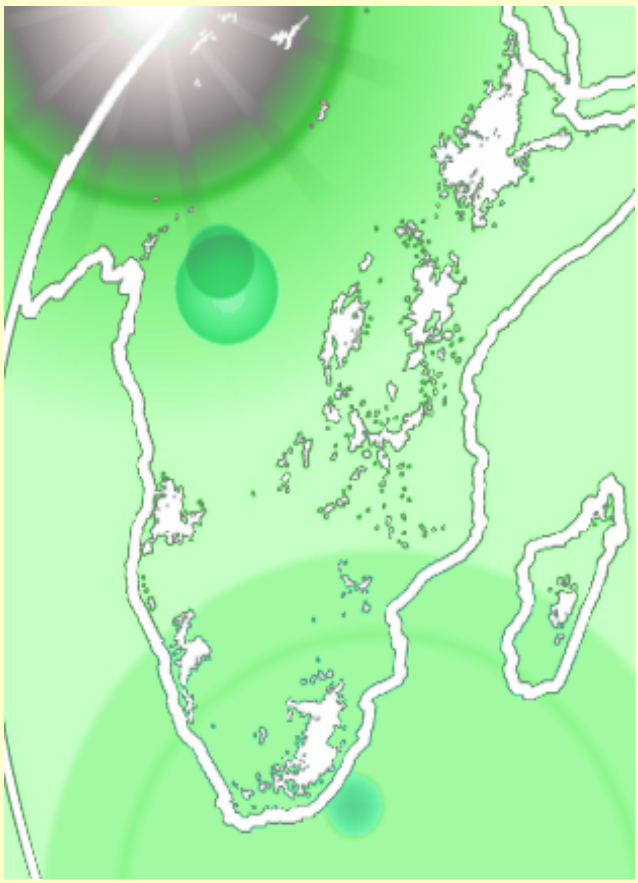

MARA/HIMAL Technical Report

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MAPPING MALARIA RISK IN THE HIGHLANDS OF AFRICA

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HIMAL

MARA ARMA

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Acronyms and abbreviations

DEM	Digital elevation model
DFID	Department for International Development (London, UK)
DMO	District Medical Officer
DVBD	Division of Vector Borne Diseases (Nairobi, Kenya)
EIR	Entomological inoculation rate
ENSO	El Niño-Southern Oscillation
GIS	Geographical Information System
GTZ	Gesellschaft für Technische Zusammenarbeit (Eschborn, Germany)
HIMAL	Epidemiology of Highland Malaria in Africa Project
IDRC	International Development Research Center (Ottawa, Canada)
IFA	Indirect fluorescent antibody
IRD	Indoor resting density
ITCZ	Inter-Tropical Convergence Zone
LSHTM	London School of Hygiene and Tropical Medicine (London, UK)
MARA	Mapping Malaria Risk in Africa project and collaboration
MRC	Medical Research Council (Durban, South Africa)
MSF	Médecins sans Frontières
NGO	Non-governmental organisation
NIMA	National Imagery and Mapping Agency (Bethesda, USA)
ORSTOM	Institut Français de Recherche Scientifique pour le Développement en Coopération (Paris, France)
PCR	Polymerase chain reaction
TDR	Tropical Disease Research Programme of the WHO and partners (Geneva, Switzerland)
USGS	United States Geological Survey
WHO	World Health Organisation (Geneva, Switzerland)

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1 Introduction

Recent concern over the potential links between climate change and disease transmission has brought to the fore the issue of malaria as an emerging disease in non-endemic areas, including areas where malaria has previously been controlled (*e.g.* Beljaev 1996; Oloo *et al*. 1996; Mouchet *et al*. 1997; Malakooti *et al*. 1998; Nchinda 1998). Particular attention has focused on the highlands of sub-Saharan Africa, hitherto regarded as areas of little or no malaria transmission – a feature commonly attributed to the negative effects of low environmental temperatures on parasite sporogony and vector development. This picture appears to be changing, with recent evidence indicating an increase in the number of malaria epidemics occurring in highland areas, as well as increasing stability of transmission in highland fringes. Various mechanisms for this apparent change in epidemiology have been put forward, of which those implicating climatic and ecological change have been most prominent. Unfortunately the lack of reliable malaria data for most highland areas has made analysis of these issues difficult, and in situations where malaria data are available, it is not always possible to separate out the effects of individual risk factors from those of potentially confounding variables.

Epidemic malaria in highland areas represents a significant public health problem. Historically, low exposure to infection has led to low levels of functional immunity in local populations, resulting in relatively high levels of mortality in adults and children during epidemics. At the same time, national malaria control programmes have proven to be poorly equipped in terms of identifying and responding to epidemics and many previous outbreaks have been allowed to develop more or less unchecked. There is, therefore, a dual need for better scientific understanding of highland malaria on the one hand and greater local capacity in epidemic surveillance and response on the other. This issue was raised at the TDR/WHO/IDRC co-sponsored Task Force Meeting on 'Highland Malaria in Africa', held in Addis Ababa in May 1996, at which a general framework for future research was proposed.

