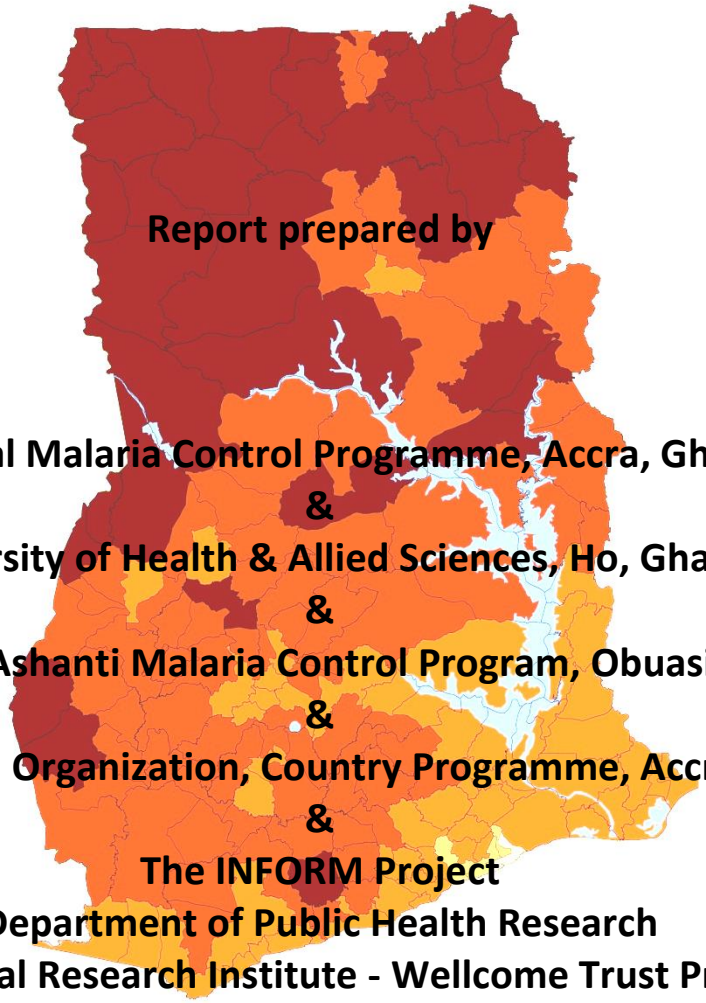
An Epidemiological Profile of Malaria and its Control in Ghana



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ROLL BACK MALARIA

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Abbreviations

ACT	Artemisinin Combination Therapy
AFRO	WHO Office for the Africa Region
AGA	AngloGold Ashanti
AGAMal	AngloGold Ashanti Malaria Control Program
AGC	Ashanti Goldfields Corporation
AJOL	African Journals Online
AMFm	Affordable Medicines Facility for malaria
ANVR	African Network for Vector Resistance
APRD	Arthropod Pesticide Resistance Database
BIC	Bayesian Inference Criteria
BS	*Bacillus sphericus*
BTi	*Bacillus thuringenensis israelinesis*
CCM	Country Coordinating Mechanism
CHAG	Christian Health Association of Ghana
CHPS	Community Health Planning & Services Compounds
CPC	Climate Prediction Centre
CRDT	Constrained Refined Delaunay Triangulation
DCW	Digital Chart of the World's Populated Places
DDT	Dichloro-Diphenyl-Trichloro-Ethane
DIC	Deviance Information Criterion
DFID	Department for International Development
DHIMS	District Health Information Management System
DHS	Demographic and Health Surveys
DSS	Demographic Surveillance Site
DVS	Dominant Vector Species
EA	Enumeration Area
EIR	Entomological Inoculation Rates
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
FBO	Faith Based Organisations
FEWS	Famine Early Systems Network
FIND	Foundation for Innovative New Diagnostics
GAUL	Global Administrative Unit Layers
GBC	Global Business Coalition
GDHS	Ghana Demographic and Health Survey
GDP	Gross Domestic Product
GHS	Ghana Health Service
GIS	Geographic Information Systems
GF	Gaussian Field
GLSS	Ghana Living Standards Surveys
GLWD	Global lakes and Wetlands
GMEP	Global Malaria Eradication Programme

GMRF	Gaussian Markov Random Field
GPS	Global Positioning Systems
GRF	Gaussian Random Field
GRUMP	Global Rural Urban Mapping Project
GHS	Ghana Health Services
GSS	Ghana Statistical Surveys
HIPC	Heavily Indebted Poor Country
HIS	Health Information Systems
HSMTDP	Health Sector Medium Term Development Plan
IGME	Inter-Agency Group for Child Mortality Estimation
IMCHC	Integrated Maternal & Child Health Campaign
IMF	International Monetary Fund
IMR	Infant Mortality Rate
INFORM	Information for Malaria Project
INLA	Integrated Nested Laplace Approximations
IPTp	Intermittent Presumptive Treatment in pregnancy
IRS	Indoor Residual Spraying
ITM	Insecticide Treated Materials
ITN	Insecticide Treated Nets
IVM	Integrated Vector Management
JICA	Japanese International Cooperation Agency
KAP	Knowledge, Attitude & Practices
Kdr	Knockdown Resistance
LLINs	Long Lasting Insecticidal Nets
LSHTM	London School of Hygiene & Tropical Medicine
MAP	Malaria Atlas Project
MAPE	Mean Absolute Prediction Error
MARA/ARMA	Mapping Malaria Risk in Africa
MaVOC	Malaria Vector Control Oversight Committee
MBG	Model Based Geo-Statistics
MCMC	Markov Chain Monte Carlo
MDA	Mass Drug Administration
MDGs	Millennium Development Goals
MERG	Monitoring and Evaluation Reference Group
MeSH	Medical Subject Headings
MICS	Multiple Indicator Cluster Survey
MODIS	MODerate-resolution Imaging Spectroradiometer
MoH	Ministry of Health
MPE	Mean Prediction Error
MPHD	Malaria Public Health Department, KEMRI, Kenya
MPR	Malaria Programme Performance Review
MRF	Markov random field prior
MTHS	Medium Term Health Strategy
NASA	National Aeronautics and Space Administration

NDC	National Democratic Council
NDPC	National Development Planning Commission
NDVI	Normalised Difference Vegetation Index
NIDs	National Immunization Days
NGOs	Non-Governmental Organizations
NHIS	National Health Insurance Scheme
NHRC	Navrongo Health Research Centre
NMCP	National Malaria Control Programme
NMSP	National Malaria Strategic Plan
NOAA	Night-time Lights Dataset
NPP	New Patriotic Party
NWS	National Weather Service
OA	Open Access
ODA	Overseas Development Assistance
PA*Pf*PR_{2-10}	Population Adjusted Age-corrected *Plasmodium falciparum* parasite rate
PCR	Polymerase Chain Reaction
PfPR_{2-10}	Age-corrected *Plasmodium falciparum* parasite rate
PHC	Population and Housing Censuses
PMI	Presidents Malaria Initiative
PNDC	Provisional National Defence Council
RBM	Roll Back Malaria
RDTs	Rapid Diagnostic Tests
SAE	Small Area Estimations
SAM	Service Availability Mapping
SMC	Seasonal Malaria Chemoprevention
SP	Sulphadoxine-Pyrimethamine
SPDE	Stochastic Partial Differential Equations
STG	Standard Treatment Guidelines
SWERA	Solar Wind Energy Resource Assessment
TBA	Traditional Birth Attendants
TDR	Tropical Disease Research
TPC	Tactical Pilotage Charts
TSI	Temperature Suitability Index
U5MR	Under-five Mortality Rate
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
WHA	World Health Assembly
WHO	World Health Organization
WRAIR	Walter Reed Army Institute of Research
WRBU	Walter Reed Biosystematics Unit

Executive summary

This report is a product of collaboration between the Ghana National Malaria Control Programme and regional and national academic/technical partners.

The report serves as a review of the epidemiological features of malaria in Ghana and how these relate to the context of historical and current malaria control activities. The work has drawn heavily on assemblies of empirical, geo-coded parasite, vector and control coverage data and the use of model-based geo-statistics to provide information at district levels, necessary for resource allocation and planning.

The review has been developed to assist national level partners involved in malaria control to understand the future impact of scaled intervention coverage and define what is required to achieve universal access. It will also assist in the prioritization of future funding needs to meet unmet interventions, setting realistic targets and responsive recommendations to accelerate impact. The granular, district-level epidemiological data should be used to design of malaria control, defining resource needs and serve as a baseline for future impact analysis.

The assembly of data platforms inevitably signals what information is missing (requiring further data collection), what remains unknown about the changing, or stagnating, epidemiological transition (requiring further operational research), and a means to better position the long-term and short term malaria epidemic cycles within broader health and development agendas. The data generated as part of this work should now feed into a more strategic priority setting for further national data collection and research enquiry.

This work, by its very nature is dynamic and new information must be assembled against changing administrative boundaries. It is therefore a living, dynamic process of evidence generation, cycles of new modelling and generating new layers of information, research and enquiry necessary for effective control planning.

Ghana is a country broadly characterised by intense malaria transmission with pockets of lower transmission associated with urbanization, private sector development and periods of long-term sustained control. Among the challenges facing the future of effective control include a more rational basis for stratified intervention delivery, better planning information and an ability to generate sufficient evidence to demonstrate impact and value for money. The initial work presented in this report serves as a catalyst to begin the cycle of using evidence to effect change.

Chapter 1

Introduction

The clinical epidemiology [Snow & Marsh, 2002], the impact of vector control [Killeen et al., 2007; Smith et al., 2009; Griffin et al., 2010], cost-effectiveness of treatment and prevention [Okell et al., 2012] and timelines to malaria elimination [Cohen et al., 2010] are all dependent on parasite transmission intensity. Effective planning of malaria control depends on a reliable understanding of the temporal and spatial determinants of parasite transmission, its seasonal patterns and the dominant vectors implicated in transmission. Epidemiological profiling should form the cornerstone of any effective national malaria strategy planning cycle.

The use of survey data, maps and epidemiological intelligence was a routine feature of control planning across many African countries during the Global Malaria Eradication Programme (GMEP) era from the mid-1950s. Data included epidemiological descriptions of transmission, vectors, topography and climate. There was a recognition, over 50 years ago, that one important source of planning data was infection prevalence among children aged 2-10 years ($Pf\text{PR}_{2\text{-}10}$). This was used to define categories of endemicity risk, designed to guide and monitor progress toward malaria elimination targets [Metselaar & van Thiel, 1959; Macdonald & Göeckel, 1964; Lysenko & Semashko, 1968].

The art and skills necessary to design malaria control based on an understanding of the spatial epidemiology was lost during the 1970s when the agenda for malaria control fell under a less specialized, integrated primary care mandate focused on managing fevers. In 1996, there was a renewed plea for better malaria cartography to guide malaria control in Africa [Snow et al., 1996] and over the last decade there has been a growth in spatial data on malaria and populations not available to malariologists or programme control managers 60 years ago. The growth in data has been accompanied by the development of statistical approaches to model and map risk and intervention access in space and in time using Model Based Geo-Statistics (MBG) [Diggle & Ribeiro, 2007].

At the launch of the Roll Back Malaria (RBM) initiative, calls for universal coverage of all available interventions was probably an appropriate response to the epidemic that affected most of sub-Saharan Africa during the mid-late 1990s [WHO, 2000; Snow et al., 2012]. At a time when the international donor community is constrained by the global financial crisis, accessing overseas development assistance (ODA) and using limited national domestic funding for malaria control will require a much stronger evidence based business-case. This future business-case must be grounded in the best available epidemiological evidence to predict the likely impact of future intervention, assess the impact of current investment and, equally important, demonstrate what might happen should funding and intervention coverage decline.

In 2011, the WHO Office for the Africa Region (AFRO) developed a manual to assist countries in developing their National Malaria Strategic Plans (NMSP) including, as a prelude, the undertaking of a National Malaria Programme Performance Review (MPR) [WHO-AFRO, 2012]. It is recommended that the MPR should include a detailed review of the malaria epidemiology and stratification including the geographical distribution of malaria burden, parasite prevalence and parasite species.

The MPR for Ghana, started in 2012, has recently been completed [NMCP, 2013]. Three recommendations under the epidemiology review section are relevant for the work outlined in this report: a) stratification of malaria endemicity to the district level; b) monitor malaria transmission patterns on account of possible climate change by compiling and linking epidemiological, entomological and meteorological data for mapping; and c) ensure the use of strategic information such as stratification data in the country decision making [NMCP, 2013].

This report attempts to fill this information void in Ghana. Chapter 2 provides the country context with special reference to health administration decision making units as part of decentralized malaria planning, human settlement patterns, urbanization and the location of health services. Chapter 3 provides a review of the first 100 years of malaria control, providing a historical narrative of control approaches nationwide up to the launch of the RBM initiative in Ghana in 2000. The recently completed MPR has assembled the narrative and information on malaria control since 2000 [NMCP, 2013]. The MPR covers all aspects of the evolution of the national malaria strategies, their ambitions, funding and the approaches taken or planned between 2000 and 2015. Given the importance of vector control on parasite prevalence (Chapter 4) and vector ecology (Chapter 5) we have re-reviewed the approaches taken to vector control in Chapter 6 and return to discussing the major ambitions of the current national malaria strategy in Chapter 7. Chapter 4 provides a detailed description on the data assembly, modelling and district summaries for parasite prevalence. This chapter also considers the evidence on multi-species infections and the distribution of acute seasonal transmission for specialized, drug-based control options. Chapter 5 describes the data assemblies on dominant vector species in Ghana, bionomics and insecticide resistance. Finally, Chapter 7 attempts to draw together the layers of information on the epidemiology of malaria in relation to the current national strategic plan and the proposed new plan for 2014-2018.

The work has been a collaborative effort between the NMCP of the Ghana Health Service, University of Health and Allied Sciences Ghana, the AngloGold Ashanti Malaria Control Program, the WHO Country Office and the INFORM Project of the KEMRI-Wellcome Trust programme in Nairobi, Kenya.

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Chapter 2

Country context, administration, population & health services

2.1 Location

Ghana lies between latitudes 4° and 12°N and longitudes 4°W and 2°E. The Greenwich Meridian passes through the country (at Tema) and Ghana is geographically closer to the "centre" of the world than any other country. The total land area of Ghana is 238,538 km^2; the distance from south to north is 840 km and from east to west is 554 km. Ghana is bordered on the east by Togo, the west by Cote d'Ivoire, in the north by Burkina Faso and has a coastline in the south along the Gulf of Guinea.

The coastline represents a sandy shore backed by plains and scrub, intersected by several rivers and streams. Conversely high plains and savannah characterize the north, the southwest and south central areas are forested plateaus, including the Ashanti uplands and the Kwahu Plateau. The highest altitude areas are the Akuapim-Togo hill ranges, found along the country's eastern border with Togo and include the highest point, Mount Afadjato (885 m). Southern Ghana has evergreen and semi-deciduous forests, oil palms and mangroves. The Volta River occupies most of central Ghana, the largest artificial inland lake in the world and the source of the Oti and Afram rivers. The Akosombo Hydroelectric Dam, which is the main source of electricity for the country, was built on the Volta River in 1965. The south experiences two rainy seasons from April to July and from September to November. The north experiences a single rainy season from April to September.

2.2 Social and political evolution

Present day Ghana was named the Gold Coast by Europeans because of its rich reserves of gold. The name was changed at independence to Ghana, the title of the warrior King of an ancient empire, located between the Senegal and Niger Rivers, 800 km north of modern Ghana.

Carbon dating of human remains suggests that modern Ghana had been inhabited since 2000 B.C. The five historical ethnic groups in Ghana comprised of the Guan, Ga-Dangme, Akan, Ewe and Mole-Dagbani. From the late 15th century the Ga coast was influenced by a multitude of people and cultures from outside the country. The Afro-Brazilian returnees and Europeans of different nationalities settled among the Ga.

Administration of the country was originally vested in traditional leaders and ruling chiefs, who through a process of influence, continue to play an important role in society today. By the 19th Century the Ashanti Empire was the most established state in Ghana. In 1874, the British formally declared the southern region a British colony. In 1901, Asante and Northern territories were made British protectorates. Colonial rule was in the form of "indirect rule" whereby the traditional rulers were allowed to rule their people under the direction and control of the British officials. Through a series of legislative ordinances, however, the colonial authorities reduced the powers of the chiefs.

Nationalism intensified after World War II with the formation of political parties like the United Gold Coast Convention and Kwame Nkrumah's Convention People's Party. In 1948, the murder by British soldiers of three WWII veterans on a peaceful march to the governor, led to a rapid revision of Britain's policies in Ghana, constitutional changes and elections in

1951 that made Nkrumah the Leader of Government Business. Eventually independence was achieved on the 6th March 1957, making Ghana the first sub-Saharan African nation to regain its independence. The delay in full independence was a result of whether trans-Volta Togoland was to join the Gold Coast and whether Ghana should become a federal or unitary state at independence. These were resolved by the 1956 when British Togoland decided to join the unitary independent state.

Since independence Ghana's political scene has been characterized by waves of democratic elections, coups and counter coups. Nkrumah's government was overthrown by a military coup in 1966 led by Gen. J.A Ankrah and later Gen. A. A Afrifa. The junta handed power to an elected civilian government in 1969, headed by Kofi Abrefa Busia. After three years he was overthrown in another military coup led by Col. Kutu Acheampong who led various military councils until he was overthrown in a coup led by Lt. Gen. Akuffo. The Supreme Military Council was overthrown in another coup by the Armed Forces Revolutionary Council led by Flt. Lt. J.J. Rawlings who handed power to a civilian administration, the People's National Party. However, in 1981 Rawlings staged another coup and overthrew the civilian government and ushered in the Provisional National Defence Council (PNDC). The PNDC was under domestic and international pressure to resume democratic elections, which were held in 1992, heralding the Fourth Republic. It was won by Rawlings's National Democratic Congress (NDC) and his party retained power in the 1996 elections. In 2000, NDC lost the elections to the New Patriotic Party (NPP) led by J.A. Kufuor who won another term in 2004. John Atta Mills took over as head of state in early 2009, but he died in July 2012 and was succeeded by his vice president John Dramani Mahama, who subsequently won a December 2012 special presidential election. Ghana is regarded as a State Democracy in the West Africa region.

2.3 Economy

The pre-colonial economy was based on agriculture, trade and industry. Trade involving cola, cloth, salt and gold existed between the people of Gold Coast (present day Ghana), their neighbours and over long distances. The arrival of the Europeans shifted trade to the coast, selling gold, cloth, beads, metal ware and trans-Atlantic slaves. The Gold Coast played a major role in the slave trade; of the 46 forts built along the west coast of Africa, 32 were in Ghana.

The abolition of the slave trade in 1833 saw an increase in the trade of agricultural products mainly palm. In 1878, Tetteh Quarshie brought cocoa from Fernando Po (Bioko island, Equatorial Guinea), which eventually resulted in Ghana becoming the world's second leading exporter. During the 1880s commercial gold mines were opened in Wassa and Obuasi. In the latter years under colonial rule cocoa and gold became important trade commodities. The Cocoa Marketing Board was founded in 1947 and revenue from cocoa was £60 million in 1951.

Post-independence governments have undertaken various economic policies ranging from the socialist, Pan-Africanist views of Nkrumah to capitalist centric policies and heavily externally influenced economic policies promoted by the International Monetary Fund and the World Bank during the 1990s. In recent years Ghana's economy has been strengthened

by a prolonged period of stability, good governance and a competitive business environment. Ghana recently revised GDP estimates put its Gross Domestic Product (GDP) at US$ 1,150 (2010) and a GDP growth rate of 7.7% making it a lower-middle-income country and [MoF&EP]. Ghana was one of the 11th fastest growing economies in the world in 2011.

Natural resources and agriculture accounts for approximately 25% of GDP and the services sector accounts for 50% of GDP [World Bank]. Gold and cocoa production and individual remittances are major sources of foreign exchange.

The Akosombo Dam provides hydro-electricity for Ghana and its neighbouring countries. Oil production at Ghana's offshore Jubilee field began in 2010, and is expected to boost economic growth and estimated reserves are expected to be almost 700 million barrels. Ghana opted for debt relief under the Heavily Indebted Poor Country (HIPC) program in 2002, and is also benefiting from the Multilateral Debt Relief Initiative that took effect in 2006 [Madavo et al., 2004]. In 2009, Ghana signed a three-year Poverty Reduction and Growth Facility with the IMF to improve macroeconomic stability, private sector competitiveness, human resource development, good governance and civic responsibility [IMF]. Sound macro-economic management along with higher prices for oil, gold and, cocoa should help sustain economic growth over the next decade.

2.4 Decentralization and administrative boundaries

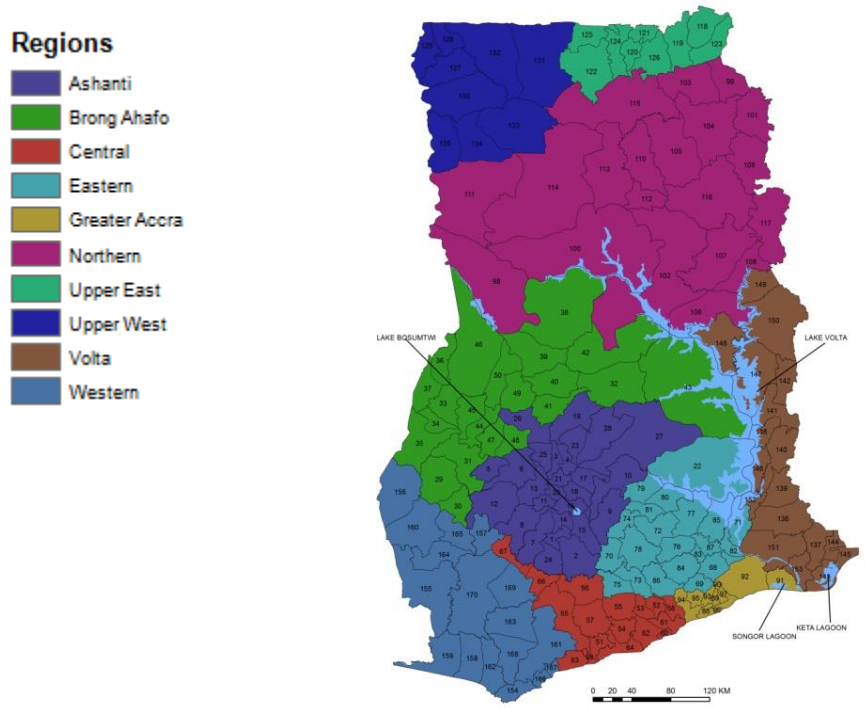
Over time, governments across Africa have embraced decentralization. Defining the health administrative units used by a country is central to resolving health information for planning and disease burden estimation. Most currently available malaria risk maps do not provide information necessary for planning at units of decision making used by national governments, for example those most recently developed by the Malaria Atlas Project [http://map.ox.ac.uk] and used by the Global Malaria Programme of the WHO in its 2012 World Malaria Report [WHO, 2013]. Without congruence to accepted health decision making units at national levels the cartographic information of risk has diminished value [Omumbo et al., 2013]. Defining the second and third level administrative regions within each country poses perennial problems as these routinely change and are different for different national administrative purposes, e.g. census units do not always correspond to health planning units or political constituency units.

Ghana supports a broad agenda on fiscal and administrative devolution, based on a comprehensive legal and regulatory framework for decentralization. Decentralization began at independence, delegating authority to the districts. The Local Government Act 452 (1993) includes devolution of the social sectors. Ghana is divided into 10 administrative regions: Ashanti, Brong Ahafo, Central, Eastern, Greater Accra, Northern, Upper East, Upper West, Volta and Western (Figure 2.1). An appointed Regional Minister who represents the President heads each region. The Regional Minister is assisted by a deputy and a Regional Coordinating Council to formulate integrated district plans and programmes within the framework of approved national development policies and priorities. The regions were subdivided into 170 districts, this has recently been increased to 237 districts. The recent boundary changes are yet to be gazetted and their digital margins are not available

[MoL&RD, 2012]. For the purposes of this report we have used 170 districts, used predominantly by the NMCP over the last five years and remain recognized units of recent health data. Districts constitute the country's local government units administered by elected district assemblies with the District Chief Executive as the head. The District Chief Executive, is nominated by the President and approved by the District Assembly.Political and administrative decentralization is being strengthened with common funding mechanisms and the institution of local government civil service. The districts are also divided into unit areas and are headed by elected executives who make the district assembly.

Within Ghana's health system follows the same decentralized system for planning, budgeting, reporting, information systems, performance measurement and financial transfer mechanisms [Saleh, 2013]. Fiscal decentralization remains a key challenge, despite more than 50% of public health expenditures being allocated to districts, most of these resources are controlled by the central government [Saleh, 2013].

Figure 2.1: 170 health administration districts across 10 regions in Ghana: administrative boundaries downloaded from Geocommons (2013). Numbers relate to district names shown in Appendix A2



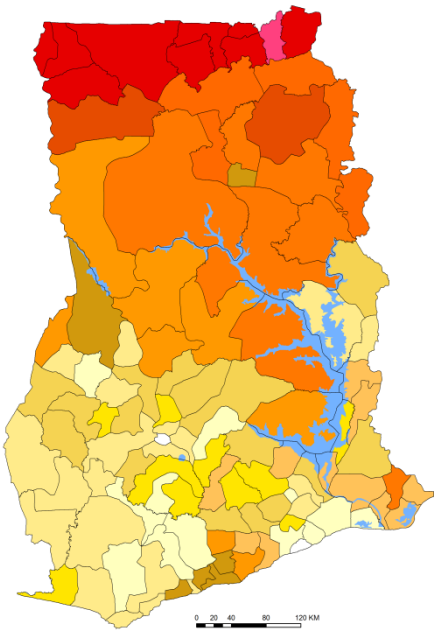
At the district level, the health system consists of the sub-district. The district health administration provides supervision and management support to the sub-districts [MoH, 2008]. Districts have an average of 4-6 sub-districts. Health facilities are situated within these sub-districts and in areas where hospitals/health centers/clinics are not available the Community Health Planning Service (CHPS) zones are set up. The NMCP provides guidelines to regional and district offices that are then tasked with implementation of the programmes [MoH, 2008]. Malaria control intervention, monitoring and evaluation activities are done at district and subdistrict level with performance reviews at district, regional and national levels of the health sector [MoH, 2008; NMCP, 2008; 2013].

2.5 Poverty

Ghana's Vision 2020 was developed in 1996 against a background recognition that "*Despite the provision of improved access to education, health care, safe water and other basic social amenities over the past decade, the social conditions of many Ghanaians are characterized by low standards and generally poor quality of life. More than one – third of Ghanaians live below the poverty line and some 7% in hard – core poverty*" [NDPC, 1996]. Poverty alleviation was therefore a key goal of Ghana's vision by 2020 through economic growth and rural/urban development. The long-term vision for Ghana was that "*by the year 2020 Ghana will have achieved a balanced economy and a middle-income country status and standard of living, with a level of development close to the present level in Singapore*" [NDPC, 1996].

Between 1988-1992, only moderate declines in levels of poverty were observed from three rounds of the Ghana Living Standards Surveys (GLSS) [GSS, 2008; Novignon et al., 2012]. Analysis of assets based indicators from 1992 to 2005-2006 GLSS surveys and 1997 and 2003 Core Welfare Indicator surveys suggest that the share of the population living in poverty was reduced from 51.7% in 1991/92 to 39.5% in 1998/99 and 28.5% in 2005/2006 [Coulombe & Wodon, 2007a; Novignon et al., 2012]. Substantial poverty reduction has been achieved over the last 15 years and Ghana is on track to reduce its poverty rate by half of the levels of poverty in 1990, well before the target date of 2015 for the Millennium development Goals [UNDP, 2013]. However, most of the poverty reduction has been concentrated in Greater Accra and Central regions, while poverty fell much more modestly or even rose elsewhere. There are large poverty disparities across the country. in the northern regions poverty reduction has been modest and despite accounting for only 25% of the population they account for 50% of the poor [Coulombe & Wodon, 2007a; 2007b; Figure 2.2].

Figure 2.2: Graduations of poverty levels from least poor (light yellow) to most poor (red) based on welfare index and assets data from GLSS5 and resolved to the 110 districts used in 2000. Reproduced from Coulombe & Wodon (2007b) but without precise details on measures used.



2.6 Child survival

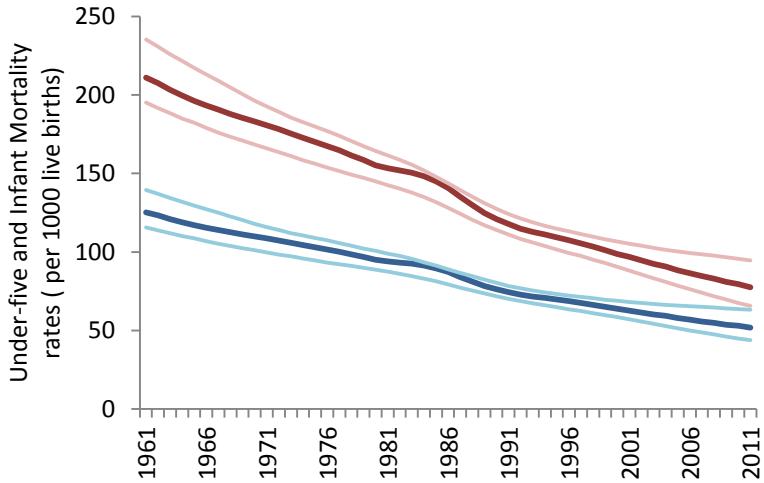
In 1888, a system of vital registration was initiated in the Gold Coast colony regulated by the Cemeteries Ordinance, and revised in the Births, Deaths and Burials Ordinance of 1912. After independence, the Births and Deaths Registration Act was passed in 1965 to ensure universal, compulsory reporting of vital events. There are currently 397 registry offices nationwide. Between 2000 and 2008, estimated coverage of deaths was approximately 20% [Addo, 2009]. The absence of a complete civil and vital registration of childhood deaths has meant that changes in child survival have to be defined using indirect methods of estimating under-five mortality rates from birth histories reported by mothers that include information on the residence and survival of their live births [Hill & David, 1988]. These data are assembled within a life table to estimate the probabilities of dying between intervals derived from reported dates of birth and death and the numbers of children of a particular age exposed to the risk of dying during the period [Hill & David, 1988].

Data have been compiled by the Inter-Agency Group for Child Mortality Estimation (IGME), who used combinations of weighted LOESS regression techniques to fit smoothed mortality trends to estimate mortality between survey periods using sample survey and census data [UNICEF-IGME, 2011]. The IGME estimates of under-five mortality (the probability of dying between birth and the fifth birthday, U5MR) and infant mortality (number deaths in the first year of life per 1000 pregnancies; IMR) for Ghana between 1960 and 2011 have been computed from national population and housing censuses (PHC) 1960, 1971 and 2000, Demographic Sample Survey 1968/69, World Fertility Survey 1980 and Demographic and Health Surveys (DHS) 1988 1993, 1998, 2003 and 2008. The results are shown in Figure 2.3 [UNICEF-IGME, 2011]. Substantial declines in both infant and under-five mortality have been witnessed since 1960, with a stalling of declining mortality rates in the mid-1980s during a period of political instability. These declines have been projected to be sustained through to 2010.

More recently, data obtained from the 2010 census were used to estimate IMR and U5MR from birth histories using indirect demographic methods and compared with previous estimates during the census 2000, DHS 2003 and DHS 2008 [GSS, 2013]. Infant mortality rates have declined from 90 to 59 infant deaths per 1,000 live births during the period 1992-2006 (the retrospective intervals from which mortality estimated during the 2000-2010 surveys). For the same period U5MR has dropped from 167 to 90 child deaths per 1,000 children [GSS, 2013].

Data from the 2010 PHC showed marked variations in U5M and IMR between regions. In the five years preceding the 2010 census, IMR ranged from 48 deaths per 1000 live births in the Greater Accra Region to 81 deaths per 1000 live births in the Upper West Region. These two regions represented the extremes of IMR and differences in U5MR were comparable between these regions. Children in the three northern regions (Northern, Upper West and Upper East) had considerably higher rates of IMR and U5M (>73 and 116 respectively) compared to all other regions (< 61 and 94 IMR and U5M respectively) [GSS, 2013].

Figure 2.3: Under-five mortality rates (red) and Infant mortality rates (blue) per 1000 live births for Ghana, 1960 to 2011 [UNICEF-IGME, 2011]



Legend: Under-five mortality rates (red) and Infant mortality rate (blue) per 1000 live births Ghana, 1960 to 2011. All rates are defined as per 1000 live births [UNICEF-IGME, 2011]. For IMR and U5MR, a country-specific local log-linear regression model is fitted to observations for one of the two indicators, within a model life table. Projections have been adjusted for projected mother-to-child HIV infection risks [You et al., 2009; Hill et al., 2012; UNICEF-IGME, 2011]. A loess line is produced with an uncertainty range (shown as boundaries to dark line in Figure 2.3).

Reliable, complete data on malaria-specific mortality rates in the community are not universally available across Ghana. The first attempt to estimate the impact of malaria on child survival in Ghana was undertaken between 1948 and 1952 using hospital records, burial certificates, civil registration and autopsy data for Accra and its environs [Colbourne & Eddington, 1954]. These data were combined with 1948 census information to derive a malaria-specific mortality estimate of between 9.61 and 12.49 per 1000 children aged 0-5 years per year; or 22% of all deaths in this age group [Colbourne & Edddington]. This estimate, together with similar data from Lagos [Bruce-Chwatt, 1952], was used for many years to provide the basis behind the "one million malaria deaths in Africa" estimate.

It took nearly thirty years for an equivalent effort to be mounted to provide an estimate of malaria mortality in Ghanaian children. At Gomoa Fetteh, Gomoa Onyadze/Otsew Jukwa and Gomoa Mprumem, in the Central Region, between 1987 and 1990 child mortality was assessed among a cohort of young children covering 832 person-years on observation [Afari et al., 1995]. Six (40%) of the 15 deaths recorded in this cohort were due to malaria providing an estimated malaria-specific mortality rate of 7.21 per 1000 children aged 0-4 years [Afari et al., 1995]. Several years later, as part of early studies on the impact of Vitamin A, at the Navrongo Health Research Centre (NHRC) in the Kasena-Nankana district in northern Ghana, malaria specific mortality between 1989 and 1991 was 11.44 per 1000 children aged 0-4 years, representing 17% of all childhood deaths [Ghana VAST, 1993]. At the same site between 1993 and 1995 the malaria-specific mortality rate was reported as 9.88 per 1000 children 0-4 years per annum representing almost a 1/3rd of all childhood deaths [Binka et al., 1996; Bawah & Binka, 2007]. However, at the Navrongo demographic surveillance site (DSS) mortality from malaria in childhood had declined by 2001-2004 to

only 4.08 per 1000 children 0-4 years per annum, 15% of all deaths in this age group [Abdullah et al., 2007].

Other DSS sites currently maintain prospective surveillance of child mortality events employing verbal autopsy techniques to establish causes of death for events that occur outside the formal health care setting: the Kintampo DSS in the Brong Ahafo Region and the Dodowa DSS in the Dangme West District of Greater Accra Region [INDEPTH, 2013]. However, no published estimates of malaria-specific mortality are available from either of these two sites.

2.7 Population growth and distribution

The first "censuses" were conducted in 1891, 1901 and 1911 by the British using a hut count method restricted to the colony only; these were repeated in 1921 and 1931 across the protectorate, colony and Togoland. The 1948 census was the first to use modern demographic methods. The first post-independence census was conducted in 1960, then in 1970, 1984 (the 1980 census was not done because of political instability) and 2000. The latest census was undertaken in September 2010 [GSS, 2013].

Ghana's population has increased from 6.73 million in 1960 to 24.66 million in 2010, a 3.5 fold increase in 50 years. The average intercensal annual growth rate has been 2.5% since 1960, with the highest rate of 2.7% observed between 1984 and 2000. If this growth rate continues Ghana's population will double within the next 28 years. Greater Accra, Northern and Central show the highest growth rates with Volta, Upper East and Upper West exhibiting relatively low growth rates [GSS, 2013]. The age structure of Ghana's population is typical of a country transiting from high to low fertility. The population remains young and therefore has a high growth potential. The crude population density for Ghana was 28.6 persons per km^2 in 1960 and 103.4 per km^2 in 2010 [GSS, 2013]. About 70% of the total population lives in the southern half of the country. The population density for the Greater Accra Region increased from 167 per km^2 in 1960 to 1,236 per km^2 in 2010, an eightfold increase [GSS, 2013].

Recently spatial modeling techniques for the reallocation of populations within census units have been developed in an attempt to overcome the difficulties caused by input census data of varying, and often low, spatial resolutions [Linard et al., 2010; 2012; www.afripop.org]. In brief, a dasymetric modeling technique [Mennis, 2009] was used to redistribute population counts within the 15,213 enumeration areas used in the 2000 PHC and adjusted for total populations presented across 10 regions reported in the 2010 PHC assisted by digital extents of parks/ national reserves land cover data sets and satellite imagery (Figure 2.4). A different population weight was assigned to each land cover class in order to shift populations away from unlikely populated areas, for example game reserves and concentrate populations in built-up areas. The net result was a gridded dataset of population distribution (counts) at 0.1 x 0.1 km resolution. The population distribution datasets were the adjusted using national rural and urban growth rates [UN, 2011] and

made to match the total national population estimates for 2010. The resulting population density map is shown in Figure 2.5[1].

Figure 2.4: 15,213 enumeration areas used in the 2000 PHC and parks (green) digitised from hard copy tourist map in combination with UNEP data of protected areas from [SWERA]

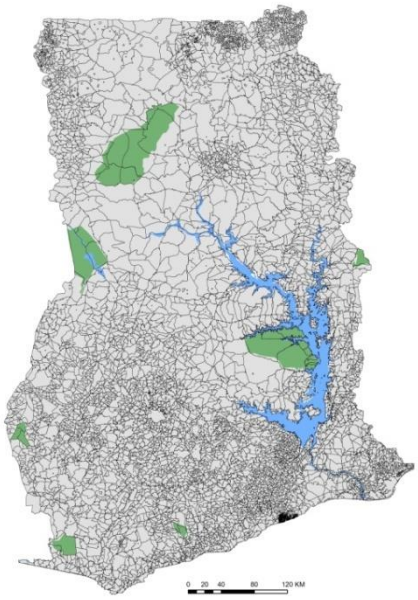
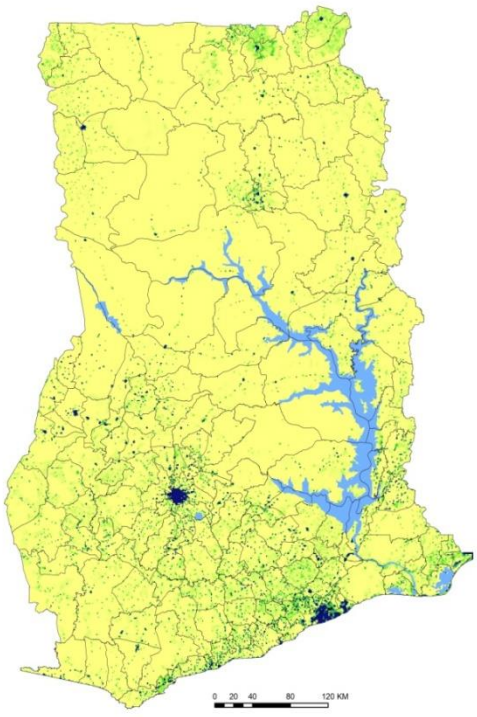


Figure 2.5: Modeled population density projected to 2010 using methods described in the text and represented as increasing density as shown in legend below. Ranging from zero to 69,000 per km^2



[1] It is worth noting that the micro-data collected during the 2010 census is expected to be released sometime soon and these would help improve population distribution modeling, age-sex compositions, projected populations per gridded count and definitions of urbanization.

