The impact of bund construction on the transmission of malaria in The Gambia

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Executive Summary

Water impoundments are known to affect the risk of many vector-borne diseases. Here I examine the impact of bund (small embankments) construction on the transmission of malaria in The Gambia. I hypothesised that bund construction, designed to collect rainwater for irrigation and keeping saltwater out, would provide ideal breeding sites for *Anopheles gambiae* mosquitoes, the major vectors of malaria in Africa, and thereby increase malaria transmission. Mosquito larvae were sampled along transects in three different areas. Each transect lay perpendicular to a bund, including an area 100m either side of the bund. These were sampled for larvae using area samplers every three weeks from May to December 2005, including the period of annual rainfall from June to October. Adult mosquitoes were caught using three emergence traps which were positioned at each side of the bund in different water bodies (i.e. six at each transect, three either side of the bunds), within 50m left and right of each transect. During a Countrywide survey, 20 transects were sampled in different parts of The Gambia in September 2005, when mosquito numbers were relatively high. 10 were situated in parts of the river where it was salt and 10 were situated in parts of the river where the water was fresh. Mosquitoes were roughly twice as common in water on the landward side of the bunds, 68% of Anopheles larvae and 84% of all mosquito larvae, (OR) = 9.37, 95% confidence intervals (95% CIs = 2.26-38.79, P <0.002), compared with the riverside. Similarly 82% of Anopheline adults and 89% of all adult mosquitoes (OR = 2.59, 95% CIs = 1.23-5.48, P = 0.013) were collected on the landward side. There is also an indication that this is also true for the countrywide survey in which more mosquitoes were collected from the landside of the bund (63% Anophelines, 65% Culicines), although this did not reach statistical significance. One possible explanation for these findings is that larvae on the riverside of the bunds are washed away with the tide and predated by the larger number of fish found there. These findings indicate that the construction of bunds for agricultural purposes increases mosquito larval density on the landward side by increasing the breeding ground for malaria vectors of the *An. gambiae* complex. These constructions increase the number of vector mosquitoes emerging from

the floodplains of the River Gambia, and thus are likely to increase the intensity of malaria transmission.

Declaration

The material contained within this thesis has not been previously submitted for a degree at Durham University of or any other Institution. The research reported in this thesis has been conducted entirely by the author unless indicated otherwise. The copyright of this thesis rests with the author. No quotation from it should be published nor any methodology implemented without the prior consent of the author. Any information derived from this thesis should be appropriately acknowledged.

Contributions of Other Authors

Prof. S. W. Lindsay (Supervisor) conceived the design of the study, identified the study sites, helped in the field work, assisted in the data analysis, critiqued and reviewed the manuscript. **Dr Urike Fillinger**, helped develop the Standard Operational Procedures (SOPs). **Silas Majambereh,** helped identify study sites, and also assisted in the field work. **Dr Clare Green** helped with the molecular analysis of specimens. **Vasilis Louca,** PhD student and fish ecologist, helped with the fish sampling, identification and measurement of fish samples.

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Balla Kandeh

Dedication

This piece of work is dedicated entirely to my late mother Mrs Jainabou Baldeh Kandeh who died in 1968 shortly after I was born. I miss you dearly. May your soul rest in perfect peace. Amen.

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List of Acronyms

1.	AS	Area Sampler
2.	AWDI	Alternate wet/dry irrigation
3.	CCF	Christian Children's Fund
4.	CDC	Centre for Disease Control
5.	CRS	Catholic Relief Services
6.	DOSH	Department of State for Health
7.	DRC	Democratic Republic of Congo
8.	FAO	Food and Agricultural Organisation
9.	GDP	Gross Domestic Product
10.	GFTAM	Global Fund for AIDS, TB and Malaria
11.	GNP	Gross National Product
12.	GPS	Geographical Positioning System
13.	HYV	High Yield Varieties
14.	ITNs	Insecticide Treated Nets
15.	LLINs	Long-lasting insecticide treated nets
16.	MCH	Maternal and Child Health
17.	MRC	Medical Research Centre
18.	NMCP	National Malaria Control Programme
19.	RBM	Roll Back Malaria
20.	RVTH	Royal Victoria Teaching Hospital
21.	SP	Sulfadoxine-pyrimethamine
22.	SS	Sub-Saharan Africa
23.	UN	United Nations
24.	UNDP	United Nations Development Programme
25.	UNEP	United Nations Environment Programme
26.	UNICEF	United Nations International Children Emergency Fund
27.	URD	Upper River Division
28.	VCU	Vector Control Unit
29.	WARDA	West African Rice Development Authority
30.	WHO	World Health Organisation

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Chapter 1: Irrigation and malaria in Africa

Population Growth and Food Production in Africa

The population of sub-Saharan Africa (SSA) is expected to double between 1997 and 2025, but there is nothing in the region's agricultural history to suggest that it will increase its food output to meet such an explosive rate of population growth. Average yields may not rise much, and only a minority of countries will be able to afford to buy sizable amounts for its people (Dyson, 1999). As a result, most African governments are developing alternative plans for the expansion of agricultural production to cope with the high demand of food for its population (Evans, 1998; Cassman, 1999).

Global food projections indicate that although the aggregate global food supply and demand picture is relatively good, with food production in the world growing fast enough for world prices of food to be falling, there will be a worsening of food security in SSA (Rosengrant *et al.*, 1995). In this region, cereal imports are projected to triple, from 9 million metric tons in 1990 to 29 million metric tons in 2020. SSA will not have the financial means to pay for these growing imports. Of even greater concern, the number of malnourished children is projected to increase by 14 million by 2020 in SSA. Thus, even with relatively abundant food in the world, there will not be enough growth in effective per capita food demand in SSA to improve the food supply situation. In order to meet this need, many governments have sought ways of improving food production by initiating large-scale irrigation projects, involving reclamation of arid and semi-arid areas for the cultivation of crops.

Nearly half of all arable land in Africa is too dry for rain-fed agriculture and large areas experience rainfall, which is sparse and, more importantly highly variable (WRI/UNEP/UNDP, 1995). The demand for food is such that the area used for irrigation in Africa is expected to increase from 11.9 million ha in 1990 to 15.9 million ha in 2020, a 33% increase in 30 years (Rosengrant and Perez, 2000). But water is becoming increasingly scarce. Countries are considered water scarce when annual internal renewable water resources are less than 1,000 cubic meters per capita per year. Below this threshold, water availability is considered a severe constraint on socio-economic development and environmental quality. Currently, some 28 countries with a total population of 338 million are considered water stressed, and 20 of these countries are water scarce, nine of these are in Africa (Engelman and LeRoy, 1993), it is likely that the number of water-scarce countries will approach 35, and number of water-scarce African countries could double to 18. Many other African countries, which may have adequate water in the aggregate, suffer from debilitating seasonal and regional shortages, which urgently need to be addressed.

Africa's share of global fresh water resources is about 9% (UNESCO, 2006) which nearly matches its share of the world population of 12%. The average water availability is about 60% of the global average and is the lowest proportional coverage of any region in the world. The situation is much worse in the rural areas, where coverage can be lower than 50%, compared with 86% in urban areas. Africa's fresh water resources are distributed unevenly across the continent, with western and central Africa having greater precipitation than northern Africa, the Horn of Africa and southern Africa. The wettest country, the Democratic Republic of Congo (DRC), has nearly 25% of the average water resources in Africa. On the other hand, the driest country, Mauritania, has 0.01% of Africa's total (UNDP, 2000).

Agriculture's share of water will decline at an even faster rate because of the increasing competition for available water from urban and industrial sectors. Because of political and societal pressures urban and industrial demands are likely to receive priority over irrigation. Although agriculture is by far the biggest water user in SSA, the full physical irrigation potential is far from being tapped. Only about 33% of the potentially irrigated area is under irrigation. Physical potential is only limiting in North Africa, where almost 75% of the irrigation potential has already been used. More than one third of the potential area is being irrigated in the Southern and Indian Ocean Islands, and the Sudano-Sahelian regions, and less than 10% in the Western, Central and Eastern regions (www.fao.org).

As the population expands, the need for fresh water will increase, and the need for more food production will also increase. While Africa has the highest rate of population growth in the world, it is also one of the regions that are most vulnerable to climate change. At least 25 African countries are expected to experience water scarcity or water stress over the next 20-30 years (UNESCO, 2006).

It becomes even more essential to develop and adopt strategies and practices that will use water efficiently in irrigation schemes, particularly in parts of Africa, where demand for rice is increasing and water is less abundant than in other parts of the world.

Rice Production and Consumption

For nearly half the world's population (2.7 billion people), rice is the staple food providing 35-60% of the calories consumed (Guerra *et al.* 1998). More than 75% of the world's rice is produced in irrigated lands, mainly in Asia. Rice cultivation increased in importance after the introduction of high yield varieties of rice (HYV) in the mid 1960s, and is now the staple diet of over 60% of the world population (WHO/FAO/UNEP, 1987). There are 700 million rice consumers in the world, out of which 35 million (5%) are in Africa and the Near East (Grist 1986). The demand for rice in West Africa has increased at an annual growth rate of 5.6% and is not expected to fall below a 5% increase in the near future (www.fao.org). Rice is the staple food in The Gambia, with annual consumption of about 78kg/person/year (Kagbo, 1983).

Between 1989-1999 the area harvested for rice globally increased by 44% due largely to new irrigation projects and the expansion or rehabilitation of old ones. However, yield increased by only 17% between 1980s and 1990s, which was attributed to poor agricultural inputs, such as fertilizers, water shortage, pest problems and abandonment of some irrigation schemes. In order that rice production keeps pace with population growth, there is a continuing need to increase land used for irrigation.

Irrigation and Health

Although crop irrigation promises one solution to alleviating hunger and encourages economic growth, irrigation has often been blamed for aggravating disease in local communities as it can provide habitats suitable for vector mosquitoes and snail intermediate hosts of schistosomiasis (Bradley 1988, Gratz 1988, Service 1989, Hunter *et al.*, 1993). Water resource development projects lead to either an increase in the number of vectors or the amount of contact between human communities and vectors. The consequence is often an increase number of disease cases. Well known examples include the Aswan, Kairaba and Volta Lake dams which were constructed to provide water for irrigation or hydroelectric power or both, but they also bestowed additional disease burdens on the local community. During a malaria epidemic in the Gezira scheme in the Sudan, 33 working days were lost per tenant, reducing cotton production by an estimated 20% (cited in Ijumba & Lindsay 2001). The development of water resources seems bound to continue, however, a concomitant rise in disease prevalence could significantly reduce the expected benefits.

Rice Cultivation and Malaria

Rice is considered to pose a threat to health since it is grown in flooded conditions, which provide ideal breeding sites for malaria mosquitoes. Malaria is one of the major tropical diseases associated with irrigation schemes, and changes in the transmission pattern of this disease following irrigation development have been a perennial subject of debate (Ijumba & Lindsay 2001).