The Highland Malaria Project (HIMAL), which came out of the Addis Ababa workshop, and which became part of the wider international collaboration 'Mapping Malaria Risk in Africa' (MARA), was designed to address both the academic and operational aspects of the highland malaria raised above. From the outset the project was divided into two phases. The major (second) phase would address issues of forecasting, early warning and detection of malaria epidemics in highland areas. This was to be preceded by a preparatory phase, focusing on the spatial prediction of highland malaria and consisting of the following activities:

1 The development of a stratification of malaria risk in highland areas, based on spatial modelling of continental datasets for climate and altitude

2 The collection of existing data on malaria transmission in highland areas, both quantitative and qualitative

3 Exploratory analyses of these data, with particular reference to:

   Elucidating the influence on altitude on various measures of malaria transmission intensity, including risk of epidemics;

   Evaluating alternative strategies for predicting areas of epidemic risk based on non-malariometric variables;

A rapid assessment of risk factors for highland malaria transmission based on a review of existing literature

4 Organisation of a workshop to bring together researchers and control programme managers to determine priorities for future research on highland malaria

It was initially envisaged that Phase I activities would be applied to all highland areas of Africa and in the event basic modelling and data collection were carried out for nine countries (see Section 3). This report, however, focuses principally on four countries in eastern Africa: Kenya, Uganda, Ethiopia and Tanzania. Together these countries account for around 64% of the total African land area above 1500 m, and 95% of that above 2000 m. They also support around 66% and 99% of the total African population living above 1500 and 2000 m respectively.

1.1 Highland malaria: contexts and definitions

There is not a straightforward definition for highland malaria. While it would be simple to describe it as 'malaria which occurs in highlands', the term 'highland' is itself a relative term which can be variously defined depending on the topic and area of interest (*e.g.* Braun *et al*. 1997). In addition, while altitude has long been recognised as an important determinant of malaria endemicity (*e.g.* Hirsch 1883), it is those transmission factors which are directly or indirectly affected by altitude that are of epidemiological significance, rather than altitude *per se*. Probably most important of these is environmental temperature, which effects the development and survival of the vector and, more significantly, the duration of *Plasmodium* development within the invertebrate host. In simple terms the duration of sporogony increases hyperbolically with decreasing environmental temperatures to a point where parasite development ceases altogether. This critical temperature varies by parasite species; for *P. falciparum* laboratory studies have estimated it to be in the range 16–19 °C (MacDonald 1957; Detinova 1962) and in practice it is commonly assumed that transmission will be limited to months in which the average temperature is above this threshold (Molineaux 1988). Field observations generally concord with these findings. In India, Gill (1923) observed that a monthly mean temperature of 61.0 °F (16.7 °C) was required for malaria transmission and a similar threshold has been applied in Kenya (Garnham 1948).

Given that altitude and environmental temperatures vary inversely (as defined by the environmental lapse rate), it follows that a threshold altitude will exist at which malaria transmission ceases to be possible. Previous authors have tried (loosely) to define this threshold either for Africa as a whole, or for specific regions (*e.g.* Schwetz 1942; Wilson 1949; Rees 1994; Lindsay and Martens 1998). There are, however, (at least) two reasons why such an approach is unrealistic. The first is that altitude, on its own, is not a particularly reliable predictor of environmental temperature, even over relatively small areas. Secondly, the assumption that temperature is the sole or principal factor limiting malaria transmission in highland areas may not always be valid. These issues are addressed separately below.

1.2 The relationship between altitude and temperature

The relationship between altitude and temperature is often oversimplified and in practice may vary substantially over time and space. At the continental scale the effect of latitude is important and its significance in the context of malaria has long been recognised (*e.g.* Deaderick 1909; Gill 1923). Solar radiation received at the Earth's surface, and consequently mean annual temperature, is greatest in the tropics and declines towards the poles

(although aspect may alter this pattern significantly at the local level). Latitude also influences the relative importance of seasonal and diurnal variations in climate, with the latter tending to predominate in tropical highlands.

Highland temperature regimes are also affected by continentality. Specifically, diurnal and annual temperature ranges tend to become smaller with increasing proximity to large water bodies, while incidence of cloud and mist increases, thereby leading to significant reductions in temperature (the Eastern Usambaras in Tanzania, situated relatively close to the Indian Ocean, offer a good example of this). In Africa, the shear extent of the upland areas enhances the effect of continentality, creating what some have termed 'continents within continents.'