2.8 Urbanization

The 2010 PHC showed that, for the first time since 1960, more than half of Ghana's population lived in urban areas: increasing from 23% in 1960 to 51% in 2010. This demographic change has occurred across all regions since 1960 but Upper West region remains the least urbanized (16.3%). In 1960, Ghana had an urban population of about 1.6 million, doubling to 3.9 million in 1984, then to 8.3 million in 2000; by 2010, 12.5 million lived in urban areas. The average growth rate of the urban population between 2000 and 2010 was 4.2% [GSS, 2013]. The main drivers of urbanization include rural-urban migration and natural increase within towns and cities [Songsore, 2009].

During the 1970 census, there were 15 settlements with a population of 20,000 or more. Between 1970 and 2010, the population in these 15 urban towns increased from 1.5 million to 6.1 million, representing 48.8% of the total urban population and 24.8% of the total population in 2010 [GSS, 2013]. In 1970, only Kumasi (346,336) and Accra (624,091) had populations above 100,000; by 2010, 11 out of the 15 towns had populations above 100,000. The exceptions were Bawku (61,151), Agona Swedru (54,417), Nkawkaw (47,968) and Sunyani (74,240). Between 2000 and 2010, Kumasi Metropolis contributed 20.2% to urban growth, the highest in the country. The Sekondi and Takoradi sub-metros recorded increases in their urban population between 2000 and 2010: from 114,157 to 228,342 and 175,436 to 311,206 respectively [GSS, 2013]. The rapid increases in the population of these twin cities is largely attributed to in-migration to the Western Region due to the oil find in the late 2000s [GSS, 2013]. The growth of other urban towns has primarily been in the Central, Eastern and Greater Accra regions. Between 1970 and 2010, the population of settlements such as Amanfrom increased from 112 to 119,467, Odupon Kpehe (Kasoa) from 863 to 69,384 and Buduburam from 380 to 50,560. Mandela which did not exist in 1984 had a population of 61,880 in 2010. Other localities which were below 40,000 in 2000, substantially increased their share of urban populations including Kintampo, Madina, Wa, Berekum, Hohoe, Yendi and Asamankese [GSS, 2013]. During the 2000s the spill-over effect of the populations of large urban settlements to peripheral towns has contributed to the rapid increase in the populations of towns at the fringes of the cities. Improved transportation combined with the challenges of finding accommodation in the urban core have influenced urban workers to take up residence in peri-urban and other nearby settlements and to commute to their places of work [Yankson, 2012]. Basic infrastructure and services such as, housing, water supply, sanitation, urban transport, storm water drainage and refuse disposal has been unable to keep up with the rapid urbanization. In 2001, almost 70% of Ghana’s urban population lived in slums [World Bank, 2013].

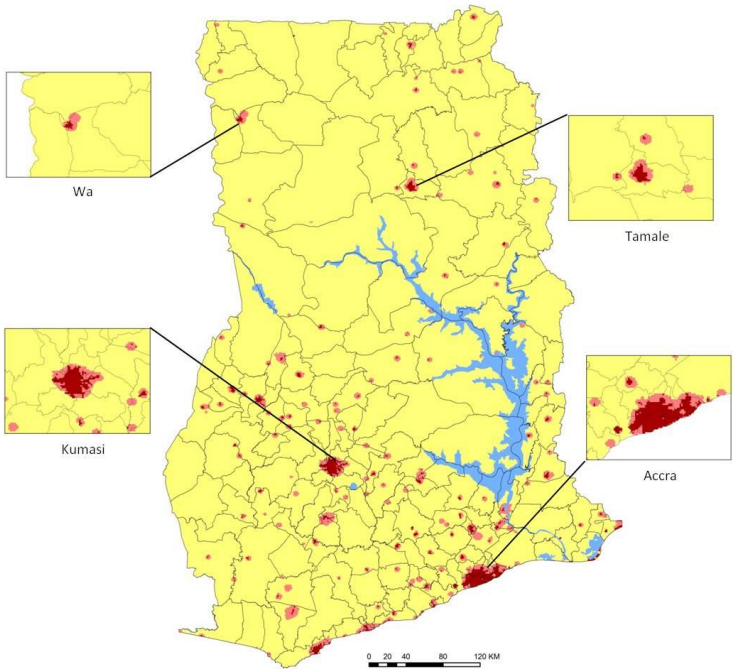
Although urbanization rates have been lower than in neighbouring countries of West Africa, Ghana is following similar trends where by 2030, 58% of the population will be located in urban areas. Currently, the five largest cities (Accra, Kumasi, Sekondi-Takoradi, Tamale and Tema) are home to half of the urban population and play an important role in creation of national wealth.

Defining an urban settlement only by the numbers of residents without a spatially constrained component poses challenges in measuring the impacts urbanization in space and time as noted by the GSS in their analytical report of the 2010 PHC: "*It is imperative for*

Ghana to consider the re-classification of an urban settlement in the face of rapid urbanization for effective urban planning and reduction in overlaps in metropolitan and peri-urban areas" [GSS, 2013].

Given this need we have used an urbanization classification that combines the spatial extent of urban settlements developed by the Global Rural Urban Mapping Project (GRUMP) and population density developed the AfriPop project [Section 2.7; Linard et al., 2012]. GRUMP urban extent grids distinguish urban and rural areas based on a combination of NOAA's Night-time lights dataset [Elvidge et al., 1997], settlements data and population counts. Population counts used were derived from GRUMP spatial population database based on areal weighted census input data [Balk et al., 2006] while settlements data sources include ESRI's Digital Chart of the World's Populated Places (DCW), Tactical Pilotage Charts (TPC) from Australian Defense Imagery and Geospatial Organization and some LandSAT-derived polygons [Balk et al., 2004; CIESIN, 2013]. To define urban extents, a border was defined around each set of contiguous lighted pixels whose total population count was greater than 5,000 persons. Because not all urban settlements are 'well-light' to be detected by satellite sensors, a buffer was drawn around settlement points to estimate spatial extents of the settlements. Similar to the Night-time lights-derived, urban extents, settlement extents with a total population count was greater than 5,000 persons were classified as urban with the rest of the grid defined as rural. The GRUMP urban extent was further refined to produce a 'peri-urban' classification constrained by population density using the Afripop data [www.AfriPop.org]. Urban areas were defined as locations with a density of more than 1000 persons per km^2 with the rest of the GRUMP urban extent defined as peri-urban (Figure 2.6).

Figure 2.6: Urban and peri-urban settlements in Ghana (see text for definitions)



2.9 Health services

2.9.1 Evolution of current health services in Ghana

At independence, Ghana inherited the colonial health system characterized by: centralized control, principles of cost sharing, predominantly curative and with a largely urban orientation [Senah, 2001]. Dr Kwame Nkrumah set the health agenda in which the country's achievements would be measured by the health of the people [Nkrumah, 1969]. The government developed a ten-year plan to drive its social and economic agenda, the health component of the plan involved: expanding the existing health facilities, reducing of user fee and in some cases adopting free healthcare, and abolishing private practice. In 1979, Ghana embraced a primary healthcare strategy as a means to achieving health for all by the year 2000, but economic turmoil of the 1980's made the primary health goal unachievable [Arhinful, 2003]. One major component started in 1987 was the Bamako initiative that involved subsidized drug sales to rural communities and upgrading of basic healthcare system by the communities from community savings [UNICEF, 1995].

In 1996, Ghana developed "Vision 2020", a long term plan for growth and development that would move it from a low income to a middle income country by 2020 with an overall health policy objective to "*improve health status of all Ghanaians*" [NDPC, 1996]. Key areas of the document related to health service provision included: increased rural health access, establishment of health system oriented to delivery of public health services and effective management of health system. The Ministry of Health developed a five-year medium term health strategy (MTHS) that would guide development of health from 1997-2001. The MTHS aimed to increase access to care both geographically and financially, focus on better quality care with improved efficiency, integrate all sector stakeholders and communities and to distribute health resources equitably [MoH, 1996]. In 2001, the National Health Insurance Scheme (NHIS) was launched to replace out-of-pocket fees and passed into law by an act of parliament in 2003 [Singleton, 2006; Agyepong & Adjei, 2008; Baidoo, 2009; Saleh, 2013].

The current Health Sector Medium Term Development Plan (HSMTDP) 2010–13 [MoH, 2011] links the latest national development framework, adopted in 2010, to the attainment of the Millennium Development Goals (MDGs) and to the Ghana Shared Growth and Development Agenda for 2010–13 [NDPC, 2010]. The Ministry of Health (MoH)/ Ghana Health Service (GHS) oversee healthcare infrastructure and delivery in Ghana.

There are four main categories of health care delivery system in Ghana – the public, private-not-for-profit, private-for-profit and traditional [MoH, 1996]. The private health sector provides an estimated 42% of curative services. The Christian Health Association of Ghana (CHAG) which represents part of the private-not-for-profit is made up of member health institutions of 16 Christian Churches involved in the provision of health care. Government provides about 80% of salaries of CHAG health staff. The role played by the traditional birth attendants (TBAs) and traditional healers is also receiving national recognition. Public health facilities are graded at different levels depending upon the complexity of services they deliver and the administrative zones they serve. The pyramid of health service provision, starting at the grass--roots level, is as follows [MoH, 2007a; 2007b; Saleh, 2013]:

- Community – comprises of village or community health planning and services compounds (CHPS) organized around small geographical areas covering of between 5 – 10 communities. These facilities predominantly provide preventive and primary health care services in rural areas and are manned by Community Health Nurses with additional training on community health planning or health volunteers and/or TBAs.

- Sub District – comprises of health centres and clinics serving geographical areas with population totals ranging from 15,000 to 30,000 people. In absence of CHPS compounds, health centres serve as first point of contact with patients. These centers provide basic curative care, disease prevention services and maternity services.

- District - A district hospital provides support to sub-districts in disease prevention and control, health promotion through public health education, referral outpatient and inpatient care, training and supervision of health centers and clinics, maternity services, management of complications, emergency services, and surgical contraception.

- Regional - A regional hospital provides specialized clinical and diagnostic care, management of high-risk pregnancies and complications of pregnancy, technical and logistical back up for epidemiological surveillance, medical research and training of medical personnel. Hospitals and polyclinics are the main providers of secondary and tertiary curative care. The polyclinics also serve as first point of contact of primary health care in urban centers and therefore provide a mixture of preventive and curative care and use the regional hospitals for referrals.

- Tertiary - At the apex of the referral system, there are three government-owned teaching hospitals (Korle Bu, Komfo Anokye and Tamale) that offer specialized clinical and maternity services, undertake research, and provide highest level of undergraduate and postgraduate training in health and allied areas.

2.9.2 Development of health facility database and mapping

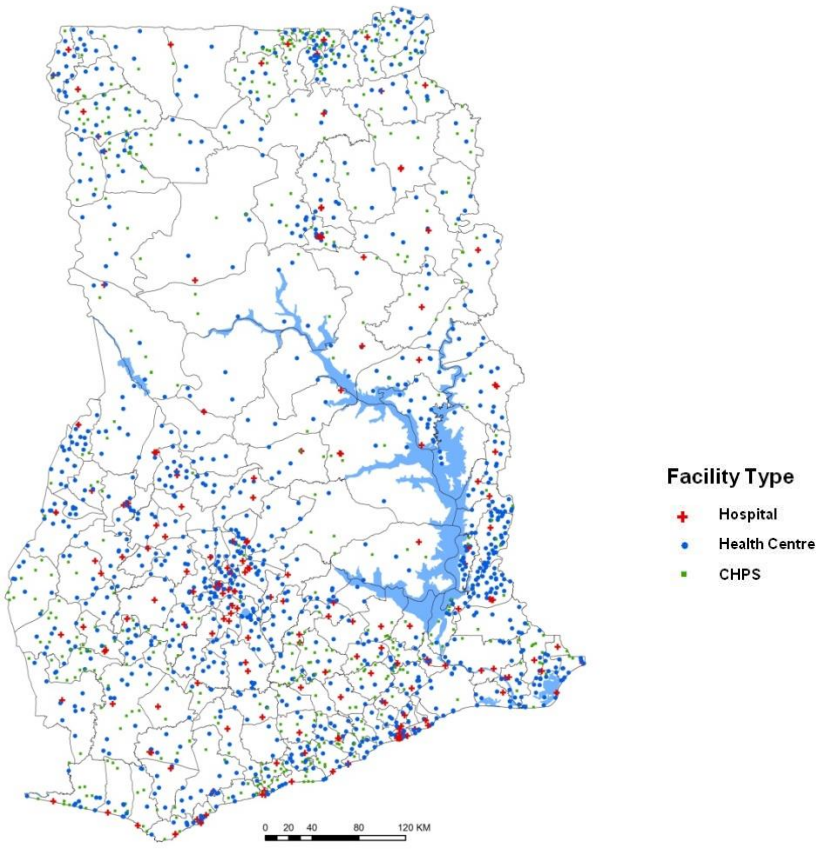
Accurate health information is the cornerstone of effective decision-making and reliable assessment of disease burden and resource needs [Detmer, 2003; WHO, 2007]. Efforts to tackle the enormous burden of ill-health in low-income countries are hampered by the lack of functioning health information structures to provide reliable health statistics [Osisobe, 1989; Boerma & Stansfield, 2007]. Central to a fully operational Health Information Systems (HIS) is a basic inventory of all functioning health facilities and the services they provide. Such an inventory requires a spatial dimension, allowing facilities to be linked to the populations they serve by level of care and other proximate determinants of health such as environment, poverty and education. This spatial linkage can be provided by geographic information systems (GIS). The use of GIS for health services planning is widespread in developed countries but there are few examples of their development and operational use in resource poor settings in Africa [Noor et al., 2009].

The current reforms in the health sector, recognizes the need for comprehensive and quality information as essential for effective health planning, management and policy development and as such sees it as a fundamental prerequisite for the reform programme [Addai et al., 2006]. In 2000, the European Commission through its technical assistance programme supported the development of a system and software that provides a "platform" that unifies the processes of collation of reports, enhances data management and generates reports required by the districts. The system was initially implemented in 20 districts to facilitate the management of reporting forms submitted to the district and to generate reports required of the districts. This led to the establishment of a nationwide District Health Information Management System (DHIMS), a web based data management software, that captures all service and surveillance data at every level. DHIMS is managed by the Centre for Health Information Management, under the Policy Planning, Monitoring and Evaluation Department of the GHS. The GHS collaborated with the University of Oslo to expand and improve the DHIMS system to DHIMS2, that uses data warehouse principles and a modular structure and is available in all district health directorates with currently 5,563 registered users [GHS, 2011]. There is a GIS component, but there appears to be, at present, no use of this element of the system and the spatial dimension of DHIMS2 is under-utilized.

The MoH have recently updated their national master health facility database which is available on-line at the Online Health Facility Registry [http://data.gov.gh/dataset/health-facility-ghana-1; accessed 15th August, 2012]. In this report, we have assumed this to be a reasonable representation of audited clinical facilities in Ghana for 2012/13. The information extracted included facility name and location (region, district, latitude and longitude), service level (hospital, health centre, CHPS), and management (private, NGO, mission or government). The database contained a total of 3,756 facilities of which 2,858 facilities had coordinates which we presumed were developed using a GPS. We identified 63 structures that were duplicates e.g. Ahenema Kokoben Health Center in Ashanti, and Swan Clinic in greater Accra region, these we removed. Another 185 facilities had their coordinates duplicated e.g. Aboabogya and Aboaso Health Centers both in Ashanti region, these were repositioned using Google Earth. In addition we noticed that the labeling of the provider was incorrect in several instances (clinics, and maternity homes), these were changed to government and private respectively. Labeling of types was incorrect for a number of facilities with clinics labeled hospitals, these we labeled clinics and were re - coded based on functionality. We also recoded the managing authority to five i.e. Government, Quasi-government, faith-based organizations (FBOs), non-governmental organization (NGO) and private. We excluded 574 structures labeled training and research institutions, maternities, psychiatry hospitals, dental clinics, eye clinics, physiotherapists, mental clinics, and youth centers that were unlikely to be providing routine curative services. 1158 facilities were labeled as being private facilities and we moved these to a separate file. The latter are significant providers of curative services in Ghana [Makinen et al., 2011], but as with previous audits of master health facility lists in Kenya, Somalia and Uganda these are often under-represented in MoH registries, located in urban centers, accessible only to those able to afford services, unregulated and do not often feature in anti-malarial and net distribution supply management systems. We have retained all facilities under the umbrella of "public" facilities that are managed by NGOs and mission groups such as CHAG and Islamic institutions; these are often included in GHS commodity distribution systems.

The final public sector facility database contained 1961 facilities; including 189 hospitals, 1137 health centres and 635 CHPS health posts. Government ownership comprised 1734 facilities while the rest (227) were managed by missions. We then undertook a cross-referencing exercise with other available digital sources to geo-code facilities without co-ordinates using Encarta Maps, Google Earth, GeoNames, and digital gazetteer databases (Section 4.2.3). We geo-located 182 facilities using these settlement and place name gazetteers; in the final database we were unable to locate 133 (6.8%) public health facilities. Final checks included matching coordinates with the health administrative boundaries described in Figure 2.1 to locate those facilities that were in the wrong administrative boundary and attempt re-positioning. In addition points along the coastline were checked using the GAUL 2008 coastline shape file. The Global lakes and Wetlands (GLWD) database developed by the World Wildlife Fund [Lehner & Doll, 2004] was used to ensure facilities were within defined land areas. We used the spatial selection tool in *ArcGIS* [ArcMap 10.1, Esri systems, Redlands, CA, USA] to identify facility coordinates that fell slightly off the coastline, located on a river/lake or in slightly outside of their correct administrative units and every anomaly was re-positioned using small shifts in combination with Google Earth. The location of 186 hospitals, 1109 health centres and 533 health posts is shown in Figure 2.7.

Figure 2.7: Distribution of geo-coded hospitals, health centers and health posts managed as part of the public sector (government and faith-based or NGO)



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Chapter 3

The first 100 years of malaria control

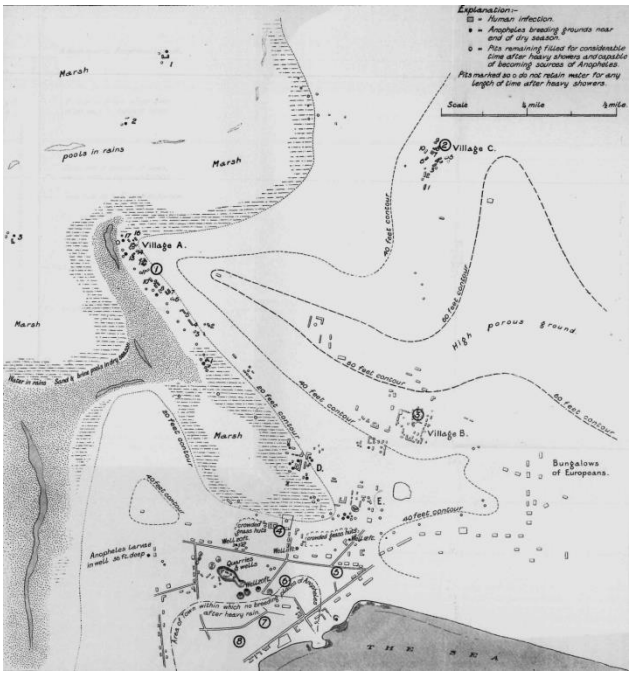
3.1 Background

In this chapter we provide an overview of the evolution of malaria control in Ghana from the period before independence, through the era of the Global Malaria Eradication Programme (GMEP), from the abandonment of elimination up to the present RBM control period. This chapter is motivated by a need to: a) capture a historical perspective of control as relevant to today's control ambitions; and b) maintain an institutional memory of malaria control in Ghana - who was involved, what was done, what worked and more importantly what did not work.

3.2 Malaria control pre-World War II

SR Christophers and JWW Stephens made an investigation of Accra, Jamestown and Christianborg in May 1900 and reported their findings to Royal Society's Malaria Committee the same year [Christophers & Stephens, 1900]. Their observations and recommendations were to have a profound effect on the organization of malaria control for the next three decades. Through the examination of mosquito breeding sites, huts, villages and European dwellings (Figure 3.1.) they concluded that the "*native is the prime agent in the malaria infection of Europeans*" and that special attention should be given to separating "native" dwellings from European settlements and ensuring that all wet-season pits and excavation areas are filled in to prevent mosquito breeding.

Figure 3.1: Detailed map of malaria reconnaissance of Accra and environs [Christophers & Stephens, 1900]



Throughout the reports of the Medical and Sanitary Department from 1910 reference was made to methods of "segregation" and environmental sanitation for malaria control in urban centres with European interests [Government of Gold Coast, 1910; 1912; 1916; 1921]. The colonial government, during the first two decades of the 20th century, had policies for

malaria and accompanying expenditure that focused almost exclusively on improving the health of Europeans. Governor Mathew Nathan wrote to Ronald Ross stating that the state's prime mission in 1901 was "*although I don't undervalue sanitation for natives, as I fear they themselves do, improvements in the health of Europeans is absolutely the first desideratum for general improvement in these colonies*" [Nathan, 1901].

Dr Dutt, at Ada, reports in 1912 that "*The European officials are well segregated and this no doubt accounts for the satisfactory record Ada*[h] *has had for them for many years past*"; the annual report goes on to highlight that segregation areas had been developed during 1912 for Accra, Sekondi, Saltpond, Cape Coast, Winneba, Dunkwa, Axim, Commassie (Kumasi) and Mangoase, because "*segregation is undoubtedly the most effective measure by which it is possible to guard against infection by mosquito borne disease*" [Government of Gold Coast, 1912]. However, the costs of segregation approaches to control were mounting. Some officials thought that segregation proved too cumbersome and too costly in terms of both money and African dissatisfaction. At Sekondi, for example, the cost of compensating Africans for eviction in one section of the town had risen to £37,000 by 1910 [cited in Dumett, 1968].

The significance of malaria to the colonial medical department was highlighted by the following statement in 1914 "*it would be difficult to adduce any sanitary measure of importance which, in this colony, does not directly or indirectly help to check the incidence and spread of malaria*" [Government of Gold Coast, 1914]. In 1914, malaria accounted for 180 of 499 sickness episodes among 644 European residents [Macfie & Ingram, 1918]. During 1914, reference was made to "mosquito brigades", a dedicated sanitary workforce that conducted house to house mosquito searches and operated under district health authorities, first recommended by Sir Ronald Ross [Ross, 1902]. In 1914, the mass distribution of quinine to school children began in major towns and was accompanied by an education programme to young students on the importance of mosquito control[2].

By 1915, the Sanitary Inspector's work increased across all major towns, and that "*it would be idle to think that [he] is a welcome visitor, but at any rate he is now tolerated where before he was actively opposed*" [Government of Gold Coast, 1915]. From 1914 onwards environmental management and household screening were promoted including the filling in of pits and borrows, drainage, inspection of tree stumps left as a result of building the railway, screening water tanks and pots, oiling (especially of ponds at Christianborg), the use by officials of a mosquito cage over the beds in their bungalows, house screening and fumigation using sulphur or compho-phenique [Government of Gold Coast, 1915; 1916; 1917]. Special efforts to plan towns to reduce mosquito breeding were undertaken, notably at mining villages such as Akyem, on the Dagwin manganese mining concession. Fish were introduced, without much success as a means of larval control, in Accra during 1921. More success was reported following the use of prisoners to drain the West Subin valley outside of Kumasi [Government of Gold Coast, 1921].

[2] Ninety years later, engaging school children in malaria control messaging to influence community behaviour was resurrected as part of a pilot project to use children attending school as agents of behaviour change in Dangme-East [Ayi et al., 2010].

Two main gold mining sites existed prior to the First World War: a) the twin towns of Tarkwa and Aboso in Wassa State; and b) Obuasi. From a tiny hamlet, Tarkwa grew into a town of over 2000 at the height of the first gold rush in the early 1880s and further expanded following the first railway from Sekondi to Tarkwa between 1899 and 1902 leading to a population of 12,417 workers living in overcrowded and poorly sanitized conditions. Tarkwa and Aboso continued to grow through to 1921 including other settlers, migrants, traders and wives and their children leading to an unplanned growth of towns, villages and camps along the Tarkwa Ridge (including Tarkwa, Tamsu, Abontiakrom and Aboso) to an estimated 26,500 people. Obuasi (meaning "under the rock"), grew from a tiny clearing in the forest to a 100 mile block "owned" under a concession by the Ashanti Goldfields Corporation (AGC) in 1897. By 1904, the AGC had a regularly employed labour force of 1500. By 1911, the total population of Obuasi and surrounding mining villages was estimated at 15,000.

The state of health of the miners and their families during the first 30 years in these mining areas was reportedly deplorable, despite poor health record keeping. Differences of opinion existed between mining concerns and the government on whose responsibility it was to maintain public health for the local work force, despite continued efforts to improve the health of their European employees [Dumett, 1993]. At Obuasi and Tarkwa, the mining companies, the colonial state and the traditional leaders vied for municipal authority, but each tried to withdraw from responsibilities for expenditure on town upkeep, public works and sanitary improvements [Dumett, 1993]. The mining companies did not accept the Town Councils Ordinances of the Gold Coast. At Tarkwa, housing, street sanitation, sewage disposal and malaria preventive measures were entrusted almost entirely to the companies, with some assistance from the local district commissioner. At Obuasi, because the AGC did not want to bear the entire burden and responsibility for public health, and these roles were delegated to a Towns Sanitary Committee, which the company, the government and the local people (through municipal taxes) made financial contributions [Dumett, 1993]. The mining companies were not cooperative with the state authorities; they accepted the need for government inspection tours of their premises grudgingly. Dr E Horn of the medical department noted that "*information as to sick rates appears to be only obtained through the courtesy of those gentlemen* [mining company doctors]" [Government of the Gold Coast, 1910].

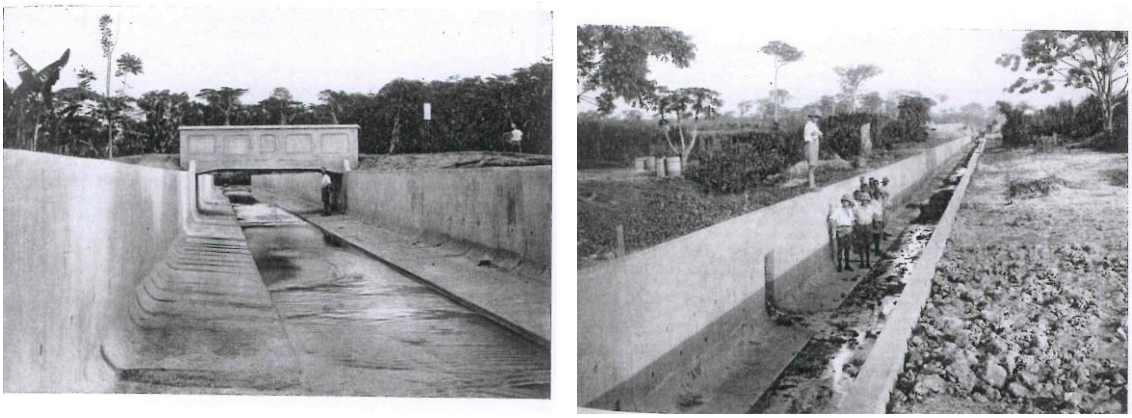
The poor health conditions of African employees of the mines was documented during a survey and report by Professor WJ Simpson from the London School of Hygiene and Tropical Medicine in 1924. The Simpson report emphasized, for the first time, that the health of African's should be on an equal footing with Europeans. This report led to the Mining Health Ordinance of 1925 and over a period of time laid the foundations for new health regulations of mining concerns. These were only variably implemented by the mining concerns through to the start of World War II, and only when it became obvious that the loss of African skilled workers (engine drivers, winch and separation plant operators) and supervisory positions affected company bottom-lines. This economic argument was made again at Obuasi, 90 years later, in support of financing malaria control operations by AngloGold Ashanti that became a model of public-private partnership (Section 6.4).

By the mid 1920s, the medical department began a concerted effort to control malaria in the major towns of Accra, Kumasi (Figure 3.2), Sekondi, Cape coast and Koforidua. The

annual report of 1926-1927 lists the measures taken to control malaria in the Colony "*Drainage and reclamation of lagoons and swamps, the filling of ponds and borrow pits, the laying of "Dutch" drains in connection with seepage areas, the construction of concrete drainage systems, the treatment of low-lying areas incapable of being economically drained or filled by oiling or by treating with copper eceto-arsenite* [Paris Green], *the inspection of school children, the distribution of quinine at hospitals and clinics, the encouragement of segregation, of the use of nets, of mosquito proofed premises and of prophylactic quinine by non-immunes, the enforcement of rules relating to residential areas, the educative propaganda by means of Health Weeks and public lectures and hygiene lessons in schools, form but a few of the methods by which the incidence of malaria is attacked*." [Government of Gold Coast, 1926-1927].

Reclamation of flooded areas and marshes around the lagoons in Accra began in 1928 notably at Adabraka, Agblogbloshie and Korle Lagoon [Government of Gold Coast, 1928-1929]. Malaria, however, continued to plague the European official population (for whom data were recorded) with an average of 1518 days off sick because of malaria per year between 1923 and 1928 among an average resident population of 750; representing approximately 25% of all sick days and two days per person per year lost from work [Government of Gold Coast, 1928-1929].

Figure 3.2: The Subin key drain at Kumasi [Government of Gold Coast, 1926-1927]



In 1930, the acting director of the Medical and Sanitary Department, G Hungerford, states that "*Malaria continues to be the greatest predisposing factor in the mortality and morbidity rates among the children, in the loss of efficiency of labour, and it apparently complicates every pathological process from birth to old age*" [Government of Gold Coast, 1930-1931]. High rates of malaria mortality were reported in 1931-1932, and an effort was made to increase propaganda to support the use of mosquito nets, taking prophylactic quinine or plasmoquine, health education of general population and expanded use of larvivorous fish and Paris Green for larval control [Government of Gold Coast, 1931-1932]. A closer engagement with the mining sector was felt important in 1933, not through any concern for the large local labour force, but because this important industry employed a few scattered Europeans, and they were hard to reach with medical services.

1935 saw the launch of a campaign to distribute quinine through post-offices and postal agencies across the country, "*to make quinine more accessible to people in the bush*". A tube

of 16 pink coloured tablets of quinine hydrochlor 4 grains was sold for six pennies per tube and a Crown was stamped on the side of the tube to signal it was Government quinine. the wrapper around the tube contained instructions in English, Ga, Twi, Fanti, Ewe and Hausa. A leaflet containing a speech by the Director of Medical Services on the life-saving properties of these drugs was distributed and read out across the Colony and Ashanti Territory. In 1935, 13,612 tubes were sold and this increased to almost 41,000 tubes in 1936. The programme was planned for expansion into the Northern territory in April 1937 [Government of Gold Coast, 1936]. This scheme continued to be highlighted as successful through to 1941 when the price was raised to between seven and eight pennies and where in the Northern territories it was distributed by the Native Administrators at a cost of one penny [Government of Gold Coast, 1941]. In 1943, it was reported that the sale of quinine at post-offices was stopped at all stations where a hospital or dispensary existed [Government of Gold Coast, 1943].

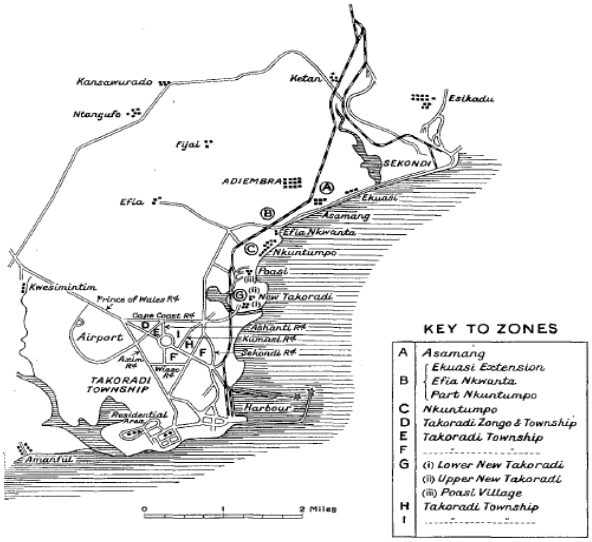
3.3 Malaria control during the Second World War

With regular reference to low staff numbers, there was little mosquito control reported in the annual medical reports from the late 1930s. During World War II, the Armed forces stationed in the Gold Coast took over some of the responsibilities for malaria control, largely to protect sea and air ports for military personnel. In 1941, Allied troops fighting in North Africa were cut off from Mediterranean supply routes and had to be supplied by air from West Africa. Accra and Takoradi became staging areas for troops recruited in the colonies. Accra became a stopover point for British and American aircraft.

In 1941, the European malaria morbidity rate was 217 per 1000 population at Takoradi, a major hindrance to the armed forces work-force during the war. Despite insisting on prophylactic drug use and house screening the situation did not improve because of the high reservoir of neighbourhood infection. Following consultations with the then director of medical services, Dr J Balfour Kirk, who had recently been instrumental in malaria control in Mauritius [Balfour-Kirk, 1934], it was decided to institute an insecticide spray campaign across central Takoradi, coastline villages and the periphery of Sekondi (Figure 3.3) between November 1942 and November 1943 [Eddey, 1944]. Initially cresol-kerosene was used as the sprayed insecticide but was replaced by supplies flown from Kenya of a) dry pyrethrum dust, b) combined with kerosene and c) pyrethrum aerosol. Teams made up from forces and civilian personnel comprised "statisticians" to enumerate population and measure room sizes, a local headman, six labourers and two spray men.

The campaign reached 528,254 (>90%) of targeted rooms during the year of operation. Eddey provides a detailed breakdown of labour and insecticide costs using different insecticide preparations per room and per person protected and estimated that the costs, depending on insecticide, ranged from 4.25 to 4.7 pennies per person protected [Eddey, 1944]. Examining the hospital admissions and morbidity rates of Europeans before and after the spray campaigns suggested that the incidence of malaria had been reduced by over 20% [Eddey, 1944].

Figure 3.3: Takoradi spray area 1942-1943 [Eddey, 1944]



Between 1942 and 1945, the British built the first hospital dedicated specifically to military personnel near the Accra airfield, a segregated facility (200 European beds and 800 African beds). A large clinical burden seen at the hospital was malaria, at one point reaching up to 50% of all European personnel stationed in Accra. US military records state that 25% of pilots arriving from Accra in Cairo were suffering from symptoms of malaria [cited in Roberts, 2010], and that this could lead to a crash of a much needed bomber plane and used as the argument to invest financially in removing malaria from Accra [Roberts, 2010]. British and American forces therefore attempted to dredge the Korle lagoon in Accra, larvicidng (Paris Green), fogging of surrounding areas (pyrethrum) and spraying of neighbouring houses using dichloro diphenyl trichloroethane (DDT) from 1944 within a one mile radius, later extended to an eight mile radius of the lagoon. The Allies also experimented with aerial spraying with DDT at the Korle, Klotey and Sakumono Lagoons [Roberts, 2010].

It would appear that aggressive environmental management and chemical control of vectors in Accra and Takoradi areas was significantly reduced after the war. Wilson, of the Rockefeller Foundation, reports in 1944 that "*The question will arise as to whether the anti-malaria campaign in Accra and Takoradi -Sekondi should be limited to the Anopheles vectors to the point where malaria incidence will be reduced to a worthwhile minimum or whether the principal vector A. gambiae should be eradicated from the urban centres and a frontier barrier maintained in which this vector is kept at such a low density that there will be little danger of re-invasion into the A. gambiae-free area. Preliminary field observations give one the impression that this will not be feasible in the Takoradi-Sekondi area but may be worthwhile attempting in the Accra area..... The initial outlay in funds will be high, more men have to be employed, and full authority give to the Malaria Service to achieve this end. For the present it seems more reasonable to initiate a service of controlling the vector and to follow this u by exploration of the feasibility of eradication*" [Wilson, 1946]. There followed a detailed cartography of Accra to enable a zonal, systematic process of anti-larval and anti-imaginal control using Malaroil, benzene hexachloride, DDT and Paris Green. DDT was proposed for use against adult vectors using indoor residual spraying (IRS). Other proposals by the Malaria Service in 1944 included use of mepacrine as a daily prophylaxis, use of

mosquito nets and large-scale drainage works. The colonial malaria service comprised of one malariologist, one entomologist, two sanitary superintendents, five laboratory technicians, two head foremen, 43 district foremen and 479 other technical and support staff [Wilson, 1946].

3.4 Malaria in the 1950s

In January 1953, Giglioli visited Accra and noted that very little was being done with exception of some IRS in Sekondi, no IRS was being undertaken in Accra and only minimal efforts at drainage and use of Malaroil was undertaken in the city [Giglioloi, 1953]. He noted that 207 labourers, employed during the war for malaria control, were still on the books of the medical department and that the department spent £64,000 in 1951 on "malaria control" works without much to show for this expenditure [Giglioli, 1953]. He goes on to state that "*the main problem in the Gold Coast does not appear to be a lack of funds, but lack of a rational plan of action and adequately trained senior and subaltern personnel to put it into effect efficiently and economically*" [Giglioli, 1953].

Reporting to the Lagos World Health Organization conference on malaria in Africa in June 1955, the Ministry of Health reported that very little IRS (Gammexane and DDT) at a cost of US$ 9,000 per year, larviciding was only undertaken in urban areas and that proposals were being developed to establish a Malaria Unit, similar to the one in Nigeria [Anon, 1955]. The Malaria Unit was eventually established in 1957 at Ho, as part of the WHO collaborative Ghana-1 project (Section 3.4.2), and lasted only for the duration of the project.

In 1950, the first malaria conference in Equatorial Africa, convened by the World Health Organization, was held in Kampala, Uganda [WHO, 1951; Dobson et al., 2000]. This historic conference was used to present and assess all the available information on the epidemiological aspects of malaria and attempted to coordinate the various methods of research and control of the disease. Its two main recommendations were: 1) that malaria should be controlled by all available methods, irrespective of the degree of endemicity of the disease; and 2) the benefits that malaria control might bring to the indigenous populations should be evaluated [WHO, 1951; Dobson et al., 2000]. The role of research as a means to address the technical problems of control in tropical Africa was stressed at this meeting and was integral to the GMEP effort. The 1950 Kampala conference catalysed many studies in Africa, including a number of important field trials aimed at the “eradication” of malaria in Ghana.