In Africa, rice fields have proved to be particularly well suited as breeding sites for *Anopheles gambiae s.l.*, the main malaria vector in SSA. This species breeds in the shallow inundated fields during tilling, transplanting during the first six weeks of the growing period (until canopy closure), and after harvest (Klinkenberg *et al*, 2003). It has often been assumed that high numbers of malaria vectors resulting from irrigation schemes lead inevitably to increased malaria in local communities. However, recent studies in Africa have revealed a more complex picture. Increased numbers of vectors following irrigation can lead to increase in malaria in areas of unstable transmission, where people have little or no immunity to malaria parasites, such as the African highlands and desert fringes (Ijumba & Lindsay, 2001; Yohannes *et al*, 2005). But for most of SSA where malaria is stable, the introduction of crop irrigation has little impact on malaria transmission (Ijumba *et al*, 2002). Indeed, there is growing evidence that for many sites there is less malaria in irrigated communities than surrounding areas. It seems likely that many communities near irrigation schemes benefit from the greater wealth created by these schemes. Consequently irrigation communities often have greater use of bed nets, better access to improved healthcare and receive fewer infective bites compared with those outside such development schemes.

However, despite conflicting results from studies evaluating the impact of rice irrigation on malaria transmission in different parts of Africa, a substantial number of studies reported similar prevalence of malaria near rice irrigation schemes compared with areas without irrigation (Ijumba & Lindsay, 2001). In a study in three communities in northern Tanzania (Ijumba *et al*, 2002), the authors evaluated the level of malaria experienced by different communities with different agricultural practices: rice irrigation, sugar-cane irrigation and traditional maize cultivation. The overall results showed a low prevalence of malaria parasites in communities near rice irrigation (12.5%) compared with sugar-cane (16.9%) and savanna village (29.4%). They reported that overall, rice irrigation was associated with less malaria with alternative agricultural practices, despite the considerable numbers of vectors produced in the paddies. This was attributed to the fact that farmers who live in irrigated rice fields can afford self protection measures such as insecticide treated nets, and due to improved socio-economic status, they can also seek treatment. Similarly in a related study in rice growing villages in Mali (Sissoko *et al*, 2004), the total malaria transmission in these irrigated villages was much smaller than in non-irrigated ones. For instance, the average entomological infection rate (EIR) was 8.7 infective bites per month for the non-irrigated villages but only 2.4 infective bites per month for the irrigated villages. This paralleled the numbers of clinically diagnosed cases of malaria in children at the same time. However, in the highlands of Burundi there was a high prevalence of malaria in communities close to irrigated rice fields and flooded areas (Coosemans *et al*, 1984).

The Gambia

The Gambia is a narrow enclave within Senegal (except for a coastal strip) lying between 13°N and 14°N and extending from the coast to about 400km inland surrounding the lower reaches of The Gambia River, which is saline for more than 150 km inland. The river is a large slow moving waterway, characterized by salt-water intrusions in its lower reaches. The flow of the river is highly seasonal and depends largely on rainfall in the Guinea highlands. During the dry season the salt front can travel as far as 200km up river. However, during the rainy season the outflow of fresh water and increased rainfall result in the saltfront being pushed down river. Importantly, the geography of The Gambia is not specific to the country as it represents similar riverine habitats across the Sahel. The country lies in the Guinea savannah vegetation zone and the climate is tropical. The average annual rainfall varies from 963 to 1202 mm throughout the country. Most of the rain occurs within a single rainy season which generally begins in late May and ends in October or November, with highest rainfall in August. In the long dry season (December to May), the maximum temperatures remain high (37– 40°C) while the relative humidity falls dramatically 40% to 55% (Department of Hydro meteorological Services, 1990).

The Gambia River originates from Futa Djallo in the mountain region of Western Guinea and flows through Senegal before entering The Gambia. Its flow is highly seasonal. The maximum flow occurs at the end of the rainy season in late September or October with a flow of about 1,500m^3/s; the minimum dry season flow is less than 4.5m^3/s http://www.eoearth.org/article/water_profile_of_Gambia). Because of the flat topography, there is a pronounced marine influence and the river's seasonality and salinity have important repercussions on land use. Agricultural farming in The Gambia is characterized by subsistence rain-fed production, depending on the distribution and amount of rainfall. Farmlands in The Gambia are classified into upland and lowland. The main crop grow in the lowlands in the wet season is rice using hand cultivation on approximately 20,000 ha, primarily along the middle and lower reaches of the Gambia River. In the dry season, vegetables are cultivated in the lowlands. In the low-lying marshy areas tidal flows are employed for irrigation. This is feasible in the middle reaches of the river, beyond the 240 km mark where river water is not salty. In 1991, approximately 13,170 ha of wetlands and inland valley bottoms were cultivated. These areas represent mangrove swamps and freshwater swamps, where rice is grown from August to January by constructing bunds to prevent salt water intrusion, soil erosion and increase the water retention capacity of the soil to facilitate rice production. Although, the impoundment of water will prevent soil erosion, increase water usage, enrich the soil in terms of nutrients and enhance rice cultivation on the landward side of the bunds, it may however, serve as potential breeding grounds for malaria vectors which may result in an increase in larval and adult densities, all of which may increase the risk of malaria transmission in The Gambia.

The Malaria Burden

Malaria is a disease of major public health concern in SSA, with 550 million people at risk with about 300 million clinical cases and up to 1 million deaths annually, mainly among children under 5 years and pregnant women (www.rbm.who.int). Malaria accounts for 30-40% of outpatient visits, 10-20% hospital admissions. Malaria drains economics in Africa, Asia and the Americas – causing a loss of up to 6% of Gross National Product (GNP) from lost productivity and health service costs, with over 50% of the world's population at risk for malaria. Thus, the vast majority of malaria deaths occur in SSA, where malaria also presents major obstacles to social and economic development. Malaria has been estimated to cost Africa more than US$12 billion every year in lost GDP, even though it could be controlled for a fraction of that sum.

There are several reasons why SSA bears an overwhelming proportion of the malaria burden. Most malaria infections in SSA are caused by *Plasmodium falciparum*, a protozoan parasite, one of the species of Plasmodium that cause malaria in humans. *P. falciparum* is the most dangerous of these infections as *P. falciparum* malaria has the highest rates of complications and mortality. This region is also home to *Anopheles gambiae*, the most efficient vector of malaria in the world. Moreover, many countries in Africa lacked the infrastructures and the resources necessary to mount sustainable campaigns against malaria and as a result few benefited from historical efforts to eradicate malaria.

In Africa today, malaria is understood to be both a disease of poverty and a cause of poverty. Annual economic growth in countries with high malaria transmission has historically been lower than countries without malaria. Economists believe that malaria (www.rbm.who.int/cmc) is responsible for a 'growth penalty' of up to 1.3% per year in some African countries. When compounded over the years, this penalty leads to substantial differences in GDP between countries with and without malaria and severely restrains the economic growth of the entire region. Malaria also has a direct impact on Africa's human resources. Not only does malaria result in loss of life and lost productivity due to illness and premature deaths, but malaria also hampers children's schooling and social development through both absenteeism and permanent neurological and other damage associated with severe episode of the disease.

One of the greatest challenges facing Africa in the fight against malaria is drug resistance. Resistance to chloroquine, the cheapest and most widely used antimalarial, is common throughout Africa, particularly in southern and eastern parts of the continent (Mbugo *et al*, 2006). Resistance to Sulfadoxine-pyrimethamine (SP), often seen as the first and least expensive alternative to chloroquine is also increasing in east and southern Africa. As a result of these trends, many countries are changing their treatment policies, and use drugs which are more expensive, including combinations of drugs, based on Artemisinin with other types of antimalarials, is expected to slow the development of resistance.

In The Gambia, malaria is also the leading cause of morbidity and mortality especially among children under 5 years and pregnant women. 20% of antenatal consultations and 40% under 5 years olds visits in Maternal and Child health (MCH) services are due to malaria (malaria situational analysis report, 2003, The Gambia). Malaria in The Gambia leads to lost days of productivity, absenteeism from school and increased household expenditure on health. A mortality survey conducted by the Department of State for Health indicates that malaria is the most frequent cause of death in the rural areas accounting to 105 deaths/1000 live births (malaria situational analysis report, 2002).

An. gambiae s.s. and *An. arabiensis* are the major vectors and are distributed throughout the country (Bryan 1979). *An. melas* is restricted to the western half of the country and probably causes less disease burden because of its zoophilic nature. *P. falciparum* is the commonest species responsible for all severe diseases and over 95% of clinical attacks.
Members of the *Anopheles gambiae* complex, especially *An. gambiae s.s.* and *An. arabiensis* prefer to breed in open sunlit pools, hoof prints, permanent or semi permanent water bodies (Gillies & De Meilljon, 1968; Surtees, 1970). Whilst *An. melas* on the other hand, is a well known salt water breeding mosquito and was found in salinities of up to

72% sea water in The Gambia., frequently in flooded areas with vegetation dominated by *Sporobolus s.*, and *Eleocharis sp.* (Bøgh *et al*, 2003).

Although the whole population is at risk of contracting malaria throughout the year, the prevalence varies from area to area. The highest rates are recorded in rural areas where children repeatedly experience 1-2 clinical attacks of malaria every year (MRC 2000, Household survey). On the other hand, there are also differences between rural areas, with more intense transmission and more severe diseases in the Upper River Division (URD) than in any other area (DOSH, 2002).

Malaria occurs in The Gambia throughout the year, but the majority of cases occur from September to December (MRC, 2000). The transmission of malaria during this period is intense and the number of cases seen at the peak of the season may increase 20 fold compared with the number seen during the middle of the dry season. Although, cases of malaria are seen during the dry season, the number of positive blood smears is low, 20-40% in comparison with a positive rate of over 70% during the peak of the malaria season, September-December (DOSH, 2002).

Malaria is the main cause of admissions to the paediatric unit of the Royal Victoria Teaching Hospital (RVTH) and accounts for between 30-40% of admissions to the unit. Clinical records from the RVTH (1993-1995) also indicate that 35% of the 1,314 children aged 5-14 years admitted to the hospital suffered from cerebral malaria.

African Initiatives in the Fight against Malaria

Although important progress in malaria control has been accomplished in recent years, much more can be done. This slow progress is partly due to lack of funding. The Center for Disease Control (CDC) recognizes that this is also due to lack of coordination between research groups, and between researchers and donors, policy makers and Government Ministries responsible for implementation. After decades of neglect, the international community is showing a renewed interest in controlling malaria. This has resulted in initiatives, including Roll Back Malaria (RBM) initiative (www.rbm.who.int), Global Fund for AIDS, Tuberculosis and Malaria (GFATM) initiatives (www.rbm.who.int/cmc) and Malaria Vaccine Initiative (www.rbm.who.int) as well as significant new funding for both research and program development. Global collaboration is now more critical than ever to ensure translation of this commitment into action and avoid fragmentation of efforts. Many of these studies require well-coordinated multi-centre trials to allow accumulation of data and account for the geographical variations in drug sensitivity, frequency of host-genetic polymorphism, and cultural references.

