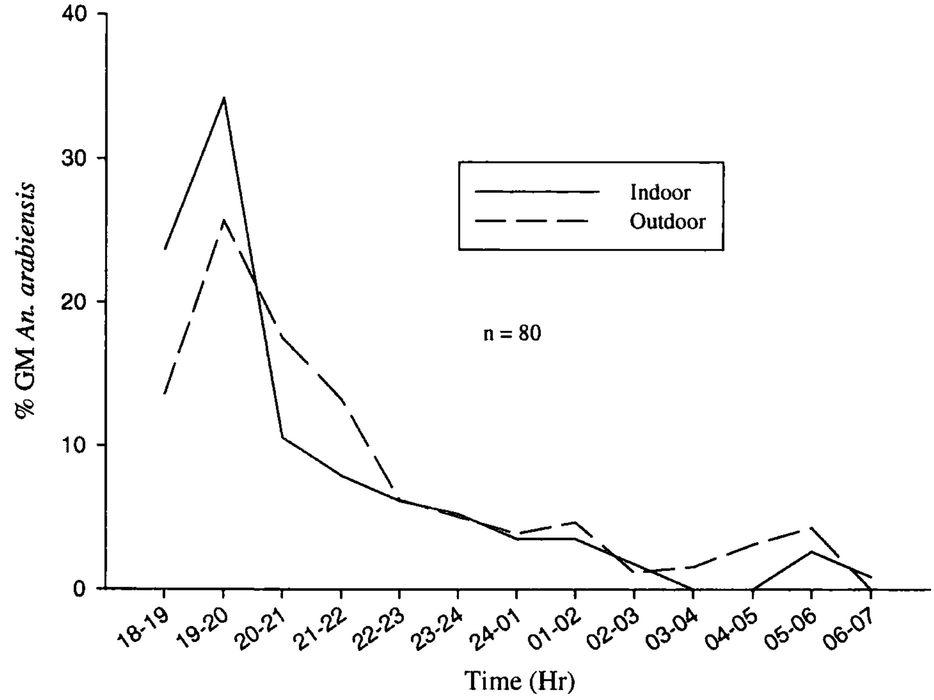


Figure 4.5. The biting rhythm of *An. arabiensis* indoors and outdoors in the dam village (pooled data 1999/2000).

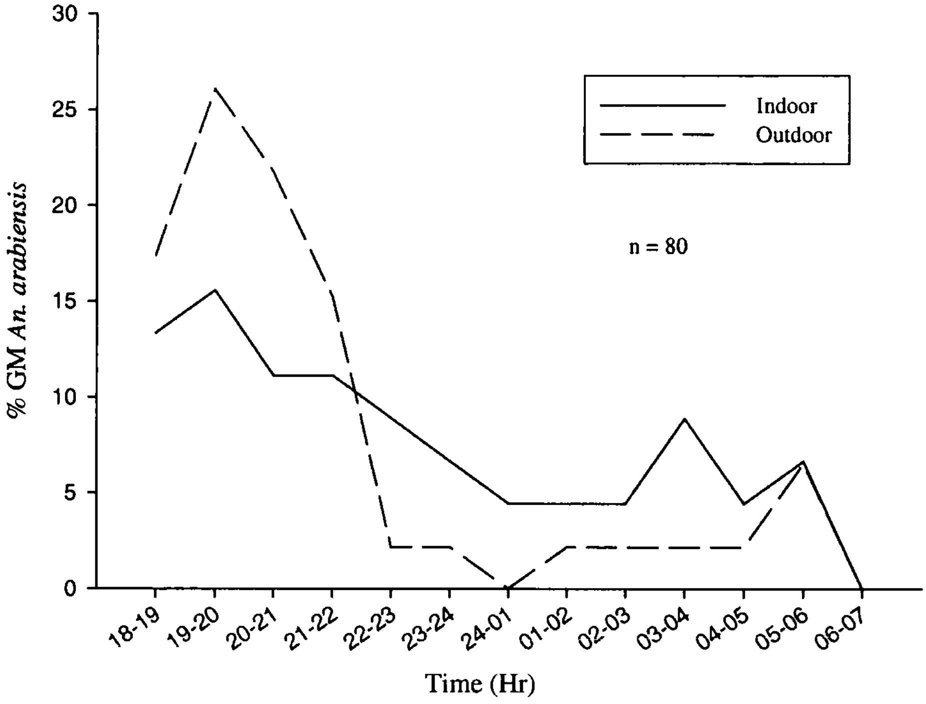


Figure 4.6. The biting rhythm of *An. arabiensis* indoors and outdoors in the remote village (pooled data 1999/2000).

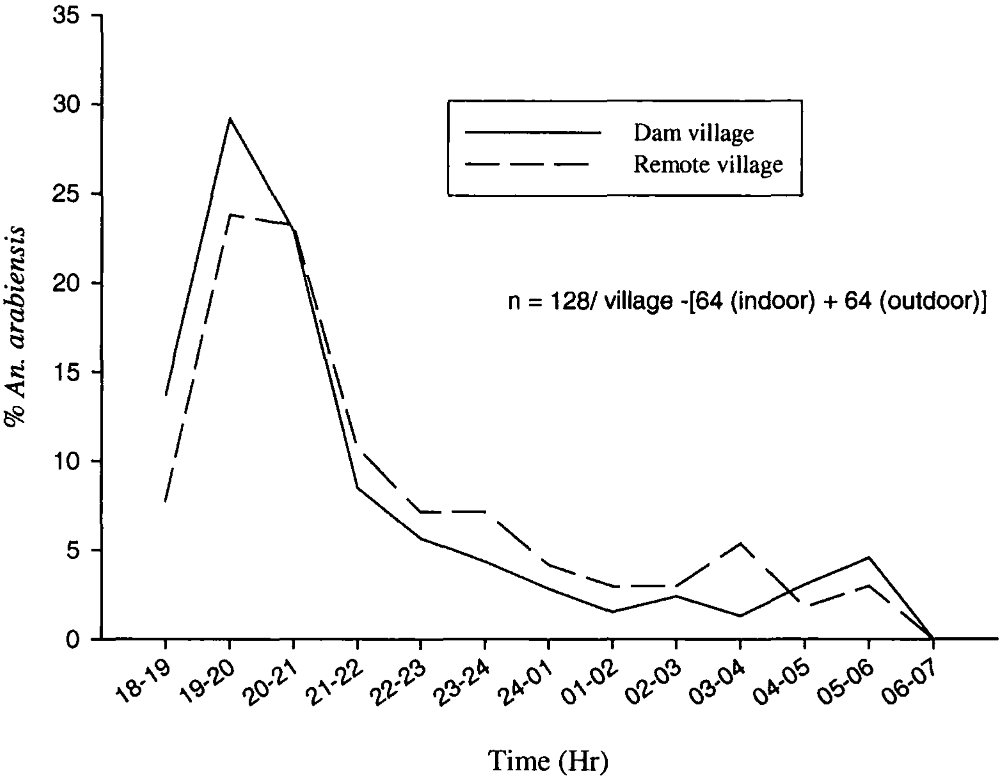


Figure 4.7. Biting cycle of *An. arabiensis* (indoor + outdoor) assessed by light traps set near sleepers under untreated bednets in the dam and remote villages (1999/2000).

The correlation between light trap catches and human landing collections was weak both indoors ($R^2 = 0.26$, $R = 0.5$, $F = 46.16$, $p<0.001$, $n=128$)) and outdoors ($R^2 = 0.17$, $R= 0.4$, $F = 27.2$ $p<0.001$, $n=128$) (Figures 4.8 and 4.9). When the mosquito density was low, light traps were efficient indoors, whereas outdoors human landing catches were more efficient at catching mosquitoes at low densities. In order to quantify the efficiency of the light trap catches compared with the indoor and outdoor human landing catches, the ratios were calculated by dividing the daily light trap catches (Ln LTC+1) by the matched human landing catches (Ln HLC+1). Light traps were 1.5 (95% CI= 1.2-1.8) times more efficient than human landing catches indoors, but were much less efficient with outdoor *An. arabiensis* populations (mean ratio =0.65, 95% CI = 0.41-0.89).

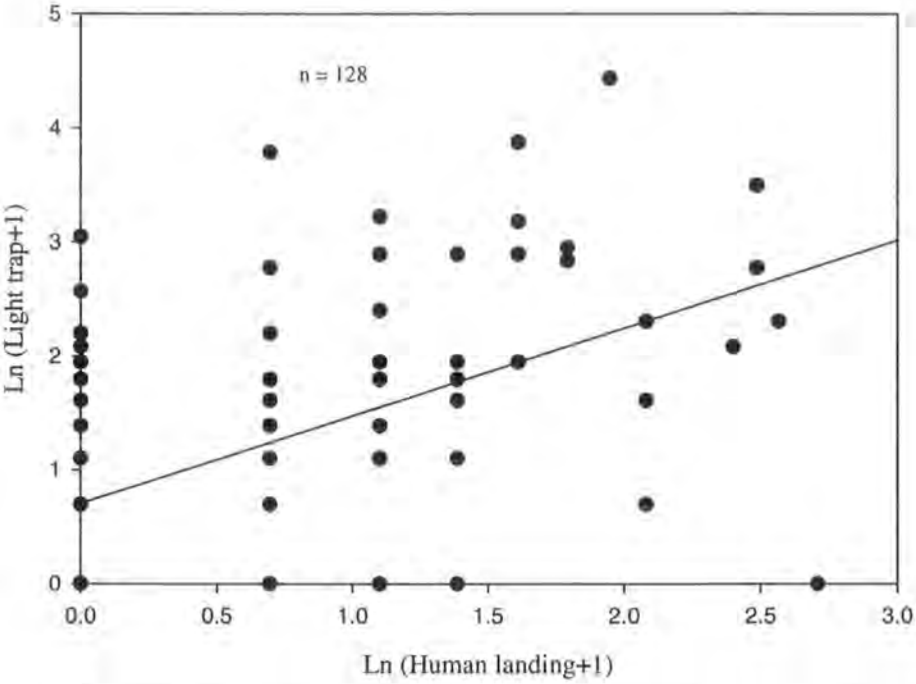


Figure 4.8. Indoor human landing catches plotted against matched light trap catches (1999/2000)[R^2=0.26, F=46.16, $p<0.001$, Lny = 0.703 + 0.770 Lnx]

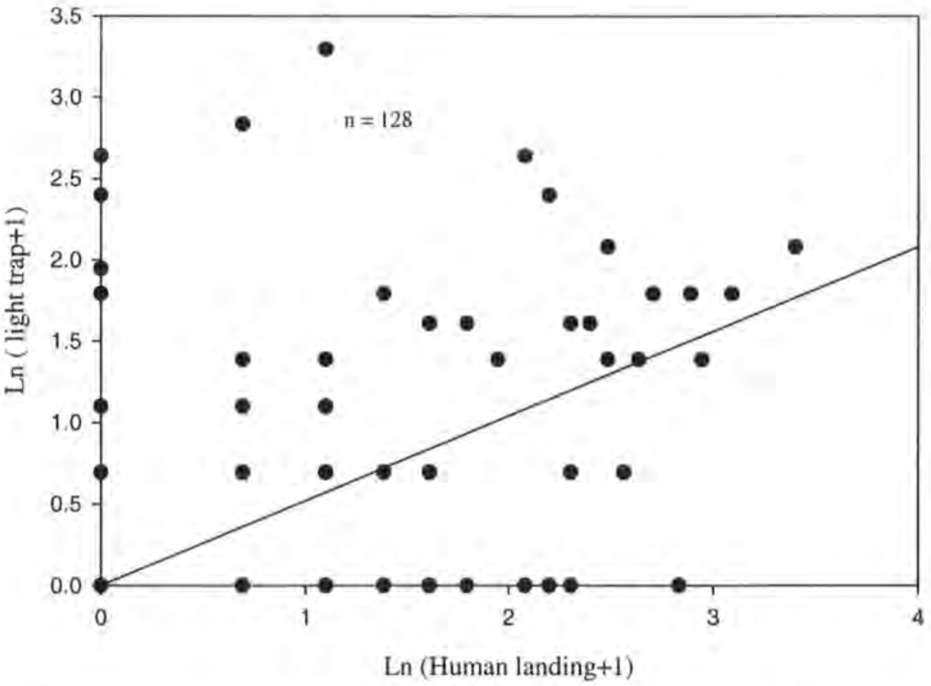


Figure 4.9. Outdoor human landing catches plotted against matched light trap catches (1999/2000)[R^2=0.17, F=27.221, $p < 0.001$, Lny = 0.330 + 0.35 Lnx]

PCR, Bloodmeal ELISA and sporozoite infection test results

All the 90 *An. gambiae s.l.* specimens tested with polymerase chain reaction were identified as *An. arabiensis*. 73.2 % of *An. arabiensis* had fed on people (142/194) and 26.8% on cattle (52/194). Of the human positive blood meals 45.1% (64/142) were mixed blood meals or were positive for bovine blood. The ratio of humans to cattle was similar in both villages - 1:2.9 (3.9:11.5) in the dam village and 1:2.2 (4.1:9.1) in the remote village. Out of 2650 head-thorax specimens of *An. arabiensis* tested in groups of 10 for *P. falciparum* and *P. vivax* circumsporozoite proteins only one positive specimen of *P. falciparum* was detected giving a sporozoite rate of 0.04%.