3.4.1: Chemoprophylaxis trials

Amodiaquine-pyrimethamine school children prophylaxis trials, Accra: Between 1953 and 1954, a controlled trial was conducted of Amodiaquine at the start of term to clear infection followed by weekly Daraprim among school children in Accra (Kaneshie and Adabraka suburbs) [Colbourne, 1955]. Absenteeism, clinical attack rates, parasite rates, spleen rates and test scores were all measured between the seven year old recipients of drugs and controls. Absenteeism was reduced by 50%, parasite and spleen rates fell; overall the scheme cost three shillings and 9 pence per child [Colbourne, 1955].

Pyrimethamine trials among military in Accra: A trial of Darachlor was started in September 1959 among Ghanaian soldiers and their families stationed in Accra. Darachlor parades were organized weekly and units randomised to different doses. The trial showed a reduction to zero of daily clinical attacks in the two tablet group and to 0.03% in the one tablet group compared to 6.3% in the control group [Thompson & Carter, 1961].

Daraprim prophylaxis trials, Ho district: Two small villages participated in a weekly chemoprohylaxis with Daraprim (pyrimethamine), "Daraprim Parade", organized by Dr Vincke of WHO at Akrofu Heviowfe (pop 721) and Akrofu Agove (pop 356) in November 1959. After four weeks parasite rates in children less than 13 years dropped from 71.5% to 6.5%, and after 12 weeks to 3%. However, following a period of reduced supervision parasite rates climbed back between weeks 22 and 37 to approximately 20%, in part due to suspicions of pyrimethamine reduced effective clearance times, incomplete weekly coverage of all household members and occasional absence of distributors [Anon, 1959].

Primaquine trials: A prophylactic experiment among 100 Ghanaian children in the forest belt of Southern Ghana was undertaken in 1959 to explore the possibility of using primaquine in an African setting [Charles, 1960]. Camoprim Infantabs, produced by Parke Davis, were administered weekly and contained amodiaquine 75 mg base and primaquine diphosphate 15 mg base. Amodiaquine cleared all *P. falciparum* and *P. malariae* infections and primaquine cleared all gametocyctes through to week 5. Eight boys with proven G6PD deficiency did show significant drops in haemoglobin concentrations during weeks 3 and 5 but this was thought not to be clinically significant and did not exclude the use of primaquine in Ghana [Charles, 1960].

Lapudrine school children prophylaxis, Ashanti: A trial of daily Lapudrine (chlorproguanil) was tried among school children at Boni village in the Ashanti forest region in 1959 but despite initial impressive results also suffered from break through infections and incomplete coverage [Charles, 1961].

Medicated salt project (Ghana 18), Bawku West: In August 1959, a collaborative WHO project (Ghana-18) was initiated in present day Bawku West district in Upper East region [Van der Kaay, 1960; Van der Kaay & Najera, 1962; Van der Kaay & Haller, 1962]. The project aimed to explore Pinotti's proposition that chloroquine medicated household salt could interrupt transmission as an alternative to Mass Drug Administration [Pinotti, 1953]. The target area covered 1000 km^2 and approximately 26,500 people. The first year involved establishing baseline transmission through parasitological and entomological surveys and a detailed investigation of salt consumption and sources of salt supply in the area. It was decided to use 30 mg chloroquine and 3.5 mg pyrimethamine as the suppressive combination in the average 5 gm salt consumption per person per day. Local salt wholesalers provided commercial salt to the project team who medicated and returned to wholesalers in re-sealed packets. A central indicator zone (Binaba) and remote peripheral areas (Namawgo, Lambari and Gode) were selected as parasite and vector surveillance sites, all seven schools were routinely visited and a system of passive case detection established. Bolgatanga, 20 km away, served as a control area. The trial ran from July 1961 to June 1962.

A large drop in parasite rates within two months, 59% to 5.7% among school children in intervention area and no change in control area, was observed but the trial was unable to maintain infection prevalence below 6% and sporozoite positive *An. gambiae* and *An. funestus* were detected throughout the trial period. Complaints included the bitter taste, the apparent fineness of the crushed medicated salt that blows away during the harmattan and the surreptitious use of non-medicated salt, 60% of households had non-medicated salt during a surprise visit in December 1961 [Van der Kaay & Haller, 1962].

3.4.2 Ghana 1 project

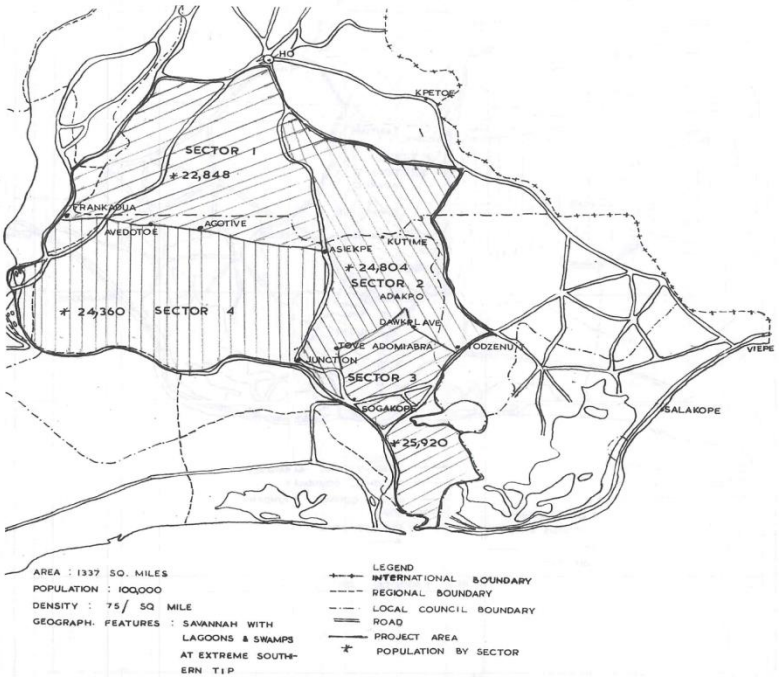
A wider collaboration between the MoH, UNICEF and the WHO began in February 1958 which initially focussed on the description of the epidemiology in the Volta Region (Tongu district, southern part of Ho district, a small part of Anlo district, Kpandu district, and the eastern part of Akwamu Anum Boso district) covering a total population of 100,000 people. The project focused on developing epidemiological data to develop plans for malaria eradication in the area based on combinations of chemoprophylaxis and IRS [Delfini & Beausoliel, 1964]. During 1959, however, *P. falciparum* pyrimethamine and chlorproguanil resistance and dieldrin resistance in *An. gambiae* were detected. It took several years to formulate a draft eradication plan submitted to the Ghanaian Government and AFRO in 1964 [Delfini & Beausoliel, 1964].

The final plan was signed in October 1964 [Kundicke & Beausoliel, 1965] and focused on efforts to increase access to anti-malarial drugs, building technical expertise in malaria reconnaissance and control, establish an epidemiological intelligence in the Volta region, after the construction of the Akosombo dam, and develop a country plan for malaria eradication [Beausoliel & Kundicke, 1965].

However, by 1967 this project came to an end and there is little evidence that a concerted malaria plan of action was ever developed or implemented. Activities continued only in support of reconnaissance (mainly at Akosombo) of the Volta Region DDT control project which used two rounds of spraying each year within a 5 km radius of the dam between 1965 and 1968, a trial of weekly administration of Lapudrine at Chawenu village near Ho, and invitations by mining companies to assess the malaria situation, for example the British Aluminium Company [Rickman & Beausoliel, 1967].

The malaria eradication experiments in Ghana, targeting primarily parasites, provided in some cases impressive findings on the impact on transmission. However, following the abandonment of the eradication goal in Africa after the recommendation of WHO in 1969, there was a general sense of disappointment and apathy, both globally and nationally, and was associated with a decline in resource allocation for malaria. By the mid-1960s ambitions for eradication had become less pronounced and as with a general global move, control became less specialized treatment of fevers. In Ghana this was directly evidenced through the recommendation of the Ghanaian Ministry of Health and WHO Advisors, Drs LJ Bruce-Chwatt and HJ Van Der Kaay, that the Ghana-1 eradication/pre-elimination project should become a project that aimed to build and strengthen basic health services in Ghana, known as the Ghana-3 WHO project [Anon, 1966].

Figure 3.4: Map of Ghana-1 project area [Delfini & Beausoliel, 1964]



In an interesting investigation during 1964, perhaps one of the first Knowledge Attitudes and Practices (KAP) surveys in Ghana, Trent examined beliefs and practices within 93 households in four sub-districts of Accra (Kaneshie, Nima, Tema and Usher Town) [Trent, 1965]. Most respondents knew malaria was a disease or illness, 25% had never heard of the word. Most thought that malaria was jaundice or a cold, 60% associated malaria with fevers. 35% linked malaria to mosquitoes and 12% associated malaria with poor weather conditions. 80% of respondents did nothing to protect their children from malaria of the remainder flitting rooms, use of mosquito coils, bed nets and occasionally IRS were mentioned, only one child received chemoprophylaxis. When asked what they did when their child had malaria, 42% said they would take child to hospital within 2-3 days and 52% said they would treat with aspirin at home. Trent concludes that "*training of the general public in the use of appropriate home treatment may be an effective control measure*" [Trent, 1965].

3.5 Malaria control 1970-1999

Urban malaria control (IRS and larval control) continued piece-meal through the late 1960s and early 1970s in Accra and Tema, however the extent of control was limited by the availability of funds and trained staff, transport and equipment and participation of the community [Chinery, 1968]. As population increased and shanty towns proliferated, urban malaria control became harder to manage through the early 1980s [Chinery, 1984; 1995]. Nevertheless, in January 1978, within the suburb of Ablekuma in Accra, only 1.4% of 417 residents had circulating malaria infections [Gardiner et al., 1984]. During this survey it was reported that 37% of respondents regularly treated themselves with chloroquine prophylactics to protect themselves against malaria, however, very few people protected themselves against mosquito bites including low use of bed nets [Gardiner et al., 1984].

During the 1980s, malaria had fallen off the health agenda of Ghana and there were no identifiable bi-lateral or multi-lateral supported "malaria" projects and no specific malaria strategy. In 1989, consultants, representing USAID (the only bilateral agency assisting the health sector at the time), came to Ghana to support the development of a new malaria plan of action [Lobel & Beier, 1989]. The primary objective of the plan was to reduce the mortality due to malaria through a national commitment, a clear rational strategy and strong intersectorial collaboration. The initial proposition was to include malaria control in USAID's family planning and child survival projects, notably through Primary Health Care, with an emphasis on ensuring prompt, effective treatment of malaria in high risk groups, maintaining surveillance of malaria treatment practices by monitoring the clinical and parasitological response to therapy and developing a stream of operational research.

In 1989, there was no national policy regarding the use of antimalarial drugs. The 1988 list of essential drugs included chloroquine, amodiaquine and quinine. Sulphadoxine-Pyrimethamine (Fansidar) was not listed as an antimalarial, but was given by health providers and used for self-medication for malaria. Mefloquine was also used for treatment. Chloroquine was imported as the raw product from several countries and formulated and marketed by some 15 to 20 producers, with no government-led quality assurance [Lobel & Beier, 1989]. There was no standardization of treatment regimens and no written treatment schedules at the MoH facilities and the health care providers. Self-medication was common [Adjei et al., 1988]. In 1985, a community-based survey covering 16 districts and 1,000 households per district, was undertaken with funds provided by UNICEF. The survey asked questions about the causes, treatment and prevention of malaria. The results showed that people's perceptions were that mosquitoes were not often associated with malaria (cleanliness and avoiding sunshine were often suggested as a means to avoid malaria), that chloroquine was used for treatment by almost 50% of recent fevers and most treated outside of formal health sector, especially in the rural areas [Adjei et al., 1988].

Widespread indiscriminate use and incomplete dosing of chloroquine was seen as a threat to a growing concern across Africa of rapidly emerging chloroquine-resistance. *In vitro* studies of chloroquine and mefloquine showed no evidence of reduced sensitivity against parasites taken from clinical patients at Agogo in 1983 [Hogerziel et al., 1985]. This changed rapidly. Between June and October 1988, *in vivo* studies were undertaken to examine the sensitivity of *P. falciparum* among 144 school children aged 6-15 years at three sites (Nima, Madina and Gomoa Fetteh) with only 72-89% of infections proving sensitive, the remaining infections showing RI and RII levels of resistance [Afari et al., 1989]. In March 1992, chloroquine was 100% sensitive at Prampram, a coastal savannah community, but reduced sensitivity to chloroquine was noted at Dodowa in the forest region (RII 15% and RI 1.4%); in both communities approxiately7% of individuals had evidence of chloroquine in their urine on cross-section [Nkrumah, 1993].

A study of local beliefs and practices at Dodowa and Prampram in 1995 revealed that caretakers of children recognized two types of fever *Asru/Atridi* and high fevers *Asraku/ Asratsutsu* which corresponded with biomedical definitions of malaria [Ahorlu et al., 1997]. Approximately 17% of households had a bed net but knowledge about malaria transmission involved several non-mosquito connections. Home treatment of malaria using over-the-counter drugs and inadequate doses of chloroquine was commonly reported. As with Trent's observations three decades earlier [Trent, 1965], the authors concluded that

"*malaria control policies should recognize the role of home treatment and drug shops in the management of malaria and incorporate them into existing control strategies*" [Ahorlu et al., 1997]. Chloroquine consumption continued to be high, during the national Demographic and Health Survey in 1998 over 60% of all paediatric fevers had been treated with chloroquine in the last two weeks, mostly from the informal sector [GSS, 1999].

In the development of the malaria plan of action for 1989 it was stated that there were no organized vector control operations in Ghana [Lobel & Beier, 1989]. It was further stated that sanitation and mosquito control was a local government and community responsibility. There were 1,544 MoH technical officers, ranging from the Chief Health Inspector to Health Inspection Assistants, trained in mosquito control, but vector control was not an MoH priority, and "*Personal protective measures, including screening of houses and the use of bed nets, pyrethrum mosquito coils and spray cans, are practiced in some urban and rural areas of Ghana. Secondary school children throughout the country are required to use mosquito nets in the boarding rooms. However, personal protective measures are not widely practiced because only 12 to 49 percent of the people are aware that mosquitoes are associated with malaria*" [Lobel & Beier, 1989].

During the 1990s, global efforts to control malaria were re-started. In 1992, a global malaria control strategy aimed at preventing mortality and reducing morbidity was adopted by the ministerial conference held in Amsterdam. This strategy was adopted by the World Health Assembly (WHA) in 1993 as the global strategy for malaria control [WHO, 1993].

A Malaria Action Plan for Ghana was finally developed and covered the period 1993-1997 [Ministry of Health, 1991]. The long-term objective of the 1993-1997 plan was to "*reduce the incidence of malaria to such low levels that it will cease to be a public health hazard*" and immediately show reductions in the incidence of malaria mortality and morbidity. The plan focuses on several approaches including increasing the knowledge and skills of health workers on malaria, strengthen capacities of health services to diagnose and treat malaria, increase community awareness and participation in malaria activities within primary care, make antimalarial drugs available and affordable to the general population, establish surveillance systems and determine the pattern and extent of malaria transmission in the country [MoH, 1991]. Emphasis was very much on the management of disease during the mid-1990s and included an accelerated action plan to integrate malaria case-management into community-based care in 30 districts from 1997. The 1993-1997 action plan did mention a long list of possible vector control approaches, including IRS and bed net use, together with several less evidence-based strategies such as outdoor space spraying [MoH, 1991]. The Malaria Control Programme, had a low visibility within the Ministry of Health during the mid-1990s being part of Primary Care Services under the Communicable Diseases Control unit. Through a re-organization of the health sector, vector control fell to environmental health with transferred responsibilities to local governments [Kondrachine & Teklehaimanot, 1994].

Following early exciting results of the clinical [Snow et al., 1988] and mortality [Alonso et al., 1991] protection afforded by insecticide treated nets (ITN) in The Gambia, the Tropical Diseases Research (TDR) Programme of the WHO launched four community randomized mortality trials in Africa, one of which was at the research centre in Navrongo, Kassena-

Nankana district between 1993 and 1995 [Binka et al. 1996]. Despite the impressive results shown at Navrongo ITN coverage in Ghana remained poor for another decade (Chapter 6).

In 1998, a Medium Term Strategic Plan for Malaria Control in Ghana (1998-2002) was launched and was intended to improve the coverage of malaria control activities nationwide through an "intersectoral approach" including the private sector and the community. There are few details on this strategy nor its achievements.

3.6 The Roll Back Malaria era 2000-2015

The Roll Back Malaria (RBM) initiative was launched in 1998 [Nabarro & Tayler, 1998] at a time when Africa was grappling with an unprecedented disease epidemic [Snow et al., 2012]. Increases in overseas development assistance, bilaterals and multilateral support including the establishment of the Global Fund in 2001, led to significant improvements in the numbers of vulnerable populations protected against malaria infection and who have access to medicines that effectively treat the disease [Snow & Marsh, 2010; WHO, 2012].

In Ghana, two malaria strategic plans were developed covering the periods 2000-2008 [NMCP, 2000] and then subsequently a revised plan covering the period 2008-2015 [NMCP, 2008]. The malaria control plans have been embedded within broader national health, development and poverty reduction strategies. Malaria as a national priority has gained significant prominence and political commitment. Most notable among its advocacy partners has been the involvement of Ghana's national football team, the Black Stars [UAM, 2013]. The current strategy has a goal of reducing the current malaria disease burden by 75% by the year 2015 and focuses on improving access and use of multiple prevention interventions, improving access to prompt and effective treatment, strengthening health systems at all levels, and creating and sustaining partnerships [NMCP, 2008].

The last decade of malaria control has been reviewed as part of the recently completed Malaria Performance Review [NMCP, 2013] and therefore the highlights are mentioned in brief here. The national plans became increasingly ambitious, setting higher vector control and case-management targets from 60% of vulnerable groups to universal coverage. These strategic plans also managed a time of a) failing monotherapy efficacy [Koram et al., 2005], that led to a difficult policy transition and implementation of ACTs, artesunate-amodiaquine, in 2007, that now includes in addition artemether-lumefanthrine and dihydroartemisinin-piperaquine as first line recommended drugs [MoH, 2009]; and b) a slow transition from a private sector emphasis on ITN delivery, through subsidized net delivery approaches to free-mass campaigns, the later only initiated nationwide, at-scale, from 2010 (Chapter 6). IRS has been slowly re-introduced into Ghana's malaria control strategy, after 50 years of neglect. Following IRS successes at the Obuasi gold mining concession in 2005, there has been an expansion of IRS across other northern districts from 2011 (Chapter 6). In 2008, 46% of pregnant women said they had taken two Intermittent Preventive Treatment (IPT) courses of sulphadoxine-pyrimethamine (SP) during their last pregnancy [GSS, 2009], rising to 65% by 2011 [GSS, 2012]. Improving access to ACTs, however, remains a significant challenge in Ghana, despite efforts to increase private sector engagement [Malm et al., 2013], pilot studies on home-based case-management [Ajayi et al., 2008] and efforts to

improve community awareness. In 2011, less than 20% of febrile children received an ACT [GSS, 2012].

In 2010, the Ghanaian NMCP participated in a global pilot to explore how to increase access to artemisinin-based combination treatments (ACT) in rural areas using the private sector as part of the Global Fund's Affordable Medicines for Malaria Facility (AMFm) project [Malm et al., 2013; Global Fund, 2012; Tougher et al., 2012]. The rationale to increase rural access to treatment, the branding with logos (Green Leaf), public awareness campaigns and affordable pricing were all features of improving drug access in 2010 [Malm et al., 2013]; not dissimilar to approaches taken during the 1930s [Section 3.2; Government of Gold Coast, 1936]. Both programmes were short-lived and neither continued as long-term national strategies.

By 2011, 96% of women could correctly define the symptoms of malaria and 86% knew that malaria was caused by mosquitoes [GSS, 2012]. During a survey in six districts in three regions in 2012, 93% of respondents identified mosquitoes as the cause of malaria [SPH, 2013]. This change in aetiological knowledge by the community is perhaps one of the most significant changes over the last 100 years in Ghana, with evidence in knowledge shifts since the 1990s [Adjei et al., 1988; Ahorlu et al., 1997; Agyepong & Manderson, 1999] and supported by detailed temporal studies of knowledge and behaviour in Kassena-Nankena district [Owusu-Agyei et al., 2007] .

No overseas development assistance (ODA) was provided for malaria control in the early 1990s [Lobel & Beier, 1989]. Virtually no ODA for malaria was available at the launch of RBM [Narasimhan & Attaran, 2003]. However, by 2010 ODA for malaria control had grown in Ghana to represent an average annual income US$ 53.6 million [Snow et al., 2010]. The 2008-2015 national malaria strategy has pledges from bilateral and multilateral partners, that includes US$ 158 million from the Global Fund and approximately US$ 17 million annually from the US President's Malaria Initiative [NMCP, 2013]. Without the significant increase in funding over the last ten years it would be hard to imagine the landscape of malaria control changing much from that described in the late 1990s.

The national malaria control programme is poised to develop a new strategy that will see malaria control defined for the decade post-2015. Despite the lack of precise national data on malaria morbidity and mortality, it seems unlikely that the malaria burden will have been reduced by 75% by 2015. The new strategy will require a stronger, evidence-based platforms to sustain continued ODA support and increase domestic financing. The following chapters serve to provide some of the basic epidemiological evidence necessary to design a revised malaria control plan and in the absence of a perfect, comprehensive health information system can be seen as a baseline estimate of infection/risk burden to assess progress over the coming years.

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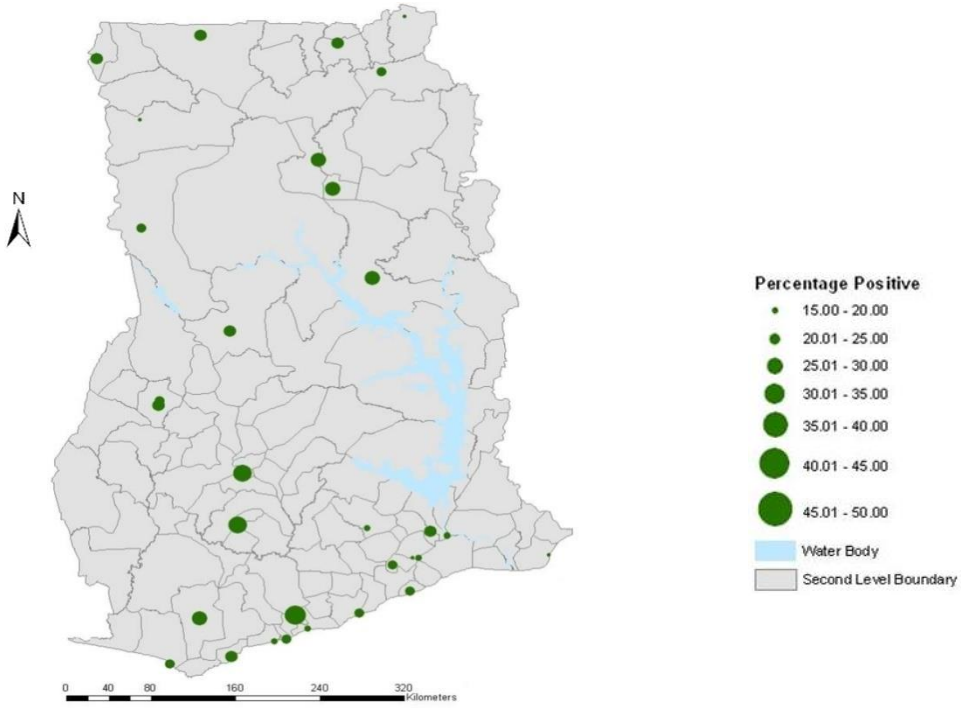
Chapter 4

Mapping malaria transmission intensity

4.1 Previous malaria map use in Ghana

There is no evidence of any national malaria risk maps for Ghana before independence, however, data were systematically collected by the colonial medical department on spleen rates [Government of Gold Coast, 1913; 1914]. Between 1913 and 1914 approximately 21,423 school children were examined at 32 sites across the country (Figure 4.1), showing wide variations in the rates of enlarged spleens but reaching levels of over 30% in many sites.

Figure 4.1: Results of combined survey location data on splenomegaly undertaken at schools between 1913 and 1914 by the Medical and Sanitary Department [Government of Gold Coast, 1913; 1914] redo districts



During the early 1950s there is reference to wide-scale parasitological surveys across Ghana, with a special emphasis on trypanosomiasis screening as part of concerted efforts to eliminate sleeping sickness [Waddy, 1956]. The medical technicians, that formed part of Medical Field Units in the Northern Territories, Ashanti and Southern Togoland, examined approximately 1000 people of all ages every five days reading slides and treating positives. These survey's included investigations of yaws, onchocociasis, yellow fever and malaria. Between 1951 and 1954, this general health survey covered 50% of the population living in the Northern Territories, 67% in Ashanti and 33% in Southern Togoland [Waddy, 1956]. The information generated from the human trypanosomiasis surveys were used to provide crude risk maps [Waddy, 1956], but no details were provided on malaria. The malaria data generated from village-to-village reconnaissance between 1951 and 1954 might still exist at government archives in Accra and should be investigated.

The WHO Ghana-1 project during the later 1950s and 1960s undertook large scale malaria reconnaissance surveys in order to develop a pre-eradication plan around the Volta region (Ghana-1 project) and in northern Ghana (Ghana-18 project) (Section 3.4.2). The data from these

surveys have never been fully assembled, despite some reports found in the WHO archives in Geneva. More importantly, the data were not used in any identifiable way by the WHO and the Ghanaian Ministry of Health to formulate a control plan.

As part of the plan of action for malaria control developed in collaboration with the USAID funded Vector Biology and Control Project in 1989, the lack of any systematic data across Ghana was highlighted as a major limitation to planning effective vector control "*The main aim of the epidemiological approach to malaria control is to develop a better understanding of the dynamics of malaria transmission and the risk of infection, illness and death, and to identify the methodologies for malaria control as part of the development of Primary Health Care. No reliable information is available on morbidity and mortality due to malaria in Ghana. Such information is needed to assess the impact of malaria control measures*" [Lobel & Beier, 1989].

The malaria plan of action that was eventually developed in 1991 states that "*up-to-date information required to plan control measures is to a great extent lacking*" [MoH, 1991]. The 1993-1997 malaria action plan defines the heterogeneity of malaria risk across Ghana based on ecological characteristics: a) tropical rainforest middle zone with 1250 to 2000 mm of annual rainfall in two major seasons with intense, perennial transmission (Ashanti, Brong Ahafo, Eastern, Central, Western and parts of mid Volta Regions) and representing an area not amenable to larviciding; b) coastal lagoons and mangrove swamps, transmission intense and perennial but with marked reductions during the dry season (Volta, Greater Accra, Central and Western Regions); c) Savannah - divided into coastal, with two acute seasonal patterns of transmission (lower Volta region, Accra Plains and parts of Central Region) and northern, with one single transmission peak (Upper East, Upper West, Northern, parts of Brong Ahafo and parts of Volta Regions); d) urban malaria zones, where IRS and fogging were not recommended but that the strategy recognized the changing epidemiology and unique features of urban settings for special control approaches, notably Accra, Kumasi, Ho, Tamale, Bolgantanga, Sunyani and Tarkwa; and finally e) areas under economic development requiring special attention - notably gold mines and open cast mines (Akwatia) and agricultural projects [MoH, 1991]. These were important narratives laying out the foundations of malaria risk across the country and some attempt to link this to specific control needs. However, the information was never empirically mapped.

During the early years of RBM, the NMCP began to spatially describe the variance in malaria across the country, based loosely on the ecological zones described in the 1991 malaria plan of action [Banda et al., 2004]. With the launch of the 2000-2010 national malaria strategy the only description of varying transmission ecology used as a context for the strategy was as follows: "*Malaria is hyper-endemic in Ghana with crude parasite rates ranging from 10 to 70%*" [NMCP, 2000]. There was no map or detailed description of the epidemiology of malaria across the country during the first, RBM national strategy, nor any evidence of spatially targeted control based on ecozones.

The first map ever to be use by national malaria control authorities in Ghana was provided in the national strategic plan 2008-2015 [NMCP, 2008]. The map accompanied a narrative on the basic malaria situation that prevailed across the country "*Malaria is hyperendemic in all parts of the*

country, with all the 22.4 million population at risk. Transmission occurs all year round with slight seasonal variations during the rainy season from April to July. The seasonal variation is marked in the northern parts of Ghana where there is a prolonged dry season from September to April" [NMCP, 2008]. The NMCP used the map developed in 2001 by the Mapping Malaria risk in Africa (MARA) project based on 450 parasite prevalence surveys undertaken between 1960 and 1999 from across West Africa among children aged below 10 years and used as the basis of a predictive model of *P. falciparum* prevalence using climate and ecological covariates within a linear regression model and krigging [Kleinschmidt et al., 2001; http://www.mara.org.za]. The input data to the model included only 24 survey locations in Ghana (Figure 4.2.a). The resulting model prediction is shown in Figure 4.2.b. This map was subsequently shown alongside a map highlighting districts to be targeted for IRS in the NMCPs' application to the Global Fund Round 8 in 2008 (Figure 4.2c) [Ghana CCM, 2008]. While not explicit in the application, the congruence with the high transmission areas in the MARA prevalence map (Figure 4.2b) suggests a degree of spatial targeting based on mapped model predictions. Other maps more recently used have attempted to quantify the ecological criteria (Northern Savannah, Tropical Forest, Coastal Savannah/Mangroves and urban development areas) in the National Integrated Vector Management Strategy in 2009 [NMCP, 2009] and the Malaria Programme Review in 2011 [NMCP, 2013].

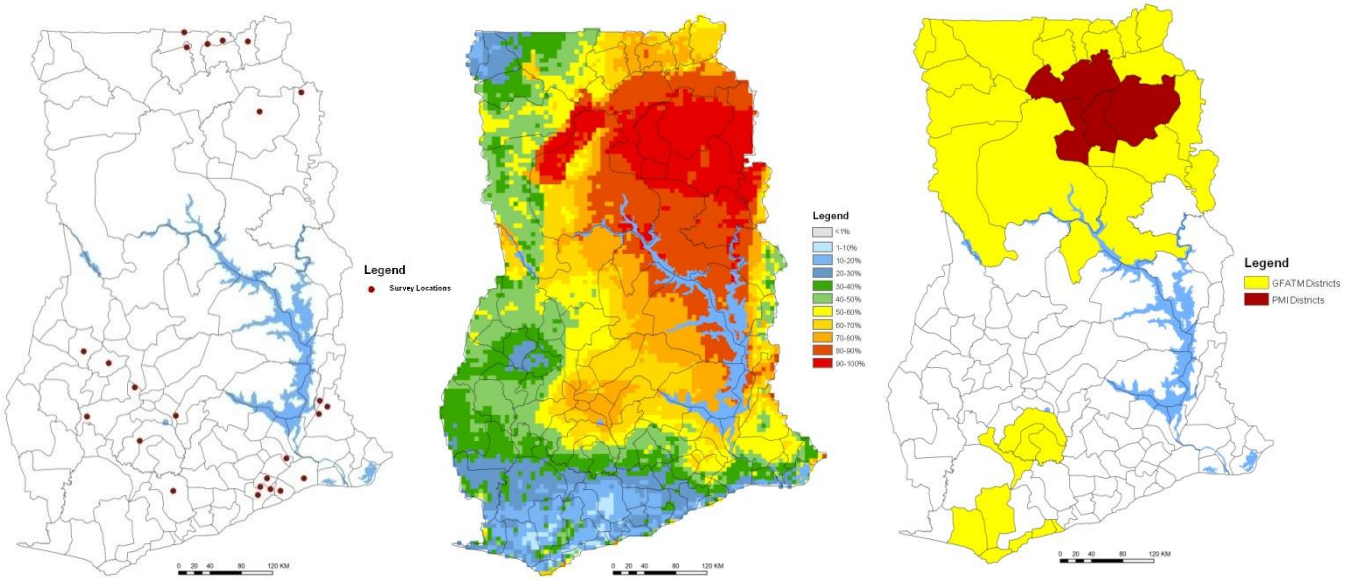
The MARA parasite prevalence prediction map has served as the main map of the intensity of malaria transmission used by the Ghanaian NMCP since the launch of RBM. Twelve years ago, when this map was developed, this was a revolutionary product but the field of Model Based Geostatistics (MBG) has evolved, Bayesian approaches are now preferred for infectious disease mapping and there has been a growth in available data to model the risks of malaria in time and space in Ghana.

Other maps that have been developed and available to the NMCP since 2000 include maps developed under the Malaria Atlas Project (MAP) initiative based on parasite prevalence data from 122 time-space locations surveyed between 1988 and 2007 using Bayesian methods with the inclusion of 14 covariates (urban, peri-urban, a temperature suitability index, land surface temperature (six variants), precipitation (six variants) and normalized difference vegetation index (NDVI, two variants) (Figure 4.3) [Gething et al., 2011a; www.map.ox.ac.uk]. The model depended heavily on over-fitted covariates and the pre-processing of remotely sensed data in this model did not exclude cloud cover anomalies leading to poor predictions along the coast-line.

In this chapter, we provide details of an extensive data assembly exercise and a robust Model Based Geostatistical (MBG) Bayesian method to provide malaria risk outputs, where information is summarized at district-levels to allow the national programme authorities to plan based on epidemiology at decision-making units linked to its decentralized health policy (Section 2.4).

Figure 4.2: a) 22 Ghanaian survey locations included in the MARA predictive model of parasite prevalence; b) model predictions of parasite prevalence in children aged less than 10 years (see footnote); c) map shown in Global fund application against malaria transmission intensity to highlight IRS districts.

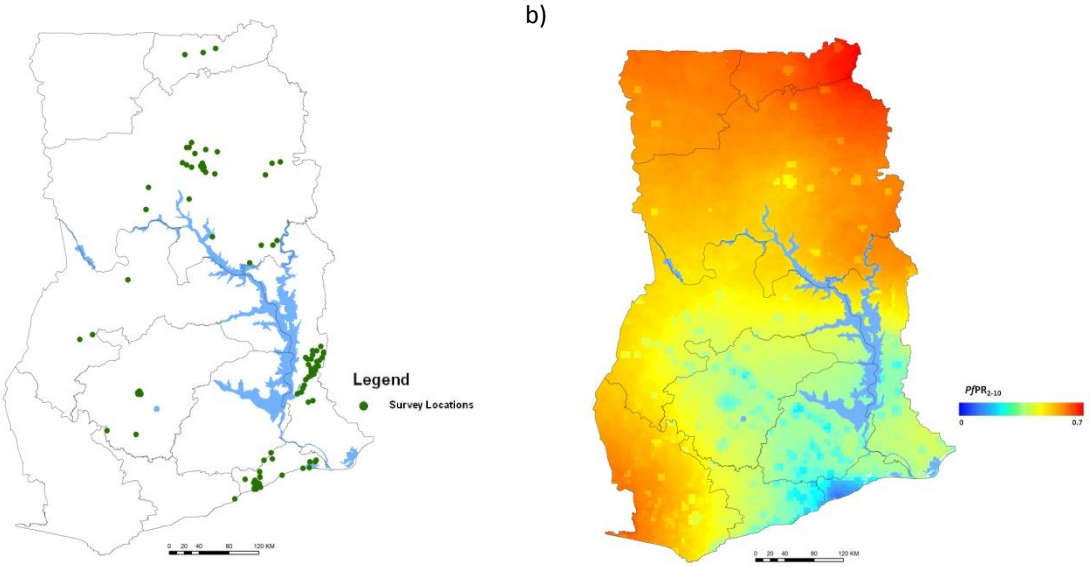
a) b) c)



Footnotes: The model used a series of climatic and ecological covariates to train the predictions of prevalence from sparse data including long-term monthly average rainfall, minimum and maximum temperature, remotely sensed satellite imagery of vegetation indices, soil drainage capacity and population density. The data were partitioned according to ecological zones used by the Food & Agricultural Organization (FAO) for crop potential: Equatorial Forest, (> 270 days of rainfall), Guinea Savannah zone (165-270 days of rainfall), and a combined Sudan and Sahel Savannah zone (less than 165 days of rainfall). The models were developed for each ecological zone using regression techniques (Generalized Linear models with logit functions) with the parasite prevalence as the dependent variable. The optimized model was then used to predict malaria prevalence among children aged less than 10 years at un-sampled 5x5 km grid squares and smoothed using a process of krigging.

Figure 4.3: a) Location of 122 survey estimates of parasite prevalence used in the MAP model to predict parasite prevalence to 2010 shown in panel b)

a) b)



4.2 Malaria parasite prevalence data assembly, modelling and risk mapping

The clinical epidemiology [Snow & Marsh, 2002], the impact of vector control [Killeen et al., 2007; Smith et al., 2009; Griffin et al., 2010], cost-effectiveness of treatment and prevention interventions [Okell et al., 2012] and timelines to malaria elimination [Cohen et al., 2010] are all dependent on pre-control, parasite transmission intensity. There was a recognition over 50 years ago that one important source of planning data was infection prevalence among children aged 2-10 years (*Pf*PR_{2-10}), used to define categories of endemic risk designed to guide and monitor progress toward malaria elimination targets [Metselaar & van Thiel, 1959; Macdonald & Göeckel, 1964; Lysenko & Semashko, 1968].

The following sections provide a detailed description of how empirical parasite prevalence data were assembled, geo-positioned and pre-processed. This description should serve as a meta-data for the final database of contemporary parasite prevalence data in Ghana; and therefore a reference source to the final curated database. The following sections provide the details on how these data were modeled to provide district level estimates of malaria risk. These data are then used to provide population-adjusted estimates of risk by district. We also describe, where possible, the distribution of parasite species in Ghana. Finally, given the importance of seasonality, urbanization and economic activity areas to previous NMCP malaria descriptions [MoH, 1991], we revisit maps of these features for planning specialized control in these target areas.

4.2.1 Parasite prevalence data search strategy

Electronic data searches: Online electronic databases were used as one means for identifying peer-reviewed, published data on malaria infection prevalence. Due to its wide coverage of the biomedical literature, PubMed [http://www.ncbi.nlm.nih.gov/sites/entrez] was used as the basis for all the initial online searches of published sources. In addition, we used the Armed Forces Pest Management Board – Literature Retrieval System [http://www.afpmb.org/publications.htm]; The World Health Organization Library Database [http://www.who.int/library]; the Institute de Recherché pour le Development on-line digital library service [http://www.ird.fr]; and African Journals Online (AJOL) [http://www.ajol.info]. In all digital electronic database searches for published work the free text keywords "*malaria*" and "*Ghana*" were used. We avoided using specialised Medical Subject Headings (MeSH) terms in digital archive searches to ensure as wide as possible search inclusion. The last complete digital library search was undertaken in August 2013.