Roll Back Malaria (RBM)

RBM is a global partnership founded in 1998 by the World Health Organization (WHO), the United Nations Development Programme (UNDP), the United Nations Children's Fund (UNICEF) and the World Bank with the goal of halving the world's malaria burden by 2010. The RBM partnership includes national governments, civil society and non-governmental organizations, research institutions, professional associations, UN and development agencies, development banks, the private sector and the media. The strength of the RBM is the diverse strengths and expertise of its many partners.

RBM was founded in response to a growing concern by governments, particularly in Africa, about the continuing and increasing burden of disease and deaths due to malaria. RBM is being built on the shoulders of recent successful efforts in malaria-affected countries and regions to improve and support capacity to scale-up action against malaria. The RBM partnership supports efforts to tackle malaria wherever it occurs. RBM seek to expand the use of interventions already known to be effective against in tackling malaria. This includes prompt access to effective treatment; promotion of insecticide-treated mosquito nets (ITNs) and improved vector control, prevention and treatment of malaria in pregnancy, and improving the prevention of and response to malaria epidemics in complex emergencies. They also support work which will result in even more effective interventions in the near future, such as better medicines and Long-Lasting Insecticidal Nets (LLINs); and encourage the research necessary for even better interventions to be developed and deployed in the future - including new and better drugs and insecticides, as well as malaria vaccines and possibly genetically modified mosquitoes that will not transmit malaria.

Malaria Control in The Gambia

Prior to independence in 1965, malaria control activities were affected through the anti-malaria unit. Subsequent re-organization led to the establishment of the Vector Control Unit (VCU), responsible for the control of all vector borne disease. However, in 1990 to 1991, in response to the emerging problems of malaria, as a major public health problem in The Gambia, the VCU was re-organized and the National Malaria Control Unit (NMCP) was set up as a separate unit with the specific aim of developing a program to control the disease. In 1993, a major re-organization review within the ministry of health reassigned the NMCP to the division of disease control.

The NMCP is responsible for co-coordinating between partners, overseeing policy implementation, technical support to the divisions and resource mobilization. A national malaria control plan was developed and is being implemented. In addition, the RBM initiative agreed and signed by Heads of States, referred to as the Abuja Declaration (www.rbm.who.int), is also used as a strategy to tackle the problem of malaria in The Gambia. The NMCP is integrated within The Gambia health care delivery system and made more accessible to communities through the country's renowned primary health care strategy. The World Health Organization (WHO) and UNICEF are the main funding partners at the moment, but the collaboration and the support of partners, such as the Christian Children's Fund (CCF), Catholic Relief Services (CRS) etc., of community based interventions, is acknowledged by the Department of State for Health.

The unit is involved in both preventive and curative efforts. The primary aim of the preventive component is to control the mosquito so as to reduce human-vector contact and vector density by sleeping under ITNs.

Water Management in The Gambia

Water in The Gambia is used for agriculture, industry and domestic purposes. Agriculture is far the biggest user accounting for over 85 % of water withdrawals. One of the major problems of water management in The Gambia is the prevention of salt-water intrusion into fertile areas used for rice cultivation. Increases in population, reduction of annual rainfall and intensive cropping make the management of soil and water resources necessary in order to meet the demands of human and livestock populations.

Water management and the construction of bunds (Fig. 1), small embankments, for agricultural purposes, have been in existence in The Gambia since the 1960s (Webb, 1992). Bunds have been constructed to impound rainwater to prevent soil erosion, extend water usage through the period of cultivation, and to prevent the encroachment of salinity of the seawater into the rice fields. Preventing saltwater intrusion is particularly important in the western half of the country, where The Gambia is perennially or seasonally saline. This zone stretches from the mouth of The River Gambia 170 km inland. In contrast, in the eastern part of the country, from 170 to 450 km inland, saline intrusion is not a problem and the bunds are used only for the storage of fresh water (Webb, 1992).

It has been found that nearly all *An. gambiae s.l.*, the major vectors of malaria in The Gambia, occur in the extensive areas of pooled sediments bordering The River Gambia during the rainy season (Bøgh *et al*, 2003). Although preliminary data have shown that larvae are found up to 1300m from the landward edge of the flooded areas, most adult mosquitoes emerge at the edges of the flooded pools. Extensive networks of bunds have been constructed across the pools to prevent the encroachment of salty river water, reducing rice production along the landward edge of the pools. Such large freshwater sites are likely to favour the development of the more competent vector species *An. gambiae s.s.*, which thrives in fresh water. This study set out to establish whether bund construction alters the local ecology of vector species and increases the risk of malaria transmission.

Figure 1: *A bund at Jattaba village during the dry season*

Chapter: 2 Study rationale

Recently extensive networks of bunds (small embankments) have been constructed in The Gambia across pools in the floodplain of the River Gambia in order to prevent the encroachment of salty river water, increase water usage, and reduce soil erosion. In the western part of the country, from the coast to just east of Farafenni town, the river water is salt, and here bunds help protect rice growing areas from salt inundation. To the east of this area the river water is fresh, but the bunds are important for impounding water and reduce soil erosion. The impoundment of large bodies of freshwater are likely to favour the development of the more competent vector species *An. gambiae s.s.*, which thrives in freshwater, and where there are likely to be few larvivorous fishes. This study sets out to establish, whether bund construction alters the local ecology of vector species and increases the risk of malaria transmission.

Study Goal:

To determine whether bund construction increases malaria transmission in The Gambia.

Specific Objectives:

1. Determine Anopheline and Culicine larval densities at 10m intervals along three transects 100-150m each side of a bund from May to November, during the main malaria transmission season;
2. Identify the Anopheles species complex and species distribution along the three transects in association with biotic and abiotic factors;
3. Determine the association of predatory organisms (insectivorous insects, amphibians and fish) at a sampling interval of 10m along each transect;
4. Identify terrestrial, submerged and floating vegetations associated with mosquito larval density;
5. Determine abiotic factors of breeding sites associated insect fauna at sampling intervals;
6. Assess the numbers of adult mosquitoes emerging from either side of the bunds;
7. Determine the species of adult mosquitoes emerging from each side of the bunds;

8. Determine Anopheles and Culicine larval densities in 10 randomly selected bunds countrywide.

To address these objectives three separate, but related studies were carried out these were; (1) larval and (2) adult mosquito longitudinal sampling at three different bunds and a (3) cross-sectional nationwide survey of mosquito larvae in different bunds.

I was responsible for data collection from the field. **Prof. Steve Lindsay** and **Silas Majambereh** helped identified study sites and also assisted in the actual work. **Vasilis Louca** did the fish sampling, identified and grouped fish into various species. **Dr. Clare Green** helped with the PCR diagnostic in identifying members of the *An. gambiae* complex. **Ousnam Njie** and **Lamin Camara**, Laboratory assistants, helped with identifying other invertebrates. **Momodou Lamin Ngum** and **Musa Drammeh** also assisted with the field work.

Chapter 3: Materials and Methods

Longitudinal transect surveys

Study Site

The study was based largely around Farafenni town (1500200mN, 435500mE), in the central part of the country, about 105 km from the capital city Banjul. The area is predominantly flat farmland and wooden land savannah. The main inland crops are sorghum, millet, groundnut and pumpkin, and in the flood plains swamp rice is grown during the rainy season (July-October, annual precipitation between 600-800mm). The villages in the area are discrete cluster of houses and not scattered as seen in many parts of Africa. The rainy season in The Gambia lasts from June to October with total rainfall varying from year to year. The peak rainfall usually occurs in August. At this time the average maximum temperatures range between 35-39°C and average maximum saturation deficit between 5-10mm. The remaining seven months of the year are hot with average maximum temperatures reaching 40°C and saturation deficit rising to 42mm. from March to May.

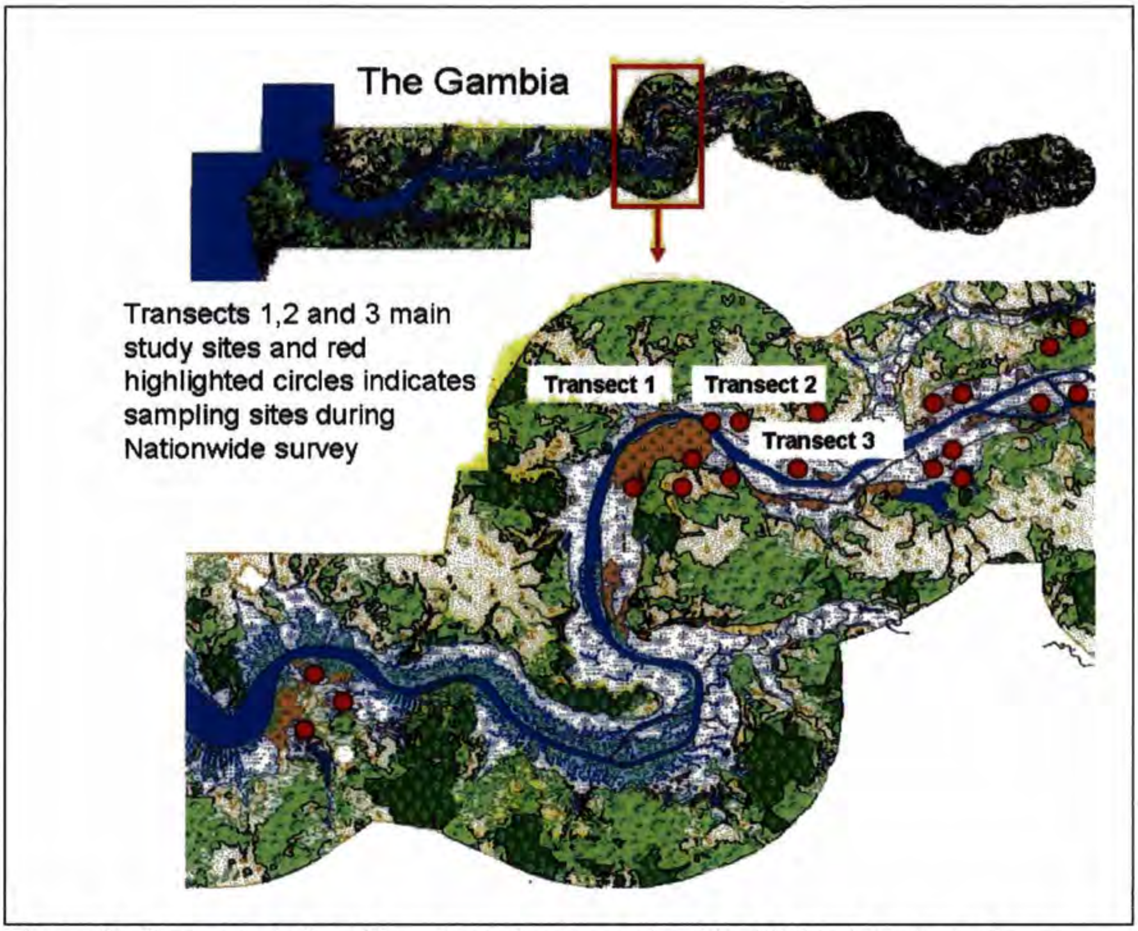


Figure 2: *Transects 1, 2 and 3 main study sites and red highlighted circles indicates sampling sites during Nationwide survey*

Sensitization of local communities

In order to get the full support and cooperation of the community in this project, it was necessary, to involve them during the planning process. A mass community sensitization in the study sites was carried out in the third week of May 2005. The sensitization was in the form of village meetings and discussions involving opinion leaders, community groups, youths and fieldworkers. The sensitization focused on the importance of the project in the fight against malaria and the need for community participation in malaria prevention and control activities. Ethical approval for this work was approved by the joint Ethics Committee of the MRC Laboratories in The Gambia and the Gambian Government, and Durham University's Ethics Advisory Committee.