Human-biting rates

An average villager was bitten by 2.3 *An. arabiensis* per night in the dam and by 0.6 in the remote villages by human landing catches during the study (Table 4.4). The difference in biting rate was highest in May and November. Two peaks in biting rate were observed in the dam village- during the dry season and at the end of the wet season in September. The peak-biting rate in the remote village coincided with the rains (September). The malaria transmission potential parameters determined during the study are summarized in Table 4.5. An average villager in the dam village was likely to get about 0.3 (95% CI=0.2-0.5) infective bites of *P. falciparum* per annum compared with 0.08 (95% CI=0.04-0.1) in the remote village, assuming that the sporozoite rate was similar in both villages.

Table 4.4. A summary of biting rates by *An. arabiensis* from human landing catches, knockdown (space and exit trap), and light trap collection in dam and remote villages (1 bait/site).

Month	Human landing		Hourly light trap		Knockdown*		Light trap	
	Dam	Remote	Dam	Remote	Dam	Remote	Dam	Remote
Mar	0.09	0	-	-	0.28	0	2.2	1.0
Apr	-	-	-	-	0.32	0.06	2.8	1.0
May	3.63	0	-	-	0.22	0	10.1	1.0
Jun	-	-	-	-	0.26	0.04	4.7	1.3
Jul	-	-	-	-	0.09	0	2.8	1.1
Aug	-	-	-	-	0.04	0	2.8	1.1
Sep	5.96	3.55	24.9	2.6	0.17	0.04	9.7	3.2
Oct	2.62	0.93	5.1	1.8	0.19	0.01	5.7	2.2
Nov	2.16	0.11	3.1	2.2	0.09	0.01	2.6	1.3
Dec	-	-	-	-	0.08	0.01	1.9	1.5
Jan	-	-	-	-	0.31	0.09	1.2	1.3
Feb	-	-	-	-	0.13	0.04	1.2	1.2
Total	2.3	0.57	7.6	2.18	0.17	0.02	2.24	0.4

* Biting rate from knock down not multiplied with human blood index

Table 4.5. The entomological inoculation rate/individual/annum calculated for human landing, knockdown and light trap collections (95% Confidence intervals in bracket).

Village	Human landing			Hourly light trap*			Knockdown				Light trap-routine collection		
	ma	s%	EIR	ma	s%	EIR	m	HBI	s%	EIR	ma	s%	EIR
Dam	840 (584-1197)	0.04	0.34	7.6	0.04	1.1	62.1 (49.6-78.3)	0.73	0.04	0.02	818 (694-949)	0.04	0.33
Remote	208 (99-354)		0.08	2.2		0.3	7.3 (5.3-12.4)	0.73		0.002	146 (110-183)		0.06

*Concurrent hourly light trap catches with human landing catches were made for 3 months at the end of the wet season- hence it represents the same.

s% = is the percentage of sporozoite positive mosquitoes,

m = average number of mosquitoes/person/night x 365 days = number of mosquitoes/person/year; with knockdown collection *m* represents number of mosquitoes with blood in their gut

a = mosquito biting habit (is 1 with human landing and light trap collections; with knockdown collection *a* is the Human blood Index (HBI)

House leaving behaviour

Of the total *An. arabiensis* collected indoors 42.5% were caught in exit traps in the dam village (95% CI= 33.3-52.2%) and 17.2% in the remote village (95% CI= 4.6-31.3). The seasonal variation in *An. arabiensis* mosquitoes caught in exit traps in the dam village is shown in Figure 4.10. There was no statistically significant difference in the proportions of *An. arabiensis* caught in exit traps before and after DDT spraying both in the dam (χ^2 = 0.43, p = 0.51) and remote villages (Fisher exact, p = 0.6). The proportion of unfed (UF), fed (F), half gravid (HG) and gravid (G) *An. arabiensis* mosquitoes caught in exit traps was 0.2:0.3:0.4:0.1 in the dam village and 0.3 :0. 1:0.6:0, in the remote village during the study period. The number of F + HG (late fed) and UF + G in exit trap and space spray was not significantly different both in the dam (χ^2 = 0.57 p=0.45) and remote villages (χ^2= 0.2, p=0.6). The mean ratio of F + HG: G *An. arabiensis* indoors was 5.2:1 in the dam village and 10: 1 in the remote village. The mean ratio of F: HG+G was 0.5:1 in the dam village and 0.7:1 in the remote village.

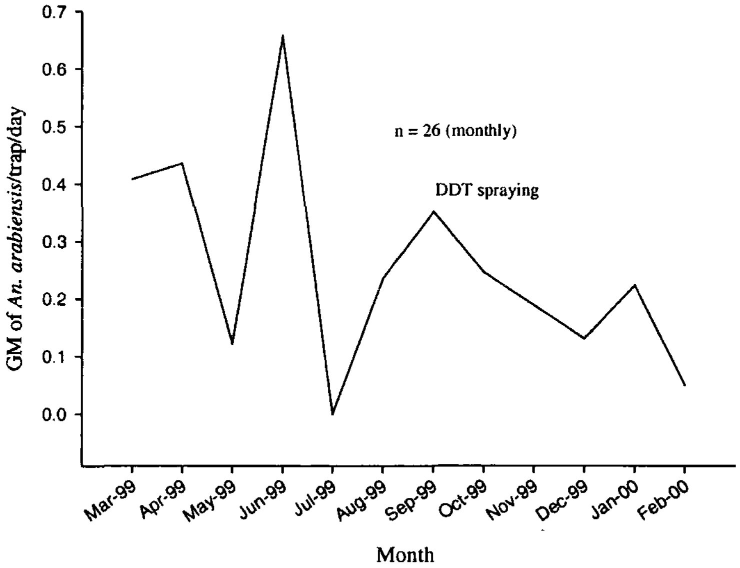


Figure 4.10. Seasonal variation of house leaving behaviour in *An. arabiensis* populations in the dam village (n = 308 for whole study period).

DDT susceptibility test results

Susceptibility tests performed on mosquitoes using the standard WHO test kits with 4% DDT impregnated papers showed 95% exposure mortality and 20% control mortality. The corrected mortality was 93.7%. The specimens for the test were collected from a neighboring village, across the dam, as mosquitoes were scanty in the dam village at the time. The temperature ranges of the exposure and holding periods were 25-30 °C and 19-27 °C respectively. The relative humidity for the exposure and holding periods were 73 and 83% respectively. Nevertheless, although according to the criteria proposed by Davidson and Zahar (Davidson and Zahar, 1973), susceptibility test results falling between 80 – 98% mortality require verification, this was not possible due to scarcity of mosquitoes when testing was carried out.

Within village variation of vector density

Both with light trap and space spray collections there was a marked difference in mosquito density between the houses, especially in the dam village. The rough division of the village into 3 zones based on proximity to the dam indicated that *An. arabiensis* populations were 3.2 times more abundant/trap/night in houses at the edge of the village towards the dam than those further away. The GM number of *An. arabiensis* /light trap/night was 7.2 in zone1 (near dam), 2.3 in zone 2 (further away), and 2.2 in zone 3 (furthest). The absence of appreciable difference in mosquito density between zones 2 and 3 was the fact that some of the houses in zone 3 with higher number of mosquitoes were near the stream coming from the dam although they were located at a greater distance from the dam. Considering the distance of individual houses sampled from identified breeding sites, a decrease in mosquito abundance with distance was apparent (Figure 4.11).

Distance of houses to nearest breeding sites was determined by calculating the distance between two GPS points by making the assumption that one degree of latitude or longitude is equivalent to 110km in the equatorial region (Ghebreyesus *et al.*, 2001). Accordingly, the latitudinal distance between two points was calculated as

$$\text{latitudinal distance} = (\text{latitude}_1 - \text{latitude}_2) \text{ x } 110 \text{ km}$$

$$e.g. \quad (14.3258^{0} - 14.3041^{0})\, x\, 110 = 2.39\, km$$

and the corresponding longitudinal distance as

$$\text{longitudinal distance} = (\text{longitude}_1 - \text{longitude}_2) \text{ x } 110 \text{ km}$$

$$e.g. \quad (38.1209^{0} - 38.1157^{0})\, x\, 110 = 0.57\, km$$

and then by Pythagoras' theorem the actual distance as

$$\text{actual distance} = \sqrt{(\text{latitudinal dist})^2 + (\text{longitudinal dist})^2}$$

$$e.g. \quad \sqrt{2.387^2 + 0.572^2} = 2.46\, km$$

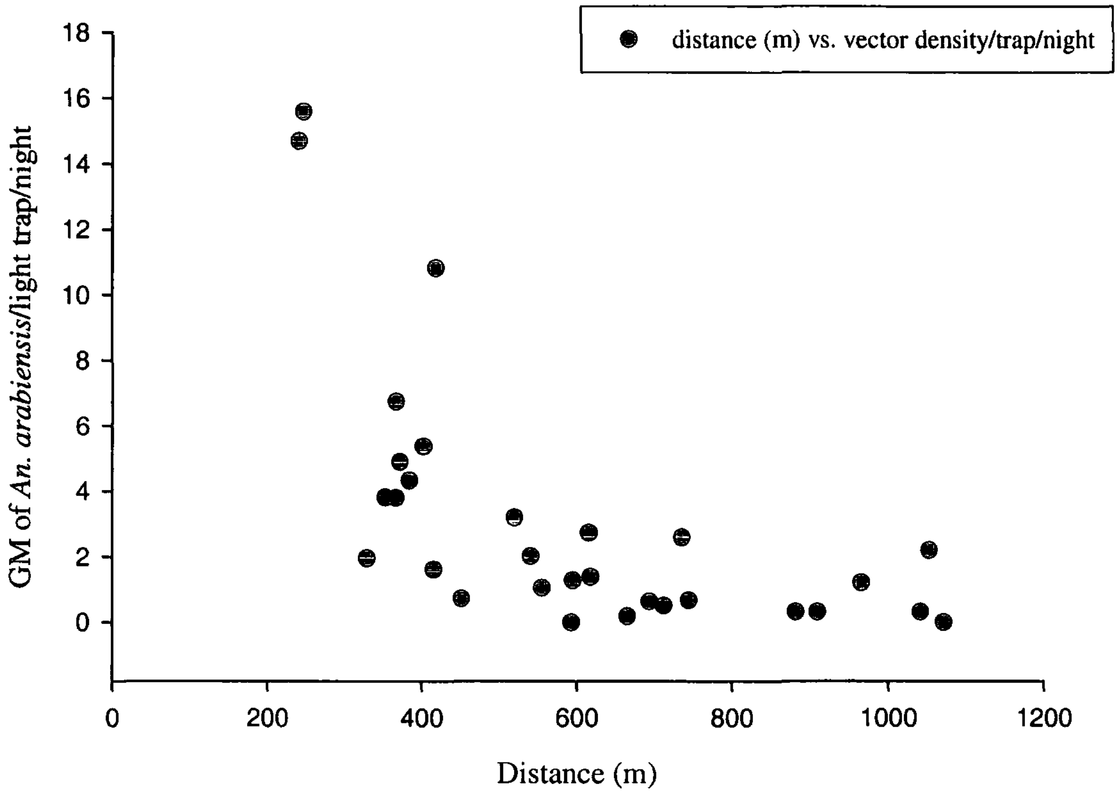


Figure 4.11. Variation of vector density/house/night with distance from breeding sites in the dam village during the dry season.

Discussion

The results of the study showed a higher potential for malaria transmission in the dam village compared to the remote village, reflecting the influence of the dam. This was despite the fact that the study was carried out amid intensive control measures- residual DDT spraying and prompt treatment of cases with the newly introduced drug (Fansidar) by village-based community health workers and enumerators. The incidence rates and the results of the spleen survey indicate that malaria was hypoendemic in the area and the population has little or no immunity. Spleen rates were 3 times higher in children living close to the dam compared with those in the remote village, illustrating the greater level of exposure experienced in the dam village. The incidence rates in the study villages were low and no statistically significant differences between them were shown. Nonetheless, the overall incidence rate was 2 fold higher in the dam village compared to the remote village during the whole year and 5.5 times higher during the dry/cold season (January/February).

This together with a 7.7 times higher *P. falciparum* prevalence rate just at the end of dry season in June 1999 (or beginning of rainy season) in the dam village compared to the remote village indicates that malaria is no longer restricted to the main malaria transmission season. Similar, but statistically significant, differences in clinical attack rates were found between dam and remote villages in a larger study (Ghebreyesus *et al.*, 1999), indicating that the difference in morbidity between the two study villages is a real one. The presence of *P. falciparum* cases during the dry season clearly indicated the presence of active transmission not associated with the rains.

Overall, *An. arabiensis* was 6.5-8 times more abundant in the dam village compared to the remote village during the study period. Peak mosquito numbers in the dam village occurred in May, during the dry season, when the fields were irrigated, indicating that transmission was no longer restricted to the rainy season as is typical for the region. Light trap catches showed that during this period *An. arabiensis* was 16 times more abundant in the dam village compared to the remote village. The human biting rate was similarly higher (3.2 times greater) during the dry season in the dam village.

These findings support those of other studies where dams have been associated with increased malaria transmission (Hunter *et al.*, 1993). Construction of small and medium-sized dams and over 100 small artificial lakes for aquaculture in Cameroon was blamed for increased prevalence of endemic diseases including malaria (Ripert and Raccurt, 1987). The building of dams in the Uasin Gishu Highlands in Kenya was associated with increased malaria transmission (Khaemba *et al.*, 1994). In Ethiopia, natural lakes in the Great Rift Valley, such as Lake Zwai at an average altitude of 1640m, maintain malaria transmission almost throughout the year (Abose *et al.*, 1998).