Titles and abstracts from digital searches were used to identify possible parasite cross-sectional survey data undertaken since January 1980 in a variety of forms: either as community surveys, school surveys, other parasite screening methods or intervention trials. We also investigated studies of the prevalence of conditions associated with malaria when presented as part of investigations of anaemia, haemoglobinopathies, blood transfusion or nutritional status to identify coincidental reporting of malaria prevalence. In addition, it was common practice during early antimalarial drug sensitivity protocols to screen community members or school attendees to recruit infected individuals into post-treatment follow-up surveys, often data from the survey sites

present the numbers screened and positive. Surveys of febrile populations or those attending clinics were excluded.

Publications with titles or abstracts suggestive of possible parasite data were either downloaded from journal archives where these have been made Open Access (OA) or sourced from HINARI [http://www.who.int/hinari]. If publications were not available OA from HINARI we visited UK library archives at the London School of Hygiene and Tropical Medicine, the Liverpool School of Tropical Medicine and the Bodleian library at the University of Oxford. References not found following these searches were requested using world catalogue searches through the Oxford libraries at a per-page cost. All publications from which data were extracted were cross referenced using the bibliographies for additional sources that may have been missed or that may correspond to unpublished or 'grey' literature (i.e. not controlled by commercial publishers). In addition, tropical medicine and malaria meeting abstract books were identified from as many sources as possible produced as part of national and international conferences and congresses. These were used to signal possible data that were followed up through correspondence with abstract authors.

Unpublished archived survey reports: We undertook manual searches of archives at the World Health Organization (WHO) libraries in Geneva and Brazzaville at separate archive locations as Project, Country and Parasitology Department files. As part of the RBM monitoring and evaluation initiative national, household surveys were resurrected as a means to monitor country-level progress [RBM-MERG; Corsi et al., 2012]. These surveys were initially embedded in the DHS as a malaria module and were largely focussed on intervention coverage measures until 2005 when it was agreed to include malaria infection prevalence into survey protocols. The only national household survey to include biomarkers of malaria infection in Ghana was undertaken as part of the Multiple Indicator Cluster Survey (MICS4) in 2011. As a result of the generous help provided by the Ghana Statistical Service it was also possible to assemble a large volume of unpublished data from this national survey [GSS, 2012].

We contacted malaria scientists based in Ghana many of whom generously provided unpublished, raw data from study sites, districts and regions for investigations of malaria they were involved with(all acknowledged at the beginning of this report).

Search completeness: Our data searches have not used systematic, traditional evidence review strategies. These would have missed many unpublished sources of information. Rather, our strategy has used a cascaded, opportunistic approach. Authors of peer-reviewed papers were often asked about additional information within their paper and directions to other possible unpublished work in their geographic area or from their institution. Importantly, there are likely to be many post-graduate theses undertaken by students of the faculties of parasitology, public health and medicine in Ghana have not been adequately searched. An unpublished conference proceeding abstract indicated that during the late 1990s a large-scale micronutrient and anaemia survey was carried out at sampled clusters across 28 districts of Ghana that included the measurement of malaria infection in sampled young children [Quarshie & Amoaful, 1998]. Despite repeated efforts to establish the location of these cluster-level data we have not been successful.

4.2.2 Data abstraction

The minimum required data fields for each record were: description of the study area (name, administrative divisions), the start and end dates of the survey (month and year) and information about blood examination (number of individuals tested, number positive for *Plasmodium* infections by species), the methods used to detect infection (microscopy, Rapid Diagnostic Tests (RDTs), Polymerase Chain Reaction (PCR) or combinations) and the lowest and highest age in the surveyed population. Given its ubiquity as a means for malaria diagnosis, the preferred parasite detection method was microscopy. No differentiation was made between light and fluorescent microscopy. The quality of slide reading [O'Meara et al., 2006; Gitonga et al., 2012], variations in sensitivity/specificity between RDTs [WHO-FIND, 2012] or the ability of field teams to reliably read RDTs [Rennie et al. 2007; Harvey et al., 2008] and selection of primers for PCR [Okell et al., 2009] all influence descriptions of prevalence and will have intrinsic variance between surveys included in the database. RDTs have been shown to yield higher false positive rates than microscopy [Endeshaw et al., 2008; Keating et al., 2009] but seem to stratify both the lowest (<1% parasite rate) and highest (>50% parasite rate) more accurately compared to microscopy [Gitonga et al., 2012].

Data derived from randomized controlled intervention trials, were only selected when described for baseline/ pre-intervention and subsequent follow-up cross-sectional surveys among control populations. When cohorts of individuals were surveyed repeatedly in time we endeavoured to include only the first survey and subsequent surveys if these were separated by at least five months from the initial survey to avoid a dependence between observations based on treatment of preceding infected individuals. If it was not possible to disaggregate repeat surveys these were finally excluded from the analysis. Where age was not specified in the report for each survey but stated that the entire village or primary school children were examined we assumed age ranges to be 0-99 years or 5-14 years respectively. Occasionally, reports presented the total numbers of people examined across a number of villages and only the percentage positive per village; here we assumed the denominator per village to be equivalent to the total examined divided by the total number of villages. Some survey results were reported as an aggregate in space (e.g. a single *Pf*PR for a group of villages) or time (e.g. a mean *Pf*PR estimated from four different surveys conducted over time). In such cases, we either sought additional reports of the same surveys with higher spatial or temporal resolution. Where this was not possible and where clusters of villages exceeded 5 km^2 we excluded the record from the analysis (see below). Where additional information to provide unique time, village specific data was necessary we contacted authors to provide any missing information.

4.2.3 Data geo-coding

Data geo-coding, defining a decimal longitude and latitude for each survey location, was a particularly demanding task. This was especially labour intensive for the MICS4 survey data which provided location names but no Global Positioning System (GPS) coordinates. According to their spatial representation, data were classified as individual villages, communities or schools or a collection of communities within a definable area, corresponding to an area within 5 km grid or

approximately 0.05 decimal degrees at the equator. Where possible we aimed to retain disaggregated village, "point" level data rather than data across a "wide-area". Where data were reported across communities that exceeded at 5 km grid we regarded these as too low a spatial resolution, with significant possible variation within the polygon of information to be included within the modeling phase. In practice, this was a difficult criterion to audit as most survey reports did not provide enough detail on the size of the area surveyed. More recent use of GPS during survey work does enable a re-aggregation of household survey data with greater precision and useful in maintaining 5 km grid criteria while combining clusters of small sample sizes in space. To position each survey location where GPS coordinates were not available in space we used a variety of digital resources, amongst which the most useful were Microsoft Encarta Encyclopedia (Microsoft, 2004) and Google Earth (Google, 2009). Other sources of digital place name archives routinely used included GEOnet Names Server of the National Geospatial-Intelligence Agency, USA [http://www.earth-info.nga.mil/gns/html/cntry_files.html]; Falling Rain Genomics' Global Gazetteer [http://www.fallingrain.com]; and Alexandria Digital Library prepared by University of California, USA [http://www.alexandria.ucsb.edu]. In addition we used digital place name gazetteers developed for various Ghanaian government ministries including a village data set [http://www.diva-gis.org/datadown], a national geo-coded health facility database [http://data.gov.gh/dataset/health-facility-ghana-1] and population census fourth level administration digital shape file [GSS, 2012].

Although standard nomenclatures and unique naming strategies are attempted in digital gazetteers [Hill, 2000], these are difficult to achieve at national levels where spellings change between authors, overtime and where the same names are replicated across different places in the country. As such, during the data extraction, each data point was recorded with as much geographic information from the source as possible and this was used during the geo-positioning, for example checking the geo-coding placed the survey location in the administrative units described in the report or corresponded to other details in the report on distance to rivers or towns when displayed on Google Earth. While in theory GPS coordinates should represent an unambiguous spatial location, these required careful re-checking to ensure that the survey location matched the GPS coordinates. As routine we therefore rechecked all GPS data from all sources using place names and/or Google Earth to ensure coordinates were located on communities.

All coordinates were subject to a final check using second level administrative boundary Global Administrative Units Layers (GAUL) spatial database developed and revised in 2008 by Food and Agriculture Organization (FAO) of the United Nations [FAO, 2008]. The Global lakes and Wetlands (GLWD) database developed by the World Wildlife Fund [Lehner & Doll, 2004] was used to ensure inland points were within defined land area. Here we aimed to identify survey coordinates that fell slightly off the coastline, located on rivers or in incorrect administrative units, every anomaly was re-checked and re-positioned using small shifts in combination with Google Earth.

4.2.4 Database fidelity checks, exclusions and pre-processing

Data checks: The entire database was first checked with a series of simple range-check constraint queries to identify potential errors that could have occurred during data entry. These queries assessed all data fields relevant to modelling for missing or inconsistent information. The final objective was to check for any duplicates introduced during the iterative data assembly process. Pairs of survey sites found within 1 km or within five months at the same location were identified. These may have been entered erroneously into the data assembly where multiple reviewed reports describing similar data. These were listed, checked and duplicates removed.

Data exclusions: The search strategy identified 504 time-survey locations where malaria infection prevalence had been recorded between August 1982 and December 2012. This final data series was then subjected to various exclusion rules as defined below.

> *Location details*: Despite repeated efforts and multiple on-line digital gazetteers, national resources and personal communications we were unable to identify with sufficient precision the geo-coordinates for 44 survey data points at 44 unique locations sampled during the 2011 MICS4 survey.
>
> *Ensuring sample precision*: Sample size is inversely related to prevalence where, at low sample sizes, biases in prevalence estimates are introduced, dependent on the true prevalence of the population and translates into large standard errors [Gregory & Blackburn, 1991]. There is a critical threshold of between 10 and 20 individuals sampled below which the standard error increases exponentially in most surveys of parasitic infections and the curve starts to flatten at a sample size of about 50 and reaches an asymptote at about 100 [Jovani & Tella, 2006]. The sample size of individual survey samples is also important in the derivation of correlations with covariates of endemicity, in testing plausible associations between say rainfall and prevalence during covariate selection small, imprecise samples can lead to over-fitting (Section 4.3.2). We aimed to combine communities in close proximity where any village had less than 15 people sampled and where communities were within 5 km of each other, sampled at exactly the same time by the same investigators. Using these criteria we were unable to merge data from 92 time-space locations and these were excluded from the final analysis. All small sample size survey data points were part of the Ghana MICS4 survey as this was not powered to detected cluster level infection prevalence.

The final database contained 368 temporally unique data points at 342 survey locations between 1982 and 2011. These data were unevenly distributed through time and in space. Importantly, only 19 survey data points at 15 locations were available for the period 1982-1999. The paucity of data before 2000 limits our ability to generate a baseline, pre-RBM map for Ghana and therefore we analyze, predict and report only for the year 2010.

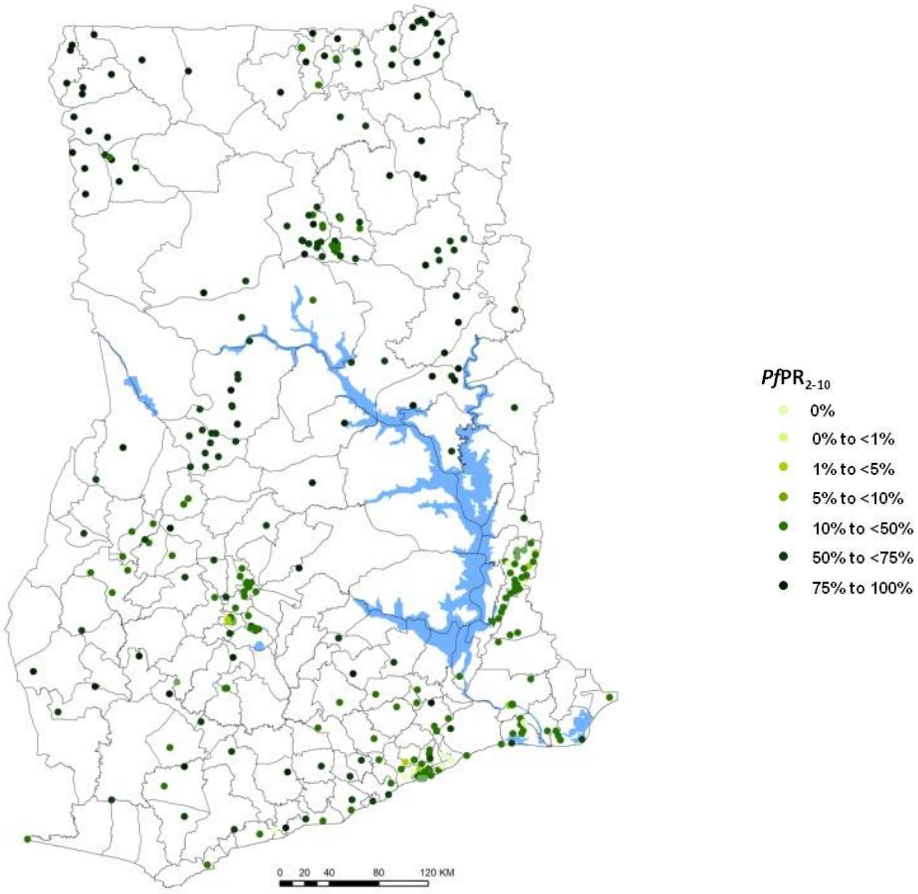
4.2.5 Age standardization

There was a large diversity among studies in the age ranges of sampled populations. To make any meaningful comparisons in time and space, a single standardized age range is required. Correction to a standard age for *P. falciparum* is possible based on the observation and theory of infectious diseases where partial immunity is acquired following repeated exposure from birth. We have retained the classical age range of 2-10 years as this best describes the exposure to infection among semi-immune hosts at any given location and conforms to classifications established in the 1950s [Metselaar & Van Thiel, 1959]. We have adapted catalytic conversion Muench models, first used in malaria by Pull & Grab (1974), into static equations in R-script that uses the lower and upper range of the sample and the overall prevalence to transform into a predicted estimate in children aged 2-10 years, $Pf\mathrm{PR}_{2\text{-}10}$ [Smith et al*.,* 2007].

4.2.6 Parasite prevalence data summaries

The overall spatial distribution of $Pf\mathrm{PR}_{2\text{-}10}$ data is shown in Figure 4.4. Of the 368 unique time-space 2000-2011 survey locations identified through the data search strategy described above, 300 (82%) were identified from unpublished sources including the 185 survey locations from the MICS4 2011 survey; three (0.8%) were sourced from other unpublished reports and 65 (17%) were directly abstracted from journals. We did not make assumptions about sample size for any of the survey data as these were provided in the reports or databases available to us. Survey data were located for time-space survey data points using GPS (46, 12.5%), Encarta (37, 10%), Google Earth (14, 4%), GeoNames (2, 0.5%), other digital place names sources, e.g. schools and village databases (236, 64%), and coordinates provided by individual scientists for which sources were not certain (33, 9%). Of the time-space survey data, infection was recorded in 179 (49%) using microscopy alone and 189 (51%) used RDTs (Hexagon Malaria Immunochromatographic; PAN *Pf*).

Figure 4.4 Data distribution of age-corrected *Pf*PR$_{2-10}$ estimates in six categories: <1%, 1-4%, 5-9%, 10-49%, 50-74.9%, >=75% from 368 surveys at 342 unique locations



4.3 Model Based Geostatistical (MBG) modelling of age-corrected parasite prevalence

4.3.1 Model form

MBG methods interpolate from observed measures of interest of known locations in space and time to provide predictions of quantities and the empirical estimates of their uncertainty at locations and times where data do not exist [Diggle & Ribeiro, 2007]. MBG methods fit the data where the spatial and temporal covariance is used to generate samples of the predicted posterior distribution from which point estimates and the uncertainty around these estimates are computed simultaneously using Bayesian inference [Chilés & Delfiner, 1999; Diggle et al., 2002].

Data were used within a Bayesian hierarchical space-time model, implemented through an adapted Stochastic Partial Differential Equations (SPDE) approach using Integrated Nested Laplace Approximations (INLA)[3] for inference [Rue et al., 2009; Cameletti et al., 2012] to produce

[3] Markov Chain Monte Carlo (MCMC) algorithms, although widely used in Bayesian inference in disease mapping, suffer from convergence and dense covariance matrices that increase computational time and cost significantly [Rue et al., 2009]. Integrated Nested Laplace Approximations (INLA) are alternative algorithms with faster computational speeds and can be undertaken in open source, easily adaptable R packages [R-INLA, project].

predictions of *Pf*PR_{2-10}. In the SPDE approach, the overall hierarchical space-time binomial model of the parasite prevalence was represented as the realization of a spatial-temporal process of the observed *Pf*PR_{2-10} at the community location and survey year, selected covariates at sampled locations, the coefficient vector and the measurement error defined by the Gaussian white noise process. The realization of state process or the unobserved level of *Pf*PR_{2-10} is defined by a spatial-temporal Gaussian field that changes temporally as a second-order autoregressive function. The space-time covariance matrix informs the spatial range and temporal lag of the prediction model for each tile such that observations have decreasing effect on the predictions at a given location the more distal in space and time they are to that location. Outside of the spatial and temporal range the autocorrelation of the contribution data becomes almost null. Continuous predictions of *Pf*PR_{2-10} at 1×1 km spatial resolutions for the year 2010 were made using the first and second data time-series. Full details of the model and prediction accuracies are provided in Annex A.1.

4.3.2 Selection of covariates

In statistical modelling, a set of independent covariates of the main outcome measure is often used to improve the model fit and increase the precision of predicted estimates. The inclusion of these covariates increase model complexity and, if not carefully selected, risk over-fitting (using up too many degrees of freedom), which occurs when more terms or covariates than is necessary are used in the model fitting process [Babyak, 2004; Murtaugh, 2009]. Over-fitting can lead to poor quality predictions because coefficients fitted to these covariates add random variations to subsequent predictions and make replication of findings difficult [Babyak, 2004]. Where too many covariates are used, the model tends to produce highly fluctuating regression coefficients increasing the chances of large covariate coefficients and an overly optimistic fit, especially with small sample sizes of empirical. This problem can be particularly pronounced when data assembled are from observational studies based on different study designs, sampling considerations and sample sizes which are then combined to describe a random process [Craig et al., 2007].

The choice of covariates should be underpinned by the principle of parsimony (few strong and easily interpretable covariates) and plausibility (a clearly understood mechanism by which the covariate influences the outcome). In disease mapping there must a pre-determined aetiological explanation of the relationship of the disease and the covariate under consideration. The determinants of malaria transmission are climatic (rainfall and temperature), ecological (potential breeding sites and urbanisation) and control interventions (anti-vector and ant-parasitic measures) [Molineaux, 1988; Snow & Gilles, 2002]. These factors affect the development and survival of the *P. falciparum* parasite and the malaria-transmitting *Anopheles* vector thereby reducing the risks of infection.

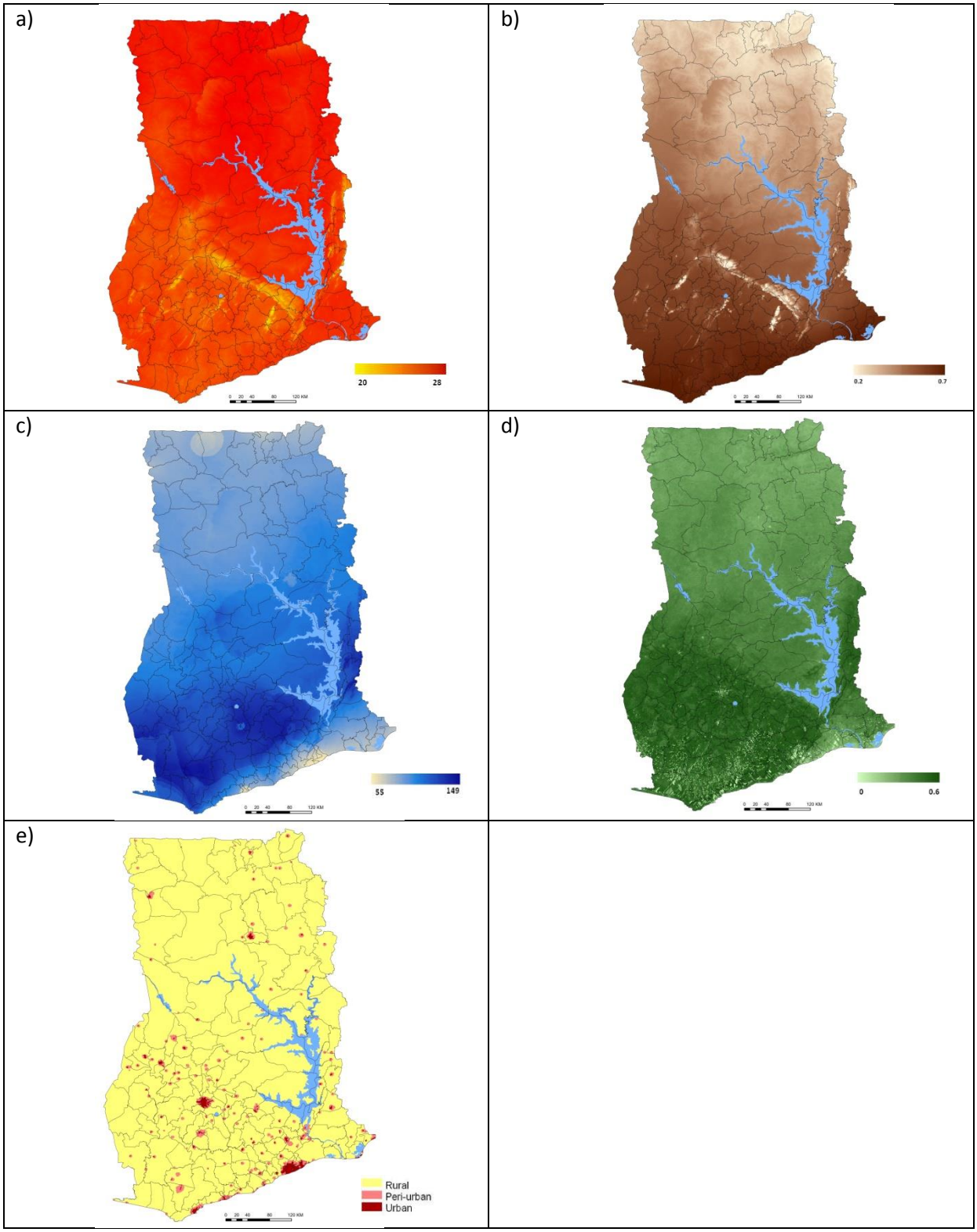
Temperature: Temperature plays a key role in determining the transmission of human malaria [Lunde et al., 2013; Beck-Johnson et al., 2013]. Laboratory experiments have shown that high temperatures (> 34 ^{o}C) lead to almost 100% larval mortality and at lower temperatures (< 16 ^{o}C) they were unable to produce viable adults [Bayoh & Lindsay 2003; 2004]. The mortality of the anopheles mosquitoes also increase sharply at ambient temperatures approaching 40 °C

[Muirhead-Thompson, 1951; Kirby & Lindsay 2004]. Temperatures of between 25°C and 30°C are considered optimum for *P. falciparum* sporogony [Molineaux, 1988]. It is on the basis of these biological relationships that we have assembled two temperature metrics in order to test their statistical relationships with *Pf*$PR_{2\text{-}10}$. These were: annual mean temperatures, and a biologically modeled temperature suitability index (TSI). The annual mean temperature surface was developed from monthly average temperature raster surfaces at 1×1 km resolution which were downloaded from the WorldClim website [http://www.worldclim.org]. These surfaces were produced from global weather station temperature records gathered from a variety of sources for the period 1950-2000 and interpolated using a thin-plate smoothing spline algorithm, with altitude as a covariate, to produce a continuous global surface [Hijmans et al., 2005; Figure 4.4a]. TSI was developed as a quantitative value of optimal *P. falciparum* sporozoite development [Gething et al. 2011b]. The TSI model uses a biological framework based on the survival of vectors and the fluctuating monthly ambient temperature effects on the duration of sporogony that must be completed within the lifetime of a single generation of Anophelines. The TSI is constructed using long-term monthly temperature time series [Hijmans et al., 2005] and represented on a scale of increasing transmission suitability, from 0 (unsuitable) to 1 (most suitable) (Figure 4.4b).

Proxies of suitable conditions for larval development (precipitation and vegetation): Rainfall, combined with suitable ambient temperatures, provides potential breeding environments for *Anopheles* vectors while humidity is associated with vector longevity. Normally, proxies of rainfall such as precipitation and vegetation are used in malaria risk predictions [Schalermann et al., 2008]. This is because actual rainfall data, typically collected from weather stations, are sparse throughout Africa [Hijmans et al., 2005]. Monthly mean precipitation raster surfaces at 1 × 1 km resolution were downloaded from the WorldClim website [http://www.worldclim.org/] and used as a proxy for rainfall compiled over a similar period and weather as for mean temperature surfaces [Hijmans et al., 2005; Figure 4.4c].

These monthly surfaces were summed to generate a synoptic annual mean precipitation surface and re-sampled 5x5 km resolutions. For vegetation, Fourier–processed enhanced vegetation index (EVI), derived from the MODerate-resolution Imaging Spectroradiometer (MODIS) sensor imagery and available at approximately 1×1 km spatial resolution [Scharlemann et al., 2008] was used to develop an annual mean EVI surface. EVI is an index of intensity of photosynthetic activity and ranges from 0 (no vegetation) to 1 (complete vegetation) (Figure 4.4d). EVI, compared to the more commonly used Normalised Difference Vegetation Index (NDVI), is developed from satellite imagery of higher spatial and spectral resolution and corrects for some distortions in the reflected light caused by the particles in the air as well as the ground cover below the vegetation [NASA].

Figure 4.5: Climate and environmental covariates tested for Ghanaian malaria prevalence model: a) mean ambient air temperature; b) Temperature Suitability Index; c) precipitation; d) EVI; e) urbanisation



Urbanization: The availability of optimum environments for the development of the malaria transmitting anopheline populations become limited in urban areas resulting in reduced vector density, biting rates and transmission intensity. Overall malaria infection rates are lower in urban compared to rural areas of Africa [Hay et al., 2005]. This has been well described across several urban extents in Ghana [Roland et al., 2006; Klinkenberg et al., 2006; Pond et al., 2013]. To develop a consistently defined surface of urbanisation, information from the Global Rural Urban Mapping Project (GRUMP) [Balk et al*.,* 2006] and the Afripop project [www.AfriPop.org; Linard et al., 2012] was used (Section 2.8). Urban areas were defined as locations with a density of more than 1000 persons per km^2 with the rest of the GRUMP urban extent defined as peri-urban (Figure 4.4e).

Pre-processing covariate grids: There were internal and coastline spatial mismatches between the various assembled raster grid covariates due to the various geographic idiosyncrasies and projection problems of the source data. A process of carefully rectifying these spatial shifts was undertaken before the covariates selection process began to minimise any potential errors. The population surface was used as the template for correcting the distortions because it had a much closer match with the defined national administrative boundaries. Reconciliations were undertaken using the *Raster-to-Point Conversion* Tool in ArcGIS 10.1 (ESRI Inc., USA) and overlaid exactly on the template grid using the *shift* tool in ArcGIS 10.1.

Statistical selection process of covariates: To begin the covariate selection process the values of the assembled covariates were extracted to each *Pf*PR_{2-10} survey location using ArcGIS 10 *Spatial Analyst* (ESRI Inc. NY, USA) tool. A correlation test was then undertaken to examine variable that were highly correlated (>0.85). Where two covariates had correlation >0.85, the aim was to select the one with the highest Bayesian Inference Criteria (BIC) for inclusion in the bootstrap and total set analysis using the results of a bivariate regression analysis (Table 4.1). Using total-set analysis, the *bestglm* algorithm selected the covariates resulting best-fit model and displayed these together with their coefficients, 95% CI and P-values.

The relationship of *Pf*PR_{2-10} with TSI, EVI, precipitation and urbanisation (combined urban and peri-urban classes) were all tested and analysis showed that only two covariates, TSI and urbanisation, contributed significantly to the variation in *Pf*$PR_{2-10}$and comprised the best fit model (Table 4.1)

Table 4.1 The results of the bivariate generalised linear regression models of *Pf*PR_{2-10} and the climatic and ecological covariates

	Coefficient	95% Confidence Interval	P-value	BIC
TSI	-1.772	(-2.0927, -1.4511)	<0.001	-984.5935
Urbanization	-0.209	(-0.2635, -0.1537)	<0.001	

4.4 Model predictions and populations at risk

We used the data from the age-corrected infection prevalence surveys (sample size, adjusted numbers positive) at known locations (longitude and latitude) and times (month and year) the

minimal set of long-term climate and human settlement covariates within the Bayesian hierarchical space-time model, implemented through SPDE INLA for inference using a super-computing facility established in Kilifi, Kenya for proteomic analysis. The model took approximately 11 days to run and was repeated to provide precision metrics. The continuous predictions of mean *Pf*PR_{2-10} at each 1 x 1 km grid for 2010 is shown in Figure 4.5a.

The continuous *Pf*PR_{2-10} maps were then classified into adapted traditional endemicity classes and generated by computing the posterior probability of belonging to a range of *Pf*PR_{2-10} from the posterior marginal distribution of the predictions at each 1 x 1 km grid:

- **Low stable endemic control**: areas supporting predicted *Pf*PR_{2-10} <1% which represent a pre-elimination transitional state [Cohen et al., 2010]

- **Hypoendemic 1**: areas supporting predicted *Pf*PR_{2-10} 1-<5%, separated from the below hypoendemic class to be able to distinguish finer resolution changes with time

- **Hypoendemic 2**: areas supporting predicted *Pf*PR_{2-10} 5-<10%

- **Mesoendemic**: areas supporting predicted *Pf*PR_{2-10} 10%-50%

- **Hyperendemic**: areas supporting predicted *Pf*PR_{2-10} >50%-74%

- **Holoendemic**: areas supporting predicted *Pf*PR_{2-10} ≥75%

The final re-classified endemicity risks are shown for 2010 in Figure 4.5b.

This newly edited population grid was then used to extract populations at risk by health district at each 1 × 1 km *Pf*PR_{2-10} grid location classified by predicted malaria risk class using the *Zonal Statistics* function in ArcGIS 10.1. The population totals (%) within each risk class for 2010 for each of the 170 districts are shown in Annex A2 Tables.

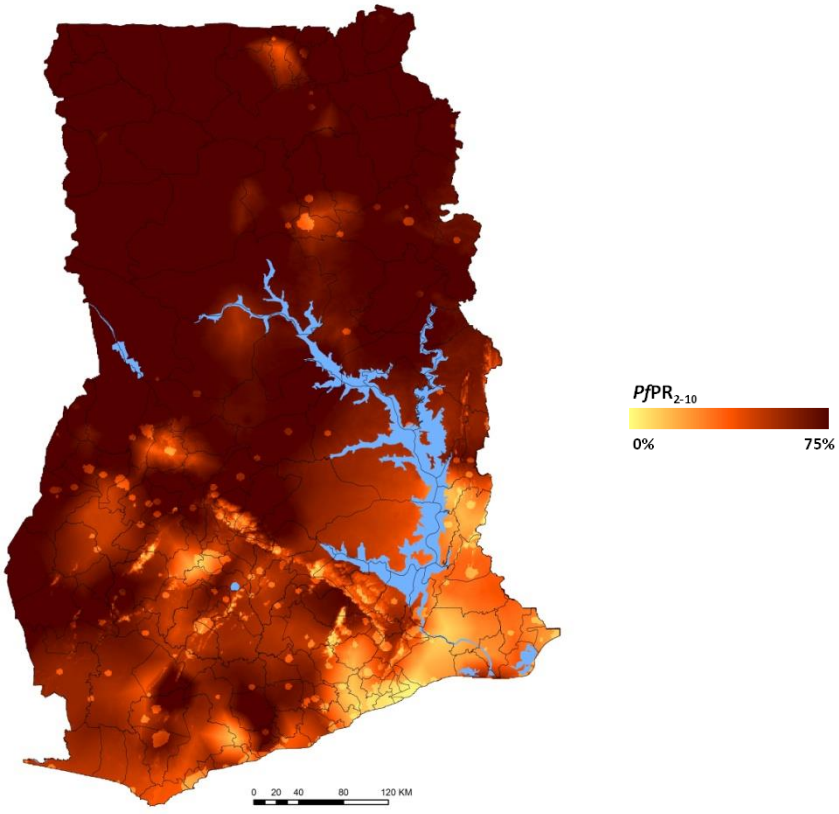
Given the over-distribution of both population density (Figure 2.5) and malaria risk (Figures 4.6a and 4.6b) within each district we computed a Population Adjusted *Pf*PR_{2-10} (PA*Pf*PR_{2-10}) for each district by first multiplying the *Pf*PR_{2-10} at each 1×1 km grid location with the corresponding population at the same spatial resolution to compute the number of people who are likely to be positive for *P. falciparum*. This surface was then used to extract the number of people positive for *P. falcipraum* in each district and divided by its total population in 2010 to compute PA*Pf*PR_{2-10} for 2010. The district values of the mean PA*Pf*PR_{2-10} in 2010 are shown in Annex Tables A2 and Figures 4.6c.

None of Ghana's population in 2010 were living in areas classified as low-stable endemicity (*Pf*PR_{2-10} <1%). 13.3% of Ghanaian's lived in areas that supported traditional hypoendemic conditions (*Pf*PR_{2-10} <10%), 40% lived in areas of mesoendemic transmission (*Pf*PR_{2-10} 10-49%), 30% of the population lived in areas of hyperendemic transmission (*Pf*PR_{2-10} 50-74%) and 16.6% of Ghana's

population lived in areas that continue to be classified as holoendemic transmission (*Pf*PR_{2-10} >= 75%) (Figure 4.7). Thirty-seven districts, home to 3.6 million people, had mean predicted PA*Pf*PR_{2-10} in 2010 above 75%: Offinso North (Ashanti Region); Assin South (Central Region); Bia, Juabeso (Western Region); Jaman North, Jaman South, Pru, Tain (Brong Ahafo Region); Bole, Bunkpurugu Yunyoo, Central Gonja, West Gonja, Chereponi, East Mamprusi, West Mamprusi, Gushiegu, Karaga, Kpandai, Nanumba North, Nanumba South, Sawla-Tuna-Kalba (Northern Region); Bawku Municipal, Bawku West, Bongo, Builsa, Garu Tempane, Kassena Nankana West, Talensi-Nandam (Upper East Region); Jirapa Lambussie; Lambussie-Karni, Lawra, Nadowli, Sissala East, Sissala West, Wa East, Wa West, Wa Municipal (Upper West Region) (Figure 4.7c and Annex A2). The Greater Accra Region had some of the lowest mean predicted PA*Pf*PR_{2-10} values in 2010 and was the only region that supported areas that were hypoendemic: Accra Metro (5.9%), Adentan Municipal (7.4%), Ashaiman Municipal (8.1%), Ga South Municipal (9.9%), Ledzokuku-Krowor Municipal (2.5%) and Tema Municipal Area (3.1%) (Figure 4.6c and Annex A2).

Figures 4.6: a) continuous 1x1 predicted mean *Pf*PR_{2-10} for the year 2010; b) re-classified endemicity classes using the posterior distribution for the year 2010; c) Population-weighted mean *Pf*PR_{2-10} per district

a)



b)

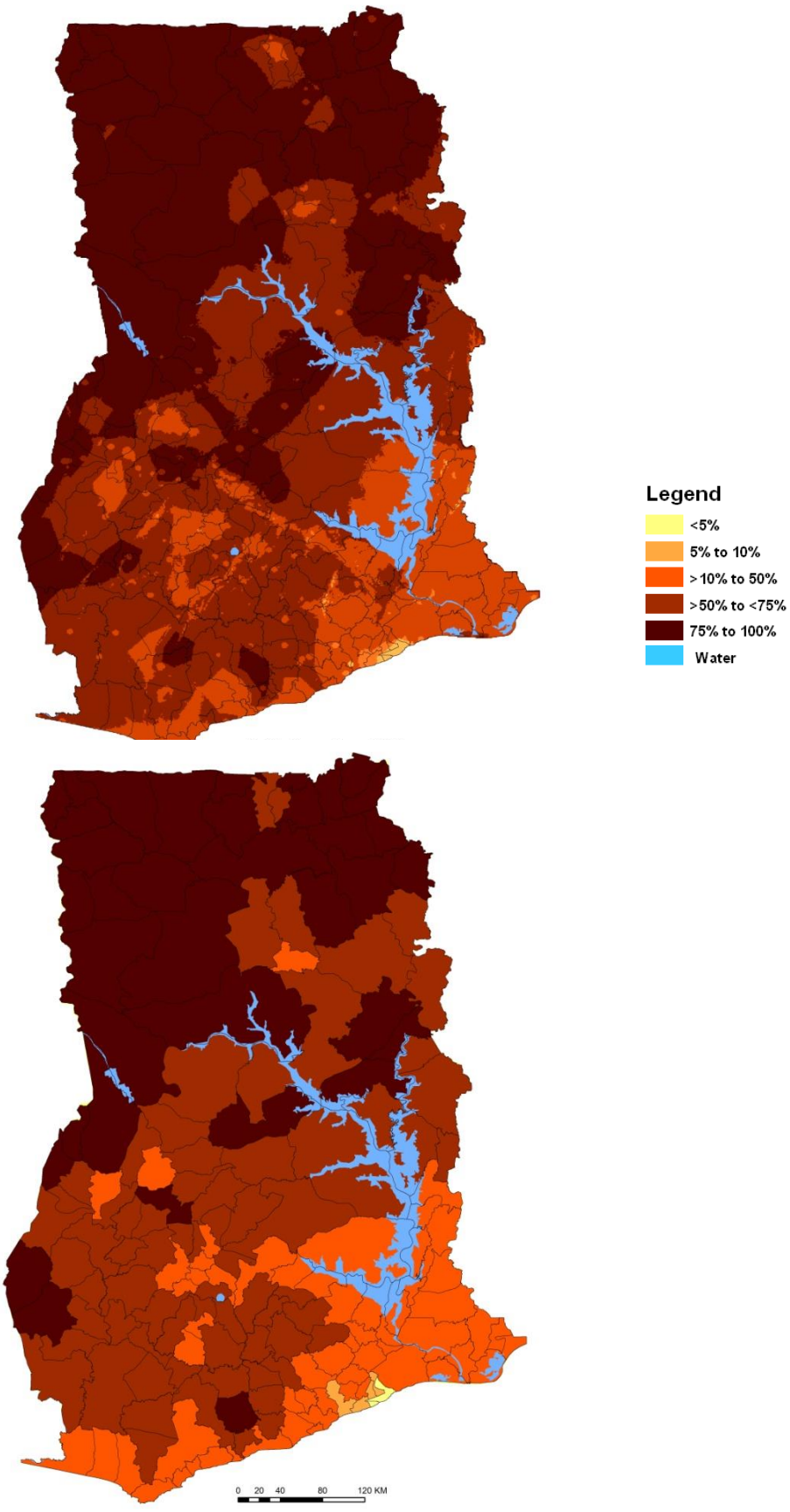
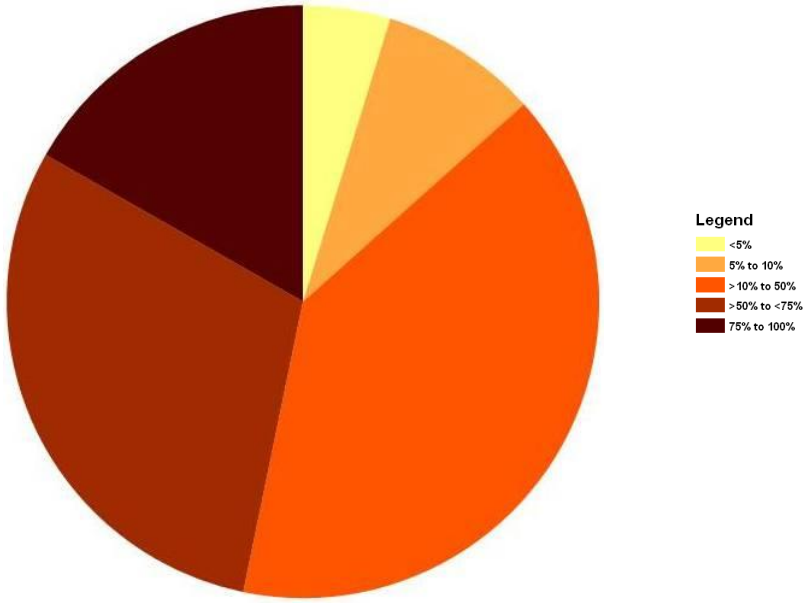


Figure 4.7: Percentage of Ghana's population at various classes of *P. falciparum* endemic risk in 2010



4.5 Model uncertainty and validation statistics

A series of model uncertainty and validation statistics were generated to assess model performance. For each prediction year, the standard deviations of *Pf*PR_{2-10} were first computed for each 1×1 km grid location. The probability of belonging to an endemicity class was also computed from the posterior marginal distributions at similar spatial resolutions. Conventional model accuracy was estimated by computing the linear correlation, the mean prediction error (MPE) and mean absolute prediction error (MAPE) of the observations and predictions of a 10% hold-out dataset. The hold-out set was selected using a spatially and temporally declustered algorithm [Isaacs & Svritsava, 1989] which defined Thiessen polygons around each survey location. Each data point had a probability of selection proportional to the area of its Thiessen polygon so that data located in densely surveyed regions had a lower probability of selection than those in sparsely surveyed regions setting a high threshold for model performance. Sampling and testing hold out sets was done for each regional and time-segmented tile. The Bayesian SPDE using INLA was then implemented in full using the remaining 90% of data and predictions were made to the 10% hold-out within each regional tile.