Larval Sampling

Three transects, each 200m in length, were sampled once every three weeks from May to December, including the period of annual rainfall from June to October. Two transects were situated along the Bintan Bolon near Illiassa (1333950N, 1544957W) and India villages (1333972N, 1544949W) in Central Badibou District. The third transect was situated to the east of Farafenni town, near Kunjo village (1334364N, 1534560E) where the bund was in a poor state of repair (Kunjo transect 3).

Each transect was 400m in length and perpendicular to the axis of the bund; 200m on either side of the bund. Transects were positioned across typical vegetation found in that area. Wooden stakes were placed along each transect at 10m intervals to aid future surveys. Measurements were made in water bodies within 50m left and right of each transect every 10m along each transect. In addition to the 10m interval sampling, when walking along each transect each new water body that was found was sampled.

Figure 3: *Area Sampler*

Sampling was done with an Area Sampler (AS), an open tube made from aluminium with serrated teeth around the bottom lip (Figure 2). It was 39.5cm long with an upper diameter of 47cm and a lower diameter of 40cm. An AS was plunged quickly into the mud in an area within 10m of the transect that was most likely to contain larvae, e.g. where there was a tuft of grass or debris nearby. The AS was left for 30 seconds to allow water to calm down from disturbance and the larvae to come to the surface. A standard dipper (350ml) was used to take out as much water and organisms in the AS and transferred into a white bowl. Enough time was taken to sample the water from area sampler for organisms and recording was done for each sampling point in a specific data-sheet (appendix 1).

The following information was recorded: study zone, distance from start of transect, GPS coordinates, land cover type, aquatic habitat, type (foot print, pond, flooded plain, rice field, water temperature 1 cm below the surface, the depth of the water, pH, salinity, water turbidity and oxygen concentration. The presence or absence of floating vegetation or debris (% coverage), submerged (water) plants, Anopheles and Culex larvae and other water insects, amphibians and fish was also recorded.

Land cover types were recorded as follows. Edge of floodwater was the landward edge of floodwater in the floodplains. The water is shallow and may either be a single large water body or consist of a number of pools and puddles. The landward edge of the floodwater is associated with barren floodplains or floodplains characterized by grasses and sedges. It is always the first water body one finds when entering the floodplains from the upland. The floodwater, in contrast to pools and ponds, is not a discrete water body. These are areas of water in the floodplains further away from the landward edge. They can be open floodwater bodies with deep water (sometimes dependent on high tides) but they can also be shallow with similar characteristics as the edge of floodwater, just that these sites are further away from the edge of the floodplains. These can also be sites where tall reeds characterize the land cover. Rice fields were flooded areas used to grow rice including rice nurseries and can be found in floodplains or in upland. Streams in the floodplains are water bodies with a more permanent character and are deep in the middle. Mosquito habitats are usually associated with the fringes of these streams. Pools are discrete standing water bodies, medium-sized to large (greater than 2 m^2), and can be natural or man-made. Pools are relatively shallow and therefore not present throughout the year. Ponds are discrete water bodies of larger size and higher depths filled by groundwater. Ponds were permanent water bodies present throughout the year although their size may decrease in the dry season. The edges of ponds may serve as mosquito larval habitats. Footprints were from people, cattle or other animals that form small depression in the ground where water collects. Footprint areas are often found on edges of large water bodies (floodwater, pools and ponds). Water channels which are often man made were also recorded. These may be used to channel water for irrigation or to drain the water (surface water run off). Puddles and tyre-tracks were also recorded. These are small to medium sized areas (less than 2 m^2) where water stands on the ground after rain; they are always natural, filled by rain and water runoff. Tyre tracks are puddles that collect water due to marks left by vehicles in the ground that get filled with water after rains.

pH, salinity (conductivity) and oxygen were measured using a portable meter (WTW Multi 340i, -Germany). The pH probe was immersed in water 10 and 15 minutes before a reading was done. The oxygen probe was immersed, and moved in a circular manner (approximately 10 cm diameter) at a steady speed (approximately 1 rotation per second) and the reading taken when the reading on the meter stabilizes, usually after 10 minutes. The conductivity probe was also immersed into the water and read as soon as the reading stabilized, usually after 10 minutes. Turbidity was measured as follows. Six water samples (three on either sides of the bund) were taken in separate glass bottles of 20mls each to measure turbidity in the laboratory. These were taken at 0m, 50m and 100m. Samples were taken from undisturbed water and turbidity measured with a meter (Hanna micro processing turbidity meter, Hanna Instrument Company, Italy). The glass cuvet were cleaned thoroughly by washing with distilled water and dried with a clean lint-free tissue to eliminate any effects of previous liquids and dust. The water sample in the plastic universal containing 20ml of water collected from the sampling point was thoroughly agitated to evenly mix suspended particles. The cuvet was filled up to 0.5cm from its rim with the sample before securing the cap and it is placed into the cell and the notch on the cap positioned securely into the groove. The turbidity value appeared after 20sec and the reading recorded.

Adult mosquito sampling

Emergence traps were constructed from a conical metal frame covered with netting, except for the base which is open (Figure 3). The trap has a perimeter of 312cm, a diameter of the base 103cm, a height of 88cm. The diameter of the top opening was 7cm. The trap floats on the water surface supported by three floats around its rim. The trap was kept in position A fixed pole with rope attached to the rim of the trap kept the trap in position. At the top of the trap there is a small outlet that connects to a light transparent container that collected all insects. This container was filled with 60% glycol or sometimes 4% formalin to kill mosquitoes and other flying species. A netting sleeve on the side of the trap allowed access to adult insects flying or resting inside the trap. Each trap was numbered separately.

Figure 4: *Emergence trap floating on the surface of water*

Three emergence traps were positioned at each side of the bund in different water bodies (i.e. six at each transect, three either side of the bunds), within 50 m left and right of each transect. Where there were more than three water bodies; sites close (0m), medium (50m) and far (100m) from the bund were selected. Traps were placed where larvae were recently seen or were expected to be present. If no larvae were previously seen, traps were placed close to the edges of vegetation (tufts of low grass, debris, etc.). The trap was anchored allowing it a 1m radius of free floating. Each trap was visited and emptied weekly.

In order to collect insects from a trap, the collection reservoir was removed and the top of the trap was closed with a rag to prevent adult insects from escaping. Most insects were trapped and killed in glycol in the top container. The top container was removed and the glycol and insects poured into a labelled bottle (the number on the bottle was the same as the trap, so that the same bottle was used for the same trap weekly). All insects in the sampling container were carefully removed using a small brush and transferred to the collection bottle. The sleeve was opened and an aspirator used to aspirate all insects on the inside of the netting. Live insects were killed and stored in the bottle containing glycol from the top of the trap. The top sampling device was refilled with 250 ml 60% glycol or sometimes 4% formalin and put back on top of the emergence trap and the sleeve tied up again. In order to ensure that the trap was not damaged and was not stuck between vegetation or surface debris, it was gently moved to allow it to float freely. The trap was always moved to where larvae were recently found.

The following information was recorded on the data sheet: Transect No (sampling Area), Emergence Trap Number, GPS coordinates, sampling zone (open floodplains, sedge zone, Phragmites zone, Mangrove forest), water depth, water temperature 1 cm below surface, tidal water or not, and salinity, type of habitat (hoof print area, ponds, flooded plain, or rice field), presence of land vegetation (grass/herbal plants, sedge, Phragmites etc.), presence of floating vegetation or debris, and presence of submerged (water) plants were also recorded.

The content of the sampling device was filtered separately for each emergence trap and the glycol recycled and used in subsequent traps before becoming too dirty. The collected insects were transferred into a glass vial and labelled.

Cross-sectional Nationwide survey

20 transects were sampled in different parts of The Gambia in September 2005 when mosquito numbers were relatively high. A list of bunds constructed in The Gambia was obtained from the Soil and Water Management Division of the Department of Agriculture at Yundum. 20 sites were selected at random, stratifying for geographical location (District). 10 were situated in parts of the river where it is salt and 10 were situated in parts of the river where the water is fresh. Each transect was 200 m long: 100m was on the riverside of the bund, perpendicular to the bund, and 100m was on the landward side of the bund. Transects included areas of typical vegetation found in that locality. Anopheles and Culicine larval densities were sampled every 10m intervals along each transect. Sampling was be done with a dipper and three dips were made at each site, one

after another, in an area within 10m of the transect that were most likely to contain larvae, e.g. if there is a tuft of grass or debris nearby. In open water each dip occurred at 3 minute intervals to wait for larvae to rise to the surface.

A GPS was used to locate the starting point. The water temperature (1cm below the surface), pH, salinity and O_2 concentration in three different water bodies (0-9m, 10-49m, and 50-99m) on both sides of the bund were recorded (i.e. six in total).

In very small breeding sites like hoof prints where a dipper does not fit, the water was stirred with a stick to make it muddy to allow larvae and pupae to rise where they were easily seen against the muddy background. Larvae was then collected with a small sieve, spoon or pipette.

Water was collected from the sampling point in a 20ml plastic universal container and taken to the laboratory to measure turbidity. Larvae were stored in 100% ethanol from each sampling position in separate bottles and labelled well with the responsible scientists initials, date of collection, transect number, side of bund (0=riverside, 1=landside) and distance (i.e. 0-9m, 10-49m or 50-99m).

Fish were sampled using a $1m^3$ throw trap. The sampling device was constructed with a metal frame and surrounded at four sides with a 1mm of mosquito net to prevent any fish from either entering or escaping from the trap. Fish were sampled at 0, 50 and a 100m interval at either sides of the bund. Lengths of fish and weight were measured, and specimens stored in 70% ethanol and labelled. The length was measured to the nearest 0.1mm using vernier calbers. Fish were identified to species using the methodology of Paugy *et al* (2003).

PCR analysis

Polymerase chain reaction (PCR) species identification within *An. gambiae* complex was followed, using the procedures described by Scott *et al*, 1993. DNA was extracted from whole mosquitoes by grinding tissues with a sterile eppendorf micropestle in a 10% chelex solution. The mixture was incubated at 56°C for 45 mins after which the temperature was increased to 94°C for 10 mins. Samples were centrifuged at 14,000 revolutions per minute, and then the top layer of the DNA in solution was removed and placed in a clean 1.5 ml eppendorf.