As described elsewhere, although dams are known to moderate climate extremes by increasing the minimum temperature at night and lowering the maximum temperature of the surroundings during the day, the main reason for increased malaria transmission around most dams is probably due to the creation of large areas of breeding sites in seepage, water ways and the fields irrigated by the dams. In some settings, dams may also create enormous breeding sites around their edges for an extended period, although no mosquitoes were found around the Meskebet dam (chapter 6) during the study. This is particularly pronounced with smaller dams, as they have a disproportionately greater shoreline development relative to the surface area, than large dams and natural lakes (Baxter, 1977; Jewsbury and Imevbore, 1988). Moreover, as small dams are mostly associated with human settlements, acting as a source of drinking water for livestock, it is possible that large numbers of pools could be created along the shore in hoof prints and puddles, providing favourable breeding sites for vectors. Besides, small impoundments, when they are not fully financed by governments and are constructed by local communities, are often affected by problems of maintenance, seepage and water discipline, all of which favour extension of vector habitats. On the other hand, deep reservoirs with regular shorelines and steeply sloped margins have a low marsh potential and are likely to support far less mosquito breeding than shallow reservoirs with a long, irregular shoreline and gently sloped margins (Hunter *et al.*, 1982; Jewsbury and Imevbore, 1988; Birley, 1991).

The relatively higher number of *An. arabiensis* recovered from outdoor resting sites in the dam village also suggests that dams provide abundant microenvironments favoured by the vectors as day-time resting sites. Irrigation water and seepage, besides creating numerous breeding sites, moistened the riverbanks or the sides of gullies and the environs thereby increasing relative humidity at a microscale in these surroundings. Apart from this, the dam, by raising the water table, increased the moisture content of the soil. This results in abundant vegetation and proliferation of innumerable microenvironments with elevated relative humidity favouring mosquitoes through out the year. Higher numbers of *An. arabiensis* were collected outdoors in the dam village from under short vegetation and from relatively cool and humid holes and crevices along stream banks, and elsewhere (well-shaded earth banks or the sides of gullies, in shaded holes of stone fences, cavities near the roots of big trees, in termite mounds, under bridges used to cross irrigation canals, etc.). The maize fields and associated plants also provided suitable resting sites for mosquitoes in the dry season. Enhanced development of *An. arabiensis* larval stages feeding on maize pollen has also been reported under field conditions from Ethiopia (Ye-Ebiyo *et al.*, 2000), suggesting that maize cultivation by irrigation further encourages the proliferation of *An.*

arabiensis populations in the dry season. Thus, dams besides extending the breeding season and facilitating rapid development of the vectors and the parasites by moderating temperature extremes, may also elevate the relative humidity in dry regions which ensures better survival of the malaria vectors (Garret-Jones, 1964a; WHO, 1975; Dye, 1986; WHO, 1997).

The relatively high HBI for *An. arabiensis* in the study area indicates its capacity to be an efficient vector. Similar feeding preferences of *An. arabiensis* were reported from different parts of the country from indoor-resting collections. White and colleagues (White *et al.*, 1981) and Krafsur (Krafsur, 1971; Krafsur and Armstrong, 1978) reported an HBI of 100% for *An. gambiae s.l.,* most probably *An. arabiensis*, collected from human dwellings in Jimma and Gambella, in southwestern Ethiopia. From mixed dwellings, White and colleagues (White *et al.*, 1981) found 46 % human-blood fed, but found no human-fed mosquitoes outdoors and in animal shelters. Adugna & Petros (Adugna and Petros, 1996), from different parts of Ethiopia in the Rift Valley, recorded a higher proportion of human blood in *An. arabiensis* from both mixed dwellings (88%) and cattle sheds (43%). In another study, which involved six malarious localities in eastern, southern and western Ethiopia, a higher proportion of human-blood meals from mosquitoes caught in human dwellings (91.5%), followed by those from mixed dwellings (20.2%), and cattle sheds (3.5%) was reported (Hadis *et al.*, 1997). Since the abdominal squashes on filter paper were made from mosquitoes collected mainly by light traps, the relatively lower proportion of human blood in this study suggests that the host seeking mosquitoes may have been deterred by the bed nets used during light trap collections and sought an alternative host outdoors (bovines). Nonetheless, the presence of a high proportion of mixed blood meals (about 45% of all human blood positive samples) suggests that some of the mosquitoes were at least partially successful at getting part of their blood meal from humans through the bed nets. Bed net use by people sleeping on the floor and on raised earth beds are unlikely to be fully protective from mosquito bites as it is difficult to tuck in the bed nets successfully the whole night. This is especially true when more than one person sleeps under one bed net.

The sporozoite rate in the study area was relatively low and as a result the entomological inoculation rate was also low- about 0.3 infective bites/individual/year in the dam village and 0.08 in the remote village by human landing and light trap catches. Although, such low sporozoite rates are to be expected under intensive control measures, previous studies from Ethiopia also show that the sporozoite rate for *An. arabiensis* is generally low, even in hyperendemic areas of perennial transmission ranging from 0.11 to 5.4% (Rishikesh, 1966; Krafsur, 1971; Krafsur and Armstrong, 1978; White *et al.*, 1981; Ameneshewa, 1995; Abose *et al.*, 1998).

My findings show that in the study area *An. arabiensis* has an early biting peak (19:00-20:00 hr), which differs from the typical pattern of biting by *An. gambiae s.l.* (Gillies and De Meillon, 1968). Typically the essential features of the biting rhythm are an initial period of very low activity up to 21:00-22:00hr, followed by a heightened activity of feeding reaching a peak in the period from midnight to 04:00hr, but with considerable activity continuing up to shortly before dawn. Many of the biting activity studies on *An. gambiae s.l.* conducted in Africa after the 1960s are presented in Table 4.6 and essentially show the same trend. In my study the decreasing trend in biting activity during the night is unlikely to be related to the colder temperatures found at higher altitudes since collections made in the hottest and coldest months of the year showed the same peak in early evening biting. The early biting activity could have a negative bearing on the currently widely recommended use of insecticide-impregnated bed nets to control malaria, since people could get a substantial number of infective bites (approximately 70 %) before going to bed under their bed nets. This pattern of biting has also been reported in villages adjacent to Lake Zwai, in Ethiopia (Abose *et al.*, 1998), although in this study few mosquitoes were collected. In the same study area, Rishikesh (Rishikesh, 1966) reported an indoor biting peak for *An. gambiae s.l.*, mainly before dawn although the biting cycle differed according to season. The peak activity was found to occur from 03:00-04:00hr in July, 04:00-05:00hr in August, 21:00 to 22:00hr in September and November, and 23:00 to 24:00hr in October. In Baekel and vicinity (near the town of Humera), western Tigray, activity of *An. arabiensis* peaked after 23:00hr (personal communication, Assefaw -Malaria Control Dept.

Tigray). Similar pattern of activity was reported from the town of Gambella, southwestern Ethiopia (Seulu *et al.*, 1989).

Table 4.6. The biting rhythm of *An. gambiae s.l.* in different parts of Africa.

Country	Author	Species	Hr of Peak biting	
			Indoor	Outdoor
Ethiopia, near Lake Zwai	(Abose *et al.*, 1998)	*An. arabiensis*	18:00-20:00 (< 1 mosquito)	22:00-24:00
Ethiopia, Gambella	(Seulu *et al.*, 1989)	*An. arabiensis*	22:00-24:00 (2300)	21:00-22:00
South Africa	(Braack *et al.*, 1994)		05:00-06:00	
Tanzania	(Maxwell *et al.*, 1998)	*An. gambiae s.l.*	01:00-03:00	
Kenya	(Githeko *et al.*, 1996)	*An. arabiensis*	05:00-06:00	02:00-04:00
Sudan	(Dukeen and Omer, 1986)	*An. arabiensis*	04:00-05:00	
Uganda	(Haddow, 1945; Haddow *et al.*, 1947)	*An. gambiae s.l.*	05:00-06:00	
Kenya, Kisumu	(Haddow, 1942)	*An. gambiae s.l.*	05:00-06:00	
Kenya	(Surtees, 1970c)	*An. gambiae s.l.*	03:00-06:00	
Kenya	(Chandler *et al.*, 1975)	*An. gambiae s.l.*	05:00-06:30	

The biting cycle of many anophelines are constant under differing conditions, and are probably manifestations of endogenous rhythms characteristic of a particular species (Corbet, 1961; Gilles and Warrell, 1993). Studies which indicate a variation in this peak activity at different times of the year may be an artefact due to the small sample size or reflect changed atmospheric conditions, such as strong winds or rain, that restrict mosquito flight. However, the reasons for the differing biting rhythms exhibited by *An. arabiensis* populations in different parts of Ethiopia are uncertain.

Haddow and colleagues (Haddow, 1945; Haddow *et al.*, 1947) working in a dense forest area in Uganda found the biting cycle of *An. gambiae s.l.* was inversely related to temperature and saturation deficiency but was directly related with relative humidity. At Mongiro and Mamirimiri forest areas they found that relative humidity remains practically constant at around 90%, throughout the night but temperature declines steadily, they therefore concluded that temperature must be among the most important microclimatic factors influencing the biting cycle. This reasoning would most probably apply to the biting activity observed in my study area as there was a steady decrease both in temperature and biting rate throughout the night which was the opposite to the trend of activity observed in their study. Braack and associates (Braack *et al.*, 1994) found no correlation between the biting cycle of *An. gambiae s.l.* and temperature in South Africa. Therefore, it seems unlikely that temperature is the major determinant of the biting rhythm (Gillies and De Meillon, 1968; Muir, 1988).

The early evening biting peak seen with *An. arabiensis* may be a consequence of residual application of insecticides, notably DDT. Shift in the biting cycle from the early hours of the morning to early evening has been shown following DDT indoor spraying in the Solomon Islands for *An. gambiae s.l.* (Taylor, 1975) and *An. minimus* in a forested terrain of northern Thailand (Ismail *et al.*, 1978). A similar change in biting behaviour was observed following the use of permethrin-impregnated bed nets in *An. farauti* populations in Papua New Guinea (Charlwood and Graves, 1987) and a slight shift in *An. gambiae s.l.* in western Kenya (Mathenge *et al.*, 2001) and in Tanzania (Magesa *et al.*, 1991) although the observed differences between treated and untreated villages were small and observed in a few treated villages. Nevertheless, many other studies from Africa (Quinones *et al.*, 2000; Ilboudo-Sanogo *et al.*, 2001) have found no evidence of a switch to outdoor rather than indoor biting and of the selection of mosquito phenotypes that might compromise the intervention with permethrin-impregnated bed nets. Moreover, if the switch to early evening biting were due to DDT (or other insecticides), consistent effect of this kind would be expected elsewhere in Africa, particularly in other parts of Ethiopia, as DDT has been in use here for over 30 years. Nonetheless, changes have been recorded in the biting cycle of *An. arabiensis*, which illustrates the genetic plasticity of this mosquito (Muir, 1988).

A weak linear relationship was observed between light trap catches and human landing collections based on nightly catches, although the relationship was stronger with hourly catches. This association was stronger with indoor collections than outdoor collections even under low mosquito density. Overall, more *An. arabiensis* were caught with light traps than human baits and light traps were particularly efficient at catching mosquitoes when few were active. These findings are in general similar to those observed in West Africa (Odetoyinbo, 1969; Costantini *et al.*, 1998), in coastal Tanzania (Davis *et al.*, 1995), and in Morocco (Bailly-Choumara, 1973a; Bailly-Choumara, 1973b).

My study suggests that light trap catches can be used as an alternative to human landing collections of indoor biting anophelines, to estimate the man-vector contact when logistic or ethical conditions do not permit night-biting catches. Besides, the catching efficiency of collectors performing all-night catches is likely to be low when few mosquitoes are biting. Moreover, light traps are easy to operate, require minimum organization and personnel and tend to reduce the inconvenience that might be caused to the owners of the houses by the mosquito collectors. In areas where effective administration is not in place to control criminals and bandits and in instances of civil unrest or war, such as during the present study, it can be unsafe to be out at night for collection or supervision in remote villages. Light traps when used in association with bed nets to protect the sleepers are also more advantageous over unprotected bait collections or indoor resting catches as they eliminate subjectivity (Lines *et al.*, 1991; Davis *et al.*, 1995) while generally catching higher numbers of mosquitoes per trap than per human bait as observed in the study.

One limitation of light traps is that they may not always sample a similar population of mosquitoes as those obtained from human baits. Whilst in some studies (Lines *et al.*, 1991;

Davis *et al.*, 1995; Costantini *et al.*, 1998) the parity and sporozoite rates of *An. gambiae s.l.* and *An. funestus* obtained by light traps were similar to those from bait collections, in others higher sporozoite rates were recorded from light trap collections than those from human baits (Davis *et al.*, 1995). Githeko and colleagues (Githeko *et al.*, 1994) from western Kenya, found lower parous rate in mosquitoes collected by light traps. They also found a positive correlation with *An. funestus* between light traps and human baits, but not with *An. arabiensis*. They concluded that the lack of correlation seen with *An. arabiensis* implies that CDC light traps may not provide correct information about human biting rates in *An. arabiensis*. Moreover, they indicated a critical vector density below which it is unlikely that females will be collected in CDC light traps. This finding contradicts my own observations in the study area. These contradictory results suggest that the correlations between light trap catches and human landing collections should be made at local levels and that inferences from correction factors derived elsewhere may be misleading.