The MPE, MAPE and the correlation coefficient of the observed and predicted *Pf*PR_{2-10} for the full space time *Pf*PR_{2-10} model for Ghana were 0.99%, 4.72% and 0.97 respectively indicating a good model accuracy. For mean predictions of *PfPR*$_{2-10}$ all pixels were within less than one standard deviation of the posterior mean *PfPR*$_{2-10}$ indicating good precision around estimates of risk.

4.6 Other parasite species

The current focus of control in Africa, justifiably *P. falciparum*, is by far the most pathogenic of the five human malaria parasites and contributes to over 95% of the world's mortality from malaria. However, it is not the only malaria parasite to affect man. *Plasmodium knowlesi,* the most recently discovered human malaria, has not been described in Africa. *Plasmodium vivax* is thought to have a restricted distribution in Africa owing to the refractory nature of duffy-negative red cells that lack a necessary receptor (Fy(a-b-)) for invasion. *Plasmodium ovale* and *P. malariae* have been reported in most regions of the world, however both parasites seem to be largely confined to sub-Saharan Africa and a few islands in the Western Pacific [Lysenko & Beljaev, 1969; Collins & Jeffery, 2005; Mueller et al., 2007]. There appears to be no duffy blood group restriction to infection for either of these parasites [Collins & Jeffery, 2005]. Recent genetic studies of parasite populations in Africa suggest that there may be more than one genetically distinct form of *P. ovale; Plasmodium ovale curtisi* (classic type) and *Plasmodium ovale wallikeri* (variant type) [Sutherland et al., 2010]. The non-falciparum human malarias are often susceptible to most antimalarial drugs including those that currently fail to treat *P. falciparum* [White, 2008], however most evade drug action as they are more often benign and/or relapse.

Plasmodium malariae is a relatively easy parasite to observe with microscopy owing to a distinctive pigmented band forms in host cells [Collins & Jeffrey, 2007]. Most *P. malariae* infections also share similar properties as *P. ovale* and are rarely uniquely associated with clinical events but persist for decades at very low parasite densities and have been associated nephritic syndromes [Hendrickse, 1980; Collins & Jeffery, 2005]. While relatively uncommon, *P. malariae*'s true burden has never been formally quantified. There is some suggestion of a suppressive effect of *P. falciparum* on *P. malariae* and a parasite density regulatory effect of *P. malariae* on *P. falciparum* clinical infections [Black et al., 1994; Mueller et al., 2007]. While the mechanisms and epidemiological significance of these potential interactions require further confirmation they might have a longer-term significance as prevalence of both parasites declines differentially with scaled prevention and treatment.

Reports from the central laboratory in Accra in 1914 indicate that among clinical samples from 108 Europeans and 142 African, 87.2% of infections were sub-tertian (*P. falciparum*), 5.2% benign tertian (presumably *P. ovale*) and 7.5% quartan (*P. malariae*) [Macfie & Ingram, 1918]. We have assembled information from 44 communities sampled during the WHO collaborative studies in Ghana between 1958 and 1967 (Ghana-1 and Ghana-18 projects) in Ashanti, Eastern, Volta and Upper East Regions (Sections 3.4.1 & 3.4.2). At these communities we have information on species-specific infection from 16,736 individuals: 43% were *P. falciparum* positive, 10% were positive for *P. malariae* and 0.8% were positive for *P. ovale*; 80% of all infections were due to *P. falciparum*, 18.5% due to *P. malariae* and 1.5% due to *P.ovale* [Anon, 1960; 1967; Beausoleil, 1967; Beausoleil & Delfini, 1963; Delfini & Beausoleil, 1964; Kudicke & Beausoleil, 1966a; 1966b; Van der Kaay, 1960; Van der Kaay & Najera, 1962; Van der Kaay & Von Haller, 1962].

For a more contemporary view of species composition of asymptomatic infections we have reviewed studies undertaken between 1990 and 2009. This database contains information from 97

site-specific reports of parasite species derived from 19 published reports and subsequent communications with authors in Ghana. Sixteen sites (20%) reported the presence of *P. malariae* in Afigya Sekyere and Kwabere districts in Ashanti Region, Asutifi and Kintampo districts in Brong Ahafo Region, Dangbe West and Accra districts in Greater Accra Region and Kasena/Nankani district in Upper East Region. Among the 15,513 people sampled at the 97 sites, overall *P. malariae* prevalence was 0.86% (2.7% of all plasmodia infections). Only five sites reported the presence of *P. ovale*: four in Afigya Sekyere (Ashanti) and one site in Accra, giving an overall prevalence of 0.05% (only 0.16% of all plasmodia infections). Although rare *P. ovale* has been associated with an infection detected in a European traveller to Ghana [Tordrup et al., 2011]. No *P. vivax* infections have been recorded since 1900.

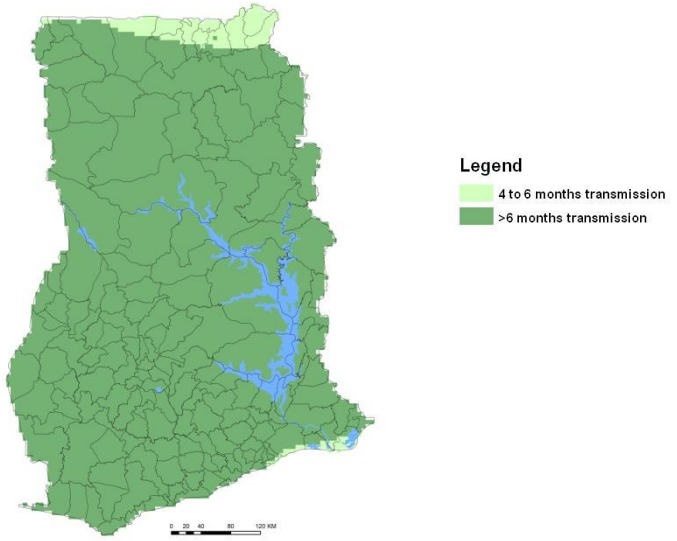
An interesting observation, although not on strictly nationally representative or congruent random sample sites, is that the prevalence of *P. malariae* may have significantly declined since the 1960s. This might be explained through the continued sensitivity of this parasite to most available and widely used mono-therapies that failed in the 1990s to clear *P. falciparum* infections. The epidemology of *P. malariae* infection deserves further investigation.

4.7 Malaria seasonality

A dominant epidemiological characteristic of malaria across much of Africa is its seasonal profile. Relationships between climate, seasonal parasite transmission and disease outcomes are complex and have been poorly defined for many years [Gill, 1938]. There is a suggestion that areas with acute transmission represent settings that are more adapted to synchronized infections leading to higher host parasite densities [Mckenzie et al., 2001]. Acutely seasonal malaria exposure areas may lead to poorly “designed” immunization for new-born children, resulting in different disease-severity profiles compared to settings with equivalent annual parasite exposure more evenly distributed throughout a year (spaced immunization) [Caniero et al., 2010; Greenwood et al., 1991]. The description of seasonality represents an important operational information platform to target the timing of vector control, most notably IRS and larval control operations, and the renewed interest in pulsed mass drug administration or restricted chemoprophylaxis in the Sahel, known as Seasonal Malaria Chemoprophylaxis (SMC) [Cairns et al., 2012; WHO, 2012].

The climate suitability maps developed by the MARA collaboration are based on the likelihood of stable transmission using a rules-based approach [Craig et al., 1999; Tanser et al., 2003; http://www.mara.org.za/] (Figure 4.8). A more robust approach has recently been developed using empirical data to define extremes of seasonality for SMC using Fourier processed daily rainfall data since 2000 [http://www.cpc.noaa.gov/products/fews/rfe.shtml] and tested against monthly clinical incidence data from 55 sites across sub-Saharan Africa. The optimal model was one where 60% of annual rainfall occurred within 3 months and best fitted the seasonal clinical profiles of >60% of cumulative cases occurring in 4 consecutive months [Cairns et al., 2012]. Using this rainfall profile, areas with incidence patterns suitable for SMC were identified, with a sensitivity of 95.0% and a specificity of 73.5% [Cairns et al., 2012].

Figure 4.8: MARA climate seasons map for Ghana [Tanser et al., 2003; http://www.mara.org.za/]



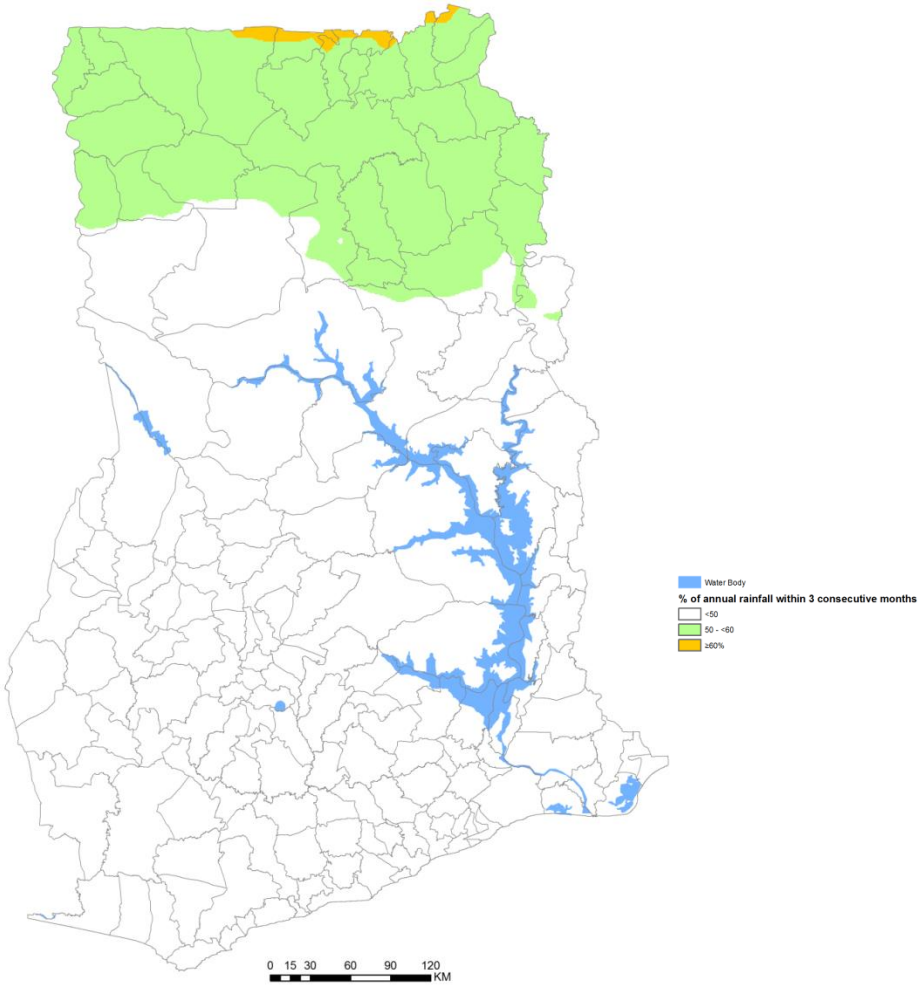
Footnotes: The MARA models of seasonality are defined using the combination of temperature and rainfall thresholds and a catalyst month. Areas where mean annual temperatures were <5^{o}C were considered not to have a malaria transmission season. A pixel was considered "seasonal" if the temperature range varied considerably or if annual rainfall was <720 mm. Seasonal zones were then classified according to the numbers of average months in which temperature was > 22^{0}C and rainfall > 60 mm within a 3-month moving window and at least one month of highly suitable conditions (> 22^{0}C, > 80 mm) occurred as a catalyst month. For areas considered "stable" the equivalent values were 19.5^{0}C and 80 mm with no requirement for a catalyst month. From these values the duration and start/end of the transmission season were predicted and the gridded surface of Africa was classified at 5x5km grids into 1-3 months of transmission (highly seasonal/epidemic), 4-6 months of transmission (representing seasonal endemic conditions) and 7-12 months reflecting perennial endemic transmission [Tanser et al., 2003; http://www.mara.org.za/].

Here, we have used daily rainfall estimates from the African Rainfall Estimates version 2 (RFE 2.0) dataset developed as a collaborative programme between NOAA's Climate Prediction centre (CPC), USAID/Famine Early Systems Network (FEWS). The RFE 2 gridded dataset combines gauge and satellite information on a near-real time basis to provide daily rainfall estimates over the African continent and is archived from January 2000 at 10 km spatial resolution [NOAA CPC, 2001; Novella & Thiaw, 2012]. To match work done by Cairns and colleagues we have selected daily-accumulated rainfall data between 2002 to 2009 per 10 km pixel to define the maximum percentage of the total annual rainfall occurring in a period of consecutive months (Figure 4.9). These predictions are more tangibly rooted in current models of disease risk and are used here in preference to MARA models described in Figure 4.8.

The most suitable areas in Ghana for SMC are those with a single annual rainfall peak, and have been defined as areas where 60% or more of the average annual rainfall occurs in three continuous months. Districts were considered SMC targets if a substantial proportion of its population lived in areas of acute seasonality (≥60% of rainfall in three consecutive months). Of the seven districts where part of the district population reside in SMC suitable areas, only four had more than 10,000 people living in SMC areas: Bawku Municipal, Bongo, Kassena Nankana and Kassena Nankana West, all in Upper East region and representing a combined population of circa 480,000 people across the four districts (Figures 4.9 and 4.10). In Kasena/Nankani district this prediction is consistent with detailed parasite density/fever incidence among infants in this district

[Baird et al., 2002]. The four combined districts have approximately 0.48 million people but only 133,411 at a predicted risk of more than 60% of rainfall within 3 consecutive months. Given the coarse resolution of the rainfall prediction surface it would be safe to include all these districts in an SMC effort. Seasonal over-distributions of vector abundance are marked across Ghana (Section 5.3) and it would be appropriate to revisit the seasonal profiling of targeted malaria using other combinations of rainfall, entomological and clinical data where these exist. As a provisional, more inclusive criteria we have also mapped areas where 50-59% of the annual rainfall falls within three continuous months. This is also displayed in Figure 4.9 and 4.10, covering 30 districts in Upper East, Upper West and parts of the Northern Regions and a total population of 3.3 million people. These might be considered suitable for more targeted seasonal control measures.

Figure 4.9: NOAA rainfall/seasonality concentration index in Ghana in classes of rainfall seasonality



Footnotes: The gridded daily rainfall estimates at 0.1 degree resolution from the RFE 2.0 dataset between January 2002 and December 2009 was acquired from the NOAA CPC/FEWS archive [NWS, 2012]. The daily rainfall estimates were then aggregated to calculate total monthly and annual rainfall. For each pixel, the maximum percentage of the total annual rainfall occurring in three month-iterations was then calculated for each year using spatial analyst tool in ArcGIS 10.1 (ESRI, USA). The average pixel value between 2002 and 2009 was then calculated and the resulting image reclassified to give a binary output of areas where rainfall in three consecutive months was < 60% or > 60%

4.8 Special control areas: combined mapped images for control

Urban municipal extents: About 34% of the urban population lives in Accra and in Kumasi. These two cities account for almost 20% of Ghana's GDP and the Greater Accra Region is home to about 3.2 million people and alone accounts for almost 51% of manufacturing activity in Ghana [Farvacque-Vitkovic et al., 2008]. Neither city is free from malaria and predicted risks remain moderately stable. There are specificities associated with urban malaria transmission in Ghana related to densely populated areas, high immigration rates and urban agriculture [Klinkenberg et al., 2005; 2006; 2008; Fobil et al., 2012]. There are large differences in childhood infection rates and entomological inoculation rates within cities and between city centres and their peripheries at Kumasi, Accra and Tamale [Pond et al., 2013; Ronald et al., 2006]. The use of ITN in these urban centres has remained low since the launch of ITN promotion in 2000 (Section 3.6.1), because urban residents do not perceive the benefits [Baume & Koh, 2011].

There has been a long legacy of urban larval control and environmental management in Ghana since the early 1900s (Section 3.2). Recent trials of mapping breeding sites and use of *BTi* have proven successful in Kumasi [Nartey et al., 2013]. Municipal assemblies have always been regarded as integral to a coordinated, partner effort for malaria control in Ghana and the proposed strategy development for 2015-2020 might provide more emphasis on inter-sectorial urban malaria control. We have, therefore used combinations of census definitions [GSS, 2013], other reported big city listings [Farvacque-Vitkovic et al., 2008] of large municipalities and the urban extent mapping described in Section 2.8 to map the location of large municipalities in Ghana (Figure 4.10). These extents represent a total of 6.7 million people in 2010.

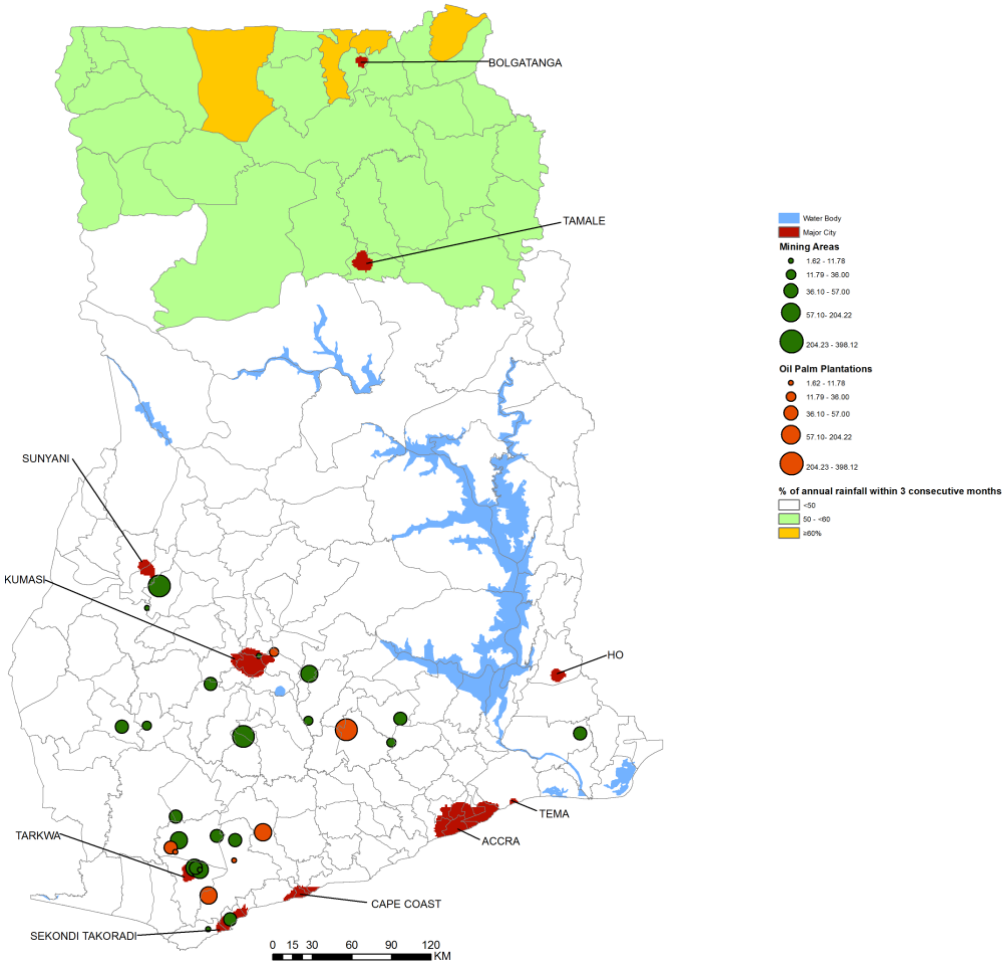
Mining areas: Mining concessions have been run by private companies who have variously over the last 100 years taken some responsibility for health care provision and public health measures such as malaria control. As with city councils, private companies, have an inter-sectorial responsibility for malaria control in Ghana [NMCP, 2000; 2008]. The best example of a working partnership between public and private sectors has been with the AngloGold Ashanti malaria programme at Obuasi [AGA, 2007]. A complete list official and unofficial mines has been hard to identify, but is currently being assembled by the NMCP and WHO country programme. Of particular importance are open cast mines which create environmental hazards and specifically changes in local mosquito breeding potential. Having these areas identified, mapped and used in future district level malaria planning is likely to be an important layer of epidemiological intelligence over the next 10 years. For demonstration purposes we have mapped a recent official listing of company locations for mineral extraction in Ghana, shown in Figure 4.10 [Ayee et al., 2011], recognizing that this is incomplete and does not capture the informal mining areas. These broad spatial extents cover 0.43 million people at risk of malaria in 2010.

Other employers: Commercial employers are a key partner in malaria control [RBM, 2011]. Creating a business case for investing in control based on healthy workforce days gained and productivity increased is a key advocacy tool for the NMCP to create a platform for private sector investment [RBM, 2011]. The AGA Obuasi business case was made on the basis of man-hours lost from malaria [AGA, 2007]. Other than mining companies, the recent discovery of offshore oil will

lead to a substantial increase in the workforce and population living at Sekondi-Takoradi Municipality, the main on-shore station, where predicted PA*Pf*PR_{2-10} in 2010 was *circa* 27%. This poses a threat to employees located in this area working for the oil companies. Other large employer sectors in Ghana are the cocoa, oil palm, inland valley rice projects and rubber plantations [MoFA, 2013]. Creating malaria risk profiles for these economically important spatial areas will be an important advocacy tool at national levels and important risk profiles for District Management teams.

An example of provisional, incomplete, topographical and employer-based mapping exercise has been shown in Figure 4.10 alongside areas suitable for SMC, to demonstrate the layered approach to malaria risk profiling for advocacy and intervention targets.

Figure 4.10: A combined epidemiological target map of urban extents (combined urban and peri-urban limits in red), mining companies (dark green dots representing increasing land mass coverage, km^2), orange circles representing major oil palm plantations with increasing surface areas in km^2 and SMC districts (orange >60% rainfall in 3 months in districts where more that 10,000 living under these conditions; green 50-59% rainfall in 3 months where more that 10,000 living under these conditions)



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Chapter 5

Dominant malaria vectors in Ghana

5.1 Background

Africa is home to the most effective and efficient vectors of human malaria [Coluzzi, 1984]: *An. gambiae*, with its sibling, *An. arabiensis* [Coetzee, 2004; White, 1974], both form part of the *An. gambiae* complex which also includes the salt water tolerant, coastal species *An. melas* and *An. merus* [Gillies & Coetzee, 1987; Gillies & DeMeillon, 1968; Harbach, 2004; White, 1974]. Other members of the *An. gambiae* Giles complex are not regarded as dominant vectors because of their restricted, focal (*An. bwambae* [White, 1985]) or zoophilic nature (*An. quadriannulatus* A and *An. quadriannulatus* B [Coluzzi, 1984]), or because they cannot, by themselves, sustain malaria transmission in an area. In addition to the four dominant vector species (DVS) within the *An. gambiae* complex, large parts of Africa are also home to other DVS including the *An. funestus* Giles, *An. nili* and *An. moucheti*. Others such as *An. rivulorum, An. coustani and An. pharoensis,* although not considered DVS in Africa, appear to play a significant minor role as weaker, but nevertheless important vectors, in some selected areas [Kawada et al., 2012; Mwangangi et al., 2013; Wilkes et al., 1996].

All national malaria control programmes across Africa implement interventions aimed at reducing human exposure to infectious malaria vectors. These include insecticides on mosquito nets, applications of residual insecticides on household walls, or the targeting of larval stages of vectors to reduce vector abundance, survival and/or human-feeding frequency. However, the distribution of vector composition linked to their intrinsic behavioural bionomics and their resistance to currently available insecticides remains largely unknown, or under-emphasized, when planning vector control on national scales. Vector resistance to insecticides and behavioural adaptive changes accompanied by changing vector biodiversity pose real challenges to the future effectiveness of currently used vector control strategies [Ferguson et al., 2010; Gatton et al., 2013; Pates & Curtis, 2005; Ranson et al., 2011]. Furthermore, a lack of reliable entomological monitoring systems that capture all major relevant phenotypes and their effect on vector population dynamics on national scales limit capacity of malaria control programs to manage ongoing vector control efforts or adapt to changing vector behaviour and insecticide susceptibility [Govella et al., 2013].

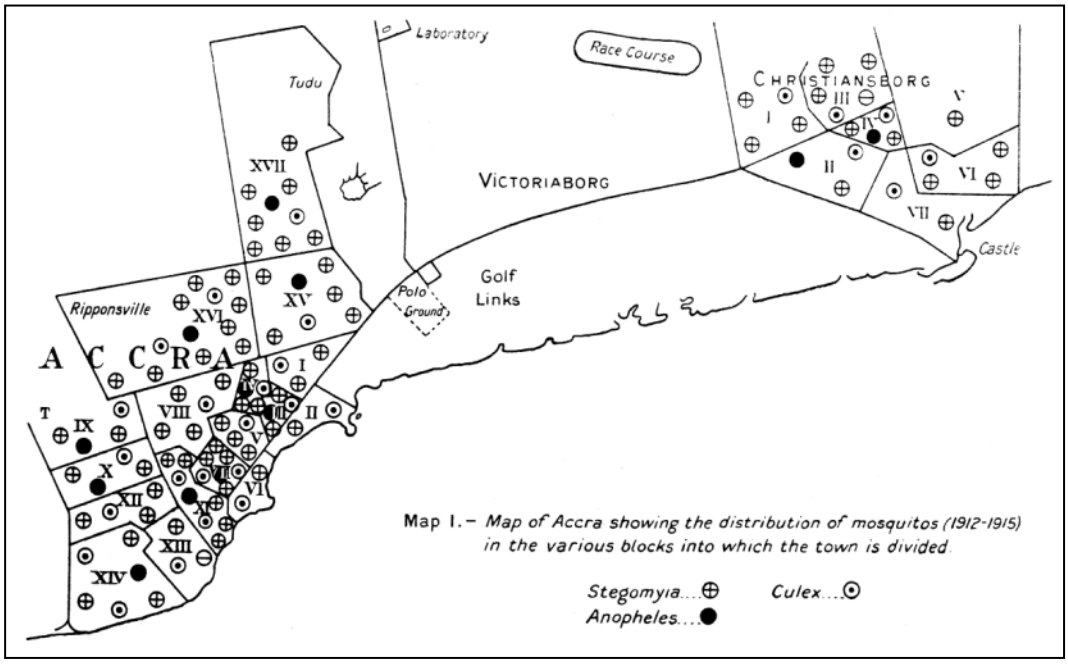
5.2 Historical vector surveillance

Studies to determine mosquito breeding habitats, vector densities and entomological indices of transmission have been conducted since 1911 in Ghana [Government of Gold Coast, 1912; Chinery, 1984]. Routine larval collections were done across stations in the Colony (Accra), Ashanti district and Northern territories. Collections included searching barrels, tanks, wells and other stagnant water sources and monthly mosquito surveys to collect adult anophelines were done inside households [Government of Gold Coast, 1912-1930].

JW Macfie, a medical officer based in the Gold Coast, identified key mosquitoes present in Accra between December 1914 and November 1915. His results highlighted the abundance of *An. gambiae* (costalis) larvae in domestic water vessels and pools, and proceeded to map the breeding sites across the neighbourhoods of Accra and Christiansborg (Figure 5.1). Other species recorded

during these pre-independence surveys included *An. funestus, An. pharoensis* and *An. umbrosus* [Macfie & Ingram, 1916; Chinery, 1984].

Figure 5.1: Map showing distribution of mosquitoes in Accra [Macfie & Ingram, 1916]



Colbourne & Wright in 1955 continued entomological surveys across Ghana, with a special reference to specific areas in Accra (Southern), the forest (Middle) belt and the Northern Savannah [Colbourne & Wright, 1955]. In Bomfa (Middle belt), during the wet season, *An. gambiae* had a sporozoite rate of 15% and *An. funestus* and sporozoite rate of 11%; the average Entomological Inoculation Rate (EIR) was 24 infective bites per person per year. In the Northern Territories at Yoruga, *An. gambiae* was observed to be 1.5 times more abundant compared to *An. funestus.* Sporozoite rates were 25% and 7.4% for *An. gambiae* and *An. funestus* respectively and resulting in an estimated annual EIR of approximately 28 infective bites per year. In Accra, *An. melas* was determined to be prevalent along the coastal-line and salt water marshes with *An. funestus* rarely collected [Colbourne & Wright, 1955].

During the Ghana-1 studies of the 1960s in the Volta Region (Section 3.4.2), detailed daytime morning catches, spray catches, night biting catches and baited trap catches were undertaken [Clarke & Von Haller, 1961; Van Der Kaay & Von Haller, 1962; Beausoleil & Delfini, 1963; Beausoleil & van der Kaay, 1963]. *An. gambiae* s.l and *An. funestus* showed a sympatric distribution with the former having a higher relative abundance and higher sporozoite rates (as high as 13% in some areas in some months). Sporozoite positive *An. nili, An. pharoensis* and *An. hargreovesi* were also described.

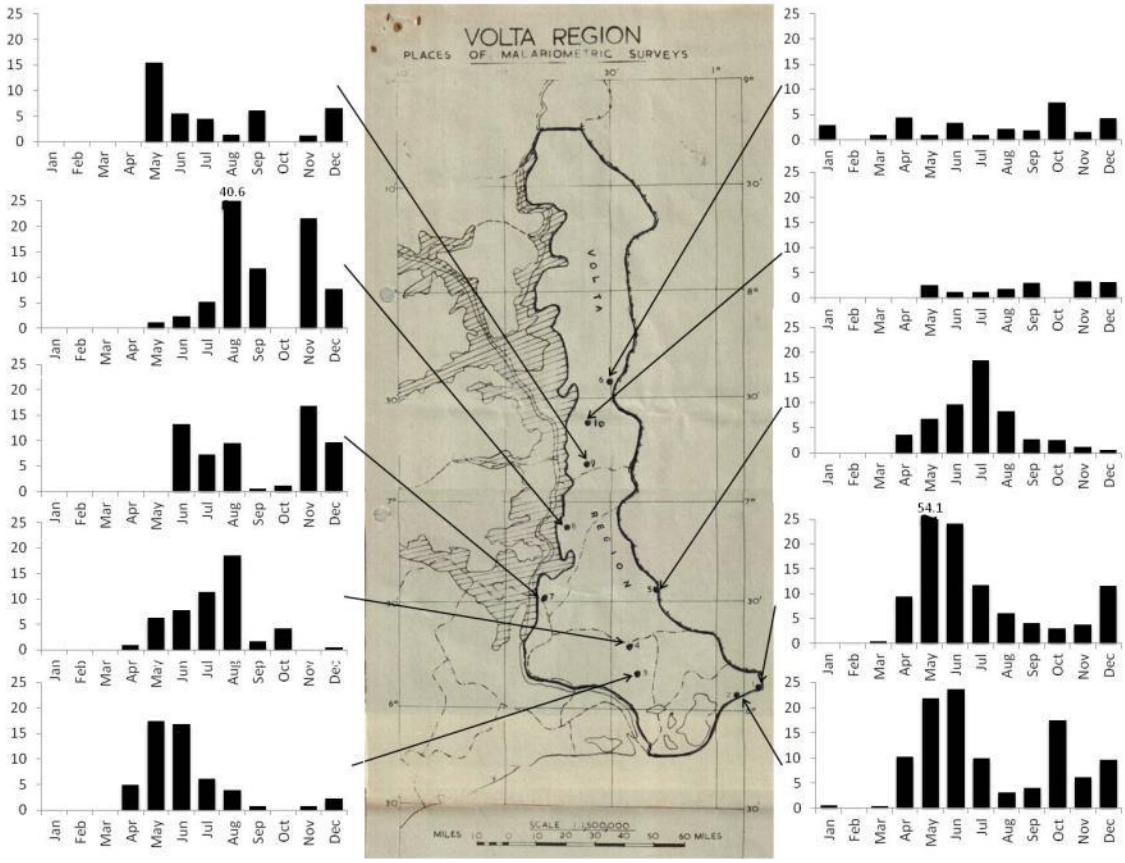
Although *An. funestus* has been rarely found across the urban extents of Greater Accra, it has been found at the periphery of these areas, breeding more commonly in slow-moving fresh water streams [Chinery, 1984]. Chinery highlights that the effects of urbanisation have led to the *An.*

gambiae complex adapting to breeding in water containers, pools and puddles in the cities increasing its densities in collections to 21.1% in 1964 [Chinery, 1969; 1984].

5.3 Vector seasonality

The acute seasonal nature of vector abundance, coinciding with rainfall patterns, has been the subject of detailed descriptions in Accra since the Second World War by the Royal Army Medical Corps entomologists Captain Mattingley and Lieutenant Robertson showing a concentration of vectors during the months of June-August [Eddey, 1944] with very similar seasonal distributions reported in the 1960s in Accra [Chinery, 1968]. The seasonal nature of vector abundance was also apparent in the southern parts of the Volta region during the 1960s (Section 3.4.2) and summarized in Figure 5.2 [Kundicke, 1965].

Figure 5.2: *Anopheles gambiae* complex densities per room per month at ten sites surrounding the Volta in 1964 [Kundicke, 1965].



More recently, the seasonal over-distribution of man-biting rates and sporozoite inoculation rates was characterised in detail at Kassena-Nankana in northern Ghana [Kasasaa et al., 2013]. For both *An. gambiae* s.s and *An. funestus* most bites were observed during the wet season (July to November) with the highest biting rates in September for all the three years 2001-2003 [Kasasa et

al., 2013]. Man-biting rates by *An. gambiae* show a less marked but equally important seasonal profile near Agona [Abonuusum et al., 2011] and for *An. funestus* at Kintampo [Dery et al., 2010].

5.4 Vector data assembly

Across Africa, detailed inventories of species distribution began during elimination campaigns launched in the 1950s, but continued in earnest only in North Africa where elimination efforts continued through the 1970s. The notion of mapping vector species was resurrected during the mid 1990s as part of the Mapping Malaria Risk in Africa (MARA/ARMA) project [Coetzee et al., 2000]. There have been several recent attempts to model the distributions of DVS in Africa using sparse data and climatic determinants notably, temperature, soil moisture and other environmental drivers of vector species presence and abundance [Lindsay et al., 1998; Moffett et al., 2007; Sinka et al., 2010; Lunde et al., 2013a; Lunde et al. 2013b]. These model predictions have used different statistical approaches and different data sets and are hard to systematically compare.

The coincidental growth of geo-located databases of vector species has, however, provided some unique resources for countries to access, augment and adapt to local planning needs; notably AnoBase [http://skonops.imbb.forth.gr/], VectorBase [https://www.vectorbase.org], MARA/ARMA collaboration [https://www.mara.org.za], Walter Reed Biosystematics Unit (WRBU) Mosquito Catalog [http://www.mosquitocatalog.org], Malaria Atlas Project (MAP) [http://www.map.ox.ac.uk], and the Disease Vectors database [https://www.diseasevectors.org]. The database on insecticide resistance, the Arthropod Pesticide Resistance Database (APRD) [http://www.pesticideresistance.org/], covers a large variety of arthropods, but only reports instances of occurrence of resistance, without any precision on geographic location nor actual data. The African Network for Vector Resistance (ANVR) was established in 2000, and amongst its objectives was the important goal of improving dissemination of resistance data [ANVR, 2005]. Over the last 10 years, a database has been developed to store the results of resistance monitoring activities by ANVR members. This database has now been integrated for open access with the launch of IRBase [Dialynas et al., 2009].

The most comprehensive available, geo-coded species-specific data is currently held on the MAP database [Sinka et al., 2010]. In addition a recent detailed review of entomological studies in Ghana has been used to augment information on the MAP database [De Souza et al., 2010]. We also re-ran on-line searches of medical literature databases including PubMed, Google Scholar and Web of Science using search terms “Anopheles AND Ghana“ for all study publications after December 1970 and post the last searches undertaken by MAP. Finally, the AngloGold Ashanti malaria programme generously provided data from 79 surveillance sites recorded as part of baseline and follow-up surveys during IRS activities.

Each study site was geo-coded using methods described in Section 4.2.3. Data abstracted from each report included the start and end of the entomological survey, species identified at complex or species member levels, methods of sampling (animal bait catches, bed net traps, CDC light traps, human landing catches, indoor resting searches, pyrethrum spray catches, exit traps, larval

searches), methods of species detection (Polymerase chain reaction (PCR), Chromosome Banding Sequences, Morphology, DNA probes) and the full citation source. For older survey data it is recognized that there is a degree of taxonomic ambiguity, for example the *Anopheles gambiae* complex was only fully categorised in 1998 and *An. quadrimaculatus* species B designated a separate species after this date [Harbach, 2004; Hunt et al., 1998]; furthermore the exact composition of the *An. funestus* complex remains unclear [Costantini et al., 1999]. In addition we developed two sub-databases on recorded entomological inoculation rates (EIR) and any information of insecticide susceptibility testing documented since 1970. The final database contained 368 site/time specific reports of DVS occurrence. We were unable to geo-locate 28 (7.6%) sites. The earliest reports were in 1988. At 305 (91%), of the 334 survey sites we could geo-locate, surveys were undertaken since 2000.