PCR was carried out with 2.5 µl of the DNA extracted as above in a volume of 25 µl containing 1x PCR buffer (Bio-labs) and 200 micro- molars (uM) of each dNTP, and 10pmol/µl primers UN, AR, GA, ME and 0.5 U Taq (Bio-labs). The primers used to identify the mosquitoes from the *An. gambiae*-complex were those of Fanello *et al*, (2002). Thermocycling was run at 94^0C for 5 minutes, followed by 30 cycles of 94^0C for 1 min, 53^0C for 1 min, 72^0C for 1 min, with a final extension of 72^0C for 5 minutes. PCR products were visualized by electrophoresis through a 1.5% agarose gel, at 100V for 45 mins followed by examination under UV light. Species were differentiated according to size in the different products.

Data Analysis

Data were recorded on paper forms and transferred to an Excel spread sheet. All data were analyzed using SPSS software version 11.0 (SPSS Inc, USA). Non-normal data were log transformed to stabilize the variance. T-tests and paired t-tests were used to compare means between two groups and ANOVA used for comparing the means of several groups. Forward conditional binary logistic regression analysis was used to determine the relative importance of variables with the presence or absence of anopheline larvae and adults either on the riverside or the landside. Wilcoxon's signed ranks test, was used to compare non parametric data.

Chapter 4 Results

Climate

Data on rainfall was collected with a rain gauge at the Medical Research Council station in Farafenni. The average monthly ambient temperature during the rainy season varied between 37-39^{0}C and reached a peak of 40^{0}C, after the rains in October 2005. The total rainfall during the study was 858.3 mm (Fig 4). In 2005 the first rains fell in June, reaching maximum levels from July to September, before declining in October at the end of the rainy season.

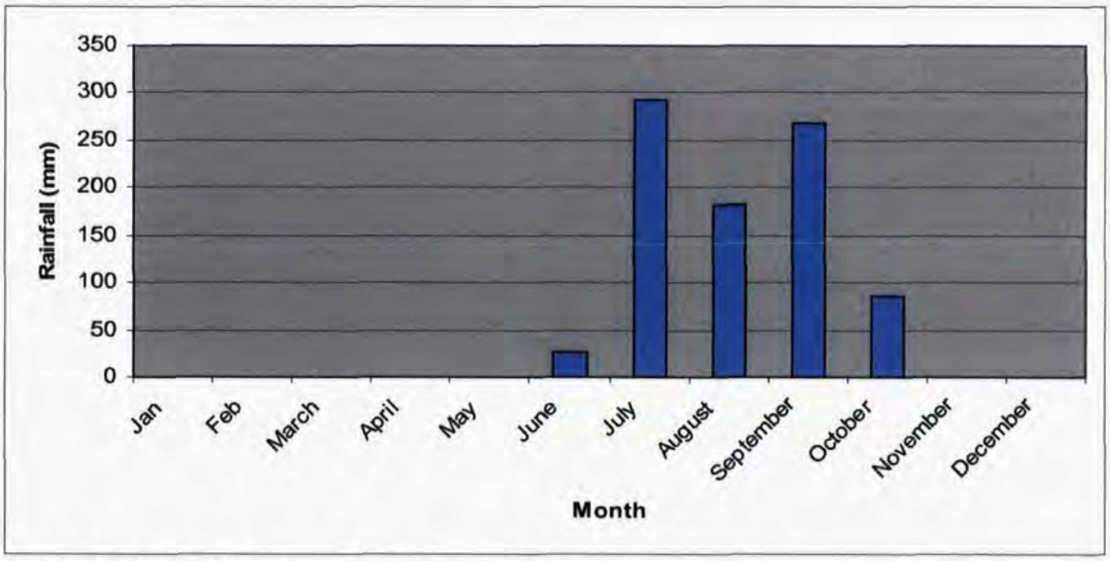
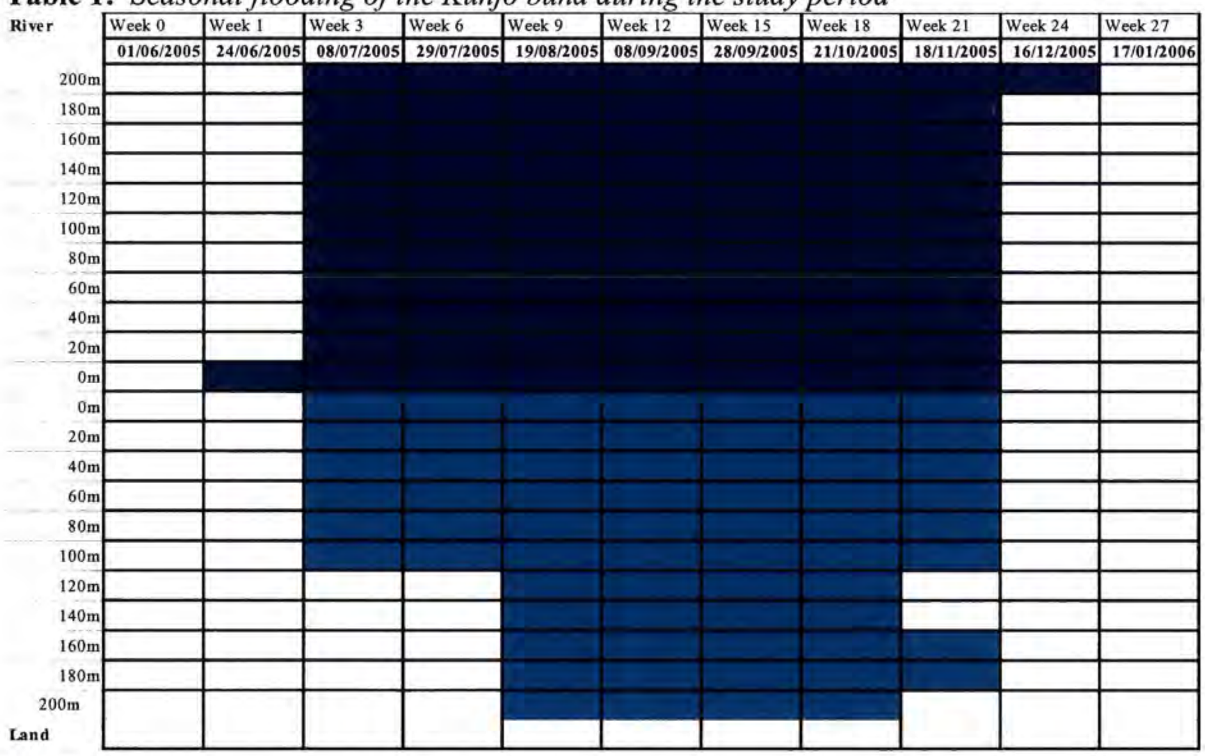


Figure 5: *Rainfall during the study period*

Transect flooding

The pattern of water on either side of the three bunds was monitored throughout the study period (Tables 1, 2 and 3). The transect at Kunjo was completely dry on both sides of the bund in the beginning of June, except for the water channel on the riverside which flooded towards the end of the month. However, the riverside of the bund quickly flooded in the first week of July 2005. The landward side of the bund became totally flooded approximately 6 weeks later in the middle of August. Both sides of the bund remained completely flooded until the end of November. By the middle of December, the only flooded area was on the riverside and by the end of December and the beginning of January 2006, the whole study site had became dry again.

Table 1: *Seasonal flooding of the Kunjo bund during the study period*

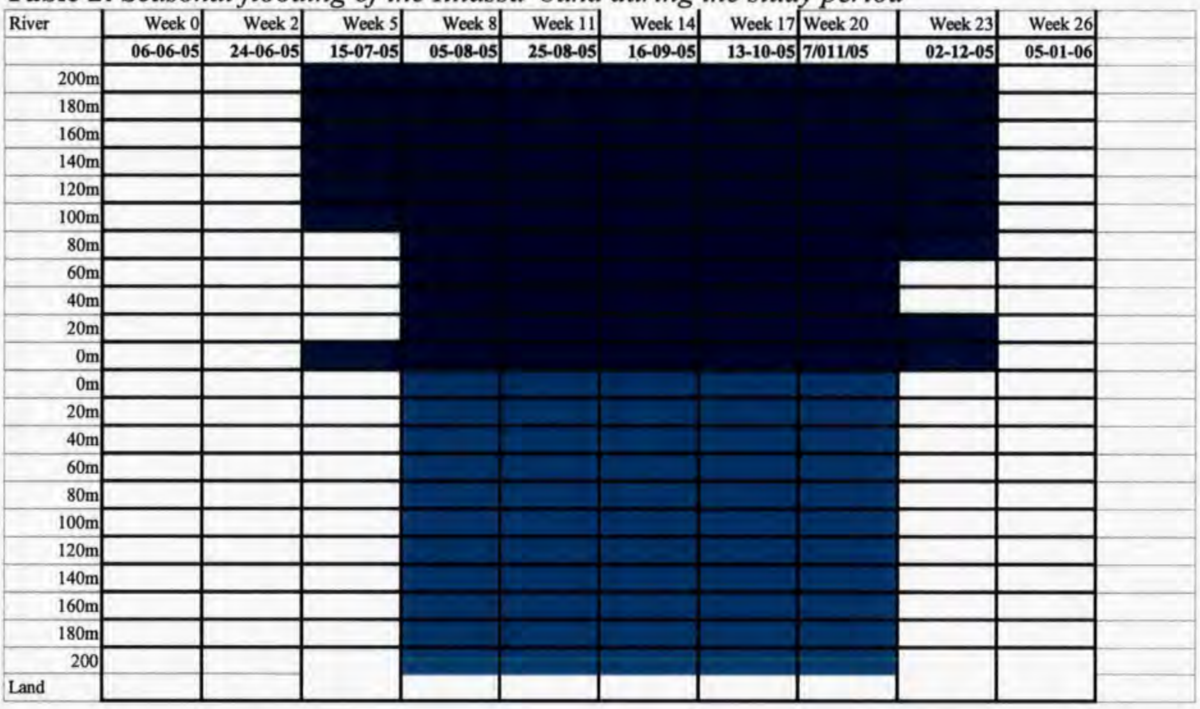


Dark blue bars represent flooded areas on the riverside of the bund

Light blue bars represent flooded areas on the landward side of the bund

Kunjo was flooded towards the end of June, whilst Illiasa and India were flooded in July. India was flooded for a slightly longer period during the study (7 weeks) than the other transects (Illiasa, 6 week, Kunjo 6 weeks).

Table 2: *Seasonal flooding of the Illiassa bund during the study period*



Dark blue bars represent flooded areas on the riverside of the bund

Light blue bars represent flooded areas on the landward side of the bund

The Illiassa study site was completely dry on both sides of the bund for the whole of June (Table 2). Flooding on the riverside of the bund started in the middle of July where as the landside was completely dry until the first week of August. Both sides of the bund continued to be flooded until the first week of December when the landside of the bund became completely dry again. However by the end of December 2005 and the beginning of January 2006, the whole area was completely dry.

Table 3: *Seasonal flooding of the India bund during the study period*

Dark blue bars represent flooded areas on the riverside of the bund

Light blue bars represent flooded areas on the landward side of the bund

Table 3 illustrates that India study site was completely dry on either sides of the bund for the whole of June. Flooding started in the early part of July until the third week of December when the whole of the landside became dry. However, the whole area became flooded in the middle of August and remained completely flooded until the end of November.