An. arabiensis, the principal vector of malaria in the area, was highly anthropophilic and partially exophilic. The small proportion of gravid among the indoor resting samples (8%) coupled with the high exit rate (42.5%) of this species in the dam village show that they are partially exophilic. Although *An. arabiensis* was considered to be highly endophilic in Ethiopia in general (Gebremariam, 1988), an incipient tendency to feed indoors and rest outdoors has been reported from different parts of Ethiopia (Krafsur, 1977; Gebremariam, 1984; Seulu, 1991; Ameneshewa and Service, 1996b; Abose *et al.*, 1998). Besides, a higher preference to rest in Tukuls (house of wood/mud walls and thatch) than in stone and mud walls has been reported (Abose *et al.*, 1998), as the former provide more concealed and safer shelters during the day than the stone-mud walled houses. The absence of significant difference between the numbers of fed and half gravid compared with unfed and gravid mosquitoes in space spray and exit trap collections also suggests that mosquitoes in all gonotrophic stages exit from indoors indicating an exophilic tendency in *An. arabiensis*. Although behavioural avoidance of DDT sprayed houses have been widely reported for *An. arabiensis* in many parts of Africa (Sharp *et al.*, 1990), the absence of a significant difference in exit rates before and after DDT spraying probably indicates that this exophilic behaviour is already established in the mosquito populations before the study period.

In conclusion the results of the present study show that dams create favourable environmental conditions for vector abundance and malaria transmission in local communities. Although the main reason for the increased abundance of mosquitoes and incidence of malaria might be due to the creation of extensive breeding sites for an extended period of time, dams may also create suitable microclimatic conditions. In addition to moderating climate extremes in the general surrounding by their "lake effect", they also create well-shaded daytime outdoor resting sites with favourable humidity and temperature at a micro scale. The raised water table and seepage, together with the irrigation water, saturate the soil and promote abundant growth of vegetation. They also wet depressions and holes in the river or gully banks and elsewhere around and provide favourable resting sites. In general, this would enhance the longevity and generation time of the vectors and the transmission of the parasites thereby extending the transmission season and exposing the non-immune population to increased risk of infection. A change from seasonal to uninterrupted transmission would prevail and if not rectified would lead to increased incidence of malaria. The more intense transmission would increase the risk of mortality and morbidity and the outcome might be that death and illness among non-immune adults would reduce productivity. In addition, poor operation of the drainage system could result in increased soil salinity and the abandonment of the irrigated land after so much was invested in it.

Chapter 5. The impact of a community-led larval intervention against malaria near a microdam in Tigray, northern Ethiopia.

Plate 5.1. Seepage area below the dam being drained (above) and shortly afterwards-reeds maintained and access prohibited to cattle and people (below).

Abstract

The construction of dams and development of irrigation schemes in endemic areas can lead to increased abundance of mosquitoes which transmit malaria by creating more breeding sites and extending their breeding season. To mitigate the increased threat of malaria around microdam sites, a longitudinal community-led larval intervention study was conducted in Deba village, situated near a microdam, in Tigray northern Ethiopia, where an extensive microdam-based irrigation scheme is in progress. The outcome was evaluated by entomological and parasitological surveys before and after intervention in the dam village, and Maisheru village, situated 3-4km away from the dam, acted as a control. Adult mosquitoes were collected by CDC light traps and the aquatic stages sampled by standard dippers. Blood samples were taken from children under 10 years of age to identify malaria parasites during the wet and dry seasons. Overall, there was a 49% reduction (95% CI = 46.6-50.0) in indoor-resting and a 27% reduction (95% CI = 5.8-30.5) in outdoor-resting *Anopheles arabiensis* relative to pre-intervention levels, adjusting for variation between different years. A significant reduction in the number of *An. arabiensis* positive pools was achieved in the major breeding sites-seepage ($p< 0.001$), man-made pools ($p< 0.001$), leakage from canals ($p< 0.001$), irrigated fields ($p< 0.001$), and drainage canals ($p<0.01$) compared with the intervention year. A statistically significant reduction in number of positive dips and number of larvae per dip was recorded in breeding sites created by seepage, leaking canals, man-made pools, drainage canals and fields irrigated from the dam ($p <0.001$). No malaria cases were encountered during the dry season of the post intervention year, unlike in the preceding year. Overall, our study, which involved minimal community involvement, showed that if serious and sustainable community-led environmental management measures could be introduced as a package, it would be possible to mitigate the impact of microdams to an appreciable extent and calls for an integrated approach to malaria control, particularly near microdams.

Introduction

The construction of dams and development of irrigation schemes in endemic areas can lead to changes in the risk of malaria transmission, by creating more breeding sites and extending their breeding season (Hunter *et al.*, 1982; Lindsay *et al.*, 1991; Hunter *et al.*, 1993; Ijumba and Lindsay, 2001). In most of sub-Saharan Africa, where malaria is endemic, irrigation schemes are unlikely to increase malaria incidence in local communities (Ijumba and Lindsay, 2001). However, in areas of fringe transmission, such as the Ethiopian Highlands increases in vector abundance can result in a serious increase in clinical episodes of malaria. People in these areas have no or little immunity to malaria and often experience periodic epidemics (Ghebreyesus *et al.*, 1999). As most small-scale irrigation projects do not consider health risks (Hunter *et al.*, 1993), local communities may be especially vulnerable to malaria. In the Tigray region of northern Ethiopia, an extensive, mainly community led, microdam-based irrigation scheme is in progress and about 60 microdams are built so far and many more are envisaged as a source of drinking water and hydropower. Over forty-five of the microdams built were constructed under the auspices of Tigray Sustainable Agricultural and Environmental Rehabilitation Commission (SAERT;(WIC, 2002). These and the other dams constructed involved high community participation. In addition to the construction of further microdams, by the Commission, 25 rivers are being harnessed to provide irrigation for farmers. Many of these projects are located at epidemic-prone areas. Incidence surveys carried out in communities near 8 microdams paired with remote from dam villages have shown that malaria incidence in children under 10 years of age was 7 fold higher in near dam village communities than those away from the dams (Ghebreyesus *et al.*, 1999). As described in chapter 4, *An. arabiensis* was 7-8 times more abundant in the dam village compared to the remote village and this was more pronounced during the dry season when the fields were irrigated.

Current control activities in Tigray, as in other parts of Ethiopia, involve Health centre-based diagnosis and treatment of cases, selective indoor residual spraying with DDT (and malathion in DDT resistant areas), larviciding in selected urban areas during the rainy season, and epidemic control. In addition, a community-based presumptive treatment of clinical cases is in place in villages where treatment is by voluntary community health workers (CHWs) (WHO, 1999). Although as a policy the CHWs have to mobilise the community for environmental management during the main transmission season, this strategy has never been effectively carried out, nor systematically evaluated. There is also emphasis on community-wide utilization of insecticide-treated bed nets although this control strategy is still in its infancy in Ethiopia. No specific control initiatives are in place to particularly address the problem with the microdams. Generally, despite increased efforts to strengthen control activities, a significant proportion of the rural population still remains without easy access to the general health services and malaria remains a major public health problem in Tigray. Apart from lack of coverage with the available control measures, resistance of parasites to treatment and the vectors to insecticides (DDT) is a growing problem. Under utilization of CHWs by women and children, low compliance to chemoprophylaxis by pregnant women has been documented (WHO, 1999).

Based on results of chloroquine-efficacy studies, the ministry of health of Ethiopia has recently changed the malaria first-line treatment from chloroquine to Fansidar (sulfadoxine- pyrimethamine) (MOVBDCU, 1999). Nevertheless, considering the resistance history of the drug in other parts of the world, coupled with its wider use at a community level, development of resistance to this drug is inevitable. The effective utilization and sustainability of bed nets is also questionable, in a society where malaria-related treatment and control was given free of charge and there is a strong belief that the government should be the ultimate provider. The outcome of a pilot community-financing scheme of insecticide-treated nets started in Humera, western Tigray, and an important area of agricultural development and highly malarious area (WHO, 1999) shows this. Preliminary surveys at the beginning showed good knowledge and attitude towards bed net use and willingness to buy at a "balanced" cost, or at times of cash availability, but the re-impregnation rate of bed nets was extremely low, although the reasons given were due to war at the time. This study took place in a relatively affluent part of Tigray, where the population is better able to pay for bed nets and re-impregnation. Besides, bed net use would not be effective in areas where the vectors bite humans early in the evening before the people settle to their beds as observed in my study villages (Chapter 4). Synthetic insecticides used as residual sprays or in bed nets are also unlikely to be a panacea given the potential for resistance to arise and reduce their efficacy.

Against this background, an integrated approach to malaria control, where strategies are combined and customized to the behaviour of particular vector species and situations is the one that will most be effective and sustainable. Such approaches should take into account under-utilised but promising strategies such as the manipulation of the environment, based on the understanding of the local ecology and the behaviour of the vectors, along with other control activities - all in an integrated fashion. Source reduction through modification in larval habitats has been a neglected area of vector research and control although it was one of the main methods of malaria control and eradication efforts in many countries including the United States, Israel, and Italy (WHO, 1982; Rafatjah, 1988; Kitron and Spielman, 1989; Ault, 1994). In the days before the introduction of DDT, the control of malaria vectors in urban and other economically important areas of tropical Africa was based mainly on source reduction, eliminating their breeding places or concentrating them for more effective chemical larviciding (Boyd, 1949; Russel *et al.*, 1963). Despite the alarming growth of unplanned urbanization and water resources development schemes in the past decades in Africa, such measures have not been maintained or adequately implemented especially in new water resources development projects. Water impoundments are designed and operated without regard to known health hazards (Stevens, 1984). Appropriate management of larval habitats in the sub-Saharan countries, particularly during the dry seasons and where mosquito density is relatively low, may help to suppress vector densities and malaria transmission. This is particularly so in fringe areas of malaria transmission where community-based irrigation schemes are in progress and communities are vulnerable to malaria, such as the highlands of Tigray. There are numerous examples of how vector control measures, like larval control and environmental management, as well as indoor spraying, have helped control or eradicate malaria in areas of marginal or unstable transmission (Russel *et al.*, 1963; Ault, 1994). Simple environmental modification or manipulation methods can be effective and may require minimal mass community participation if proper guidance is given especially in communities where the citizens recognize malaria as a burden. At a minimum level, the method used may involve the householder doing repairs or renovation on his or her home or irrigation canal at their own pace (Ault, 1994).

Thus, the main objective of this study was to test whether environmental manipulation, notably source reduction, shading of breeding sites with vegetation, and other physical methods such as filling and draining could reduce vector breeding. The study was based on the results of the pre-intervention period where larval habitats and the behaviour of local *An. arabiensis* populations were defined.

Materials and methods

Study Area

The longitudinal study was conducted in Deba village near Meskebet microdam in Tigray, northern Ethiopia. The topographically similar village, Maisheru, located 3-4km in a neighbouring valley was used as a control village. A detailed description of the study area is given in chapters 2 and 3. Briefly, the area is characterised by a single rainy season extending from end of May to October. November through January is the coldest period of the year, followed by the hottest months of March-May. Deba village had a population of 347 inhabitants and Maisheru about 1253, all of whom were subsistence farmers, mainly growing cereals and keeping livestock. In the dam village, fields near the dam were irrigated from January to June, and preparation of the fields and seedling plots were conducted from last week of November to December.

The dam had a 4.9km shoreline and a 570m long and 27m high embankment made of a pile of compacted earth and had a nominal capacity of water to irrigate 65ha. Nevertheless, only 15ha of land was under cultivation during the study period. There was an extensive area of seepage at the bottom of the dam embankment, irrigation canals leaked, irrigation waters overflowed, and puddling was frequent in the fields and in the irrigated valley below the dam. This was exacerbated due to substantial tunnelling under the fields, due to termites, resulting in the production of numerous small pools and considerable wastage of water. The main, 2km long, irrigation canal followed the edge of the village. This canal was not lined, except the first 200m from the outlet where it leaked at several places, water logging the surrounding fields. Moreover, in some places, the main canal was inclined upwards, against the flow of water, causing water to overflow and leak from the sides. Bad construction of feeder canals resulted in leakage at unwanted places, especially where they were constructed from soft soil. As a consequence, the farmers abandoned most of these canals and led the irrigation water through temporary channels of their own, parallel to the original canals. Most of the main and secondary canals were congested with vegetation. The local villagers owned most of the irrigated land, although people living outside the village – in neighbouring towns and villages, also owned many plots. Each beneficiary owned only one irrigable plot of about 50 x 50m^2 size.

Maize was the main crop grown by irrigation, followed by onion, green paper, potato, and tomato. Fruits like banana and sugarcane were cultivated on the swampy area created by seepage of water from the base of the dam but without success. Elephant grass (*Pennisetum purpureum*) was transplanted into the gullies and *Sespania* plants were grown for animal fodder along the edges of the fields. The dam, irrigation canals, major waterways, seepage and the coordinates of each positive breeding site was recorded and mapped by GPS (Garmin 38, USA). Both villages were not sprayed with DDT during the intervention phase of the study.