5.5 Species occurrence and bionomics

Here we present only a mapped distribution of DVS, however, with a complete spatial and temporal database it is planned to develop a more mathematical approach to defining species distribution in Ghana with the geo-located species data and using Boosted Trees Regression methods [Elith et al., 2008]. The mapped presentation of species distribution derived from the assembled data is shown in Figures 5.3a-d with a comment on each vector's traditional bionomics [Sinka et al., 2010]. Unfortunately 187 reports of the occurrence of *An. gambiae* s.l did not report species identification of the complex and have not been displayed in subsequent distribution maps. It is also notable that there are few available data in the southern parts of the Volta Region, eastern parts of Brong Ahafo Region and southern parts of the Northern Region.

There is a sympatric, distribution of both *An. gambiae s.s* and *An. funestus* across Ghana; and *An. gambiae* s.s. appears to be more ubiquitous than *An. arabiensis* [Figure 5.3]. It had been postulated that urban growth in Ghana had led to a displacement of dominance of *An. gambiae s.s.* from its fresh waters habitats by the more versatile, cosmopolitan *An. arabiensis* [Chinery, 1984; Appawu, 1994]; however the precise extent of the displacement has not been quantified temporally in urban and the peri-urban areas of Ghana. De Souza and colleagues analysed the distribution of *An. gambiae* s.s S and M forms among sampled vectors in Ghana, finding the M form more prevalent in the most northern regions including the Kassena-Nankana district, dominant M forms along the coastal savannah and equivalent, sympatric distributions of M and S forms in the central region [De Souza et al., 2010]. However, complex mixes of molecular forms have been shown within small micro-epidemiology of the Central Region at Kintampo [Dery et al., 2010].

An. melas is only a minor contributor to transmission across the coastal belt range, relative to *An. gambiae* s.s. and *An. arabiensis* [Appawu et al., 1994]. Although this is varied depending on the sampling sites, for example in Goma district, at Hwida village, 40 of 67 sampled *An. gambiae* s.l vectors were *An. melas*; at the neighboring Mampong village (part of the Okyereko Irrigation Scheme) almost all of the 1087 sampled members of the gambiae complex were *An. gambiae* s.s. [Amuzu et al., 2010], suggesting very localized effects of water typologies. At two sites 20 km inland from the coast, *An. melas* was more prolific than other members of the gambiae complex

and *An. funestus* and showed significant outdoor feeding where people slept on mats [Tuno et al., 2010].

Anopheles nili was detected in 1993 and 2001 in Greater Accra and Upper East regions respectively [Afari et al., 1995; Appawu et al., 2001] and infected *An. nili* prevalent in Bawku during the 1960s [Van der Kaay & Haller, 1962]. Isolated observations of *An. pharoensis* have been made since 1992 in Greater Accra, Ashanti, Central, Eastern, Western, Upper East and Upper West regions [Afari et al., 1995; Amuzu et al., 2010; Charlwood et al., 2011; Hunt et al., 2006; Dzodzomenyo et al., 1999; Ughasi et al., 2012; Dery et al., 2013]. *An. coustani* has been reported at sampled sites across Accra in 2003-2004 [Klinkenberg et al., 2008] and *An. rufipes* described in Bongo district (Upper East Region) in 2013 [Dery et al., 2013].

5.6 Entomological Inoculation Rates (EIR)

One vector based measure of transmission intensity is the (EIR); the number of infective bites per person per unit time expressed across species or individually by species. Earlier studies in 1992 examining malaria transmission in the different ecological zones in the southern towns of Dodowa and Prampram had EIRs ranging between 10.2 to 28.8 infective bites per person per year [Afari et al., 1995]. Significant EIRs have been described in Accra; in 2003,19.2 and 6.6 infective bites per person per year was observed in urban agricultural and non-agricultural areas respectively [Klinkenberg et al., 2008]. In the forest-savannah areas of the Brong Ahafo region, in 2005, peak monthly EIR was approximately 170 infective bites per person per month (ib/p/m) in September, and annual EIRs varied across small distances from 490 to 866 [Abonuusum et al., 2011]. Exceptionally high, and varied, annual EIRs have been documented recently at Kasena-Nankana district ranging from 157 to an astounding 1132 i ib/p/y [Kasasa et al., 2013]. EIRs in the Kintampo area range from 231-269 ib/p/y [Dery et al., 2010].In the forest zone of the Akwapim-Mampong moutain range annual EIRs ranged from 40 to 158 ib/p/y [Badu et al., 2013]. These contemporary vector based estimates of transmission correspond with the high predicted mean *Pf*PR_{2-10} in the areas where EIR has been estimated (Section 4.4) and suggest that despite selectivity of areas much of Ghana has a very high vectorial capacity.

Figure 5.3: Maps of *An. gambiae s.s.*, *An. arabiensis*, *An. funestus* and *An. melas* sampled across Ghana between 1970 and 2013 and their bionomics

***a. Anopheles gambiae s.s*:** *Anopheles gambiae* s.s larvae typically inhabit sunlit, shallow, temporary bodies of fresh water such as round depressions, puddles, pools and hoof prints. This aspect of their bionomics may allow members of the *An. gambiae* complex to avoid most predators, and the larvae are able to develop very quickly (circa 6 days from egg to adult under optimal conditions). *An. gambiae* s.s has been reported from habitats containing floating and submerged algae, emergent grass, rice, or 'short plants' in roadside ditches and from sites devoid of any vegetation. It is considered to be highly anthropophilic, with many studies finding a marked preference for human hosts, typically feeds late at night and is often described as an endophagic and endophilic species, i.e. biting and resting mostly indoors. The species is considered to be one of the most efficient vectors of malaria in the world.

b. Anopheles arabiensis: *Anopheles arabiensis* is considered a species of dry, savannah environments or sparse woodland. Evidence is growing of a more ubiquitous range of *An. arabiensis* across Africa. Its larval habitats are generally small, temporary, sunlit, clear and shallow fresh water pools, although *An. arabiensis* is able to utilize a variety of habitats including slow flowing, partially shaded streams, large and small natural and man-made habitats, turbid waters and there are reports of larval identification in brackish habitats. *Anopheles arabiensis* is described as a zoophilic, exophagic and exophilic species but has a wide range of feeding and resting patterns, depending on geographical location. This behavioural plasticity allows *An. arabiensis* to adapt quickly to counter indoor residual spraying control showing behavioural avoidance of sprayed surfaces depending on the type of insecticide used. Blood feeding times also vary in frequency; peak evening biting times can begin in the early evening (19:00) or early morning (03:00). This species usually has a greater tendency than *An. gambiae s.s.* to bite animals and rest outdoors.

c. Anopheles funestus: A typical *An. funestus* larval habitat is a large, permanent or semi-permanent body of fresh water with emergent vegetation, such as swamps, large ponds and lake edges. *An. funestus* is a highly adaptable species, allowing it to occupy and maintain its wide distribution and utilise and conform to the many habitats and climatic conditions. *An. funestus* is considered to be highly anthropophilic with a late-night biting pattern (after 22.00 hours). Endophilic resting behaviour is also commonly reported, and these characteristics are responsible for rapid disappearance of this vector following expanded indoor residual spraying and insecticide-treated nets. Compared to other dominant vector species in Africa, *An. funestus* shows fairly consistent behaviour (generally anthropophilic and endophilic) throughout its range. In the absence of insecticide use, the endophilic resting behaviour of *An. funestus* combined with a relatively high longevity, makes it as good a vector, or better in some areas, as *An. gambiae s.s*.

d. Anopheles melas: *Anopheles melas* is commonly associated with brackish water, yet does not appear to require brackish water for larval stage development. It is generally found to be more abundant in coastal areas and goes inland as far as 150km given the right environmental conditions. The density fluctuations of *An. melas* are closely associated with tidal changes rather than seasons. The larvae of this species are associated with salt marsh grass and mangroves *Anopheles melas* has been described as both highly anthropophilic with biting preference starting from 19.00 to dawn (peaks at 02.00 and 04.00 hours). It usually tends to feed on animals. However, in coastal villages with larger human populations it is occasionally observed to bite more humans, with preference to resting outdoors after feeding.

5.7 Resistance

The two single base substitutions in the sodium channel commonly referred to as knockdown resistance (*kdr*) mutations confer cross-resistance to DDT and pyrethroids and are associated with resistance in *An. gambiae* s.l populations [Ranson et al., 2011]. The gene mainly responsible, the *1014F* alleles (West), are at high frequency in West Africa [Santolamazza et al., 2008]. Presently, 40 malaria endemic countries have reported pyrethroid resistance [Gatton et al., 2013; WHO, 2012]. Recent studies outlined evidence to support claims of behavioural changes with *An. gambiae, An. funestus* and other dominant species to reflect exophagic feeding preferencing. LLINs and IRS act as contact irritants driving vectors to rest outside human dwellings. Anthropophilic species such as *An. gambiae* complex are reported more frequently biting outdoors during the early hours of the evening when people are usually out socialising [Mbogo et al., 1995; Gatton et al. 2013].

Recently, *kdr* mutations have been observed at low frequencies in *An. gambiae* M form in northern regions of Ghana, in areas with extensive insecticide treated net trials; The maximum frequency (3.38%) of the *kdr* allele in the M form in northern Ghana [Yawson et al., 2004].

During the mid 1960s, after several years of DDT and dieldrin use for IRS in the Volta Region, dieldrin resistance was demonstrated in both *An. gambiae* s.l. and *An. funestus*, and more pronounced in the later. At the same time complete sensitivity to DDT was recorded in both vector species [Delfini & Beausoliel, 1964].

In July 2000, field caught *Anopheles gambiae s.l* from rural areas in Western Region of Ghana were exposed to WHO-recommended concentrations of DDT, permethrin and deltamethrin. Mortality rates recorded over 24 hours showed high levels of susceptibility to DDT (94-100%), deltamethrin (97-100%) and fully susceptible to permethrin (100%) [Kristian et al., 2003]. Later, reports in the mining areas of Obuasi indicated signs of *An. gambiae* S form being resistant to DDT (50-75%), carbamates (69.2-90.7%) and pyrethoids, such as: λ-cyhalothrin (40%), cyfluthrin (12.5%), etonfenprox (57.1%) and deltamethrin (75.9%); *An. funestus* was resistant to DDT and beniocarb (carbamate). *An. gambiae* was fully susceptible to Fenitrothion and both *An. funestus* and *An. gambiae* to Malathion. There was little association between the bioassay results and presence of the *kdr* mutation [Coetzee et al., 2006; Okoye et al., 2008].

More recent WHO bioassays have been conducted in Ahafo mines, Tarkwa, Obuasi, Kumasi and Akyem based on carbamates, pyrethroids, organophosphates and organochlorines. The major vectors *An. gambiae s.s* and *An. funestus* showed high survival rates (6.6-100%) except for organophosphates with a mortality in most locations being greater than 90%. No conclusions could be drawn for *An. arabiensis. Kdr* mutations (L1014F) with wild *An. gambiae* ranged from 53.9% to 100% kdr frequency, with the highest found in Ahafo [Hunt et al., 2011]. In 2006, WHO susceptibility tests in Kassena-Nankana district observed 93.3% cyfluthrin susceptibility in *An. gambiae* and 94.5% in *An. funestus* with cyfluthrin 0.15% concentration having the highest

knockdown effect. Overall cyfluthrin susceptibility ranged between 80 to 98% inferring there are low levels of resistance [Hunt et al., 2011].

From 2011, systematic sensitivity testing of all classes and types of insecticides for malaria control began as a partnership between AGA as the co-recipient of Global Fund support for IRS and research institutes including Ngouchi Memorial Institute for Medical Research, Kumasi School of Medical Sciences, Kintampo Health Research Centre and Navrongo Health Research Centre. These collaborations have generated a large volume of empirical evidence on insecticide resistance across the country.

In 2011, 41 communities in three districts in Upper West Region (Wa Municipal, Wa West and Wa East) and three districts in the Ashanti Region (Adansi North, Adansi South and Amansie Central) adult and larvae of *An. gambiae* s.l were tested against a range of insecticides. *An. gambiae* mosquitoes in all the 6 districts were resistant to DDT and all the pyrethroids tested. Mortalities for pyrethroids ranged from 3.3 - 75.0% in all the districts with permethrin giving the highest mortality of 75% in Amansie Central. In all the districts, *An. gambiae* showed marginal susceptility (82-97.5%) to carbamates (Propoxur and Bendiocarb). Mortality results for organophosphates (Malathion and Fenitrothion) ranged from 97.5 – 100% with the exception of Adansi North where 90% mortality was recorded [Boayke et al., 2011].

Between June and July 2012, susceptibility tests were carried out on wild caught *An. gambiae* s.l from 69 communities in six districts (Jirapa-Lambussie, Nadowli, Lawra, Sissala West - Upper West region and Upper Denkyira - Central Region). *Anopheles* mosquitoes from all the districts showed highest susceptibility (89-100% mortality) to Organophosphates (Malathion, Fenitrothion and Pirimiphos-Methyl). The susceptibility of *Anopheles* mosquitoes to Carbamates (Propoxur and Bendiocarb) was restricted to Sissala West and Upper Denkyira. The remaining districts (Lawra and Nadowli) recorded marginal susceptibility with the exception of Bendiocarb in Jirapa and Lambussie districts which were significantly susceptible. Resistance was documented to all the pyrethroids tested across all districts. Mortalities for pyrethroids ranged from 28-77%; Permethrin showing the highest mortality of 77% in Sissala-West. Similarly resistance was noted for all Organochlorides tested in all districts; between 32-78% mortalities, with the highest susceptibility for Dieldrin at Sissala West district (78%) [Sarpong et al., 2012].

Between October 2012 and November 2013, sensitivity testing was conducted across 10 districts: Sissala East (Upper West Region), Builsa, Kassena-Nankana, Bolgatanga, Bongo, Talensi-Nabdam, Bawku West (Upper East Region), Nzema East, Wasa West (Tarkwa Nsuaem & Prestea Huni Valley) and Ahanta West (Western Region) [Dery et al., 2013]. All organophosphates (Malathion and Fenitrothion) showed high mortalities as did the carbamate, Propoxur in almost all districts. DDT was shown to have very poor sensitivity when tested against *An. gambiae* s.s. (4% mortality after 1 hour). The pyrethroid classes showed evidence of reduced sensitivity and the *kdr* gene was detected in both M and S forms of *An. gambiae* s.s, although varied between districts, the highest frequencies detected in Navrongo, Kassena-

Nankana (Upper East Region) and Bogoso, in the Prestea Huni Valley (Western Region) [Dery et al., 2013].

Clearly, the use of organophosphates for IRS are the preferred choice at present in Ghana, however there remain very few reports of the susceptibility of *An. funestus* to Malathion, Fenitrothion or Pirimiphos-Methyl. In addition, while knockdown and mortality rates remain high there are few systematic studies on changing bionomics and behavioural adaptation to insecticide use. The relative high prevalence of low mortality rates to all currently available pyrethroid insecticides is a concern for the effectiveness of wide-scale ITN programmes nationwide.

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Chapter 6

Vector control: two decades of changing coverage

6.1 Expanding Insecticide treated net (ITN) coverage: 2000-2012

Reports of mosquito net use, or "mosquito cages", date back to the first half of the last century, promoted as a means to protect colonial officials and expatriate workers from malaria (Section 3.2). From the 1960s to the early 1990s very few people used mosquito nets [Trent, 1965; Gardiner et al., 1984; Lobel & Beier, 1989] and the association between mosquitoes and malaria was a poorly formed community concept [Adjei et al., 1988; Ahorlu et al., 1997; Agyepong & Manderson, 1999].

In 1993, a large-scale community-randomized trial of insecticide (Permethrin 50% EC) treated nets was undertaken at Navrongo in Kassena-Nankana district, Upper East Region [Binka et al., 1996]. 21,500 ITN were distributed across half the population living in *circa* 6,000 compounds in June 1993; nets were re-treated every six months and the trial was completed in July 1995. Compliance was over 70% between July and December but lower (50%) during the hot seasons between January and June. Mortality was significantly reduced by 17% in children aged 1 month to 4 years [Binka et al., 1996]. The cost per person protected per year was approximately US$ 1.2; and 16,800 child years were protected resulting in 74 child deaths averted at an estimated cost of US$ 8.8 per child year protected and US$ 2,003 per death averted [Binka et al., 1997]. Despite the impressive child survival gains demonstrated during the Navrongo study, very little concerted effort was made to expand ITN coverage across Ghana for at least a decade.

In 1999, an ITN task-force was established that provide inputs into the design of the ITN dilevery appoaches articulated in NMSP 2000-2010 to "*Increase the number of people especially children and pregnant women sleeping under an adequately treated net from about 4% to 70% by 2010*" [NMCP, 2000]. In 2002, the Government of Ghana waived taxes on the importation of nets into the country, but retained Value Added Tax. A few development partners and NGOs began to provide ITNs for distribution at subsidised or full costs to pregnant women and children under five in some areas of the country.

The focus of ITN distribution during the early 2000s was on private-sector promotion, social marketing or cost-retrieval based on voucher schemes to pregnant women [NetMark, 2005]. The 2000-2010 NMSP specifically stated that the aim was "*...to create a demand for both ITMs* [Insecticide Treated Materials] *and retreatment and then for the commercial sector to service this demand. The essence of this project is the development of partnerships between key public and commercial players, which have different, though complimentary, reasons for promoting a common goal, that of increasing the use of ITMs in Ghana*" [NMCP, 2000]. The national Insecticide Treated Materials Policy, launched in 2002, was anchored on a market-driven approach to delivery "*strategies to promote ITM shall focus on product supply, distribution, promotion and product pricing. An integrated, multifaceted, consumer orientated campaign based on market research shall be adopted and shall aim at improving knowledge and changing attitudes towards ITMs*" [NMCP, 2002]. The dual approach to be taken was a) full commercial cost through private sector; and b) to protect vulnerable groups who could not afford full costs at subsidized prices distributed by district health management teams and NGOs [NMCP, 2002].

In December 2002, in Lawra district, Upper West Region, free ITN were distributed as part of a mass measles vaccination campaign for all children aged 9 months–15 years. The programme was supported by the Ghana Health Service, the Ghana Red Cross and UNICEF and provided within a single week 4,520 pre-treated nets (with the brand name of DAWA) and 10,080 nets pre-treated with 20 mg/m² deltamethrin. Prior to the campaign only 4.1% of children under the age of five slept under an ITN, five months following the campaign this had increased to over 60%. The marginal operational cost was US$ 0.32 per ITN delivered [Grabowsky et al., 2005].

In May 2004, DFID and USAID supported a pilot voucher system for ITN distribution in the Volta Region, that later expanded to the Eastern Region with Global Fund support. The pilot scheme was developed to learn lessons ahead of scaling up nationally as a scheme based on a mixed public-private sector approach to ITN distribution. The scheme provided discount vouchers to pregnant women during their first presentation at antenatal clinics, entitling them to ¢ 40,000 (*circa* US$ 4.20) discount on an ITN (PermaNet, Dawanet or K-O Net) available through private commercial retail outlets if they could afford the top-up cash required. The retailer removed a 'proof-of-purchase' sticker from the ITN pack and attached to the voucher. The retailer was then able to exchange the voucher for more stock and kept the top-up value of cash from the client. The distributors (Transcol Ltd, AgriMat and NetCo Rockville) then exchanged the voucher with its proof-of-purchase sticker for cash from a management agent. The management agent was responsible for redeeming vouchers, supplying vouchers to the health facilities, and for monitoring voucher supplies and redemptions [Burns & Aziz, 2007; de Savigny et al. 2012].

During the first year of the pilot in 11 districts in the Volta Region, 43,050 vouchers were provided to the clinics across the region, 60% of these were issued to eligible women from the clinics. Of the vouchers issued from the clinics 67% were redeemed by distributors back to the management agent. Not all target women were reached and this varied by location: in the central zone of the region 71% of registrants were issued with a voucher, compared with only 38% and 37% in the northern and southern zones, respectively. Of the 133 health facilities provided with vouchers, 11 did not issue any to registrants. 63% of vouchers issued from urban health facilities were redeemed compared with 47% of those issued from rural clinics [Kweku et al., 2007].

In October 2004, the WHO country programme, JICA, UNICEF and Rotary Polio Plus supported the delivery of over 275,000 ITN during the National Immunization Days (NID) in the Central Region. Post-distribution surveys showed that the coverage of ITN through the NID delivery had managed to increase the proportion of children sleeping under a net to 35% [George, 2004], from less than 9% during the DHS survey in 2003 in Central Region [GSS, 2004].

The voucher scheme in Greater Accra and Ashanti Regions was supported for 6 months during 2004 by Exxon Mobil. With Global Fund Round 4 assistance, the voucher scheme expanded across Volta, Eastern, Ashanti and Brong Ahafo Regions. ITNs were offered to women at registered retail outlets or clinics at a discounted price of US$ 4.20. At Lawra district, three

years following the free mass ITN campaign, the voucher scheme served as a "keep-up" campaign for clinic attendees but there was no outreach to women who did not attend the clinic. At Lawra, in February 2006, 38-months post-free mass campaign, a survey of ITN use was undertaken which showed a high rate of retention of the nets provided during the mass, "catch-up" campaign that occurred 3 years prior to the survey. Among children less than five years, 73% slept under any type of net and 60% slept under an ITN. Of all nets, 78% came from the original campaign, 2% were obtained before the campaign and 21% after the campaign. Following the campaign, most of the nets acquired were from routine "keep-up" activities through voucher scheme at ante-natal clinics (75%). The contribution of "keep-up" nets acquired through the commercial sector was small (5%) and that the ANC clinic voucher system was able to meet the need for "keep-up" nets [Grabowsky et al., 2007]. Between April 2006 and July 2007, over 10 million nets were distributed through the voucher scheme in Volta, Eastern, Ashanti and Brong Ahafo Regions [Burns & Aziz, 2007]. The voucher scheme was partially implemented in the Central Region from 2008.

A small project was initiated in Accra and Kumasi in 2006, as a collaboration between NMCP, Noguchi, LSHTM, NetMark and Malaria Consortium and EXP-momentum, funded by DFID. The project involved local tailors to sew nets of different consumer preferred designs and provided with treatment kits. A total of 2,535 and 1,440 nets were treated in Accra and Kumasi respectively.

During the first week of November 2006, a nationwide integrated measles/polio/vitamin A/ITN distribution campaign was carried out with the support of DFID, UNICEF and the Government of Japan, that managed to deliver 2.1 million ITNs free to children under two years of age. This was repeated in 2007 through the Integrated Maternal and Child Health Campaign (IMCHC) with the distribution of over 1.5 million nets provided by the UNICEF and the World Bank. In addition, the World Bank supported the delivery of 200,000 nets towards the Malaria Nutrition Project in selected districts in Northern, Upper East, Upper West, Volta and the Central regions. In 2008, about 250,000 nets were provided by UNICEF and distributed free during IMCHC to infants in the Northern, Upper East, Upper West and the Central regions. These campaigns could not reach the entire country, however in 2008, DFID provided support for 350,000 nets to be delivered to the Western Region as part of routine distribution.

Up to 2009, the NMCP had adopted a mixed model approach to ITN distribution, subsidized distribution through the public and private sector, workplace and NGO distributions, full-cost sales and occasional free distribution "catch-up" campaigns. However, there was a realization that these approaches were slow to reach pre-set targets and older children and adults, who contribute to transmission, were not being reached. There was therefore a significant policy move toward "universal coverage" and the expansion of free mass campaigns [NMCP, 2009]. The 2008-2015 national malaria strategy states as one of its primary objectives to ensure that 100% of households will own at least one LLIN and that 80% of the population sleep under a treated net, and 85% of young children and pregnant women sleep under a treated net by 2015 [NMCP, 2008].

In 2010, the NMCP began focusing on a "catch-up" strategy of implementing free mass distribution campaigns with the goal of achieving universal coverage of LLINs in all ten regions by 2012. This campaign provided free LLINs during door-to-door, hang-up exercises using community volunteers nationwide, distributing over 12.4 million LLINs over two years. The majority of funding for these nets came from the Global Fund, however DFID (4.35 million LLINs), PMI (3 million LLINs) and the World Bank (650,000 LLINs) provided significant contributions. The door-to-door and hang-up approach started in May 2010 in the Northern Region, through a campaign targeting just children under five and pregnant women. Over 560,000 LLIN were distributed and did ot reach targets because of insufficient numbers of nets. The remaining campaigns aimed at universal coverage of the general population, defined as one net per every two persons. The NMCP goal for these campaigns was to achieve 100% of households owning at least one LLIN. By July 2011, over 2.2 million LLIN had been distributed across districts in the Eastern and Volta regions. By the end of 2011, 2.4 million LLIN had also been distributed to households in the Western and Central Regions. Populations living the Central, Ashanti, Upper East, Upper West and Brong Ahafo regions were targeted between February and May 2012 to receive *circa* 4.9 million LLIN. The Northern region was revisited in August 2012 to distribute a further 1.3 million LLIN to reach the whole population. Finally, in the Greater Accra Region over 2 million LLIN were distributed in October 2012. Households in the elite areas of Greater Accra were not covered by the free campaign.

The mass distribution campaign generated a large amount of plastic pollution from the empty packs. The NMCP worked with partners, including PMI-Deliver, to collect empty packs from districts which were recycled at the Cyclus Recylcing Plant at Aburansa in the Elmina sub-district in the Central Region into environmentally friendly pavement blocks.

6.2 Measuring ITN coverage and use

6.2.1. 2003-2005

Between July and October 2003, the Ghana Demographic and Health Survey (GDHS) undertook a two-stage sample survey of 6,600 households in 412 enumeration areas (EAs). Overall, 18% of households owned a mosquito net (treated or untreated), while only 3% of households owned at least one currently treated net (ITN). Rural households were more likely to own any kind of net (24%) compared with urban households (10%). Net ownership was highest in the Volta Region (46%)and lowest in the Central Region (9%). 15% of children below five years slept under a mosquito net (treated or untreated) the night before the survey but only 4% slept under an ITN the night prior to the survey. Children in rural areas were twice as likely to sleep under a mosquito net (18%) compared to urban children (9%) and lowest among children in the highest wealth quintile. 10% of pregnant women slept under any net and only 3% slept under an ITN the night before the interview [GSS, 2004].

A survey of 1500 households was undertaken almost a year after the GDHS, in August 2004, in five selected areas (Accra, Keta, Kumasi, Wa and Tamale - 120 households from each urban centre and 180 households from up to 200 km from the urban centre) [NetMark, 2005]. This

survey showed that 19% of households owned at least one ITN, use of an ITN the night before the survey was 13% among children aged less than five years, 8% among pregnant women and there were few socio-economic or urban-rural differences [NetMark, 2005]. The most common reason given for not owning a net was lack of money (63%). Another 17% of respondents (46% in Tamale) cited lack of availability; and 13% of respondents (31% in Accra) said they did not need nets or used something else for protection against mosquitoes [NetMark, 2005].

During a study in 2004 among 13 communities in the Afram Plains District of the Eastern Region and 20 communities in the Asikuma-Odoben-Brakwa District of the Central Region, only 9.5% of children less than five years of age slept under a bed net the night before the survey while only 1.4% slept under an ITN [De la Cruz et al., 2006]. Importantly, the study showed that mothers from food secure households were 2.5 times more likely than their food-insecure peers to have children sleep under nets, suggesting that choices for purchasing a net over food had been made by these poor communities [De la Cruz et al., 2006].

6.2.2 2006-2008

In 2006, a Multiple Indicator Cluster Indicator Survey (MICS3) was undertaken at 6,302 households at 300 EAs (124 urban and 176 rural) between August and October 2006 [GSS & UNICEF, 2007]. 18.7% of households owned an ITN, 33% of children under the age of five years were reported to have slept under any form of net the night before the survey, while only 22% had slept under an ITN, a small increase over the 2003 GDHS survey results. Consistent with earlier observations rural children were more likely to use an ITN than urban children. Regional differences in under-five ITN use were noted, the highest coverage was observed in Upper East Region (39.3%), coverage in Volta Region had dropped from 43% in 2003 to 21.5% inn 2006 and the lowest coverage was reported from Western Region (11.5%) and Greater Accra Region (16.3%) [GSS & UNICEF, 2007].

Between September and November 2008, a GDHS was repeated at 412 EAs and 11,778 households [GSS et al., 2009]. During this survey household ownership of at least one ITN had increased to 40%. Poorer and rural households were more likely than wealthier, urban households to own an ITN. Overall 41% of children under the age of five were reported sleeping under an ITN the night before the survey, with no significant wealth quintile differentials although still higher in rural communities (45%) compared to urban communities (34%) [GSS et al., 2009]. The highest reported under-five ITN use were in the Upper West (64%), Upper East (42%) and Brong Ahafo Regions (57%); the lowest coverage was reported in Central (29%) and Greater Accra (30%) regions. At the time of the survey 32% of pregnant women reported sleeping under an ITN [GSS et al., 2009].

In August 2008, NetMark undertook a second household survey (n=1,796) at urban and matched rural communities in six sites in the Greater Accra, Ashanti, Central, Volta, Northern and Upper West Regions [NetMark, 2009; Baume & Koh, 2011]. During this survey 61% of households owned at least one ITN. Among all 1852 nets observed 76% were Long-Lasting Insecticide Treated Nets (LLINs), 10% were ITNs and 14% were non-ITNs (untreated or the

treatment had expired). The most common colour was white (63%), followed by light blue (18%), dark blue (7%) and green (7%). 43% of nets were less than a year old, 18% were at least one year old, 25% were at least two years old, 8% were at least three years old and 5% were four or more years old. The majority (64%) of nets had been acquired free of charge, 34% had been purchased and 2% were acquired as a gift or through trade or barter. Interestingly only 59% of nets owned had been reported as used the night before the survey; approximately 21% of nets were still in the sealed package, thus had never been used [NetMark, 2009; Baume & Koh, 2011]. Multivariate analysis of a range of factors was used to establish possible reasons why almost 40% of owned nets were not used. Factors identified included: old nets were less likely to be used than newer ones as old nets are likely to be worn and unattractive; light blue nets were more likely to be used than white nets, possibly because the darker colour does not show dirt as readily as white [Baume & Koh, 2011].

6.2.3 2011

The MICS4 survey began in September 2011 and was completed in December the same year, providing information on net among 11,925 households [GSS, 2012]. The survey followed universal-coverage campaigns in the Eastern, Volta and Western Regions, while the Central Region began its campaign toward the end the survey period. It is therefore worthwhile only considering net coverage in 2011 in these districts as representative of the changes in coverage since 2008. In the Eastern Region household ownership of at least one ITN increased from 36% in 2008 to 78% (almost all LLIN) in 2011 with over 60% of children aged less than 5 years and 51% of the total population protected by an ITN. In the Volta Region household ownership of at least one ITN increased from 43% in 2008 to 85% (almost all LLIN) in 2011 with over 71% of children aged less than 5 years and 66% of the total population protected by an ITN. However, in the Western Region, household ownership of at least one ITN appeared not to have changed from 41% in 2008 to 42% (almost all LLIN) in 2011 with only 33% of children aged less than 5 years and 24% of the total population protected by an ITN. Overall, the results showed that almost 29% of Ghanaian's reported sleeping under an ITN the night before the MICS4 survey in 2011, 42% of children aged less than five years and 33% of pregnant women [GSS, 2012].

The MICS4 2011 survey included data on disposal of old nets. 8% of households had disposed of at least one net in the last year, where 47% of disposed nets had been kept for less than 2 years, 36% had used the net between 2 and 4 years and 17% had used the net for more than 4 years. The major reason cited for disposing of the net was that the net was torn (81%) [GSS, 2012].

6.2.4 Modelling and mapping ITN Coverage

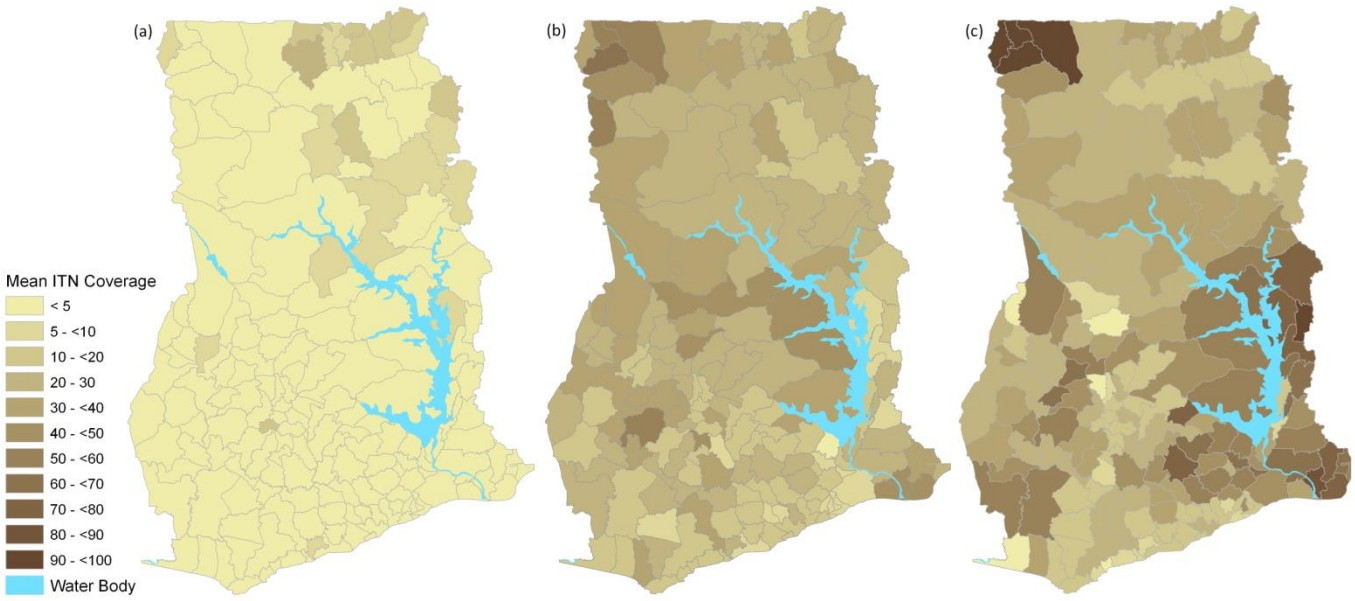
As described above several important national household surveys have been undertaken across Ghana since 2003.

Typically, national household surveys are designed to be precise at national and regional levels and rarely at lower levels such as districts. Therefore, simply aggregating survey data to provide

district level estimates of an outcome of interest will lead to values of low precision. District level estimates, however, are more important to planners in order to accelerate policy interventions, optimise inputs and improve coverage of health interventions. Small Area Estimation (SAE) methods handle the problem of making reliable estimates of a variable at these areal units under conditions where the information available for the variable, on its own, is not sufficient to make valid estimates [Rao, 2003; BIAS, 2007].

We have used hierarchical spatial and temporal SAE techniques with a fully Bayesian geo-additive regression approach [Banerjee et al., 2004; Best et al., 2005; Fahrmeir & Lang 2001; Kamman & Wand 2003] to estimate the ITN coverage in all age groups by district for the years 2003, 2008 and 2011. Importantly we have elected to predict quantities among all age groups as this now represents the important indicator for universal coverage and necessary when computing likely impacts on malaria transmission [Smith et al., 2009; Griffin et al. 2010]. Details of model procedures are presented in Annex A3. The data-driven, modelled predictions of the proportions of all age groups sleeping under an ITN for the survey years 2003, 2008 and 2011 are shown in Figure 6.1.

Figure 6.1: The mean ITN coverage predictions in Ghana (using neighbouring information for the years: a) 2003 b) 2008 and c) 2011



6.3 Indoor Residual Spraying

Indoor Residual Spray (IRS) has not been a dominant form of vector control in Ghana since its use during World War II at Takoradi and Accra [Eddey, 1944; Roberts, 2010], limited use during urban malaria control in the 1940s-1960s in Accra [Chinery, 1968] and moderate experimental DDT and dieldrin use during the Ghana-1 project in the Volta Region during the early 1960s

[Delfini & Beausoliel, 1964]. During the first national malaria strategy 2000-2010, IRS did not feature prominently [NMCP, 2000].

Interest in IRS was resurrected following adoption in the Obuasi Municipal Assembly Area (Ashanti Region) as part of AngloGold Ashanti's (AGA) Integrated Malaria Control Program from 2005. The programme aimed to halve the incidence of malaria within two years across the mining concerns catchment area, on the basis that the disease significantly impacted on labour productivity and illness among employee's families. A multi-strategy approach was taken including mapping vector breeding sites, larviciding, 120 community volunteer advocates, the use of IRS (starting with the pyrethroid, alpha-cypermethrin) and the distribution of ITN to orphanages, maternity homes and the children's wards of two main hospitals. The total costs were US$ 1.7 million during the first year of operations and averaging US$ 1.3 million per year thereafter. The programme trained 116 spraymen and covered over 130,000 dwellings [AGA, 2007; RBM, 2011]. An average of 6,600 malaria cases reported per month in 2005 fell to 1150 cases per month in 2009; average monthly lost days of work due to malaria fell from 6,983 in 2005 to 282 in 2009;; and average monthly medication costs to the company fell from US$ 55 000 in 2005 to US$ 9,800 in 2009 [RBM, 2011]. This effort by a mining company in Ghana was in stark contrast to the less corporate responsibility shown almost a century earlier [Dumett, 1993; Section 3.2] and earned AGA the Global Business Coalition Award in the United States in 2007 [GBC, 2013].

The NMSP for 2008-2015, aims to provide IRS to at-least 90% of all houses in targeted districts by 2011 and sustain this coverage through to 2015 [NMCP, 2008a]. The Malaria Vector Control Oversight Committee (MaVCOC) was established in June 2009 as an advisory committee and to develop national standard operating procedures and entomological/insecticide resistance management strategies, and to support capacity building [NMCP, 2009].

The AGA success encouraged PMI to support five districts of Northern Region (Savelugu Nanton, Gushiegu, Karaga, Tolon Kumbugu and West Mamprusi) from May 2008 with a single spray round before the rains. Over 330 spray operators and 138 community volunteers were trained and deployed. In 2008, a total of 304,217 rooms in 68,252 houses were sprayed protecting an estimated population of over 602,000 people. The program expanded to six districts in 2009, and eight districts in 2010 covering a population of over 849,000. In 2011, PMI IRS activities protected 926,699 persons and achieved 92% coverage of sprayable structures in an expanded nine districts in the Northern Region. In 2008, 2009 and 2011 alpha-cypermethrin was used and deltamethrin was used in 2010. IRS activities continued to be supported by PMI including insecticide procurement, environmental assessment, compliance monitoring, resistance monitoring, community mobilization, spray operations, data collection and reporting. Furthermore, from 2012 and as part of the US$ 158 million financing provided under the Global Fund Round 8 support, with technical support from AGA in addition to PMI supported spraying, IRS was targeted for 40 districts by the end of 2013. By the end of 2012, following wide-spread evidence of pyrethroid resistance (Section 5.7), the organophosphate, Pirimiphos methyl was introduced and planned to be rotated over the coming years with the

carbamate, proxpur across all original PMI supported districts, Obuasi and the new districts supported under the expanded Global Fund support (Table 6.1).