Water depth

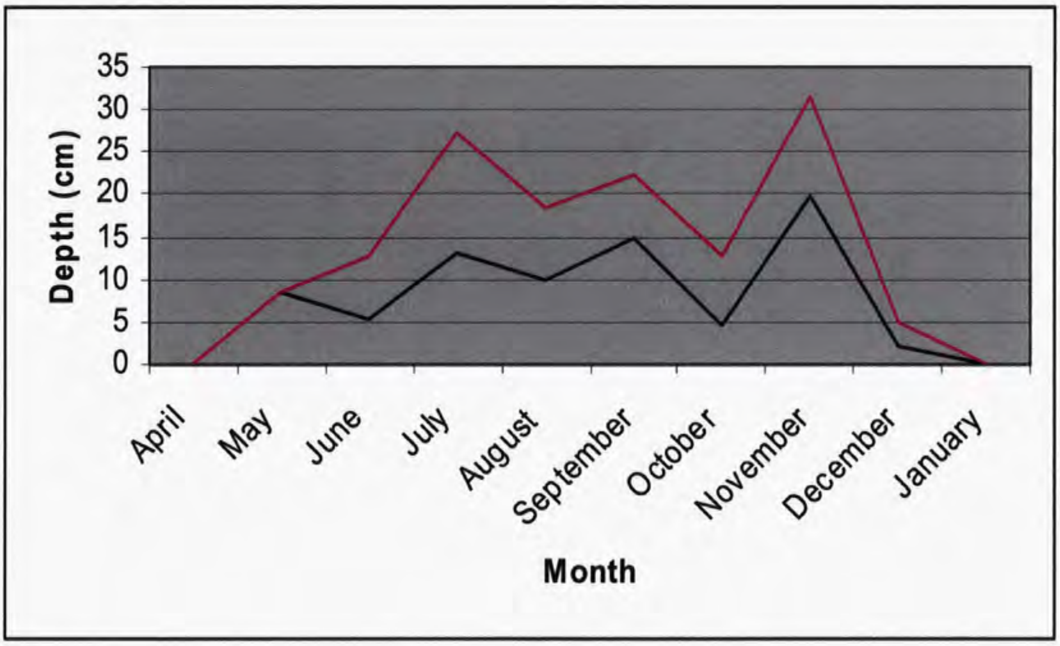


Figure 6: *Changes in water depth during the rainy season in Kunjo, where the pink line represents water depth on the river side and the blue line represents water depth on the landside.*

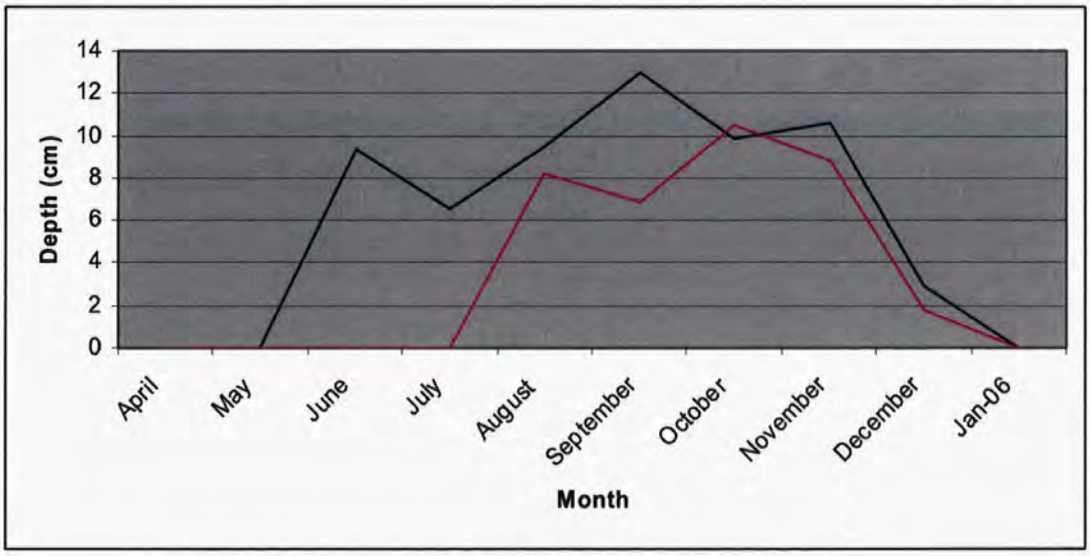


Figure 7: *Changes in water depth during the rainy season in Illiassa, where the pink line represents water depth on the river side and the blue line represents water depth on the landside.*

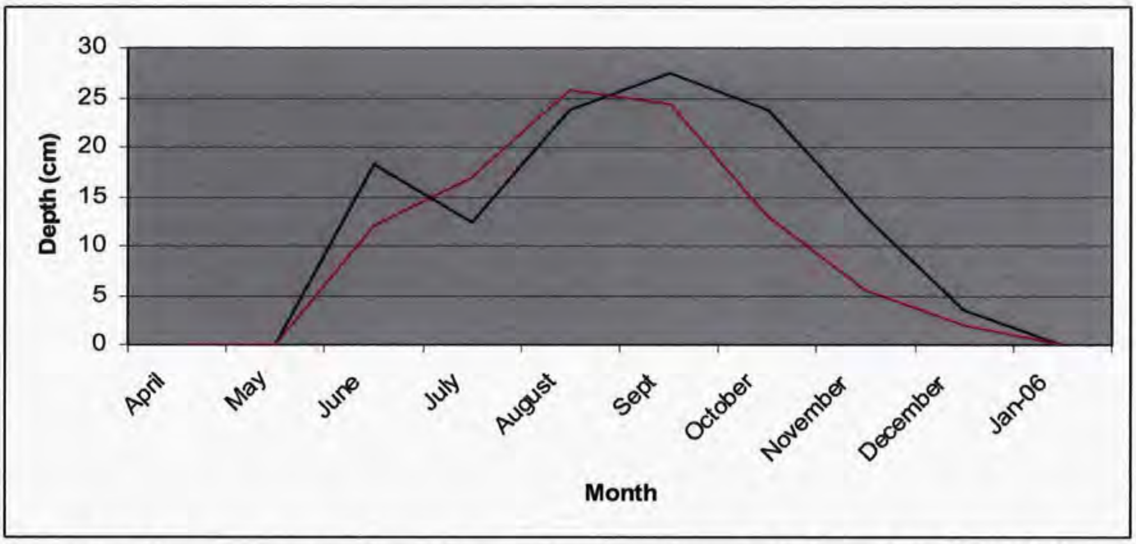


Figure 8 : *Changes in water depth during the rainy season in India, where the pink line represents water depth on the river side and the blue line represents water depth on the landside.*

Water characteristics

The different characteristics of the water either side of the three bunds are shown in Table 4. There were significant difference in water depth between transects (ANOVA. $F = 32.3$, $P = <0.001$) and between different sides of the bunds (ANOVA, $F = 4.3$, $P = 0.039$). However there was no difference in water turbidity, conductivity, pH or temperature on either side of the bunds.

Anopheles and culicine larvae were more common in water on the landward edge of the bund than on the riverside (Table 5). Of the 423 insects caught in all the three transects, 27 (6.4%) were caught in India, 395 (93.3%) in Illiassa and only 1 (0.24%) was from Kunjo. It is important to note that all these insects in the three transect were caught on the landward edge of the bunds. This suggests that there was little invertebrate life on the riverside of the bunds.

Table 4: *Summary of biotic and abiotic variables in the different sides of the bunds in each transect*

Variable	Transect					
	Kunjo N =99		**India** N =88		**Illiassa** N =77	
	Riverside	Landside	Riverside	Landside	Riverside	Landside
Water Depth (cm)[a] **	9.1 (7.6-10.8)	8.9 (6.7-10.4)	15.1 (12.7-17.8)	14.2 (12.0-15.8)	8.5 (7.1-10.1)	6.1 (5.2-7.4)
Water Turbidity (NTU)	3.18 (1.8-5.3)	3.85 (2.0-6.8)	2.0 (1.11-3.3)	3.26 (2.2-7.6)	3.90 (2.5-6.0)	2.53 (1.3-4.5)
Conductivity (µS)	5485 (3294-9131)	1421 (870-2320)	9135 (6011-10670)	7707 (6212-9561)	9227 (6113-13926)	8349 (6862-10156)
Water pH[c]	7.38 (7.02-7.63)	7.40 (7.05-7.73)	7.45 (7.02-7.80)	7.48 (7.03-7.78)	7.50 (7.04-7.79)	7.14 (7.01-7.31)
Water Temp ^{O}C	29.9 (28.5-31.3)	30. (28.4-31.6)	31.9 (29.3-34.5)	32.1 (29.9-34.3)	31.9 (29.9-33.9)	32.4 (30.4-34.4)
Anopheles larvae	0	80	33	90	0	121
Culicine larvae	0	90	29	90	0	103
Dragonflies	0	0	0	0	0	34
Damselflies	0	0	0	0	0	51
Coleoptera larvae	0	0	0	0	0	35
Coleoptera adults	1	0	0	0	0	2
Heteroptera	0	0	0	11	0	0
Hydrometridae	0	0	0	0	0	3
Notonectidae	0	0	0	6	0	15
Corixidae	0	0	0	8	0	5
Nepidae	0	0	0	7	0	16
Algae	0	0	0	0	55	50
An.gambiae s.s.	0	0	0	1	0	0
An.melas	0	0	1	0	0	0
An.arabiensis	0	0	0	0	0	1

a is the geometric mean with 95% confidence interval,, **b** is the arithmetic mean , **c** is the median with the Inter-quartile Range (IQR) of the 25 percentile and 75 percentile, ** is where $P<0.01$.

Mosquito larvae

Of the 324 anopheline larvae collected only three were *Anopheles gambiae s.l.* Of these one was *An. gambiae s.s.*, one *An. melas* and one *An. arabiensis*. Table 4 illustrates that insect life was more common on the landside of the bunds than on the riverside and that mosquito larvae were also much more common on the landward edge of the bunds as compared to the riverside. Binary logistic regression demonstrated that mosquito larvae were more common on the landward side of the bunds than the riverside (Odds ratio (OR) = 9.37, 95% confidence intervals (95% CIs = 2.26-38.79, P <0.002), on the edge of the water body (OR = 12.78, 95% CIs = 3.18-51.24, P <0.001) and in water channels (OR = 4.763 95% CIs = 1.11-20.49, P =0.036). Similarly when the analysis was confined to anophelines, larvae were more common on the landward side of the bunds than the riverside (OR = 12.51, 95% CIs = 3.45-45.29, P <0.001), on the edge of the water body (OR = 5.67, 95% CIs = 1.40-22.98, P = 0.015) and in water channels (OR = 6.10, 95% CIs = 1.93-19.30, P =0.002).

Mosquito adults

A total of 50 adult anophelines and 102 culicines were caught on 48 trapping occasions during the study period (Figs 9-11).