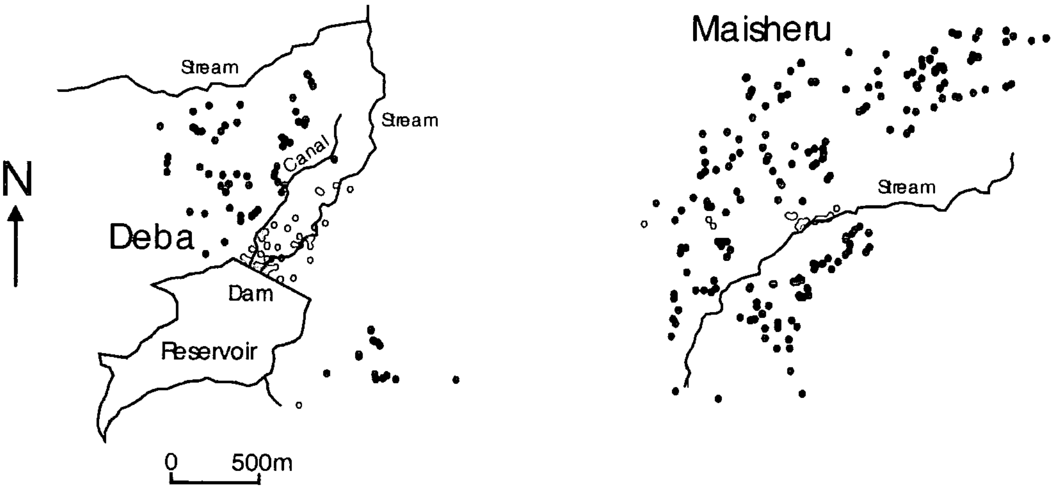


Figure 5.1. GPS point coordinates of reservoir, major waterways, irrigation canal, houses (black circles) and breeding sites (red) in the dam and the remote village (GPS points plotted by a SigmaPlot graphic software and the x-y axes removed).

Larval Intervention Activities

Regular bi-monthly community-led larval intervention activities were carried out in the dam village from end of February 2000 to December 2000 and evaluations made by regular entomological and parasitological surveys. Entomological and parasitological surveys were also carried out in the remote village for comparative purposes. Larval control was focused on water seepage areas and leaking canals, as these were the predominant breeding sites of *An. arabiensis* (Figures 5.1 and 5.2). Thus, the swamp created by seepage below the dam embankment was drained at the beginning of the study in February 2000 and the drains regularly cleaned thereafter. Papyrus and reeds were propagated and maintained in the dam seepage and along the gully below so as to shade the breeding sites of *An. arabiensis.* Entry of people and livestock was prohibited into the seepage area to avoid the creation of breeding sites in hoof and footprints. The streams in the gully were regularly straightened so that pooling did not occur. Simple drainage ditches were constructed to intercept the leaking water from the canals that had created water logging in the fields and these and the irrigation canals were regularly repaired. Sediment and vegetation were also removed from the irrigation and drainage canals to encourage water flow and prevent pooling. Puddles and abandoned water pools dug in the river or streambed for drinking purposes were filled with earth or sand. The crossing points of cattle and humans along the riverbed were filled with rocks and gravel to prevent the creation of breeding sites in hoof and footprints. Puddles and pools that were difficult to drain or fill were covered with the remains of reeds, grass and weeds so that mosquitoes could not reach the water. Decomposition of the plant material also rendered it less attractive for *An. arabiensis* breeding, which prefer unpolluted water. For mobilizing the community we used the existing administrative hierarchy and different local committees in the community. It would be appropriate to point out here that, stimulated by what was going on in the dam village, the inhabitants of the remote village also carried out limited source reduction activities beyond our control at the end of the rainy season.

Entomological Surveys

Larval survey

Monthly larval surveys were carried out both during the pre-intervention (March 1999-February 2000) and the intervention phases (end of February 2000-December 2000) in both villages to identify the major vector breeding sites and evaluate the intervention activities. The different types of water bodies at each site were identified and classified. Larval collections were made twice monthly between 09:00 and 16:00hr each day using standard dippers (350mm). Each type of breeding site was recorded as negative or positive only once at each survey. From each type of breeding site a maximum of 10 dips were taken in each survey. As the majority of breeding pools were too small for dipping more than once, only one dip/pool or site was made in most cases and then other pools of the same type were searched in the same way until a maximum of 10 dips were obtained from each type of breeding site. In other words 10 dips were taken from 10 different pools of the same type of breeding site at each survey. In case of larger pools or water bodies, such as the edge of the dam, each dip was taken at about 5m intervals. Larvae from each type of water body were pipetted into separate vials with screw caps and labelled. Larvae were killed by gently heating the water in the vials and preserved in 70% alcohol after draining the excess water. The larvae were then transported to the laboratory where they were counted and identified. Stages III and IV anopheline larvae were used for identifying larval stages (Verrone, 1962b). Some of the pupae were reared to the adult stage, for confirmation of the species identity at the beginning of the study. The type and characteristic of the breeding sites was noted and their location recorded using a GPS at each sampling time.

Adult collection

Indoor visiting adult mosquitoes were collected from 30 houses each month (6/day- 5 days/month) by light trap collections as described in chapter 4. At each catch, demographic information including human and animal occupants the previous night both indoors and outdoors, whether a fire was set on the previous night or in the morning and whether the light trap was working at time of collection was recorded. Outdoor monthly adult mosquito collections were made at 5 sites/day for 3 days/month in both villages. Mosquitoes were counted, identified and classified into abdominal stages during same day of collection.

Parasite surveys

Thick and thin blood films on the same slide were taken from children under 10 years old both actively and passively in the dry season (April-May 2000, October-November 2000-main transmission season) and during the wet season (July-August, 2000) to determine the incidence of the disease as described in chapter 4.

Data analysis

The presence of potential larval habitats and those containing at least one *An. gambiae s.l.* larva was compared graphically, both for the pre- and post-intervention surveys. The reduction in number of positive dips during the intervention year compared to the pre-intervention period was tested for each type of breeding site using Chi-square test. For each village, the GM number of female *An. arabiensis* collected per catching effort was calculated for indoor and outdoor resting mosquitoes, both before and after intervention period. To stabilise the variance, the data of each catch was transformed (ln [x+1]) prior to analysis. From the antilogarithm of the summary value one was subtracted to obtain the GM.

The relative reduction of adult mosquitoes during the intervention year was determined for the dam village. To correct for variation in mosquito numbers between the years, the GM of mosquitoes in the remote village before (c_1) and after (c_2) intervention was used to adjust the mosquito numbers in the intervention village before (i_1) and after (i_2) intervention. The relative reduction (R) in the intervention was expressed as a percentage and calculated as follows according to Curtis and colleagues (Curtis, 1990):

$$R = 100\left(1 - \frac{i2}{i1} \times \frac{c2}{c1}\right)\% = 100\left(1 - \frac{i2 \times c1}{i1 \times c2}\right)\%$$

Comparisons of the mosquito numbers were made between the pre-intervention and the intervention year using Mann-Whitney U test.

Results

Parasitological survey

The incidence rates in children less than ten years old, both for the pre-intervention and intervention years, are shown in Table 5.1. The numbers of cases are too small to make any valid statistical comparisons, although the results suggest that there may be active transmission in the dam village in the pre-intervention year during the dry season, but not in the intervention year.

Table 5.1. Incidence of malaria in the dam and remote villages before and after larval intervention.

Survey	Malaria incidence/100 child months at risk			
	Dam village		Remote village	
	Pre-intervention	Intervention	Pre-intervention	Intervention
July-August (Peak rains)	-	2.7 (2)*	-	0.3 (1)
October-November (End of rains)	0	0	0.7 (2)	0
January-February (cold & dry)	1.1 (1)	-	0.2 (1)	-
April-May (Hot dry)	-	0	-	0

* Number of cases shown in parentheses

Entomological findings

Larval habitats

A total of 1465 larvae were collected from 13 types of breeding sites searched twice each month in the dam village during the pre-intervention year. A total of 61 positive sites were recorded. Of these 68.8% were from four types of breeding sites –seepage at the base of the dam (27.9%), leaking canals (16.4%), streambed pools from the dam

(13.1%), and man-made pools (11.5%). In the remote village, from 3 types of breeding sites 444 larvae were recovered. 79.2% of the positive records were from riverbed pools associated with the rains. No mosquitoes were found breeding in the dam although 3 (4.9%) positive records were noted in the mouth of one of the streams feeding the dam. Breeding occurred all the year round in the dam village. In contrast, in the remote village, breeding was restricted to rain pools in the wet season and the following couple of months in a swamp and riverbed pools associated with the rains.

Of those larvae collected in the dam village, 745 were 1st and 2nd stage and 720 of them 3rd and 4th instars (ratio, 1:0.97). Of the 3rd and 4th instars identified, 93.5% (673/720) were *An. arabiensis* and the rest constituted other anophelines. The highest number (24%) of the 3rd and 4th instars identified as *An. arabiensis* came from the seepage area. In the remote village, 235 1st and 2nd and 209 3rd and 4th instars were recovered (ratio, 1:0.92). Of the latter, 96.2% (201/209) were *An. arabiensis*. 73.6 % (148/201) of the total *An. arabiensis* collected in the remote village were from riverbed pools. The remaining 26.4 % came from a swamp.

During the intervention year, 278 1st and 2nd and 163 3rd and 4th anopheline larvae (ratio 1:0.56) were collected from 10 types of breeding sites from the dam village. Of the 3rd and 4th instars identified, 73 % were *An. arabiensis* and the rest were other anophelines. In the remote village, 321 1st and 2nd and 302 3rd and 4th anophelines (ratio 1:0.94) were collected. Of the 3rd and 4th anophelines identified, 250 (82.8 %) were *An. arabiensis* and the rest constituted other anophelines.

The total number of anopheline larvae collected from each type of breeding site during the pre-intervention year is shown in Figure 5.2 for the dam village. Seepage had the largest number of larvae followed by man-made pools in the riverbed, leakage from canals, and dam-related pools in the riverbed. Seepage water was also the highest with respect to the number of larvae per dip (Figures 5.3) followed by man-made pools. Seepage water and leaking canals also dominated with the percentage of positive pools (or encounters) for *An. arabiensis* in the dam village (Figure 5.4). In general, seepage water and the dam related streambed pools constituted the largest sources of vector breeding throughout the year. The numbers of man-made pools were limited and searches were confined to these sites. In the remote village, pools in the streambed and nearby swampy area, as well as rain puddles, in that order, were the main breeding sites throughout the study (Figure 5.5).

A significant reduction in the number of positive dips (and number of larvae) was evident in seepage ($\chi2 = 56.7$, $p < 0.001$), man-made pools ($\chi2 = 15.64$, $p < 0.001$), leakage from canals ($\chi2 = 26.56$, $p < 0.001$), irrigated fields ($\chi2 = 19.78$, $p < 0.001$), and drainage canals ($\chi2 = 8.75$, $p < 0.01$), during the intervention year compared with pre-intervention levels (Table 5.2). However, there was no reduction in dam related riverbed pools and a few (2) positive breeding sites were identified in irrigation canals during the intervention year.

Table 5.2. Comparison of number of positive dips, larvae and number of positive sites or encounters during the pre-intervention and intervention years in the dam village.

Breeding sites	No. positive Dips*		No. larvae		No positive** Encounters/records	
	Pre-	Inter	Pre-	Int.	Pre-	Inter
Dam	0	0	0	0	0	0
Dam edge	0	0	0	0	0	0
Spillway	7	7	10	15	1	1
Seepage	134	41	329	83	17	7
Manmade pools	67	25	294	57	7	3
Irrigation canal	0	16	0	40	0	2
Canal leakage	79	24	279	53	10	3
Irrigated field	40	7	140	22	6	1
Drainage canal	32	10	80	34	4	1
Dam riverpools	56	60	163	129	8	8
Nondam riverpool	22	0	45	0	3	0
Nondam swamp	0	0	0	0	5	1
Rain pools	47	4	125	8		

*For each breeding site, n = 240 dips pre-intervention year & 200 intervention year

**For each site, n = 24 records pre-intervention & 20 intervention year;-each breeding site is recorded as negative or positive/survey, although the 10 dips taken each time may be positive

In the remote village a significant increase in vector breeding was seen in riverbed pools ($\chi2$ =10.7, p< 0.05) and rain pools and puddles ($\chi2$ = 37.17, p< 0.001) during the intervention year compared with pre-intervention (Figure 5.5 and Table 5.3).

Table 5.3. Comparison of number of positive dips, number of larvae and number of positive encounters recorded during the pre-intervention and intervention years in the remote village (n values same as in Table 5.2)

Breeding sites	No. positive Dips		No. larvae		No positive Sites	
	Pre-	Inter	Pre-	Int.	Pre-	Inter
Nondam riverpool	125	135	360	472	19	16
Nondam swamp	26	28	84	74	5	3
Rain pools	0	29	0	77	0	4

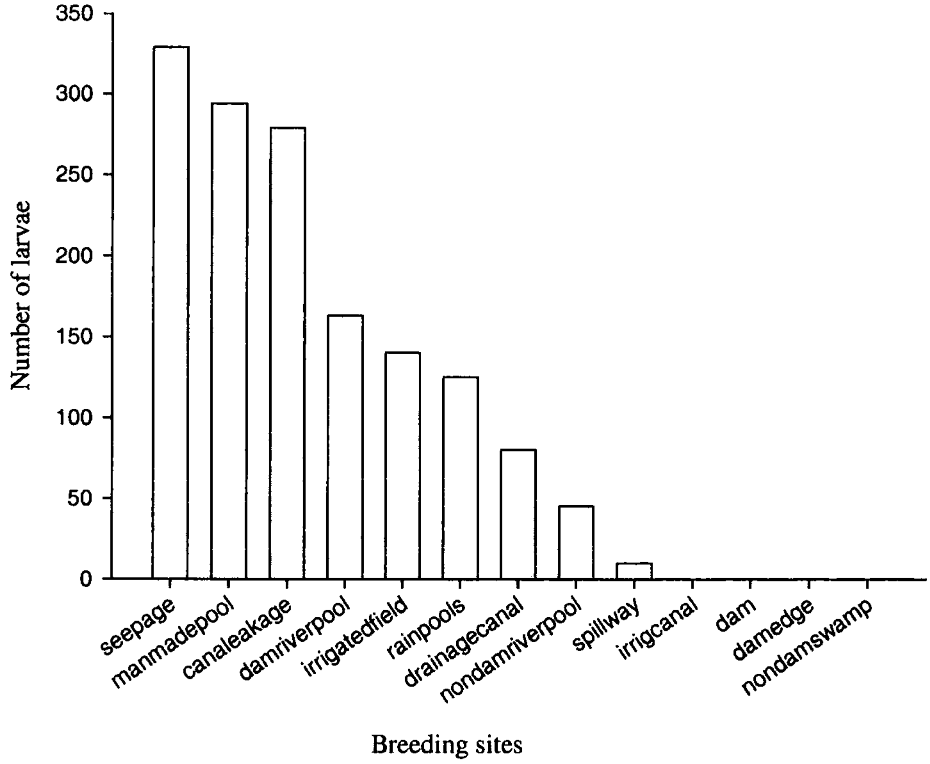


Figure 5.2. Total number of anopheline larvae collected from each type of breeding site in the dam village during the pre-intervention year.