Table 6.1: 2011-2015 IRS schedule with Global Fund support

IRS Start Date	District	Region	2013 Pop. Projection
Jul-11	Obuasi Municipal	Ashanti	186,741
Jan-12	Amansie Central	Ashanti	101,091
	Adansi South	Ashanti	128,013
	Adansi North	Ashanti	119,164
	Wa West	Upper West	90,945
	Wa Municipal	Upper West	115,702
	Wa East	Upper West	80,466
Jul-12	Upper Denkyira (Split District)	Central	147,387
	Sissala West	Upper West	55,463
	Nadowli	Upper West	105,219
	Jirapa - Lambussie (Split Districts)	Upper West	156,365
	Lawra	Upper West	111,534
Jan-13	Ahanta West	Western	117,338
	Wassa West (Split District)	Western	272,776
	Nzema East Municipal	Western	67,036
	Sissala East	Upper West	63,092
	Builsa	Upper East	104,762
Jul-13	Bolgatanga	Upper East	146,739
	Kassena Nankana (Split District)	Upper East	200,712
	Talensi Nabdam	Upper East	129,193
	Bawku West	Upper East	105,253
	Bongo	Upper East	95,034
Jan-14	Bawku Municipal	Upper East	243,455
	Garu Tempane	Upper East	145,525
	Sawla Tuna Kalba	Northern	111,874
Jul-14	West Gonja	Northern	94,180
	East Mampurisi	Northern	135,312
	Central Gonja	Northern	97,790
	Bole	Northern	68,240
Jan-15	Nanumba North	Northern	157,724
	Nanumba South	Northern	102,174
	Yendi	Northern	223,598
	Zabzugu Tatale	Northern	138,043
Jul-15	East Gonja	Northern	150,635
	Saboba Chereponi (Split District)	Northern	133,616

During the MICS4 2011, households were asked whether their interior walls had been sprayed in the last 12 months. Only 5% of households nationwide had received IRS, however as might be expected 36% of households had been sprayed in the Northern Region and Ashanti Region had 9% of households sprayed. All other regions reported less than 2% [GSS, 2012].

6.4 Larval control

Environmental management and larval control were the mainstay of vector management strategies between 1900 and the 1950s (Section 3.2). With the exception of occasional urban control initiatives during the 1960s, this approach to malaria control has not been aggressively pursued in Ghana. There is some reference to an initiative involving local government and the Ministry of Water and Sanitation in the first NMSP of 2000-2008, referred to as the Expanded Sanitary Inspection and Compliance Enforcement programme [NMCP, 2000], however few details exist on its activities or accomplishments. From the late 1990s, the World Bank provided the Ghanaian government two credit loans of over US$ 144 million and US$ 10 million for the Accra District Rehabilitation Project. Each loan was specifically for projects addressing various elements of environmental sanitation and urban upgrading in low income areas; the projects focused on Accra, Kumasi, Sekondi-Takoradi, Tamale, and Tema. A collateral ambition to reduce disease vector breeding sites through better drainage management and protecting from flooding low lying areas. The Bank considered that the projects had been only moderately successful at the end of the funding cycle [World Bank, 2013].

The Integrated Malaria Vector Management Policy, launched in 2009, promotes a) biological control using *Bacillus thuringenensis israelinesis* (*BTi*) and *Bacillus sphericus* (*BS*), where several locally produced strains of *BS* gram positive spores are toxic to local anopheline larvae [Thiery et al., 1992; Ampofo, 1995]; b) the use of lavivorous fish, including local guppies *Poecilia reticulata*; c) chemical larviciding; and d) environmental management, which encompassed filling in of borrow pits, ditches, irrigation, ponds and canals notably in urban, mining, irrigation and other development settings [NMCP, 2009].

Despite these recommendations, there are few documented examples of integrated vector management or environmental management since 2009, with a few notable exceptions. Larviciding was used extensively by AGA at Obuasi using Temephos (Abate) as the chemical agent and *BTi and BS* as the biological control agents [AGA, 2007]. A pilot investigation using mapping of larval breeding sites and the application of *BTi* in the Asokwa sub-metropolis, Kumasi was undertaken in 2011 [Nartey et al., 2013]. Finally, Labiofam, a Cuban biological company signed a US$ 74 million deal with the Ghana Government to develop a factory on the outskirts of Tamale and provide biological larvicides for a nationwide attack on malaria [Myjoyfonline, 2010; Citifmonline, 2011]. There are some reports of limited larviciding programmes in the urban areas of Accra, Sunyani and Kumasi. Very few details of the Labiofam activities have been shared with the MaVOC.

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Chapter 7

Summary, recommendations and action points

7.1 The epidemiology of malaria in Ghana

We have assembled the largest ever repository of parasite and vector survey data in Ghana from a wide range of published and unpublished sources. These data have been used to explore the spatial patterns of parasite transmission intensity using model based geo-statistical (MBG) methods to provide quantities of risk across 170 health districts.

Plasmodium falciparum remains the dominant plasmodial species (97%). *Plasmodium vivax* has not been reported in Ghana. Both *P. malariae* (2.7%) and *P. ovale* (0.2%) are rare parasites, and there is some suggestion that *P. malariae* has become increasingly rare over the last fifty years (Section 4.6).

Overall, the mean population weighted childhood parasite prevalence (PA*Pf*PR_{2-10}) across Ghana in 2000 was 47% and in 2010 it was 45%, suggesting that over the last decade there has been little change at a national scale in the level of malaria risk.

It has not been possible to provide a district-by-district estimate of changing malaria risk as there were too few data and too over-dispersed to provide aggregates of sub-national risk around the 2000 time period. Data were more nationally ubiquitous around 2010, allowing for greater precision in sub-national predictions. We have therefore focused on describing the patterns of malaria for the year 2010 and have presumed little overall change since 2000. The findings, discussed below, suggest that 2010 is likely to be a reasoned estimate of "baseline" infection risks for the planning of future control strategies over the next 5-10 years.

Ghana is a country that supports intense *P. falciparum* transmission. In 2010, we predicted that 11.3 million people, 47% of the population, were living in areas where the parasite rate in children (*Pf*PR_{2-10}) was 50% or greater, including 4 million people (17%) who lived in areas where *Pf*PR_{2-10} was greater than 75%. These intense transmission conditions were most prevalent in the most northerly two-thirds of the country (Figures 4.6a-c). Ghana represents one of the most intense transmission countries in Africa.

Short-term impacts on transmission intensity, following scaled ITN coverage, will be harder to achieve in high transmission settings like Ghana compared to areas where the majority of the population start control with a lower intensity transmission profile [Smith et al., 2009; Griffin et al., 2010]. Ghana's current malaria status would also suggest that the majority of febrile events presenting to clinic will harbour infections, making unique parasitological diagnosis and attribution difficult and less cost-effective. The broad transmission profile for Ghana would be characteristic of a disease burden concentrated in very young children [Snow & Marsh, 2002] and a heavy, sub-clinical, burden among pregnant women contributing to poor pregnancy outcomes and infant survival [Guyatt & Snow, 2004; Desai et al., 2007; Asante et al., 2013; Amegah et al., 2013].

However, there are important transmission intensity differentials within the country. Over 3 million people (13% of the population) live in areas where the *Pf*PR_{2-10} is less than 10%. The

urban extents of Accra and neighbouring municipalities have considerably lower transmission compared to the rest of the country. The risks of infection are lower in Ghanaian cities compared to neighbouring rural areas [Pond et al., 2013]. The unique ecologies of urban extents for transmission offer opportunities for different vector control strategies and areas where parasitological diagnosis would be more cost-effective for case-management strategies. Just 10 large municipalities (Figure 4.10) account 6.4 million people who, while at much lower incident risks of malaria, will account for a significant number of infections.

There is an "island" of lower intensity parasite transmission, surrounded by a sea of intense transmission, at Kassena Nankana district in the Upper East Region, where sustained surveillance and intervention has been maintained over many years [Bawah & Binka, 2007]. A similar "island" of lower transmission is observed around Obuasi, where IRS has been sustained since 2005 (Section 6.3). In both areas it is likely that an epidemiological transition is beginning to emerge.

Other parts of Ghana are best described as meso-endemic (*Pf*PR_{2-10} 10-50%), affecting 9.6 million people, largely located in the east and south of the country (Figures 4.6a-c). The 58 districts that supported meso-endemic transmission in 2010 are likely to witness a larger reduction in transmission intensity following scaled single approaches to vector control, such as ITN, compared to higher transmission northern districts over the next five years. These spatial heterogeneities are important to recognize in the future design of control. A detailed summary of district risks is provided in Annex A2.

The parasite based estimates of transmission intensity are supported by very high entomological inoculation rates from dominant vector species (DVS) recorded across multiple sites in Ghana recorded since 2000 (Section 5.6). The principal vector remains the highly efficient *An. gambiae* s.s. with a smaller contribution provided by *An. funestus*. *An. melas* has a restricted range along the coast. *Anopheles nili, An. pharonesis, An. coustani* and *An. rufipes* have all been described in Ghana but their role in transmission is unclear. Resistance has now been documented for pyrethroid, organochloride and carbamate insecticide classes (Section 5.7). Vector abundance has repeatedly been shown to be acutely seasonal across all areas of Ghana following the two rainy seasons in the southern part of the country and the single seasonal rains in the north (Section 5.3).

Using rainfall concentration indices we have shown that there are 0.48 million people living in four Northern districts (Bawku Municipal, Bongo, Kassena Nankana, Kassena Nankana West) who would benefit from Seasonal Malaria Chemoprevention (SMC) (Section 4.7). If a more liberal definition of seasonality is applied this would include many more northern districts and cover approximately 3 million people.

7.2 The control of malaria in Ghana

Ghana has a rich history of malaria control. Strategies initiated during the pre-independence period have re-emerged as deserving renewed attention in contemporary control (Chapter 3).

These include the use of drug-based, community prevention strategies, improving access to treatment using government approved medicines and advice, outside of routine clinics (post-offices in the 1930s and commercial retailers in the 2000s), the role of school children as agents of behavioural change, urban municipality malaria control and the use of IRS. Drug and insecticide resistance have been a seen as threats to sustainable, effective control for over fifty years. There are three important differences between today's control landscape and those before independence. First, the populations knowledge about malaria and its aetiology has changed dramatically, communities today are aware that mosquitoes transmit malaria and that malaria is a serious febrile disease. Second, malaria has been perceived as a threat to national economic development for over 50 years, however, today the control of malaria has a unique position within national development policies and an unprecedented political commitment. Finally, adequate and sustained financing of malaria control plagued colonial authorities, whose interest was largely only restricted to European settled areas and mining concerns. Over the last decade Ghana has received substantive amounts of Overseas Development Assistance dedicated to the support malaria control, including since 2008 US$ 158 million from the Global Fund. These funds have supported a change in drug treatment policy, increased access to ITN and IRS and complimentary support structures necessary to meet targets laid out in two national malaria strategic plans covering 2000-2008 and 2008-2015 (Section 3.6).

The changing landscape of community, political and funding commitments has resulted in improvements in malaria prevention coverage since 2008. In 2003, only 3% of children slept under an ITN, by 2008 this had increased to 41% of children and by 2011, following mass free distribution campaigns in many parts of the country, this had increased to over 60% of children protected (Section 6.2). IRS began on a small scale at the AGA mining concern in Obuasi and PMI supported its gradual expansion in the northern districts by 2011 to protect approximately 1 million people (Section 6.3). A sustained effort to achieve universal vector control coverage requires additional resources and commitment over the next five years. Accessing effective treatment with ACTs remains a huge challenge.

By 2010, despite recent progress, demonstrable changes in disease risks and outcomes remain poorly defined, including a paucity of data on the impact of combined IRS and ITN. Routine HMIS data, collated for the MPR in 2013, suggests that since 2000 there has been almost no change in the annual reported cases of malaria, and some evidence of increasing disease rates since 2005 [NMCP, 2013]. Evidence of a steady rise in paediatric in-patient malaria admissions at 83 hospitals has also been documented [NMCP, 2013].

There are only a few sites able to provide a more detailed long-time series analysis of change, at Navrongo, Dodoma and Kintampo DSS sites (Section 2.6). To-date only the Navrongo DSS site has attempted to unpack the impact of years of changing intervention coverage on child health outcomes [Bawah & Binka, 2007].

This report, data assembly and analysis provides a platform to start a more detailed, informed retrospective analysis. The value of this work will be increased if it is possible to triangulate with other data, where available, on hospitalization rates, changing out-patient slide positivity

rates, detailed DSS household mortality data and longitudinal vector sporozoite positivity data. These data should be positioned within a contextual framework of changing intervention coverage and temporal aberrations and cycles in climate.

What will be possible is a more informed basis for the analysis of future changes associated with investment in control. How this analysis framework might be improved is discussed below.

7.3 Future work and action points

7.3.1 Monitoring the future epidemiological transition

Parasite prevalence is a far less ambiguous measure of malaria than estimated disease burdens from imperfect HIS or presumed causes of death using verbal autopsies. Parasite prevalence was used as a routine measure of intervention impact over 50 years ago as part of pilot investigations of drug and insecticide-based strategies to control malaria in Ghana (Section 3.4).

The MPR, undertaken in 2013, noted a number of challenges and key issues related to its review of the epidemiology, including: a) the absence of stratification of malaria endemicity up to the district level - tackled now in the work presented in this report; and b) the need to monitor parasite prevalence and malaria transmission [NMCP, 2013].

The modelled descriptions of parasite prevalence by health district in 2010 should serve as a baseline measure of semi-controlled malaria and repeated at least every three years with new data captured using new survey techniques.

The MICS4 survey was not powered to provide a robust index of malaria in sampled communities. Only young children were included and cluster sample sizes were small, reducing the spatial precision of infection risk when incorporated in MBG methods to provide estimates at district levels. There is a growing recognition that school-based parasite sampling procedures are a more cost-efficient sampling method, where school attendance is high and transmission intensity is above 5% [Gitionga et al., 2010; 2012; Brooker et al., 2009].

In Ghana's Global Fund Round 8 proposal it is stated that as part of strengthening M&E structures "*Parasitological cross-sectional surveys among schoolchildren and communities will be conducted as proxies for monitoring the impact of interventions on malaria transmission. These will be performed annually in order to establish trends by year*". Since 2008, there have been almost no systematic approaches to school-based parasite surveys, however, there is a growing use of this methodology as part of assessments of IRS [Owusu-Dabo et al., 2013].

It is recommended that a national schools parasite sampling protocol be developed as an important M&E collaboration between the NMCP and its research partners (**Action Point 7.1**). These data would serve to compliment additional data generated as part of the DHS in 2014 and the NMCP will need to work closely with partners involved in designing and funding the DHS 2014 to ensure that an RDT biomarker is included during this national household survey

(**Action Point 7.2**). The NMCP should also endeavour to harness any future research or intervention evaluation data likely to be collected by research and delivery partners in Ghana into a standard geo-coded format necessary for future risk modelling and mapping work. This responsibility could be devolved to a single research group and connected to the MPHD in Kenya (**Action Point 7.3**).

Any impact of the ITN mass campaigns undertaken in 2010 would not be reflected in the transmission intensity predictions made as part of this report for the year 2010. The impact upon transmission takes several years of sustained community use of treated nets and these impacts will not be equal as they depend importantly on baseline transmission. Repeating this work with new data in 2015 is therefore critical to understand the heterogeneous impact of increasing ITN and IRS coverage in Ghana.

7.3.2 Sustaining the vector occurrence and resistance database

We have assembled as much detail as possible on the current knowledge of DVS and their susceptibility to insecticides. This represents a composite of information from many sources and a valuable resource for future ecological modelling and operational application. It is, however, an equally important tool to identify where in Ghana, we have least detail on DVS and where data on insecticide susceptibility remains poorly defined. Importantly, there is a need to ensure that a) speciation of the gambiae complex is undertaken in future vector studies to investigate a changing composition and role of *An. arabiensis*; and b) insecticide sensitivity is conducted on populations of *An. funestus* (**Action Point 7.4**).

The database and Chapter 5 will be shared with MaVOC to assist in the planning of future vector surveillance and resistance monitoring and serve as a template database for further updates (**Action Point 7.5**).

7.3.3 Reconciling new health administration units

In this report we have analyzed data in accordance with 170 health administration levels used in Ghana for over five years. These are reasonably well recognized, devolved levels of decision-making and resource allocation. They have, however, recently been re-defined to 237 districts. These have yet to be finalized and cartographically defined. It will be important to repeat the resolution of all malaria and intervention coverage data at these new decision-making units ahead of the drafting and launch of the revised national malaria strategic plan.

It has been agreed that when these new administrative boundaries have been finalized by the GSS, the shape-files will be shared with the MPHD in Kenya who will re-define 2010 risks and hopefully 2010 ITN coverage in accordance with these district boundaries. This will be scheduled for completion in Version 2.0 by June 2014 (**Action Point 7.6**).

7.3.4 Mapping the employer sector

Engaging the private sector in the delivery of malaria prevention as part of national control has been an important feature of ITN and IRS delivery since 2005. Ghana has an ever growing commercial, private-sector involved in oil and gold mining and oil-palm, cocoa and rice agriculture. These companies are employers of large work forces and their families. AGA recognized the impact malaria posed to productivity during the mid-2000s and launched an independent campaign to control malaria in the vicinity of their Obuasi mine. The success and experience generated from this private-sector malaria control initiative led to further public sector funded initiatives in northern Ghana with a defined technical support role of AGA.

In addition, mining and agriculture intrinsically change the local transmission ecology. Open cast mining, in-land rice cultivation and irrigation are well recognized modifiers of malaria transmission. How these commercial interests effect the malaria burden within districts has not been well described and articulated in Ghana.

Beyond corporate responsibility, demonstrating the economic and human capital costs of malaria to a wider mining and agricultural private sector might lever additional commitments beyond AGA. A provisional mapping exercise of the location of these concerns is shown in Figure 4.10. Maps of employer locations, malaria risks and district profiles might serve as a useful advocacy tool to increase specific engagement of the private sector in district-level control. This would require a more detailed mapping, collaboration with other ministry sectors and an attempt to capture the informal, less well regulated mining activities across Ghana (**Action Point 7.7**).

7.3.5 Mapping health service access

Developing a single, geo-located health facility database has proved challenging since the early 2000s [Addai et al., 2006]. A renewed effort to provide a spatial platform for health service provision has gained momentum within the GHS and MoH in recent years. We have used various place name gazetteers to complete and clean the current national master health facility database (Section 2.9.2; Figure 2.7). This remains incomplete, with approximately 7% of facilities not spatially defined, however relatively easy to complete with DHMTs under some guidance from the NMCP (**Action Point 7.8**).

Access to clinical services is an area well suited to MBG methods using layers of mapped road networks, human settlement and locations of service providers. Several provisional applications of service accessibility have been undertaken in Ghana to look at usage of services in Ahafo-Ano South district [Bour, 2013] and access to maternity services nationwide [Gething et al., 2012; Masters et al., 2013]. There have been no applications developed for malaria treatment and diagnosis accessibility in Ghana.

The spatial data on population, malaria risk and health facility location could be used in a variety of innovative ways for practical application, including: a) defining vulnerable populations

most distal to curative care, requiring increased community-based services; b) computing and mapping the location and numbers of women of child-bearing age most distal to ANC services and hence IPTp; c) modelling populations with appropriate access to hospital services best suited to introduce supportive level rectal artesunate; d) developing novel methods for incorporating commodity data on drug use to improve drug management supply within and between districts, targeting zero stock-outs; and e) developing ways to improve the visual display and analysis of DHIS 2 reports of malaria clinic diagnosis data, improving with time the ability to define disease burden in combination with transmission risk. This will strengthen the value of district-level decision making [De Souza, 2009].

These innovations are likely to require a collaboration with national geo-spatial scientists, where some capacity already exists [Prosper & Duker, 2012], and will be tabled at relevant MoH and academic forums from 2014 as a catalyst for future national research enquiry (**Action Point 7.9**).

7.3.6 Maintaining national malaria data archives

A huge effort has gone into identifying malariometric survey data undertaken over the last 30 years in Ghana. These data have been carefully checked, geo-coded and stored in relevant databases. These represent important national resources for future work and investigations by control and academic communities within Ghana.

The metadata describing these databases is provided as part of this report. Housing, up-dating, further iterations of the metadata and creating access to the data demands a commitment and capacity within the NMCP. Creating this dedicated capacity requires greater investment in skills, equipment and finances. Ways in which this might be created as a national academic and GHS/MoH partnership should be explored with bi-lateral donor agencies (**Action Point 7.10**).

It is notable that the NMCP did not have immediate access to the final MICS4 datasets related to malaria. Harnessing the capacity to identify, house and use other national data will increase the culture and immediacy of evidence-based planning within the NMCP.

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Annexes

Annex A.1: Parasite prevalence model development

A.1.1 *Pf*PR$_{2\text{-}10}$ Model specification

A Bayesian hierarchical spatial-temporal model was implemented through SPDE approach using R-INLA library [R-INLA, 2013] to produce continuous maps of *PfPR*$_{2\text{-}10}$ at 1 × 1 km spatial resolution using data ranging from 1960-2011. The continuous indexed GF with covariance function was represented as a discretely indexed random process, that is, as a Gaussian Markov Random Field (GMRF) [Rue & Held, 2005; Lindgren et al., 2011; Cameletti et al., 2012]. This is where an explicit link between Gaussian Field (GF) and GMRF formulated as a basis function is provided through (SPDE) approach [Lindgren et al., 2011; Bolin & Lindgren, 2011; Simpson et al., 2012a; 2012b]. The solution for SPDE can be expressed as

$$(k^2-\Delta)^{\alpha/2}(\tau x(u)=W(u),\quad u\in\mathbb{R}^d,\quad \alpha=v+d/2,\quad \sigma^2-\Gamma(\mathrm{v})(\Gamma(\alpha)(4\pi)^{d/2}k^{2v}\tau^2)^{-1}$$
$$k>0,\ v>0, \qquad \text{(Equation A.1.1)}$$

This SPDE is a Gaussian random field with Matérn covariance function where W, is the spatial Gaussian white noise, Δ is the Laplacian, α controls the smoothness of the realization and τ controls the variance. The link between Matérn smoothness v and variance σ^2 is $\alpha=v+d/2$ and $\sigma^2-\Gamma(\mathrm{v})(\Gamma(\alpha)(4\pi)^{d/2}k^{2v}\tau^2)^{-1}$, where d is the spatial dimension [Lindgren & Rue, 2013]. An approximation of this SPDE can be solved using a finite element method (FEM), which is a numerical technique for solving partial differential equations [Lindgren et al., 2011]. In this case, the spatio-temporal covariance function and dense covariance matrix of the GF are replaced by a neighbourhood structure and a sparse precision matrix respectively and together define a GMRF. A GMRF can be described as a spatial process that models spatial dependence of data observed at a spatial unit like grid or geographical region and it can be expressed as $u=(u_1\ldots\ldots,u_n)'$ with $u\sim(\mu,Q^{-1})$. This is an n-dimensional GMRF with mean μ and a symmetrical positive definite precision matrix Q computed as the inverse of the covariance matrix [Cameletti et al., 2012]. Thus the density of u is given by

$$\pi(\mathrm{u})=(2\pi)^{-n/2}\left|Q\right|^{1/2}\exp(-\frac{1}{2}(\mathrm{u}-\mu)'\,\mathrm{Q}(\mathrm{u}-\mu)) \qquad \text{(Equation A.1.2)}$$

The sparse precision matrix Q offers computational advantage when making inference with GMRF. This is because the linear algebra operations can be performed using numerical methods for the sparse matrices which results in a considerable computational gain and this is further enhanced by using INLA algorithm for Bayesian inference [Rue & Held, 2005; Rue et al., 2009; Cameletti et al., 2012]. The infinite-dimensional Gaussian Random Field (GRF) is replaced with a finite-dimensional basis function representation

$$x(u)=\sum_{i=1}^{n}\psi_i(u)w_i \quad , \qquad \text{(Equation A.1.3)}$$

where w_i represents the weights and Ψ_i are piece-wise linear basis functions defined on a triangulation of the domain with n nodes which are defined as mesh in the code [Lindgren et al., 2011]. The basic functions are deterministic and are defined by each node in the triangulation while the stochastic property of the process is determined by the weights. The model used in this paper assumed non-stationary GRFs because environmental phenomena which are known to influence *PfPR*$_{2\text{-}10}$ are non-stationary in nature and therefore the distribution of *PfPR*$_{2\text{-}10}$ is non-stationary [Daly et al., 1994]. This non-stationary model was made possible by the flexible nature of SPDE models which allows modification of the SPDE rather than the covariance function to obtain the GRFs with other dependence structures other than the stationary Matérn covariance. The stationary isotropic Matérn covariance function, between locations u and v in $\mathbb{R}^d$ is expressed as

$$C(u,v) = \frac{\sigma^2}{2^{\nu-1}\Gamma(\nu)}(k\|v-u\|)^{\nu} K_{\nu}(k\|v-u\|) \ , \qquad \text{(Equation A.1.4)}$$

Where K_V is the modified Bessel function of the second kind, $\|\cdot\|$ denotes the Euclidean distance and order $\nu > 0$. $k > 0$ is a scaling parameter and σ^2 is the marginal variance. For the stationary model, k and ν are constant in space. The parameter k is linked to the range p by the empirically derived relationship $p = \sqrt{8}/k$. k, here can be described as the range parameter presiding over the spatial dependence structure of the GRF [Lindgren et al 2011]. For the non-stationary, τ and k space-dependent covariance parameters are introduced as functions of the spatial location u, $u \in D$, where D is the spatial domain. Therefore the modified SPDE becomes

$$(k(u)^2 - D)(t(u)x(u)) = W(u) \ , \ u \in \mathbb{R}^2 \ , \qquad \text{(Equation A.1.5)}$$

where x is a non-stationary GRF because τ and k vary by location and as the consequence the variance and correlation range vary by location. The non-stationary described above is defined on the mesh because it controls the local distance metric in the manifold. $\log \tau(u)$ and $\log k(u)$ can be defined as the sum of the basis function, where the basis functions $\left\{ \mathrm{B}_i^{(\cdot)}(\cdot) \right\}$ are smooth over the domain of interest.

$$\log(k^2(u)) = \sum b_i^{(k^2)} \mathrm{B}_i^{(k^2)}(u) \ \text{ and } \ \log(\tau(\mathrm{u})) = \sum \beta_i^{(\tau)} \mathrm{B}_i^{(\tau)}(\mathrm{u}) \, , \qquad \text{(Equation A.1.6)}$$

Using this SPDE approach, the overall hierarchical space-time binomial and zero-inflated binomial models of the prevalence to malaria parasite were used denoted by

$$y(s,t) = z(s,t)\beta + \xi(s,t) + \varepsilon(s,t) \, , \qquad \text{(Equation A.1.7)}$$

This model is characterised by a GF ***y(s, t)*** built from covariate information ***z(s, t)***, measurement error ***ε(s, t)***, and a second order autoregressive dynamic model for the latent process ***ξ(s, t)*** with spatially correlated innovations ***ω(s, t)***. The *Pf*PR$_{2-10}$ survey data were modelled as realizations of this spatial process (random field) changing in time. These realizations were used to make inference about the process and predict it at desired locations and at a specified time. This is where $y(s_i,t)$ was the realization of a spatial-temporal process representing the *Pf*PR$_{2-10}$ at the community location s_i , where $i=1...n$, and year t_j where $j=1...m$, $z(s_i,t_j)=(z_1(s_i,t_j)\dots z_p(s_t,t_j))$ represents fixed effect from the covariates for cluster s_i at time t_j , $\beta=(\beta_1\dots,\beta_p)'$ is the coefficient vector, $\varepsilon(s_i,t)\square N(0,\sigma_\varepsilon^2)$ is the measurement error defined by the Gaussian white noise process, and $y(s_i,t_j)$ is the predicted posterior mean prevalence of the plasmodium parasite in cluster i at time j . In the model formulation the large scale component that depends on the covariates is defined as $Z(s_i,t_j)\beta$ while the measurement error variance or the nugget effect is σ_e^2 . The realization of state process or the unobserved level of *Pf*PR$_{2-10}$ in this case is defined by $\xi(s_i,t_j)$ as a spatial-temporal GRF that changes in time as a second-order autoregressive function.

The prior for the SPDE model by default are Gaussian. In the latest version of SPDE function, the default priors are chosen heuristically to match the spatial scale of the MeSH domain. The user can override the defaults by supplying a "hyper" parameter [Lindgren, 2013]. This is normally suitable when the dataset lacks enough information for the likelihood to fully identify the parameters for the prior distribution. In this paper the SPDE default priors were sufficient for the model.

A.1.2 Constructing a suitable MESH

A finite element representation is used to outline the GRF as a linear combination of basic functions defined on a triangulation of the domain, say D. This is achieved by subdividing D into non-intersecting triangles meeting in at most common edge or corner, thus a *mesh*. The GRF in the triangulation is given by Equation (SI 3.3), where n is the total number of vertices, $\{\psi,(s)\}$ are the basis functions and $\{\omega_l\}$ are normally distributed weights [Lindgren et al., 2011; Cameletti et al., 2012].

The mesh function (*inla.mesh.create.helper*) in INLA is used to create a Constrained Refined Delaunay Triangulation (CRDT). The overall effect of the triangulation construction is that, if desired, one can have smaller triangles, and hence higher accuracy of the field representation. However, this will have an effect on the computation of the model. There is therefore a need to balance the number of triangles and the computation time required. If the data points (cluster coordinates) are used to construct the mesh, a cut-off value (specified in the function represents the maximum distance in which data points are represented by a single vertex. If the boundary of the area domain is used to construct the mesh, (i.e using the function points.domain=border), then the mesh is constructed to cover the border of the domain using

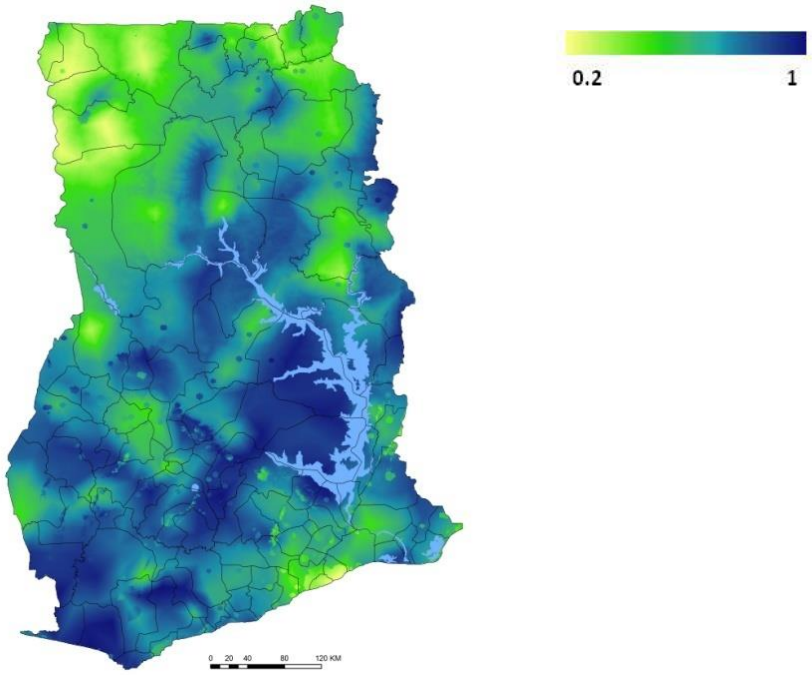
restrictions provided in other arguments. But if both data points and area domain (boundary) are used the restrictions are combined. In this model, the mesh was constructed using the boundary of the area domain. This method produces a mesh with regular size of triangles. A cut-off value was specified to avoid building many small triangles around *Pf*$PR_{2\text{-}10}$ input locations. A reasonable offset value was used to specify the size of the inner and outer extensions around the data locations. The maximum edge value was used to specify the maximum allowed triangle edge lengths in the inner domain and in the outer extension. The inner maximum edge value was made small enough to allow the triangulation to support representing functions with small enough features, and typically smaller than the spatial correlation range of the model. Therefore this value was adjusted to fit the range of the area domain in the model.

A matrix was then constructed to link the *PfPR*$_{2\text{-}10}$ input locations to the triangles on the mesh defined by η* as $\eta^* = A(x + 1\beta_0)$ and in the inla code in the following *inla.spde.make. A* function. This makes each row in the matrix to have three non-zero elements since every data point is inside a triangle and the corresponding columns are expected to have non-zero elements. In order to obtain a square matrix for the model, the response was linked to the index of the random field, where the length of the index vector was the same as the length of the projection matrix. In order to estimate the intercept, the stack function introduces a vector of ones in the matrix and this is removed in the formula by putting [-1] [Lindgren 2013].

A.1.3 Prediction accuracy

The standard deviation is a measure of the variability or dispersion of an expected value of a variable from its mean. High/low standard deviations indicate that data points are far/close to the mean. In scientific measurements it can be used as a measure of uncertainty. Of particular importance is the distance of the standard deviation (SD) from the mean. This is because the absolute value of the standard deviation could be both because of uncertainty but also a function of generally high base (mean) values of the measure under consideration. In this study, the distance (number) of the standard deviations of the mean *Pf*$PR_{2\text{-}10}$ were computed for the years 2000 and 2010. Both predictions were highly accurate with no where greater than one SD. For purposes of display we have shown gradations of less than 1 SD in Figure A.1.1.

Figure A.1.1: Standard deviation maps from posterior distributions of predicted mean *Pf*PR $_{2\text{-}10}$ for 2010: darker blue the less precise the predictions; however all predictions highly accurate.