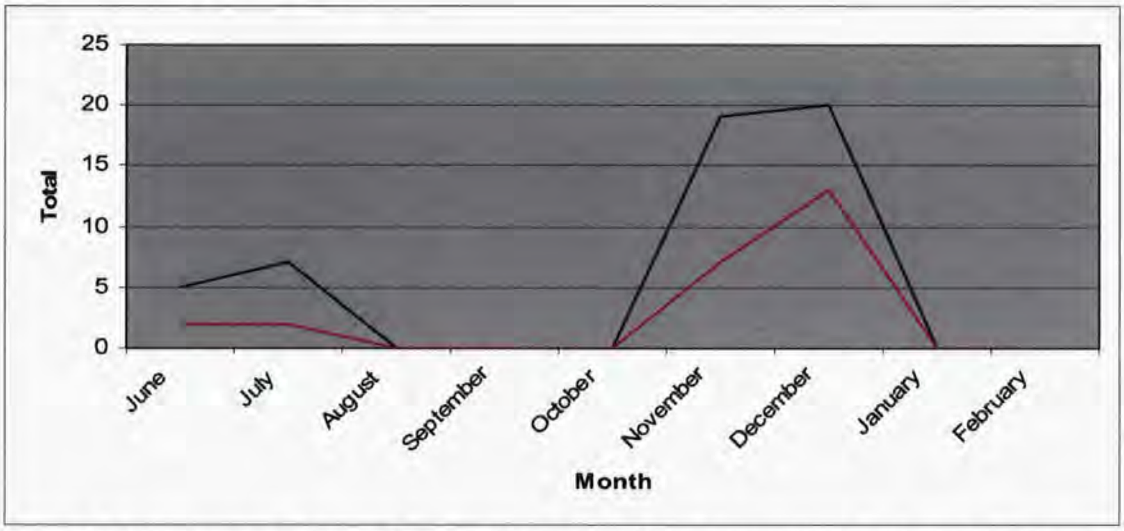


Figure 9: *Changing numbers of anopheline and culicine mosquitoes collected in Kunjo. Pink line represents collections on the river side whilst the blue line represents those on the landside.*

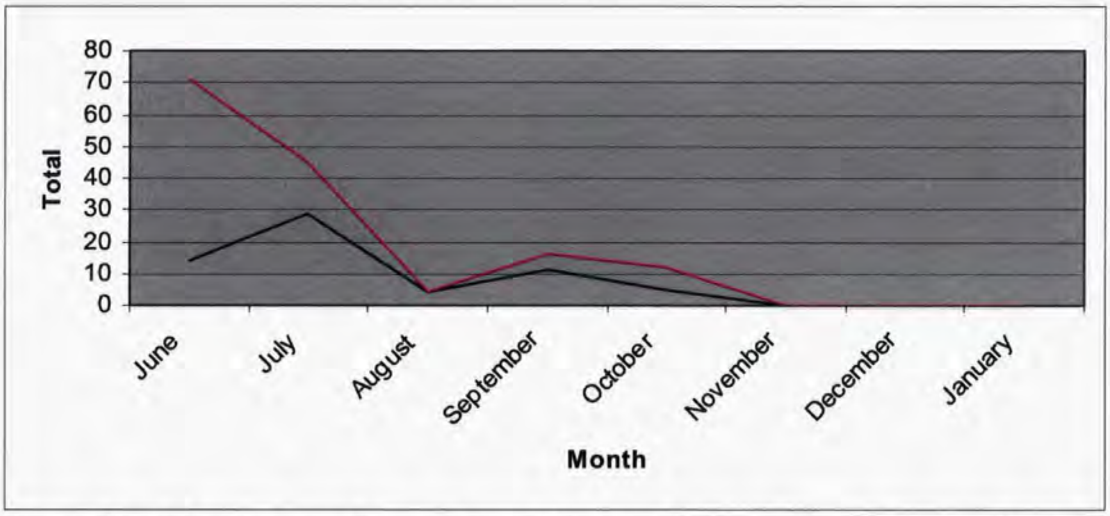


Figure 10: *Changing numbers of anopheline and culicine mosquitoes collected in Illiassa. Pink line represents collections on the river side whilst the blue line represents those on the landside.*

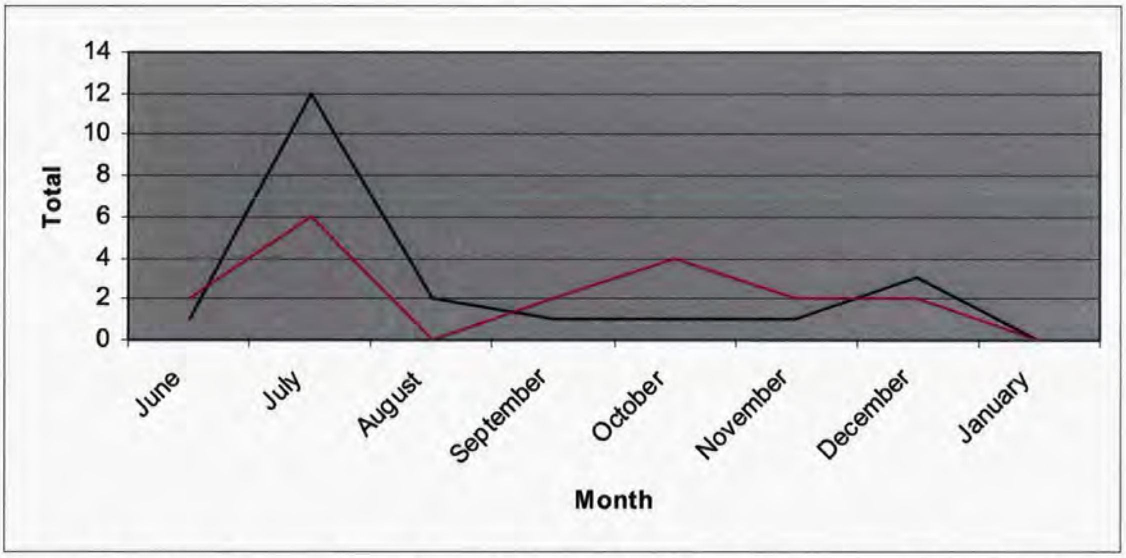


Figure 11 : *Changing numbers of anopheline and culicine mosquitoes collected in India. Pink line represents collections on the river side whilst the blue line represents those on the landside.*

Figures 9, 10 and 11 show the changing abundance of anophelines and culicines during the study period. Fig. 9 illustrates that the number of adult mosquitoes started emerging in Kunjo study site June and July and then suddenly decline in July and August. However, adult emergence reached its peak in September and October in the middle of the rainy season before declining in November. In Illiassa, adult emergence reached its peak in June when the site was newly flooded at the beginning of the rains just like in India and then suddenly declined in week July to December. In India, adult mosquito emergence reached its peak in July and August after which there was a sharp drop from September to December.

Table 5 : *Abiotic and biotic characteristics of sites where adult flying insect collections were made on either side of the bunds*

Variable	Transect					
	Kunjo		**India**		**Illiassa**	
	Riverside	Landside	Riverside	Landside	Riverside	Landside
Water depth[a] (cm)	9.1 (7.6-10.8)	8.9 (6.7-10.4)	15.1** (12.7-17.8)	14.2 (12.0-15.8)	8.5 (7.1-10.1)	6.1 (5.2-7.4)
Anopheles mosquitoes	3	6	11	17	12	69
Culicine mosquitoes	20	34	26	28	25	104
Odonata	5	23	15	22	35	9
Coleoptera	27	62	55	18	40	3
Hydrometridae	13	3	7	7	21	50
Notonectidae	4	12	4	11	6	17
Corrixidae	4	6	0	3	4	0
Nepidae	0	0	0	0	0	1
Gerridae	6	4	14	1	1	31
Naucorridae	1	1	0	2	0	3
Pleidae	0	0	0	0	0	0
Veliidae	1	7	0	1	0	0
Chironomidae	2043	1034	1391	1774	1314	1900
Chaoboridae	0	0	4	0	0	0
Simulidae	147	157	104	102	207	112
Non aquatic beetles	95	209	88	95	59	135
Hymenoptera	36	32	24	24	37	23
Lepidoptera	2	6	60	59	33	2
Blatoidea	0	55	8	2	2	4
Orthoptera	0	46	0	49	4	46
Isoptera	0	0	0	24	23	5
Heteroptera	0	0	8	8	0	0
Trichoptera	0	1	38	50	28	9
Brachycera	220	572	229	422	242	218
An.gambiae s.s.	0	1	0	2	0	4
An. melas	0	0	0	0	0	1
An. arabiensis	0	0	0	0	0	1
[redacted]						

** is where P<0.01.

Table 5 shows that there is a greater variety of insect life on the landward side of the bunds (53% of all insects) than on the riverside (47% of all insects) except for Kunjo where there were more diptera than on the landward edge.

The presence of adult anophelines using forward conditional regression (excluding traps that were not operating) was positively associated with culicine mosquitoes (odds ratio, OR = 1.62, 95% confidence intervals = 1.22-2.14, P = 0.001), water depth (OR = 1.06, 95% CIs = 1.02-1.10, P = 0.001), dragonflies (OR = 1.19, 95% CIs = 1.04-1.37, P = 0.015), orthopterans (OR = 1.14, 95% CIs = 1.00-1.29) and water lilies (OR = 7.52, 95% CIs = 2.34-24.11, P = 0.001). The presence of algae was negatively associated with anophelines (OR = 0.22, 95% CIs = 0.09-0.56, P = 0.002). Since anophelines were associated with culicines I repeated the analysis for all mosquitoes combined using binary logistic regression. The presence of adult mosquitoes was associated with the landward side of the bunds (OR = 2.59, 95% CIs = 1.23-5.48, P = 0.013) and notonectidae (OR = 2.16, 95% CIs = 1.18-3.98, P = 0.013).

Fish surveys

Table 6 : *Fish collections in 2005*

Transect	Transect					
	Kunjo		India		Illiasa	
	Riverside	Landside	Riverside	Landside	Riverside	Landside
Tilapia guineensis	75	12	255	31	148	60
Hemichromis bimaculatus	1	0	2	0	1	0
Hemichromis fasciatus	0	0	2	0	0	0
Median number of fish/throw (IQR)	2 (0-8)	0 (0-0)	10 (6-24)	0 (0-2)	2 (1-20)	0 (0-2)

Overall 587 fish were collected, of which 98.9% (581/587) were *Tilapia guineensis*. Generalised linear modelling of $\log_{10}$ values demonstrated that there were significant differences between the total number of fish collected from different bunds (F = 4.47, P = 0.014) and between different sides of the bunds (F = 25.8, P <0.001), with 82% of the fish captured on the riverside of the bunds

Countrywide survey

The results of the countrywide survey are shown in Table 11. The sites are arranged in an easterly order with Sibanor being found on the coast and the sites that follow occur further east. There was no significant difference between water temperatures experienced either side of the bunds (paired t test = 0.112, df = 18, ns). Whilst more mosquitoes were collected from the landside of the bunds (63% anophelines, 65% culicines) these differences were not statistically significant (anophelines, Wilcoxon signed ranks test, Z = -1.6, ns) or of borderline significance (culicines, Z = -1.73, P = 0.084; all mosquitoes, Z = -1.83, P = 0.067).