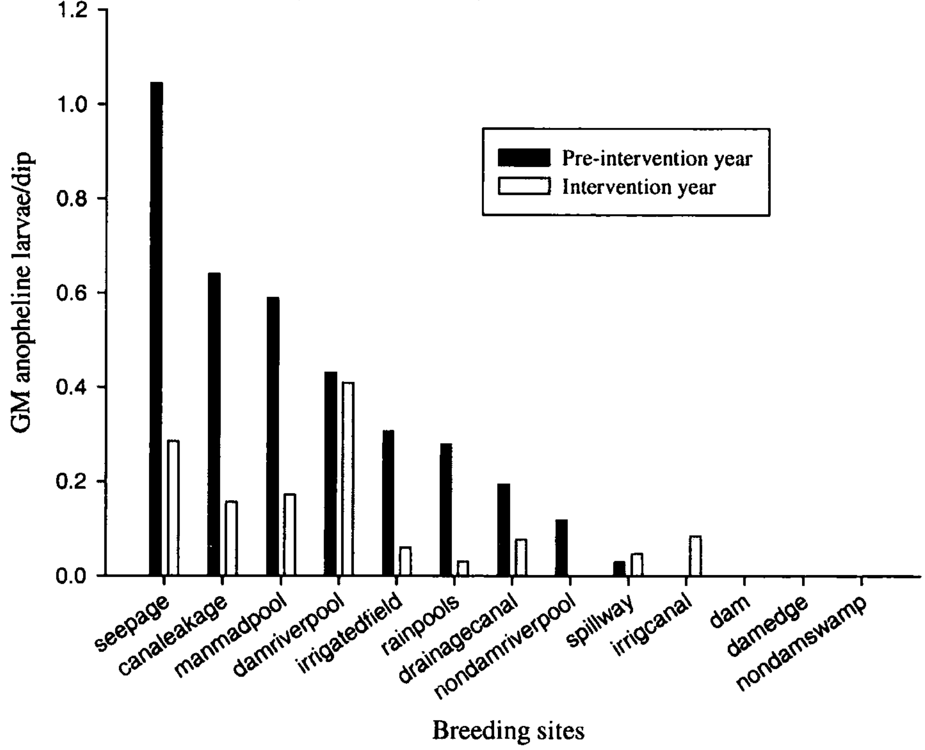


Figure 5.3. Geometric mean of anopheline larvae per dip for each type of breeding site in the dam village during the pre-intervention and intervention years.

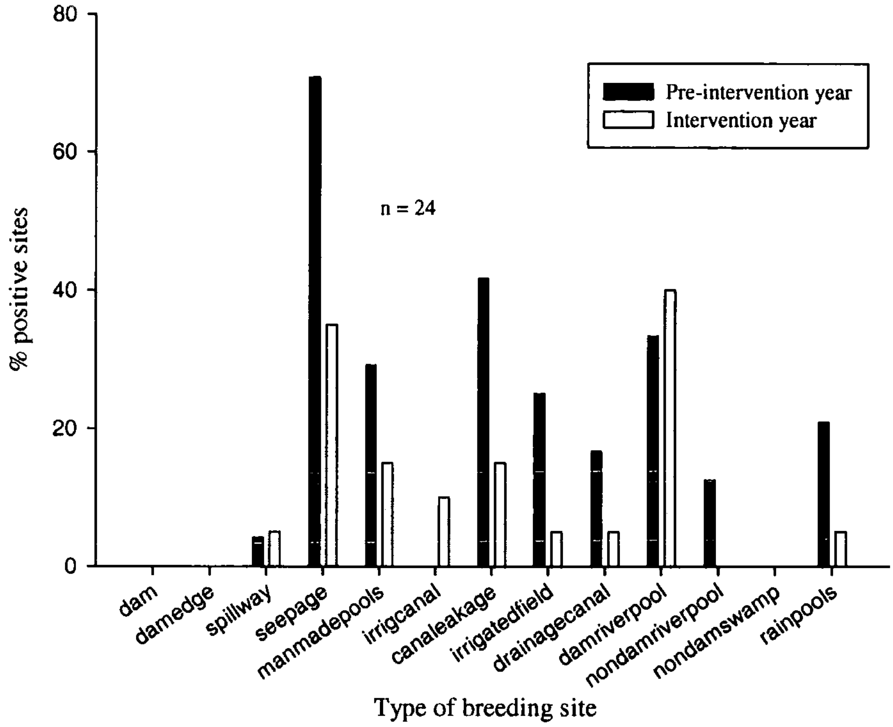


Figure 5.4. Percentage of larval positive pools encountered for each type of breeding site in the dam village during the pre-intervention and intervention year surveys.

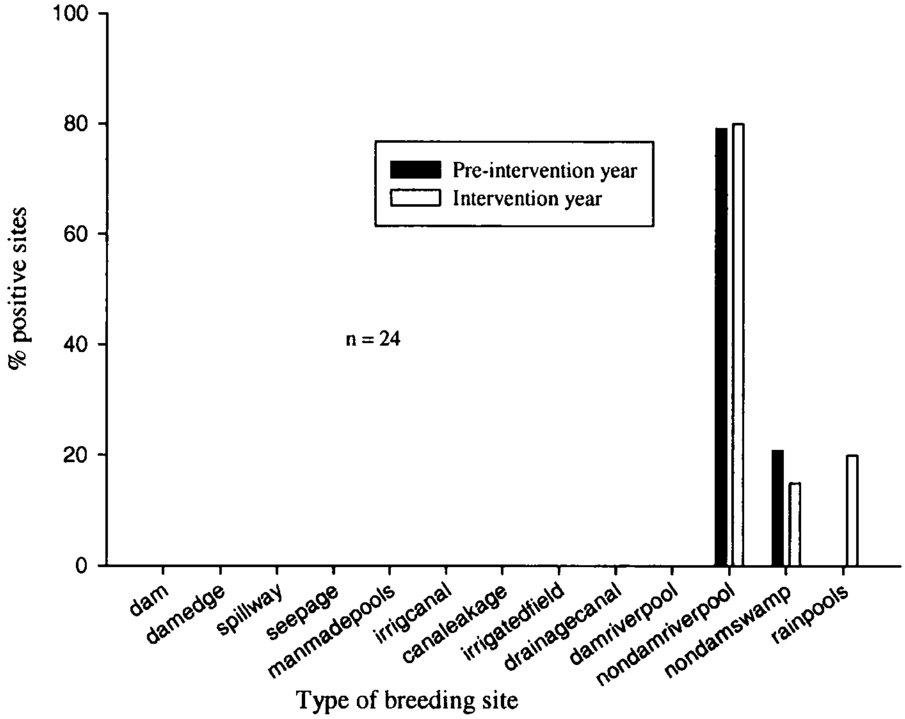


Figure 5.5. Percentage of larval positive pools encountered for each type of breeding site in the remote village during the pre-intervention and intervention year surveys.

Adult collection

Indoor light trap collection

Overall, 457 *An. arabiensis,* 916 other anophelines, and 488 *Culex* species were collected during the intervention period in the dam village using light traps. In the remote village, the numbers caught were 112 *An. arabiensis,* 1 *An. pharoensis*, 531 other anophelines, and 361 *Culex* species. The seasonal trend of *An. arabiensis* by light trap collection in the dam village both during the pre-intervention and the intervention period is shown in Figure 5.6. Unlike during the pre-intervention period, the dry season peak in the dam village was absent during the intervention period and only a slight increase in mosquito density was apparent at the end of the rainy season. It is apparent from the figure that mosquito density in the dam village during the intervention year was brought down to the level of (or below) mosquito abundance during the pre-intervention year in the remote village. It is important to note here that during the pre-intervention year, all the houses were sprayed with 75% DDT in September. During the intervention period, there was a dramatic increase in abundance of other anophelines and the majority of them were *An. demeilloni.* Other anopheline species caught included *An. squamosus*, *An. cinereus*, *An. preterionsis*, *An. christyi, An. natalensis, An. turkhudi, An. dancalicus, An. rivulorum,* and *An. maculipalpis.*

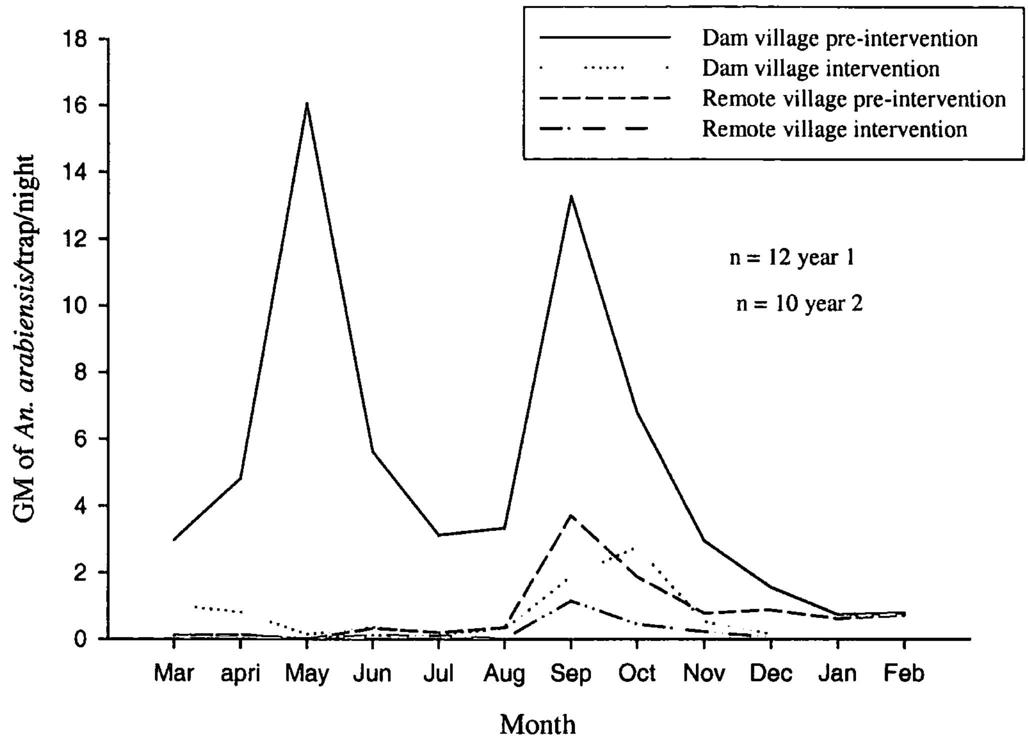


Figure 5.6. Seasonal abundance (geometric mean) of *An. arabiensis* during the pre-intervention and intervention periods in the dam and remote villages.

Comparisons of the GM *An. arabiensis* caught per light trap both during the pre-intervention and intervention periods and the relative reduction in mosquito density in the dam village is shown in Tables 5.4 and 5.5. The GM of *An. arabiensis* collected/trap-night in the dam village during the intervention months was significantly lower (GM= 0.7, 95% CI = 0.5-0.8, Mann-Whitney U=25404.5, z = -12.823, $P < 0.001$) than the pre-intervention months (GM= 4.0, 95% CI=3.4-4.6). Overall there was a 83% reduction in *An. arabiensis* abundance during the intervention year compared with the pre-intervention year, and a 49% relative reduction if one adjusted for the drop in mosquito numbers in the remote village during the intervention year. The abundance of vectors was much lower during the wet months of the year-June through October compared to the previous year (Table 5.4). On a month-to-month basis, the reduction was highest during the dry month of May, when a second peak was observed during the pre-intervention year (Table 5.5).

Table 5.4. The GM of *An. arabiensis* collected in light traps during the pre-intervention and intervention periods in the dam and remote village and the percentage reduction in vector abundance (in GM/trap/night) in the dam village during the intervention period (March1999-February 2000 vs. March- December 2000).

Month	Light trap collection				
	Pre-intervention		Post intervention		
	Dam village	Remote village	Dam village	Remote village	Reduction %
Dry season	3.10	0.43	0.49	0.10	35.6
Wet season (June-October)	5.66	0.96	0.85	0.31	53.8
Mean	4.01	0.63	0.66	0.20	49

Table 5.5. The percentage reduction (Red.) in *An. arabiensis* abundance in the dam village during the intervention period on a month-to-month basis as assessed by light trap catches (March 1999-December 1999 vs. March 2000 vs. December 2000).