A.1.4 References

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Annex A2. Population (%) in 2010 exposed to various classes of malaria and population-adjusted *Pf*PR_{2-10} and SMC suitable populations where 60% and 50-59% of annual rainfall within 3 months

Region/District	District Number	Total Pop 2010	*Pf*PR_{2-10} <5%	*Pf*PR_{2-10} 5-10%	*Pf*PR_{2-10} >10-50%	*Pf*PR_{2-10} >50- 74.9%	*Pf*PR_{2-10} 75%+	Population-weighted mean *Pf*PR_{2-10}	SMC 60%	SMC 50-59%
Ashanti										
Adansi North	1	104,244	0 (0%)	0 (0%)	45,077 (43.2%)	59,168 (56.8%)	0 (0%)	47.13	0 (0%)	0 (0%)
Adansi South	2	114,880	0 (0%)	0 (0%)	1,547 (1.3%)	113,334 (98.7%)	0 (0%)	57.49	0 (0%)	0 (0%)
Afigya Kwabre	3	131,473	0 (0%)	0 (0%)	13,470 (10.2%)	118,003 (89.8%)	0 (0%)	59.52	0 (0%)	0 (0%)
Afigya Sekyere South	4	95,649	0 (0%)	0 (0%)	33,032 (34.5%)	62,617 (65.5%)	0 (0%)	45.88	0 (0%)	0 (0%)
Ahafo Ano North	5	92,766	0 (0%)	0 (0%)	19,172 (20.7%)	73,594 (79.3%)	0 (0%)	57.05	0 (0%)	0 (0%)
Ahafo Ano South	6	118,017	0 (0%)	74 (0.1%)	23,918 (20.3%)	88,223 (74.8%)	5,802 (4.9%)	58.13	0 (0%)	0 (0%)
Amansie Central	7	93,865	0 (0%)	0 (0%)	29,943 (31.9%)	63,922 (68.1%)	0 (0%)	56.93	0 (0%)	0 (0%)
Amansie West	8	130,619	0 (0%)	0 (0%)	43,306 (33.2%)	87,313 (66.8%)	0 (0%)	50.44	0 (0%)	0 (0%)
Asante Akim South	9	121,212	0 (0%)	0 (0%)	16,504 (13.6%)	104,708 (86.4%)	0 (0%)	52.09	0 (0%)	0 (0%)
Asante-Akyem North Municipal	10	139,860	0 (0%)	399 (0.3%)	97,672 (69.8%)	39,923 (28.5%)	1,866 (1.3%)	38.02	0 (0%)	0 (0%)
Atwima -Kwanwoma	11	105,263	0 (0%)	360 (0.3%)	103,312 (98.1%)	1,590 (1.5%)	0 (0%)	25.98	0 (0%)	0 (0%)
Atwima Mponua	12	116,186	0 (0%)	10 (0%)	3,273 (2.8%)	87,891 (75.6%)	25,012 (21.5%)	67.23	0 (0%)	0 (0%)
Atwima Nwabiagya	13	180,007	0 (0%)	853 (0.5%)	165,315 (91.8%)	13,839 (7.7%)	0 (0%)	26.31	0 (0%)	0 (0%)
Bekwai Municipal	14	112,489	0 (0%)	0 (0%)	25,556 (22.7%)	86,933 (77.3%)	0 (0%)	59.20	0 (0%)	0 (0%)
Bosome Freho	15	62,367	0 (0%)	15 (0%)	5,315 (8.5%)	57,037 (91.5%)	0 (0%)	54.41	0 (0%)	0 (0%)
Bosumtwe	16	94,400	0 (0%)	0 (0%)	17,127 (18.1%)	77,273 (81.9%)	0 (0%)	59.64	0 (0%)	0 (0%)
Effiduase	17	60,875	0 (0%)	0 (0%)	8,903 (14.6%)	51,972 (85.4%)	0 (0%)	57.20	0 (0%)	0 (0%)
Ejisu/Juabeng Municipal	18	123,822	0 (0%)	0 (0%)	65,717 (53.1%)	58,105 (46.9%)	0 (0%)	47.76	0 (0%)	0 (0%)
Ejura Sekyidumasi	19	84,619	0 (0%)	0 (0%)	2,322 (2.7%)	52,639 (62.2%)	29,659 (35%)	64.95	0 (0%)	0 (0%)
Kumasi Metro	20	1,974,030	0 (0%)	1,232 (0.1%)	1,972,430 (99.9%)	364 (0%)	0 (0%)	23.17	0 (0%)	0 (0%)
Kwabre	21	125,688	0 (0%)	0 (0%)	105,574 (84%)	20,114 (16%)	0 (0%)	34.64	0 (0%)	0 (0%)
Kwahu North	22	215,906	0 (0%)	0 (0%)	172,865 (80.1%)	43,041 (19.9%)	0 (0%)	45.13	0 (0%)	0 (0%)
Mampong Municipal	23	84,573	0 (0%)	0 (0%)	45,156 (53.4%)	23,567 (27.9%)	15,850 (18.7%)	50.07	0 (0%)	0 (0%)
Obuasi Municipal	24	169,561	0 (0%)	0 (0%)	78,688 (46.4%)	90,873 (53.6%)	0 (0%)	44.32	0 (0%)	0 (0%)
Offinso Municipal	25	78,448	0 (0%)	0 (0%)	0 (0%)	68,281 (87%)	10,168 (13%)	66.34	0 (0%)	0 (0%)
Offinso North	26	57,102	0 (0%)	0 (0%)	0 (0%)	21,313 (37.3%)	35,789 (62.7%)	79.18	0 (0%)	0 (0%)
Sekyere Afram Plains	27	90,199	0 (0%)	0 (0%)	34,372 (38.1%)	45,184 (50.1%)	10,643 (11.8%)	54.42	0 (0%)	0 (0%)
Sekyere Central	28	70,803	0 (0%)	0 (0%)	25,914 (36.6%)	18,795 (26.5%)	26,094 (36.9%)	58.26	0 (0%)	0 (0%)

Region/District	District Number	Total Pop 2010	*Pf*PR$_{2-10}$ <5%	*Pf*PR$_{2-10}$ 5-10%	*Pf*PR$_{2-10}$ >10-50%	*Pf*PR$_{2-10}$ >50- 74.9%	*Pf*PR$_{2-10}$ 75%+	Population-weighted mean *Pf*PR$_{2-10}$	SMC 60%	SMC 50-59%
Brong Ahafo										
Asunafo North Municipal	29	122,049	0 (0%)	0 (0%)	13,556 (11.1%)	108,493 (88.9%)	0 (0%)	57.60	0 (0%)	0 (0%)
Asunafo South	30	96,813	0 (0%)	0 (0%)	0 (0%)	58,831 (60.8%)	37,982 (39.2%)	71.60	0 (0%)	0 (0%)
Asutifi	31	104,664	0 (0%)	0 (0%)	49,557 (47.3%)	55,107 (52.7%)	0 (0%)	52.65	0 (0%)	0 (0%)
Atebubu Amantin	32	104,505	0 (0%)	0 (0%)	0 (0%)	49,008 (46.9%)	55,496 (53.1%)	71.77	0 (0%)	0 (0%)
Berekum Municipal	33	127,838	0 (0%)	0 (0%)	11,941 (9.3%)	84,140 (65.8%)	31,757 (24.8%)	58.69	0 (0%)	0 (0%)
Dormaa East	34	50,866	0 (0%)	0 (0%)	0 (0%)	0 (0%)	25,960 (51%)	69.11	0 (0%)	0 (0%)
Dormaa Municipal	35	154,137	0 (0%)	0 (0%)	36 (0%)	68,798 (44.6%)	85,303 (55.3%)	71.24	0 (0%)	0 (0%)
Jaman North	36	80,724	0 (0%)	0 (0%)	0 (0%)	21,906 (27.1%)	58,468 (72.4%)	79.39	0 (0%)	0 (0%)
Jaman South	37	91,876	0 (0%)	0 (0%)	0 (0%)	8,289 (9%)	83,527 (90.9%)	78.84	0 (0%)	0 (0%)
Kintampo North Municipal	38	86,760	0 (0%)	0 (0%)	0 (0%)	57,729 (66.5%)	29,031 (33.5%)	69.18	0 (0%)	0 (0%)
Kintampo South	39	86,066	0 (0%)	0 (0%)	0 (0%)	35,873 (41.7%)	50,193 (58.3%)	73.78	0 (0%)	0 (0%)
Nkoranza North	40	62,257	0 (0%)	0 (0%)	91 (0.1%)	46,012 (73.9%)	16,154 (25.9%)	69.25	0 (0%)	0 (0%)
Nkoranza South	41	94,763	0 (0%)	0 (0%)	22,411 (23.6%)	62,216 (65.7%)	10,136 (10.7%)	61.44	0 (0%)	0 (0%)
Pru	42	128,388	0 (0%)	0 (0%)	0 (0%)	46,854 (36.5%)	81,533 (63.5%)	79.35	0 (0%)	0 (0%)
Sene	43	115,167	0 (0%)	0 (0%)	31,522 (27.4%)	78,104 (67.8%)	5,540 (4.8%)	57.74	0 (0%)	0 (0%)
Sunyani Municipal	44	120,938	0 (0%)	0 (0%)	65,548 (54.2%)	55,232 (45.7%)	159 (0.1%)	52.00	0 (0%)	0 (0%)
Sunyani West	45	85,366	0 (0%)	0 (0%)	62,982 (73.8%)	16,025 (18.8%)	6,358 (7.4%)	49.67	0 (0%)	0 (0%)
Tain	46	108,641	0 (0%)	0 (0%)	449 (0.4%)	32,547 (30%)	75,645 (69.6%)	79.74	0 (0%)	0 (0%)
Tano North	47	78,118	0 (0%)	0 (0%)	26,911 (34.4%)	47,025 (60.2%)	4,182 (5.4%)	57.73	0 (0%)	0 (0%)
Tano South	48	77,929	0 (0%)	0 (0%)	3,727 (4.8%)	48,117 (61.7%)	26,086 (33.5%)	67.41	0 (0%)	0 (0%)
Techiman Municipal	49	212,673	0 (0%)	0 (0%)	136,573 (64.2%)	76,100 (35.8%)	0 (0%)	44.38	0 (0%)	0 (0%)
Wenchi Municipal	50	88,274	0 (0%)	0 (0%)	44,595 (50.5%)	24,780 (28.1%)	18,898 (21.4%)	56.09	0 (0%)	0 (0%)

Region/District	District Number	Total Pop 2010	*Pf*PR$_{2-10}$ <5%	*Pf*PR$_{2-10}$ 5-10%	*Pf*PR$_{2-10}$ >10-50%	*Pf*PR$_{2-10}$ >50- 74.9%	*Pf*PR$_{2-10}$ 75%+	Population-weighted mean *Pf*PR$_{2-10}$	SMC 60%	SMC 50-59%
Central										
Abura/Asebu/Kwamankese	51	117,318	0 (0%)	0 (0%)	19,377 (16.5%)	74,533 (63.5%)	23,409 (20%)	61.68	0 (0%)	0 (0%)
Agona East Municipality	52	90,700	0 (0%)	0 (0%)	77,652 (85.6%)	13,049 (14.4%)	0 (0%)	36.21	0 (0%)	0 (0%)
Agona West	53	113,766	0 (0%)	0 (0%)	54,677 (48.1%)	59,089 (51.9%)	0 (0%)	48.61	0 (0%)	0 (0%)
Ajumako/Enyan/Esiyam	54	138,566	0 (0%)	0 (0%)	41,400 (29.9%)	97,167 (70.1%)	0 (0%)	54.81	0 (0%)	0 (0%)
Asikuma/Odoben/Brakwa	55	117,884	0 (0%)	0 (0%)	10,121 (8.6%)	105,221 (89.3%)	2,543 (2.2%)	66.61	0 (0%)	0 (0%)
Assin North	56	162,212	0 (0%)	0 (0%)	1,385 (0.9%)	154,235 (95.1%)	6,592 (4.1%)	66.41	0 (0%)	0 (0%)
Assin South	57	99,945	0 (0%)	0 (0%)	279 (0.3%)	23,669 (23.7%)	75,997 (76%)	76.47	0 (0%)	0 (0%)
Awutu/Senya	58	198,427	26,817 (13.5%)	20,772 (10.5%)	150,838 (76%)	0 (0%)	0 (0%)	14.61	0 (0%)	0 (0%)
Cape Coast	59	150,653	0 (0%)	0 (0%)	150,653 (100%)	0 (0%)	0 (0%)	28.10	0 (0%)	0 (0%)
Effutu Municipal	60	51,773	0 (0%)	0 (0%)	51,755 (100%)	18 (0%)	0 (0%)	27.31	0 (0%)	0 (0%)
Gomoa East	61	199,060	31 (0%)	526 (0.3%)	178,673 (89.8%)	19,829 (10%)	0 (0%)	29.08	0 (0%)	0 (0%)
Gomoa West	62	126,944	0 (0%)	0 (0%)	54,808 (43.2%)	72,136 (56.8%)	0 (0%)	48.02	0 (0%)	0 (0%)
Komenda/Edna Eguafo/Ebire	63	150,760	0 (0%)	0 (0%)	114,463 (75.9%)	36,297 (24.1%)	0 (0%)	37.58	0 (0%)	0 (0%)
Mfantsiman	64	176,242	0 (0%)	0 (0%)	122,946 (69.8%)	47,420 (26.9%)	5,876 (3.3%)	45.17	0 (0%)	0 (0%)
Twifo-Heman/ Lower Denkyira	65	115,851	0 (0%)	0 (0%)	47,831 (41.3%)	67,215 (58%)	805 (0.7%)	50.82	0 (0%)	0 (0%)
Upper Denkyira East	66	68,939	0 (0%)	0 (0%)	12,545 (18.2%)	54,059 (78.4%)	2,336 (3.4%)	54.53	0 (0%)	0 (0%)
Upper Denkyira West	67	59,047	0 (0%)	0 (0%)	5,274 (8.9%)	53,773 (91.1%)	0 (0%)	53.86	0 (0%)	0 (0%)

Region/District	District Number	Total Pop 2010	*Pf*PR$_{2-10}$ <5%	*Pf*PR$_{2-10}$ 5-10%	*Pf*PR$_{2-10}$ >10-50%	*Pf*PR$_{2-10}$ >50- 74.9%	*Pf*PR$_{2-10}$ 75%+	Population-weighted mean *Pf*PR$_{2-10}$	SMC 60%	SMC 50-59%
Eastern										
Akwapim North	68	134,690	0 (0%)	0 (0%)	83,630 (62.1%)	35,627 (26.5%)	0 (0%)	35.54	0 (0%)	0 (0%)
Akwapim South Municipal	69	126,132	0 (0%)	0 (0%)	125,785 (99.7%)	347 (0.3%)	0 (0%)	22.50	0 (0%)	0 (0%)
Akyemansa	70	97,539	0 (0%)	0 (0%)	90 (0.1%)	97,449 (99.9%)	0 (0%)	53.63	0 (0%)	0 (0%)
Asuogyaman	71	98,006	0 (0%)	0 (0%)	95,871 (97.8%)	2,135 (2.2%)	0 (0%)	29.99	0 (0%)	0 (0%)
Atiwa	72	110,657	5 (0%)	23 (0%)	570 (0.5%)	110,058 (99.5%)	0 (0%)	70.78	0 (0%)	0 (0%)
Birim Central Municipal	73	139,011	0 (0%)	0 (0%)	15,288 (11%)	123,723 (89%)	0 (0%)	57.57	0 (0%)	0 (0%)
Birim North	74	77,948	0 (0%)	0 (0%)	15,526 (19.9%)	62,423 (80.1%)	0 (0%)	56.08	0 (0%)	0 (0%)
Birim South	75	116,847	0 (0%)	0 (0%)	0 (0%)	116,847 (100%)	0 (0%)	61.44	0 (0%)	0 (0%)
East Akim Municipal	76	166,826	121 (0.1%)	398 (0.2%)	69,138 (41.4%)	97,168 (58.2%)	0 (0%)	53.74	0 (0%)	0 (0%)
Fanteakwa	77	107,216	0 (0%)	576 (0.5%)	64,146 (59.8%)	42,494 (39.6%)	0 (0%)	46.52	0 (0%)	0 (0%)
Kwaebibirem	78	187,763	0 (0%)	55 (0%)	40,272 (21.4%)	147,436 (78.5%)	0 (0%)	51.50	0 (0%)	0 (0%)
Kwahu East	79	72,079	0 (0%)	8,003 (11.1%)	21,430 (29.7%)	42,646 (59.2%)	0 (0%)	39.67	0 (0%)	0 (0%)
Kwahu South	80	67,391	0 (0%)	2,330 (3.5%)	43,767 (64.9%)	21,293 (31.6%)	0 (0%)	35.08	0 (0%)	0 (0%)
Kwahu West Municipality	81	92,048	10 (0%)	0 (0%)	25,937 (28.2%)	66,101 (71.8%)	0 (0%)	55.86	0 (0%)	0 (0%)
Lower Manya	82	86,858	0 (0%)	1,369 (1.6%)	76,687 (88.3%)	8,802 (10.1%)	0 (0%)	30.24	0 (0%)	0 (0%)
New Juabeng	83	175,636	0 (0%)	0 (0%)	148,783 (84.7%)	26,852 (15.3%)	0 (0%)	33.36	0 (0%)	0 (0%)
Suhum/Kraboa/ Coaltar	84	167,306	0 (0%)	86 (0.1%)	167,221 (99.9%)	0 (0%)	0 (0%)	29.18	0 (0%)	0 (0%)
Upper Manya	85	70,676	0 (0%)	0 (0%)	52,088 (73.7%)	18,589 (26.3%)	0 (0%)	43.73	0 (0%)	0 (0%)
West Akim	86	197,666	0 (0%)	252 (0.1%)	162,219 (82.1%)	35,195 (17.8%)	0 (0%)	35.15	0 (0%)	0 (0%)
Yilo Krobo	87	89,438	0 (0%)	195 (0.2%)	63,589 (71.1%)	25,655 (28.7%)	0 (0%)	39.09	0 (0%)	0 (0%)
Greater Accra										
Accra Metro	88	1,833,830	337,517 (18.4%)	1,496,310 (81.6%)	0 (0%)	0 (0%)	0 (0%)	5.93	0 (0%)	0 (0%)
Adentan Municipal	89	70,680	7,413 (10.5%)	56,206 (79.5%)	7,061 (10%)	0 (0%)	0 (0%)	7.44	0 (0%)	0 (0%)
Ashaiman Municipal	90	194,657	164,236 (84.4%)	3,752 (1.9%)	26,670 (13.7%)	0 (0%)	0 (0%)	8.06	0 (0%)	0 (0%)
Dangbe East	91	127,724	0 (0%)	0 (0%)	102,866 (80.5%)	24,858 (19.5%)	0 (0%)	36.66	0 (0%)	0 (0%)
Dangbe West	92	114,734	4,499 (3.9%)	10,440 (9.1%)	99,796 (87%)	24,906 (21.7%)	0 (0%)	20.32	0 (0%)	0 (0%)
Ga East Municipal	93	221,375	0 (0%)	75,983 (34.3%)	145,392 (65.7%)	0 (0%)	0 (0%)	14.25	0 (0%)	0 (0%)
Ga South Municipal	94	487,557	9,436 (1.9%)	283,856 (58.2%)	194,265 (39.8%)	0 (0%)	0 (0%)	9.88	0 (0%)	0 (0%)
Ga West Municipal	95	245,148	0 (0%)	82,951 (33.8%)	162,197 (66.2%)	0 (0%)	0 (0%)	17.64	0 (0%)	0 (0%)
Ledzokuku-Krowor Municipal	96	212,958	212,958 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2.53	0 (0%)	0 (0%)
Tema Municipal Area	97	390,395	382,362 (97.9%)	1,999 (0.5%)	6,035 (1.5%)	0 (0%)	0 (0%)	3.09	0 (0%)	0 (0%)

Region/District	District Number	Total Pop 2010	*Pf*PR$_{2-10}$ <5%	*Pf*PR$_{2-10}$ 5-10%	*Pf*PR$_{2-10}$ >10-50%	*Pf*PR$_{2-10}$ >50- 74.9%	*Pf*PR$_{2-10}$ 75%+	Population-weighted mean *Pf*PR$_{2-10}$	SMC 60%	SMC 50-59%
Northern										
Bole	98	60,808	0 (0%)	0 (0%)	0 (0%)	4,820 (7.9%)	55,960 (92%)	82.89	0 (0%)	0 (0%)
Bunkpurugu Yunyoo	99	116,809	0 (0%)	0 (0%)	0 (0%)	0 (0%)	113,831 (97.5%)	86.98	0 (0%)	116,809 (100%)
Central Gonja	100	87,562	0 (0%)	0 (0%)	0 (0%)	44,993 (51.4%)	42,569 (48.6%)	76.57	0 (0%)	0 (0%)
Chereponi	101	53,352	0 (0%)	0 (0%)	0 (0%)	5,064 (9.5%)	46,281 (86.7%)	75.90	0 (0%)	53,352 (100%)
East Gonga	102	136,843	0 (0%)	0 (0%)	31,606 (23.1%)	78,797 (57.6%)	26,440 (19.3%)	65.26	0 (0%)	7,961 (5.8%)
East Mamprusi	103	120,461	0 (0%)	0 (0%)	0 (0%)	11 (0%)	120,451 (100%)	88.74	0 (0%)	120,461 (100%)
Gushiegu	104	109,766	0 (0%)	0 (0%)	0 (0%)	0 (0%)	109,766 (100%)	86.26	0 (0%)	109,766 (100%)
Karaga	105	74,653	0 (0%)	0 (0%)	0 (0%)	15,419 (20.7%)	59,234 (79.3%)	83.05	0 (0%)	74,653 (100%)
Kpandai	106	108,644	0 (0%)	0 (0%)	0 (0%)	47,347 (43.6%)	61,297 (56.4%)	78.48	0 (0%)	0 (0%)
Nanumba North	107	144,826	0 (0%)	0 (0%)	0 (0%)	32,663 (22.6%)	112,163 (77.4%)	83.88	0 (0%)	0 (0%)
Nanumba South	108	86,656	0 (0%)	0 (0%)	0 (0%)	11,831 (13.7%)	74,791 (86.3%)	85.82	0 (0%)	0 (0%)
Saboba	109	63,942	0 (0%)	0 (0%)	0 (0%)	40,843 (63.9%)	21,374 (33.4%)	72.94	0 (0%)	63,081 (98.7%)
Savelugu Nanton	110	138,312	0 (0%)	0 (0%)	5,286 (3.8%)	94,437 (68.3%)	38,589 (27.9%)	65.14	0 (0%)	138,312 (100%)
Sawla-Tuna-Kalba	111	98,701	0 (0%)	0 (0%)	0 (0%)	0 (0%)	98,682 (100%)	93.65	0 (0%)	2,113 (2.1%)
Tamale Municipality	112	362,645	0 (0%)	0 (0%)	253,885 (70%)	108,478 (29.9%)	282 (0.1%)	41.65	0 (0%)	361,686 (99.7%)
Tolon Kumbugu	113	115,806	0 (0%)	0 (0%)	6,613 (5.7%)	61,298 (52.9%)	47,909 (41.4%)	71.99	0 (0%)	94,722 (81.8%)
West Gonja	114	84,967	0 (0%)	0 (0%)	0 (0%)	19,984 (23.5%)	64,984 (76.5%)	84.30	0 (0%)	17,452 (20.5%)
West Mamprusi	115	166,780	0 (0%)	0 (0%)	0 (0%)	63,820 (38.3%)	102,960 (61.7%)	78.19	0 (0%)	166,780 (100%)
Yendi Municipal	116	198,689	0 (0%)	0 (0%)	3,506 (1.8%)	111,984 (56.4%)	83,200 (41.9%)	67.99	0 (0%)	160,785 (80.9%)
Zabzugu Tatale	117	121,417	0 (0%)	0 (0%)	7,750 (6.4%)	72,255 (59.5%)	39,261 (32.3%)	68.93	0 (0%)	8,467 (7.0%)
Upper East										
Bawku Municipal	118	215,614	0 (0%)	0 (0%)	0 (0%)	69,438 (32.2%)	144,206 (66.9%)	79.83	16,643 (7.7 %)	198.970 (92.3%)
Bawku West	119	92,415	0 (0%)	0 (0%)	0 (0%)	746 (0.8%)	89,964 (97.3%)	86.42	6,961 (7.5%)	85,454 (92.5%)
Bolgatanga Municipal	120	131,101	0 (0%)	0 (0%)	260 (0.2%)	104,377 (79.6%)	26,463 (20.2%)	70.41	0 (0%)	131,101 (100%)
Bongo	121	81,501	0 (0%)	0 (0%)	0 (0%)	0 (0%)	79,493 (97.5%)	89.14	22,329 (27.4%)	59,172 (72.6 %)
Builsa	122	91,658	0 (0%)	0 (0%)	1,308 (1.4%)	25,263 (27.6%)	65,123 (71%)	79.26	0 (0%)	91,658 (100%)
Garu Tempane	123	129,076	0 (0%)	0 (0%)	0 (0%)	0 (0%)	124,267 (96.3%)	83.09	0 (0%)	129,076 (100%)
Kassena Nankana	124	115,508	0 (0%)	0 (0%)	26,930 (23.3%)	33,480 (29%)	44,186 (38.3%)	60.86	63,847 (55.3%)	51,661 (44.7%)
Kassena Nankana West	125	66,607	0 (0%)	0 (0%)	0 (0%)	32,037 (48.1%)	34,174 (51.3%)	75.10	32,575 (48.9%)	34,032 (51.1%)
Talensi-Nandam	126	113,636	0 (0%)	0 (0%)	0 (0%)	4,496 (4%)	108,926 (95.9%)	90.46	358 (0.3%)	113,277 (99.7%)

Region/District	District Number	Total Pop 2010	*Pf*PR$_{2-10}$ <5%	*Pf*PR$_{2-10}$ 5-10%	*Pf*PR$_{2-10}$ >10-50%	*Pf*PR$_{2-10}$ >50-74.9%	*Pf*PR$_{2-10}$ 75%+	Population-weighted mean *Pf*PR$_{2-10}$	SMC 60%	SMC 50-59%
Upper West										
Jirapa Lambussie	127	86,858	0 (0%)	0 (0%)	0 (0%)	0 (0%)	86,858 (100%)	96.83	0 (0%)	86,858 (100%)
Lambussie-Karni	128	50,187	0 (0%)	0 (0%)	0 (0%)	9 (0%)	47,820 (95.3%)	88.07	0 (0%)	50,187 (100%)
Lawra	129	101,346	0 (0%)	0 (0%)	0 (0%)	4 (0%)	99,946 (98.6%)	93.61	0 (0%)	101,346 (100%)
Nadowli	130	92,983	0 (0%)	0 (0%)	0 (0%)	34 (0%)	92,771 (99.8%)	92.50	0 (0%)	92,983 (100%)
Sissala East	131	55,948	0 (0%)	0 (0%)	0 (0%)	0 (0%)	53,593 (95.8%)	91.35	1,975 (3.5 %)	53,972 (96.5%)
Sissala West	132	51,767	0 (0%)	0 (0%)	0 (0%)	0 (0%)	47,011 (90.8%)	86.85	0 (0%)	51,767 (100%)
Wa East	133	68,894	0 (0%)	0 (0%)	0 (0%)	0 (0%)	68,894 (100%)	93.71	0 (0%)	63,763 (92.6%)
Wa Municipal	134	106,671	0 (0%)	0 (0%)	0 (0%)	55,457 (52%)	51,214 (48%)	82.38	0 (0%)	105,404 (98.8%)
Wa West	135	81,795	0 (0%)	0 (0%)	0 (0%)	6 (0%)	81,789 (100%)	95.30	0 (0%)	75,554 (92.4%)
Volta										
Adaklu-Anyigbe	136	64,243	0 (0%)	0 (0%)	63,111 (98.2%)	0 (0%)	0 (0%)	32.93	0 (0%)	0 (0%)
Akatsi	137	126,242	0 (0%)	0 (0%)	124,579 (98.7%)	0 (0%)	0 (0%)	31.03	0 (0%)	0 (0%)
Biakoye	138	64,403	120 (0.2%)	729 (1.1%)	63,555 (98.7%)	0 (0%)	0 (0%)	22.11	0 (0%)	0 (0%)
Ho Municipal	139	262,834	1,014 (0.4%)	5,265 (2%)	255,308 (97.1%)	0 (0%)	0 (0%)	27.03	0 (0%)	0 (0%)
Hohoe	140	252,332	2,069 (0.8%)	7,464 (3%)	241,540 (95.7%)	0 (0%)	0 (0%)	22.57	0 (0%)	0 (0%)
Jasikan	141	60,198	0 (0%)	0 (0%)	37,822 (62.8%)	19,743 (32.8%)	0 (0%)	42.74	0 (0%)	0 (0%)
Kadjebi	142	57,843	0 (0%)	0 (0%)	2,440 (4.2%)	51,239 (88.6%)	0 (0%)	57.95	0 (0%)	0 (0%)
Keta	143	144,615	0 (0%)	0 (0%)	133,065 (92%)	11,550 (8%)	0 (0%)	32.65	0 (0%)	0 (0%)
Ketu North	144	92,078	0 (0%)	0 (0%)	91,576 (99.5%)	0 (0%)	0 (0%)	25.64	0 (0%)	0 (0%)
Ketu South	145	226,434	0 (0%)	17,891 (7.9%)	124,330 (54.9%)	0 (0%)	0 (0%)	12.69	0 (0%)	0 (0%)
Kpando	146	97,299	0 (0%)	11 (0%)	97,288 (100%)	0 (0%)	0 (0%)	22.88	0 (0%)	0 (0%)
Krachi East	147	115,768	0 (0%)	0 (0%)	1,489 (1.3%)	114,279 (98.7%)	0 (0%)	58.69	0 (0%)	0 (0%)
Krachi West	148	120,482	0 (0%)	0 (0%)	1,521 (1.3%)	113,967 (94.6%)	4,994 (4.1%)	65.96	0 (0%)	0 (0%)
Nkwanta North	149	65,236	0 (0%)	0 (0%)	0 (0%)	38,230 (58.6%)	25,868 (39.7%)	73.94	0 (0%)	0 (0%)
Nkwanta South	150	117,155	0 (0%)	0 (0%)	1,501 (1.3%)	111,996 (95.6%)	2,622 (2.2%)	65.35	0 (0%)	0 (0%)
North Tongu	151	148,423	0 (0%)	477 (0.3%)	147,945 (99.7%)	12,968 (8.7%)	0 (0%)	21.60	0 (0%)	0 (0%)
South Dayi	152	49,726	0 (0%)	0 (0%)	49,726 (100%)	0 (0%)	0 (0%)	32.62	0 (0%)	0 (0%)
South Tongu	153	87,115	0 (0%)	0 (0%)	85,116 (97.7%)	1,999 (2.3%)	0 (0%)	27.45	0 (0%)	0 (0%)

Region/District	District Number	Total Pop 2010	*Pf*PR$_{2-10}$ <5%	*Pf*PR$_{2-10}$ 5-10%	*Pf*PR$_{2-10}$ >10-50%	*Pf*PR$_{2-10}$ >50- 74.9%	*Pf*PR$_{2-10}$ 75%+	Population-weighted mean *Pf*PR$_{2-10}$	SMC 60%	SMC 50-59%
Western										
Ahanta West	154	101,981	0 (0%)	0 (0%)	101,981 (100%)	0 (0%)	0 (0%)	34.17	0 (0%)	0 (0%)
Aowin-Suaman	155	140,425	0 (0%)	0 (0%)	3,728 (2.7%)	108,091 (77%)	28,507 (20.3%)	64.53	0 (0%)	0 (0%)
Bia	156	118,006	0 (0%)	0 (0%)	0 (0%)	34,087 (28.9%)	83,282 (70.6%)	77.64	0 (0%)	0 (0%)
Bibiani/Anwiaso/Bekwai	157	121,624	0 (0%)	0 (0%)	6,930 (5.7%)	90,084 (74.1%)	24,611 (20.2%)	68.51	0 (0%)	0 (0%)
Ellembelle	158	80,946	0 (0%)	0 (0%)	33,416 (41.3%)	47,530 (58.7%)	0 (0%)	48.91	0 (0%)	0 (0%)
Jomoro	159	129,083	0 (0%)	0 (0%)	23,579 (18.3%)	104,214 (80.7%)	0 (0%)	48.08	0 (0%)	0 (0%)
Juabeso	160	109,125	0 (0%)	0 (0%)	74 (0.1%)	11,766 (10.8%)	97,286 (89.2%)	81.75	0 (0%)	0 (0%)
Mpohor Wassa East	161	137,334	0 (0%)	0 (0%)	78,843 (57.4%)	58,053 (42.3%)	438 (0.3%)	46.40	0 (0%)	0 (0%)
Nzema East	162	50,602	0 (0%)	0 (0%)	37,634 (74.4%)	0 (0%)	0 (0%)	43.86	0 (0%)	0 (0%)
Prestea Huni Valley	163	157,351	0 (0%)	0 (0%)	58,254 (37%)	68,954 (43.8%)	30,142 (19.2%)	55.52	0 (0%)	0 (0%)
Sefwi Akontombra	164	79,362	0 (0%)	0 (0%)	47 (0.1%)	71,657 (90.3%)	7,659 (9.7%)	69.38	0 (0%)	0 (0%)
Sefwi Wiawso	165	138,807	0 (0%)	0 (0%)	6,719 (4.8%)	61,133 (44%)	70,955 (51.1%)	71.87	0 (0%)	0 (0%)
Sekondi Takoradi Municipal	166	508,663	0 (0%)	0 (0%)	508,382 (99.9%)	281 (0.1%)	0 (0%)	27.47	0 (0%)	0 (0%)
Shama Ahanta East	167	70,026	0 (0%)	0 (0%)	27,424 (39.2%)	42,602 (60.8%)	0 (0%)	44.88	0 (0%)	0 (0%)
Tarkwa Nsuaem	168	90,339	0 (0%)	0 (0%)	63,993 (70.8%)	26,346 (29.2%)	0 (0%)	50.72	0 (0%)	0 (0%)
Wassa Amenfi East	169	83,503	0 (0%)	0 (0%)	20,344 (24.4%)	48,757 (58.4%)	14,402 (17.2%)	58.95	0 (0%)	0 (0%)
Wassa Amenfi West	170	161,194	0 (0%)	0 (0%)	35,117 (21.8%)	126,078 (78.2%)	0 (0%)	56.15	0 (0%)	0 (0%)

Annex A3: Survey data with information on ITN utilisation and Bayesian mapping procedures

A 3.1 Bayesian geo-additive regression models

The presentation of ITN coverage data is often limited only to the lowest sampling precision estimates of national surveys, 170 districts in the case of Ghana. Here, we use the properties of intervention coverage at geo-coded cluster levels combined data within a regression framework using a geo-additive semi-parametric mixed model constructed within a Bayesian framework [Kammann & Wand, 2003]. A fully Bayesian approach based on Markov priors was employed that uses MCMC techniques for inference and model checking [Fahrmeir & Lang, 2001; Lang & Brezger, 2004] where the classical linear regression model forms are as follows

$$y_i = w_i'\gamma + \varepsilon_i, \qquad \varepsilon_i \sim N(0,\sigma^2), \qquad \text{(Equation A.3.1)}$$

for observations $(y_i, w_i), i = 1,....,n,$ on a response variable *y* and a vector *w* of covariates assume that the mean $E(y_i \mid w_i)$ can be modeled through a *linear predictor* $w_i'\gamma$. In our application to ITN coverage no covariate was used. The geographical small-area information was given in form of a location variable *s*, indicating the areal unit to which predictions of ITN coverage are to be made. In our study, this geographical information is given by the 170 health districts of Ghana. Attempts to include such small-area information using district-specific dummy-variables would in our case entail 169 dummy-variables and using this approach we would not assess spatial inter-dependence. The latter problem also cannot be resolved through conventional multilevel modeling using uncorrelated random effects [Goldstein, 1999]. It is reasonable to assume that areas close to each other are more similar than areas far apart, so that spatially correlated random effects are required.

To overcome these difficulties, we replace the strictly linear predictor through a *geo-additive predictor*, leading to the *geo-additive regression model*

$$y_i = f_{spat}(s_i) + f_j(x_j) + w'_i \gamma + \varepsilon_i \qquad \text{(Equation A.3.2)}$$

here, f_{spat} is the spatial effect $s_i \in \{1,...,S\}$ labelling the districts in Ghana. Regression models with predictors as in (2) are sometimes referred to as geo-additive models.

In a further step we may split up the spatial effect f_{spat} into a spatially correlated (structured) and an uncorrelated (unstructured) effect: $f_{spat}(s_i) = f_{str}(s_i) + f_{unstr}(s_i)$. The rationale is that a spatial effect is usually a surrogate of many unobserved influences, some of them may obey a strong spatial structure and others may be present only locally.

In a Bayesian approach unknown functions f_j and parameters γ as well as the variance parameter σ^2 are considered as random variables and have to be supplemented with appropriate prior assumptions. In the absence of any prior knowledge we assume independent diffuse priors $\gamma_j \propto const,\ j=1,...,r$ for the parameters of fixed effects. Another common choice is highly dispersed Gaussian priors.

Several alternatives are available as smoothness priors for the unknown functions $f_j(x_j)$ [Fahrmeir & Lang, 2001; Fahrmeir et al., 2004]. We use Bayesian (Penalized) – Splines, introduced by Eilers and Marx in a frequentist setting. It is assumed that an unknown smooth function $f_j(x_j)$ can be approximated by a polynomial spline of low degree. The usual choices are cubic splines, which are twice continuously differentiable piecewise cubic polynomials defined for a grid of k equally spaced knot *p* on the relevant interval $[a,b]$ of the x-axis; written in terms of a linear combination B-spline basis functions $B_m(x)$,

$$f(x)=\sum_{m=1}^{l}\beta_m B_m(x) \qquad \text{(Equation A.3.3)}$$

These basis functions have finite support on four neighbouring intervals of the grid, and are zero elsewhere. A comparably small number of knots (usually between 10 and 40) is chosen to ensure enough flexibility in combination with a roughness penalty based on second order difference of adjacent B-spline coefficients to guarantee sufficient smoothness of the fitted curves. In our Bayesian approach this corresponds to second order random walks

$$\beta_m = 2\beta_{m-1} - \beta_{m-2} + u_m, \qquad \text{(Equation A.3.4)}$$

with Gaussian errors $u_m \sim N(0,\tau^2)$. The variance parameter τ^2 controls the amount of smoothness, and is also estimated from the data. More details on Bayesian P-Splines can be found in Lang and Brezger (2004). Note that random walks are the special case of B-Splines of degree zero.

For the spatially correlated effect f_{str} (s), s = 1, … S, we have chosen Markov random field priors common in spatial statistics [Besag et al., 1991]. These priors reflect spatial neighbourhood relationships. For geographical data one usually assumes that two sites or regions *s* and *r* are neighbours if they share a common boundary. Then a spatial extension of random walk models leads to the conditional, spatially autoregressive specification

$$f_{str}(s) \mid f_{str}(r), r \neq s \sim N\Big(\sum_{r\in\partial_s} f_{str}(r)/N_s, \tau^2/N_s\Big) \qquad \text{(Equation A.3.5)}$$

where N_s is the number of adjacent regions, and $r \in \partial_s$ denotes that region r is a neighbour of region s. Thus the (conditional) mean of $f_{str}(s)$ is an average of function evaluations $f_{str}(s)$ of neighbouring regions. Again the variance τ^2_{str} controls the degree of smoothness. For a spatially uncorrelated (unstructured) effect f_{unstr} a common assumption is that the parameters $f_{unstr}(s)$ are i.i.d. Gaussian

$$f_{unstr}(s) \mid \tau^2_{unstr} \sim N(0, \tau^2_{unstr}) \qquad \text{(Equation A.3.6)}$$

Variance or smoothness parameters τ^2_j, *j=1,...,p, str, unstr,* are also considered as unknown and estimated simultaneously with corresponding unknown functions f_j. Therefore, hyper-

priors are assigned to them in a second stage of the hierarchy by highly dispersed inverse gamma distributions $p(\tau^2_j) \sim IG(a_j,b_j)$ with known hyper-parameters a_j and b_j. For model choice, we routinely used the Deviance Information Criterion (DIC) as a measure of fit and model complexity [Spiegelhalter et al., 2002].

A.3.2 Model selection

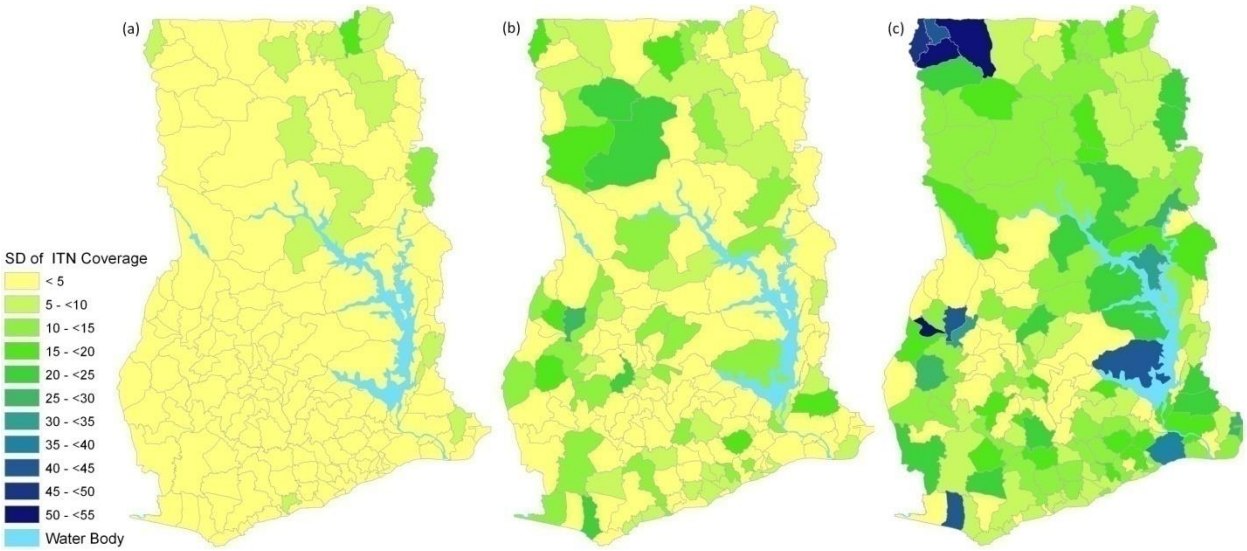
The spatial effects were modelled through the Markov random field prior (MRF) with penalized splines (P-spline) with second-order random walk penalty. With MRF prior, it was possible to predict ITN coverage in districts with no coverage data based on information of neighbouring districts. Two model forms were explored: a spatial model with district as random effect and with MRF priors (Model A); and geo-spline model with weights applied as inverse proportional to the distance of the centroids of neighbouring districts (Model B). Table A.2.1 summarises the models' DIC and prior sensitivities for the surveys years 2003, 2008 and 2011.

Table A.3.1 Summary of the DIC & sensitivity analysis of the choice of spatial priors for model selection

Hyper-parameters	Year	Diagnostics	Spatial	
			With MRF(A)	With geo-spline(B)
a=1, b=0.005	2003	Deviance	338.1	354.8
		pD	70.8	55.2
		DIC	479.8	465.2*
a=1, b=0.005	2008	Deviance	327.9	328.8
		pD	75.2	71.5
		DIC	478.4	472.0*
a=1, b=0.005	2011	Deviance	709.8	717.5
		pD	99.4	89.0
		DIC	908.6	895.6*
Model with asterisk (*) is the best fitting				

The results indicated for the year 2003, 2008 and 2011, the model with geo-spline outperformed the models with MRF. In addition to the sensitivity analysis (Table A.3.1), the standard deviations (SD) of the mean ITN coverage predictions per district were computed for each year with higher values of the SD indicating greater uncertainty (Figure A.3.1).

Figure A.3.1: standards deviations of mean ITN coverage predictions in Ghana for the years: a) 2003; b) 2008; c) 2011



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