Table 7 : *Illustrates collections of Anopheline and Culicine mosquitoes at different sites in The Gambia.*

Transect	Parameter							
	Salinity (Units)		Temperature (°C)		No. anophelines		No. culicines	
	Riverside	Landside	Riverside	Landside	Riverside	Landside	Riverside	Landside
Sibanor	17	0	38.6	39.8	0	0	0	7
Killy	18	0.7	36.9	36.3	0	0	0	0
Faraba Banta	8	0	39.4	38.9	13	23	17	19
Salikeni	7.1	2	39.0	39.5	5	21	0	13
Mandori	0	0	30.0	32.0	2	27	0	48
Kinteh kunda Jannehya	1	0	38.5	36.8	0	0	0	0
Jolly	0	0	30.8	33.6	1	29	8	33
Gissay	28	0	30.0	28.4	0	5	0	0
Jattaba	-	0	40.0	39.0	68	10	53	10
Soma	0	0	41.0	43.0	0	28	0	12
Dobong Kunda	0	0	41.7	30.7	3	47	0	11
Wellingara Jahaly	0	0	29.1	30.0	1	1	0	6
Fass Abdou/Boiram	0	0	30.0	29.8	8	9	0	0
Jarumeh Koto	0	0	29.3	28.3	14	0	0	0
Karantaba Tabokoto	0	0	38.3	36.9	41	30	17	19
Mamasutu	0	0	39.9	43.2	23	12	0	10
Kossemer	0	0	33.8	41.4	7	26	0	0
Madina	-	0	-	31.2	0	22	0	25
Sutukonding	0	0	37.3	37.7	0	3	0	16
Garrowol	2.9	0.6	29.4	29.4	9	19	33	4
Total					187	313	118	223

It also indicates that although water temperatures were higher in the eastern part of the country (last 10 villages), the water was less saline in this area compared with the western part.

Chapter 5: Discussion

This study represents a snapshot of a highly dynamic system on the floodplains of the River Gambia. It provides evidence that the construction of bunds for agricultural purposes in The Gambia can increase the transmission of malaria, by increasing the breeding habitat for anopheline mosquitoes. This study revealed that mosquito larvae, although relatively rare in these habitats, were roughly twice as common on the landward side of the bunds than on the riverside. 68% of Anopheles larvae and 84% of all mosquito larvae were found on the landside of the bund. Similar findings were also found in the countrywide survey where out of the 500 Anopheles larvae caught, 313 (62.6%) were found on the landside of the bunds, while only 37.4% were found on the river side.

Not surprisingly, more adult mosquitoes were found on the landward side of the bunds compared with the riverside. 82% of Anopheline adults and 89% of all adult mosquitoes were collected on the landward side. Similar increases in mosquito production have been found with the introduction of irrigated agriculture and large-scale impoundments in other parts of Africa (Gillies & De Meillon, 1968; Surtees, 1970; White, 1974; Coluzzi, 1984; Ijumba & Lindsay, 2001), but this is the first report to demonstrate this with small water impoundments.

Of the anophelines collected during this study only 8 (1.6%) were *An. gambiae s.s.*, 4 (0.8%) were *An. melas*, 3 (0.6%) were *An. arabiensis* and 485 (97%) were other anophelines. These findings illustrate how rare members of the *An. gambiae* complex are in the river floodplains. Most of the anophelines collected during the study period were *An.coustani, An. ziemanni* and *An.pharoensis*. These, according to Gilles and DeMeillon (1968), are regarded as accidental or incidental vectors and are of doubtful public health importance. Nonetheless when malaria transmitted by the main vectors has been controlled, some degree of low-grade transmission by non-domestic vector species may still occur in certain areas. However, for now, those anopheles species that were found breeding in the study area are considered unimportant until proven otherwise.

A detailed survey of three water impoundments showed that although dry for most of the year (January to June) they filled with water two to three weeks after the start of the rains in July. This study represented three distinct types of bund. The bund at Kunjo, east of Farafenni town, had been breached and salt water was found on both sides of the bund. The bund at Illiasa was closer to the village and holds freshwater on the landside which was used to grow rice, a habitat ideally suited for producing high numbers of mosquitoes (Lindsay *et al*, 1995). Even where rice is not grown, the landward edges of the flooded alluvial pools bordering the river are ideal breeding sites for mosquitoes (Lindsay *et al*, 1995; Lindsay & Thomas, 1996; Bøgh *et al*, 2003). The bund at India was damaged and did little to hold back the river water. As a consequence there was no difference in water salinity on either side of the bund. This was breached probably as a result of heavy down pours of rain and water flooding over the bund.

The higher larval densities on the landside of the bunds may partly reflect that this side of the bunds were nearer the higher ground, where most hosts were located, than the riverside. It is likely that gravid mosquitoes feeding on people and animals on the higher land away from the river habitats would travel the shortest distance before laying their eggs. This conclusion is supported by a number of studies. Shidrawi (1972) observed that more than 90% of anophelines adults were found in houses less than 300 meters from larval habitats. Similarly Charlwood & Edoh (1996) found that larval densities were greatest close to cattle, whilst, Minakawa *et al*. (1999, 2002) reported that anopheline adult densities were greater when larval habitats were close to houses.

However, the shorter flight distance of gravid females it is unlikely to be the sole reason for the higher abundance of vectors on the landside of the bunds. The landside was also richer in invertebrates. The higher abundance of invertebrate life on the landside may be partly due to the freshwater, undisturbed water and, possibly, higher nutrients, than on the riverside. However it is likely that the main reason for the high number of invertebrates on the landside is due to fewer fish, major predators of aquatic fauna. 82% of the fish captured were caught on the riverside of the bunds. It can therefore be concluded that the high presence of fish on the riverside of the bunds might explain why there was low larval density in theses sites, since the fish are known predators of mosquito larvae (Mohamed, 2002). Predation by insect predators was less important, since anophelines were always found in close proximity with other insects. This is a surprising finding since predation by insects affects the population dynamics of anophelines and may, in some circumstances, be the most important single factor determining population size (Service 1993). In Asian rice fields, larval mortality was estimated to be >98% and has been attributed mainly to invertebrate predators (Mogi *et al.* 1984, 1986). In Kenyan rice fields larval mortality of *An. arabiensis* has been estimated at 93% (Service 1977). In wells, which are permanent stagnant water, the importance of predators has also been recognized (Gillies and De Meillon 1968).

The finding that most anophelines were found on the landward side of the bunds indicates that impoundment of water in The Gambia increases the risk of malaria transmission. Although, the impoundment of water will prevent soil erosion, increase water usage, enrich the soil in terms of nutrients and enhance rice cultivation on the landward side of the bunds, it may however, serve as potential breeding grounds for malaria vectors which may results to increase in larval and adult densities, all of which may increase the risk of malaria transmission in The Gambia.

Development of irrigation schemes, particularly of those involving rice cultivation in areas of unstable malaria transmission, have been a focus of attention because of the fear, that they might exacerbate the problem of malaria in local communities. This is because rice cultivation encourages the proliferation of malaria vectors (Surtees, 1970; White, 1974; Coluzzi, 1984, Gilles & De Meillon, 1968; Ijumba & Lindsay, 2001). However, conflicting results have been obtained from studies evaluating the impact of rice irrigation on malaria transmission in different parts of Africa. Perhaps rather surprisingly, most studies reported similar or reduced prevalences of malaria near rice irrigation schemes compared with adjacent areas without irrigation (Ijumba & Lindsay, 2001). The exception to this occurs in areas of unstable malaria, where both exposure to malaria parasites and immunity to the disease were low.

The explanation for the 'paddies paradox' discussed by Ijumba and Lindsay (2001), are as follows: firstly, irrigation of crops lead to greater wealth creation (Robert *et al*, 1985, Boudin *et al,* 1992, in Ijumba and Lindsay, 2001), it allows farmers to improve their homes, increase their personal protection against mosquitoes and seek improved medical care (Ijumba and Lindsay, 2001), resulting in fewer cases of malaria. Secondly, the high density of mosquitoes in irrigated areas is unpleasant enough to prompt people to use bed nets, more so than if mosquito numbers were fewer. A study by Lindsay *et al* (1989) showed that bed nets in good condition significantly reduce biting rates, and Clarke *et al* (2001) revealed that this can subsequently reduce malaria. High bed net coverage may therefore be an explanatory factor. The author suggests that, due to combination of high mosquito densities, and high bed net coverage, individual mosquitoes find it difficult to find and obtain a blood-meal.

Irrigated rice fields represent ideal breeding sites for mosquitoes and they can generate large numbers of individuals, although smaller proportions are infective in rice field villages than control communities (Ijumba *et al*, 2001). In Africa, rice fields have proved to be particularly well suited as breeding sites for freshwater members of the *An. gambiae* complex. This species breeds in the shallow inundated fields during tilling and transplanting during the first six weeks of the growing period (until canopy closure), and after harvest (Klinkenberg *et al*, 2003). Irrigated-rice cultivation, depending on the number of cropping cycles, may also extend their breeding season and hence increase their annual duration of transmission. Moreover, in dry regions, irrigation will elevate relative humidity that aids survival of these vectors.

In general, the predominant vector in irrigated rice systems is that found in surrounding areas, although there is at least one notable exception to this rule. The Mopti form of *An. gambiae s.s.* thrives in rice fields in West Africa, in the northern fringes Sahel. In Burkina Faso this cytotype was common in the centre of the rice fields, but at the edge of the irrigated area the savanna form was more abundant (Robert *et al*, 1989).

This study revealed that the construction of bunds for agricultural purposes by holding back fresh water would increase the transmission of malaria in The Gambia, by providing ideal conditions for members of the *An. gambiae* complex. Most of the mosquitoes collected were *An. gambiae s.s.* which are the principal malaria vectors in the county, as they are highly anthropophilic and feed indoors. I did not find more An. melas, a brackish water breeder on the river side of the bunds as expected. Even if I had, this would not be so serious a malaria threat as *An. gambiae s.s.* since it feeds largely on animals and has very low rates of infection.

The finding that most Anophelines were found on the landward side of the bunds indicates that impoundment of water in The Gambia increases the risk of malaria transmission. Although, the impoundment of water will prevent soil erosion, increase water usage, enrich the soil in terms of nutrients and enhance rice cultivation on the landward side of the bunds, it may however, serve as potential breeding grounds for malaria vectors which may results to increase in larval and adult densities, all of which may increase the risk of malaria transmission in The Gambia.

Conclusion

The results lead to the conclusion that the construction of bunds for agricultural purposes increases mosquito larval density on the landward side, as it increases the mosquito density. There is also an indication that this is true for countrywide survey in which more mosquitoes were collected from the landside of the bund (63% anophelines, 65% culicines). The increase in mosquito larval density will result in an increase in the mosquito adult population, which may have a significant impactn the malaria transmission pattern especially in areas where human settlements are in close proximity to breeding sites.

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