Month	Light trap collection				
	Pre-intervention		Post intervention		
	Dam village	Remote village	Dam village	Remote village	Red.%
March	2.98	0.11	1.02	0.1	62.3
April	4.81	0.13	0.81	0.12	81.8
May	16.05	0	0.14	0.02	100
June	5.62	0.32	0.35	0.11	81.9
July	3.12	0.2	0.15	0.1	90.4
August	3.33	0.35	0.3	0.02	*-57.7
September	13.27	3.7	1.88	1.15	54.4
October	6.8	1.87	2.76	0.45	*-68.7
November	2.95	0.78	0.52	0.22	37.5
December	1.56	0.88	0.15	0.07	*-20.9

* Negative values represent less reduction for intervention (dam) village than for the control (remote from dam) village, month on month. ** 1 was added to the geometric means in order to avoid division and multiplication by zero. This does not bring any difference in the relative reduction

The reduction in abundance was unlikely to be due to meteorological conditions since no significant difference was found in rainfall (t= 1.27, d.f. =7, p= 0.244) or monthly mean temperatures (t=-0.207, d.f. =7, p=0.842) between the pre-intervention and the intervention period. Nevertheless, although no significant difference was noted in temperature ((t= 0.179, d.f. =7, p= 0.863) or in rainfall (t= 0.773, d.f. =7, p= 0.465) in the remote village between the intervention and pre-intervention period, a significant reduction in *An. arabiensis* abundance was noted (GM = 0.2, CI = 0.15-0.26, Mann-Whitney U=41285, z= - 6.07, d.f = p < 0.001) compared to the previous year (GM = 0.63, 95% CI= 0.51-0.76). It was for this reason that the GM of mosquitoes in the remote village before and after intervention was used to adjust the mosquito number in the dam village before and after intervention.

Outdoor resting collection

A decrease in *An. arabiensis* abundance (pre-intervetnion=131, intervention=37) and an increase in other anophelines (pre-int.=7, interv.=154) was observed during the intervention year. Roughly 71.8% reduction or 27% (95% CI = 5.8-30.5) relative reduction was noted in *An. arabiensis* and this could be attributed to the general reduction in the overall output during the intervention period. In the remote village, only 8 *An. arabiensis* were caught during the pre-intervention compared with 3 during the intervention period (62.5% overall reduction). Number of other anophelines collected increased from 2 to 106 in the intervention period.

Community participation

The villagers participated in the larval intervention activities at individual and community level, organised by the local Baito (village level administration). At individual level, the activities involved digging drainage channels across their fields and clearing vegetation from irrigation canals. Other organised activities included draining the seepage area, filling and draining puddles near irrigated fields and the riverbed, maintenance of irrigation canals, construction of drainage channels, straightening of streams, filling of man-made pools in the river/stream bed and propagation of reeds. Overall, approximately 5000 man-hours were utilized to perform the source reduction activities during the 10-month intervention period. Drainage of the seepage area and construction of a crossing canal (for labour only) to the other side of the gully took the largest share of the man-hours (about 2420 man-hrs). At the end of the study, the community and the local administration were briefed about the outcome of the pre-intervention and post intervention results. This was followed by on site evaluation of the larval intervention study and impact of dams by community members together with representatives of various government and non-governmental institutions of the region, including the Bureaus of Health, Agriculture, SAERT (a commission responsible for constructing dams), the local administration and others.

Discussion

This study has shown that dams create favourable breeding sites for vector species. Seepage from the base of the dam and pools along the streambeds that collect excess water from the irrigated fields were the main source of breeding during the study. This was reflected in the percentage of positive encounters, in the total number of positive dips in these breeding sites, total number of larvae collected, and total number of larvae per dip. Despite there being few man-made pools, the high densities of larvae found here meant that the total number of larvae recovered from these sites approached that of seepage and pools from leaking canals. Other breeding sites included, waterlogged fields created by raising the water table, in spillways and in irrigated fields where drainage canals were absent and water allowed to settle. The situation was made worse due to excessive release of water from the dam to compensate for the poor slope in irrigation canals. As a result canals overflowed and leakage increased. Excessive flooding of fields by the locals and wastage of water, hoof and footprints also created breeding sites. The substantial tunnelling of the fields due to termites exacerbated the problem as the fields situated far away from the unlined leaking canals got water logged due to the subterranean movement of water through the tunnels and this made it difficult to locate the source of the leakage.

The almost one to one ratio of 1st and 2nd vs. 3rd and 4th larvae shows low mortality of the former and illustrates the high survival of larvae in these breeding sites. During, or just after, the rainy season enumerable collections of water are observed teeming with early stage larvae but many of them dry up quickly before the aquatic stages complete their development. But under raised water table conditions, seepage, leaking canals and excessive flooding of fields and careless release of water, elsewhere around the fields, maintains residual pools of water that can support successful production of adults. This shows that, although it is difficult to avoid the creation of pools of water under irrigation conditions, it would be possible to reduce the high abundance of adult vectors by periodic draining and adhering to strict water management practises. This was well illustrated in a study conducted in Mwea rice irrigation scheme in Kenya, where intermittent irrigation was tested for controlling the breeding of *Anopheles* mosquitoes (Mutero *et al.*, 2000). They found very high numbers of *An. arabiensis* 1st instar larvae in the intermittently irrigated subplots compared with the continuously flooded control subplots, indicating that the water regime, by creating clear and sunlit pools, provided very attractive environment for egg laying. Nonetheless, the ratio between the 4th and 1st larvae in the subplots was only 0.08 compared with the ratio of 0.3-0.7 in the continuously flooded control plots, indicating very low survival rates in the former due to short life span of the pools. The failure to arrest the development of the aquatic stages to the 4th stage in the continuously flooded water regimen was attributed to residual pools of water standing long enough to allow completion of development.

Most importantly, my study has demonstrated that it is possible to reduce the abundance of vector species substantially with minimum participation of the community and by utilizing local resources. A significant reduction in number of larvae and positive breeding sites in seepage, leaking canals, irrigated fields, man made pools and in other types of breeding sites was achieved during the intervention year in the dam village. This was reflected in the dramatic decrease in abundance of adult *An. arabiensis* during the intervention period - 83 % reduction (49 % relative reduction) was achieved as evaluated by light traps. A 72% reduction (27% relative reduction) was also observed in outdoor resting populations, indicating the overall decrease in abundance of the vectors. Unlike the pre-intervention year, there were few mosquitoes during the dry season of the intervention year indicating the effectiveness of the source reduction methods employed. This suggests that community-led larval intervention activities could be effectively employed to reduce breeding sites created by the irrigation scheme and minimize dry season transmission of malaria parasites. At the end of the rainy season, a slight increase in mosquito density was apparent. It is important to note here that during the pre-intervention year the houses were sprayed with DDT. As a result, the relative reduction due to suppression of breeding sites is underestimated, as it was based on the already reduced vector population by DDT the preceding year. Although DDT spraying together with prompt treatment of cases with Fansidar appeared to have a great influence on the incidence of the disease in the villages, the absence of cases during the dry season, compared with the pre-intervention year may reflect the effectiveness of the community led larval intervention to reduce or arrest dry season transmission of malaria.

Environmental management (EM) has been used successfully in different parts of the world since the 1900s (Russel *et al.*, 1963; WHO, 1982; Stevens, 1984; Rafatjah, 1988; Kitron and Spielman, 1989; Ault, 1994). Since the advent of DDT, residual insecticides have replaced or dominated the traditional methods of source reduction directed towards the elimination or reduction of vector-breeding sites. This was due to the ease of use, the high persistence of residual insecticides and the concept that the prevalence of malaria can be more effectively reduced by attacking the adult stage of the vectors derived from models of malaria transmission of Macdonald (Kitron and Spielman, 1989). Yet, despite their perceived conceptual weakness, source reduction measures provided the basis for an early series of successful antimalarial programs in the United States, Europe, the Middle East, and other areas of low endemicity (Sharma *et al.*, 1986; Sharma, 1987; Kitron and Spielman, 1989; Ault, 1994). These methods mainly involved environmental manipulation techniques to reduce larval habitats through filling, draining, cleaning and improving drains, planned water level fluctuations in reservoirs. Many of these were combined with improving malaria surveillance and chemotherapy, public health education, and motivating communities to help themselves (Dua *et al.*, 1988; Rafatjah, 1988; Kitron and Spielman, 1989; Ault, 1994; Brewster, 1999).

Environmental manipulation is often a cost effective strategy for vector control and can be integrated relatively easily with other intervention measures used for the control of malaria that requires community participation (WHO, 1982; Rafatjah, 1988; Ault, 1994). For example, in India, Sharma and colleagues (Sharma *et al.*, 1986) have shown that environmental control measures would cost about 15% of the expenditure being incurred in areas under malathion spraying. Nevertheless, despite its cost effectiveness and environmental friendly nature, progress has been slow in the wider use of these measures. This was due in part to the unwillingness or reluctance of programme officials to utilise such control activities that require longer preparation, perseverance and are relatively slow to produce results (Rafatjah, 1988) when the quick deployment and sharp effect of insecticides spares them extra work burden and from taking responsibilities of outbreaks. On the other hand, especially in vast countries such as

Ethiopia, budgetary, logistic, and other constraints associated with the socio-economic conditions of the countries make it difficult to effectively coordinate, supervise, and execute the measures. Nevertheless, increasing problems with the effectiveness of insecticides, their high cost and toxic risks associated with them have emphasized the need for alternative or supportive control measures such as EM in the past decades (WHO, 1982). The increasing pressure by environmental scientists and politicians for major cuts or total ban in the use of DDT and others in recent years also indicates the need for more environmentally friendly approaches in malaria control programmes. The drastic health deterioration and consequent economic losses associated with water development projects where such measures have not been incorporated from the start or neglected in the course of the project are also increasingly calling for the incorporation of alternate strategies, mainly EM to control the disease in recent years (Rafatjah, 1988).

One of the main methods used in reducing breeding sites in this study was the propagation and maintenance of reeds and other grasses associated with water in the seepage area and down along the length of the gully below. Reeds were well established in the gully where the velocity of the water was slow. Prohibition of free access to livestock and humans to the swampy area covered with reeds prevented their destruction and exposure of water pools to sunlight and formation of breeding sites in hoof and footprints. At crossing points of the gully, both of human and livestock, gravel and stones were laid to avoid the creation of water pools in mud. The well-drained swampy area with maintained reeds shaded the breeding sites making it difficult to access and made it unattractive for *An. arabiensis* breeding. A slimy brownish material produced by the roots of the reeds in the drainage canals may have also reduced breeding. In areas where it was difficult to drain and/or where the reeds could not be established, cut grass, weeds, reed and other plant remains were used to cover the breeding sites and appeared to be effective both by denying access and by making the water less attractive due to decomposition.

Although reports on deliberate propagation and maintenance of reeds/papyrus (*Cyperus papyrus*) in swampy areas to control mosquito breeding are scarce, the unsuitability of swamps covered with these swampy plants to *An. gambiae* breeding were long recognized, especially in Africa (Hancock, 1934; Steyn, 1946; Goma, 1960). The papyrus swamps of Uganda are the well-established examples for their unsuitability for *An. gambiae* breeding under their natural condition (Hancock, 1934). Varied reasons were suggested for the unsuitability of papyrus or similar swampy plants for anopheline breeding. Goma (Goma, 1960) suggested that the water from the interior of papyrus swamps does not support or inhibits the development of *An. gambiae* larvae. On the other hand, mechanical obstruction offered by the tangled vegetation around the breeding sites, rather than shade itself, was considered to be the main factor for the avoidance of these sites by this species (Muirhead-Thompson, 1945). Nonetheless, there is a consensus as to the rapid colonization of these sites by *An. gambiae* breeding following reclamation and cultivation. The drainage of swamps containing reeds or papyrus and other swamp grasses to increase the land available for cultivation in south-western Ugandan highland areas has long been blamed for increased breeding of *An. gambiae s.l.* and other anophelines (Hancock, 1934; Steyn, 1946) and for establishing the transmission of malaria in these areas (Mouchet *et al.*, 1998; Lindblade *et al.*, 2000). Removal of the papyrus provided abundant small sunlit pools favored by vectors of malaria such as *An. gambiae s.l.* Reclamation of swamps in other parts of Africa have also been associated with increased breeding sites of malaria vectors (De Meillon, 1947). For example, clearing for cattle of the seasonally waterlogged pans (mbugas and dambos) of eastern and central Africa, or for cultivation of vegetables, provided profuse breeding sites for *An. gambiae* (Gillies and De Meillon, 1968).

In India, the density of anopheline larvae was shown to be 3 times greater in clear stretches of a stream than where the banks were naturally overgrown with *Ipomea biloba*. This observation was exploited to achieve even greater reductions in breeding artificially by planting *Vitex negundo,* although it was difficult to say whether this was due to the aromatic leaves of the plant or due its shading effect (Bhasker Rao and Ramoo, 1942). Community led environmental management measures involving massive planting of eucalyptus trees in swampy areas produced appreciable results in reducing breeding sites of *An. culicifacies* in India. In this case the trees dried up the puddles where the local vector bred (Sharma *et al.*, 1986; Sharma, 1987; Dua *et al.*, 1988). This form of social forestry has also created a source of income for local people. Deliberate pollution of breeding sites with plant materials against anopheline mosquito breeding has been identified long ago (De Meillon, 1947) although not pursued further. Pollution with sisal and sugar cane waste has been used with success in Sri Lanka and the

Philippines (Rajagopalan *et al.*, 1990) although this may not be applicable in all areas. In this study, reed mats and associated grasses, as well as weeds and other plant remains were used to cover exposed breeding sites, which were difficult to drain.

The reduction in *An. arabiensis* abundance was obtained with minimal community involvement. Better results would have been achieved had we not faced some substantial problems. One of the major problems was the Ethio-Eritrean war during the study period. As the area was at the frontline, the large part of the population, including the local administration, was directly and indirectly involved in the war effort. As a result, their participation was not as required. The other major problem was lack of coordination between the various sectors involved in rural development such as SAERT, a commission responsible for coordinating and executing dam construction, and the Bureau of Agriculture and Bureau of Health. Nonetheless, it was apparent that a minimum coordination could bring about dramatic results. Avoiding water logging not only resulted in less malaria transmission it also reduced the possibility of salinisation in the fields. Other problems encountered included problems associated with land distribution, livestock, and excessive use of water. Many people who lived outside the village had irrigation plots. These people were not directly affected by malaria and were reluctant to actively participate in the control activities and in passing and enforcing community laws or regulations to this effect. As most of the traditional grazing land was either covered by the dam water or incorporated into the irrigation scheme, during the dry season, the best available grazing area was below the dam – near and around the seepage area and at the edges of irrigated fields and the gully below. However, in an endeavour to ensure that crops were not damaged by cattle, grazing was prohibited in this area although herdsmen were allowed to cut and remove grass from this area. Moreover, owing to a shortage of grazing land and to avoid overstocking and consequent deterioration of the land and environmental degradation, people were normally encouraged to reduce the number of their livestock and manage the rest efficiently. Nevertheless, there was a general reluctance to get detached from the traditional way of life and some people managed to sneak their livestock into these areas and encouraged the creation of breeding sites in hoof prints.

Since there were no wells in the dam village the local community dug small temporary pools in the river or gully bed as a source of drinking water by natural filtration. These small, easy to dig, pools were often abandoned immediately as they get dirty quickly, to be replaced elsewhere by others, and favoured *An. arabiensis* breeding. Some people got their water from the spring at the bottom of the dam embankment formed by seepage. In doing so, they created breeding sites in footprints and by destroying the reeds. Excessive release of water from the outlet of the dam to overcome the barrier of bad slope (and leaking canals) and ensure that water reaches the tail end of the village or irrigation scheme exacerbated the problem. In doing so, water would overflow from the shallow, flattish and unlined irrigation canals and this coupled with over flooding of the fields by farmers resulted in water logging and the creation of enormous breeding sites. Termite tunnelling made this worse, as water from the unlined irrigation canals would soak in and through the subterranean tunnels come out at unexpected and unwanted places. Most importantly, the locals, often overlooked the small seemingly harmless pools favoured by *An. arabiensis*, such as those created by hoof prints, and persistent reminding was required.

Despite these problems an appreciable level of reduction was achieved and the community, who evaluated the outcome at the end of the study, hailed the overall activities and outcomes. My results show that not only should development projects be designed and operated so as to avoid mosquito breeding in inhabited areas, but also as part of the integrated malaria control activities the local communities should be helped to organize individual and community action against malaria vectors. Individuals, including children, as routine hygiene measures, might undertake many measures on their plots and others might be organized as routine community efforts with the guidance of local community health staff and community health workers. Village based agricultural extension workers, in addition to their responsibility to give the farmers guidance in agricultural activities and efficient use of irrigation water, could organise and oversee the reduction of breeding sites (together with CHWs) as this is directly linked with their work. This does not require intensive training and a few days workshop would suffice to arm them with the basic knowledge that would help them identify main breeding sites and the aquatic stages of the vector mosquitoes and basic control methods. For new recruits, the elementary aspect of health/hygiene including malaria could be incorporated in the training programme or curriculum. Nevertheless, in my view, as the extension workers are currently overburdened with work, relative to the salary they get, it would be wise to either increase their number or consider salary increment (or both) and make them multipurpose extension agents. Dams, as far as possible, should be constructed further away from habitations. The community-led larval intervention measures employed in this study could be extended to many areas with similar settings-terrain, agroclimatic conditions and epidemiological considerations. The strategy could be more appropriate in water development project areas of Africa with similar eco-epidemiological settings, notably in fringe areas of malaria transmission where *An. arabiensis* (and *An. gambiae, s.s.*) is the predominant vector, provided that they can be adapted to local situations.

Chapter 6: Conclusion

Plate 6.1. Digging a drainage canal (below) and a crossing canal (above) to cultivate more land on the other side of the gully below the dam.

Overall, the results of my study showed that the construction of microdams close to villages has the potential to alter the ecology of the surroundings in favour of vector abundance and parasite development extending the transmission season and thereby increasing the risk of exposure in nearby communities. More specifically, the construction of dams near human settlements not only provided abundant breeding sites but also moderated climate extremes by increasing minimum temperatures as well as by creating profuse and favourable outdoor resting microclimates for *An. arabiensis* throughout the dry season. The higher difference in minimum temperature observed between the dam and remote village during the cool dry season (November-January) following the main transmission months of September-October is especially noteworthy as malaria transmission normally declines or comes to a halt at this time of the year, mainly due to low temperatures for parasite development within the mosquito and long generation time of the vector population. Thus, the pronounced increase in minimum temperature evident in the dam village during this period, together with abundant breeding sites and favourable microclimate indoors and daytime outdoor resting sites, would speed up the development of the parasites and vector populations extending the transmission season. Small increases in minimum temperature may not have dramatic results in the already warm hyper or holoendemic parts of tropical areas. Nonetheless, whilst seemingly small in magnitude, such changes might significantly alter aspects of local climate important in determining vector species survival and preponderance adjacent to the reservoirs in areas of unstable malaria, such as the highlands of Tigray in northern Ethiopia. This is because small increases in temperature, especially near the lower threshold, can result in disproportionate increase in development of the parasite within the mosquito and the aquatic stages of the latter in water. This could be more so when the cumulative effect of many dams is considered in these areas.

The presence of abundant standing water and mismanagement of irrigation water, and perhaps together with increased minimum temperatures, may also have important implications for agriculture, since it can influence the mix and diversity of weeds. New weeds could be introduced and flourish under the changed conditions near dams and salinisation could be a major problem if strict water management is not followed and excessive water is allowed to settle in irrigated fields. Environmental monitoring in these transitional zones is thus a priority for detecting any change in disease (and ecology of weeds as well as salinity) driven by the construction of dams and water impoundments as well as other human incursions in the environment such as deforestation or reforestation.

The construction of microdams mainly for irrigation and as a source of drinking water is indispensable in the drought prone Tigray and other parts of Ethiopia which experience recurrent drought conditions. This aims to ensure food self-sufficiency and should contribute to the overall economic development of the country. Nonetheless, the positive outcomes could be outweighed by the impending health risks - the spread of water and vector-borne diseases, such as malaria and schistosomiasis, unless the necessary measures are taken to counteract this at the outset and in the course of the projects. In this respect, the outcome of my study has shown quantitatively that it is possible to reduce the increased risk to malaria by community-led larval intervention measures using local resources. If it were possible to reduce vector abundance to the level attained in this study with minimal involvement of the community, much better results could be anticipated if such measures are regularly and selectively carried out with maximum community participation. Physical environmental manipulation, such as the drainage of stagnant water bodies and filling of hollows and borrow pits, maintenance of swampy plants, especially in agriculturally unsuited areas near water bodies, to shade breeding sites and physically inhibit mosquitoes from egg laying, maintenance of irrigation and drainage canals, when carried out routinely, where appropriate, and supported by health education, chemotherapy, and other control activities can also be effective not only near microdams but also under differing situations- in irrigation projects and around industrial complexes, in urban centres, resettlement schemes, military camps, and the like.

Near microdams, community-led intervention measures can effectively reduce malaria transmission especially during the dry season. This would spare the cost of residual insecticide spraying, at least the second spray round in areas where it is difficult to control the disease during the main transmission season due to the availability of numerous mosquito breeding sites and suitable environmental conditions as well as when it is difficult to mobilise the community as this is the busiest time of the year for farmers. In fringe areas of malaria transmission it is also possible to contain malaria transmission to an acceptable level even during the main malaria transmission season by community involvement. Environmental management methods can also be easily integrated with other control measures during the peak transmission season. In situations, such as in the present study area, where the vectors exhibit a degree of exophily and an early evening biting peak, community led environmental management is indispensable as residual spraying may not achieve the desired level of protection from infective bites. The early biting activity found in my study also means that people could get a substantial number of infective bites (approximately 70%) before going to bed and tends to diminish the effectiveness of the currently widely recommended use of insecticide-impregnated bed nets to control malaria. Thus, before large-scale use of bednets, the biting rhythm of *An. arabiensis* should also be taken into account and this could be ascertained by hourly light trap catches in sentinel sites. Concurrent human landing catches can also be used but they are expensive and require high organisation in terms of logistics and manpower besides the ethical consideration.

Mobilisation of communities to control malaria could also boost the morale of the locals to sort out other problems themselves and in this way would strengthen self-help strategy, rather than looking for help from the government all the time. This, however, does not mean that development projects should not consider minimal allowance to health risk when they are anticipated. At least they should be designed to provide minimum drainage facilities and constructed as far away as possible from human settlements. In termite-infested areas, such as the present study area, partial or complete lining of the primary irrigation canals may be required. At the outset, the beneficiary communities should also enter into commitment for maintaining sustainable and minimal hygienic measures after the construction of the dams. As the inhabitants near microdams are the ones directly exposed to increased risk of infection and if full participation in the intervention and maintenance effort is to be guarantied, the communities near microdams should be the direct beneficiaries of the irrigation schemes.

The task of malaria control activities should not be left totally to the Bureau of Health. Once the construction of dams is completed, the Bureau of Agriculture normally takes the responsibility of overseeing the effective use of the water and provide expert guidance on irrigation. In doing so, it can play a major role in counteracting the health risks, as all the measures that should be normally taken to ensure effective utilization of irrigation water are the key to control of vector-borne diseases, such as malaria.

Effective drainage not only eliminates mosquito-breeding sites, but also avoids water logging and the consequent loss of crops in the short term and salinisation and total abandonment of the project in the long run. The presence of agricultural extension workers living and working at a community level near dams, and other rural areas, in the region, together with the highly organised system of administration, would make it easier for routine follow up and coordination of activities with the health sector and the community health workers. What would be needed is training of the extension workers and community health workers with basic knowledge of the biology of the vectors and intervention methods by organising workshops. Alternatively, booklets addressing this could be distributed and the contents clarified or discussed locally. This could be organised by the local administrative bodies together with the representatives of the health and agriculture bureaus. Such forums have been effectively organised with respect to political matters and would not be difficult with health issues. It should be emphasised that the major breeding sites, which are small and often overlooked, should be clearly identified and dealt with, as this would save energy for other activities. For new recruits, the elementary aspect of health/hygiene including malaria could be incorporated in the curriculum. Nongovernmental organisations can play a major role in terms of financing the workshops and dissemination of information in the form of posters, booklets, and the like. Moreover, in my view, considering the huge responsibility of extension workers, it would be wise to revise their salary and make them multipurpose extension agents. Moreover, community health workers must be elected to work with the extension workers in all near dam villages.

Health education should not solely focus on the adult members of the community. Children, most of who are involved in herding animals and doing other agricultural activities as well, are the ones who often stay close to the breeding sites of mosquitoes and play with water in the river beds and lead cattle to drink from water bodies. Besides, they are the ones who take over in the long run. So spreading awareness in this part of the community, both those who attend school and those who do not, would also help reduce mosquito-breeding sites. Extending the programme to include elementary school teachers working in rural areas would strengthen this. They can increase awareness in school children not only on malaria but also on other diseases of major public health problem in their localities, if supplied with supportive teaching or demonstration materials. In this way, knowledge could be disseminated easily to the community and major risks avoided, at least in the long run.

Provision of pumped water in near dam villages could help reduce *An. arabiensis* breeding in abandoned man-made pools dug in the river/stream bed for drinking purposes and which were highly favoured by this species when present. The raised water table near dams would help avoid the need to dig very deep wells, which may be quite expensive. Alternative sources, such as spring-water development and using surface water by sand filtration, could also be utilized, depending on the local situation, using local knowledge and resources. Local communities could provide labour and locally available construction materials for this and other purposes including for lining poorly constructed or damaged irrigation canals. Similarly, construction of watering troughs, wherever feasible, could help reduce breeding sites in hoof prints. Alternatively, at watering points and at livestock crossing points in gullies below dams, stones and gravel could be laid to avoid the creation of breeding sites in mud by hoof prints. Encouraging cutting and removing grass and other feeds from the irrigation area and planting fodder plants in the seepage area and along the length of the gully not under cultivation would also help reduce breeding sites.

Limitations of the study

Although the study was comprehensive and attempted to see the situation from different angles, it was not without its limitations. The most important weaknesses include:

- In ecological studies, as the group rather than the individual is the unit of comparison, the main limitation was confinement of the study to one dam and a pair of villages owing to economic limitations to buy the expensive automatic weather stations
- Absence of data on malaria incidence and on the weather in both villages before the construction of the dam;
- DDT spraying during the pre-intervention period in both villages and source reduction activities carried out by the community in the control village during the intervention phase, although of limited duration.
- The negative impact of the Ethio-Eritrean war on the full participation of the community in the intervention study

Future prospects

- Base line data should be collected prior to the construction of dams and other water development projects. This would enable one to assess the impact on the spread or increase of diseases during the construction phase. The data would also be very important in evaluating control efforts to curb the diseases.
- Evaluation of low cost intervention measures in terms of improved housing and construction of cattle sheds detached from human dwellings;
- Cross-sectional survey studies of *An. arabiensis* biting rhythm over a wide area covering different ecological settings in Tigray region;
- Identification of economically beneficial plants adapted to swampy conditions near microdams that could replace reeds/papyrus in seepage/swampy areas and discourage *An. arabiensis* breeding by shading and other effects.

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