Finally, the adiabatic lapse rate (ALR), which describes the reduction in day time temperature with increasing elevation, is itself not a constant term, and depends on the degree to which the air is saturated. In completely unsaturated air, the (dry) ALR is 0.98 °C per 100 m, but this rate decreases as saturation increases. In reality air is almost always partly saturated, and while lapse rates of around 0.6 °C per 100 m are most common, spatial and temporal variations in humidity can make lapse rates extremely variable (*e.g.* Yacono 1968). At night, the situation may be quite different and temperature inversions are not uncommon.

1.3 Other risk factors for highland malaria

The discussion has so far assumed implicitly, and for the sake of illustration, that temperature is the principal factor limiting malaria transmission in highland areas. Indeed this is often assumed to be the case, so that a picture emerges for tropical Africa in which the boundary of endemic malaria is constantly pushing up against its climatological limits. Future projections of malaria endemicity (*e.g.* Jetten *et al.* 1996; Lindsay and Martens 1998) also usually assume that the transmission system is controlled largely by temperature.[1] In high altitude areas this assumption may be well grounded, but in more 'marginal' fringe areas a host of other factors may be significant in determining the extent to which transmission occurs. These have been reviewed elsewhere (within the more general context of malaria epidemiology) and are outlined only briefly here.

1.3.1 Rainfall and humidity

As this report will go on to argue, it is likely that spatial and temporal variations in precipitation are critically important in determining the nature and scale of malaria transmission in highland areas. Moreover, from a geographical perspective it is probably significant that (in addition to temperature) rainfall totals are usually strongly correlated with altitude. On tropical mountains rainfall maxima mostly occur at about 1500 m, above and below which totals can decline rapidly (*e.g.* Lauscher 1976).[2] Many highland areas are in fact relatively dry, but abnormal rainfall events been shown to precipitate malaria epidemics even in wetter areas – as evidenced by recent (and not so recent) epidemics in Uganda, Kenya and Ethiopia.

The effect of rainfall is inherently linked to that of humidity, which has a particularly significant effect on the longevity of adult vectors. In general relative humidities of 60% or more are deemed necessary for effective malaria transmission (Molineaux 1988). In India Gill (1923) attributed the absence of malaria at high altitudes to low relative humidities during the period when environmental temperatures were suitable for transmission.

1.3.2 Non-meteorological factors

Vertebrate and invertebrate hosts

Malaria transmission depends upon the presence of suitable vectors and human hosts, as well as that of the *Plasmodium* parasite. In the African highlands the principal vector appears to be the relatively inefficient *An. arabiensis*. *An. gambiae s.s.* and *An. funestus* are important secondary vectors in most cases, however, and can create foci of relatively stable transmission in some highland localities. Much of the evidence presented in this report suggests that the type of vector present (if any) is a major determinant of local levels of malaria transmission. In this respect rainfall clearly has an important influence on the availability of water for breeding sites, but local topographical and ecological properties will also determine the suitability of these sites for specific vectors.

The malaria transmission cycle is not complete without available human hosts and, as Table 1 in Appendix 1 illustrates, average population densities in highland areas are usually relatively high. High population densities translate into large populations at risk from infection (and epidemics) and it is partly for this reason that concern over future patterns of malaria transmission in the highlands is so great.

Human activities

Anthropogenic factors may alter malaria transmission dynamics by increasing the emergence of efficient vectors (*e.g.* increasing the number of breeding sites through land use change; reduction in vector control activities) and/or by increasing contact between man and vector (*e.g.* occupational activities; seasonal migration). Within the highlands (*i.e.* excluding the migration of non-immunes to endemic areas) the most important impacts on transmission are probably brought about by water resource development and land use change (and particularly by land clearance for agricultural development). In Cameroun, for example, forest clearance for cultivation has been associated with invasion of malaria vectors such as *An. gambiae s.s.* (Livadas *et al.* 1958). In Uganda clearance of papyrus swamps at the bottom of highland valleys has created suitable conditions for *An. gambiae* and *An. funestus* (*e.g.* Steyn 1946), and marsh clearance has had similar effects in Rwanda (*e.g.* Vincke and Jadin 1946). Dam construction has also had demonstrable effects on local levels of malaria transmission, as evidenced in Kenya (*e.g.* Khaemba *et al.* 1994) and Rwanda/Burundi (*e.g.* Meyus *et al.* 1962). The issue of rice cultivation is perhaps more complex in Africa than elsewhere; in Madagascar the association between rice fields (which support *An. funestus*) and malaria risk has been clearly demonstrated (*e.g.* Lepers *et al.* 1991), but this is not always the case in continental Africa.

Many authors have pointed out that reported increases in highland malaria transmission have occurred at a time when, for one reason or another, basic health services and malaria control activities have been in decline. It is likely that this problem is being compounded by an emerging drug resistance problem, and in certain instances by uncertain drug supplies. Under these conditions, a rise in observed morbidity and mortality may not necessarily reflect an increase in malaria transmission, but nevertheless represents a significant problem for national malaria control programmes.

1.4 Towards a definition of highland malaria

From the previous discussion it seems clear that highland malaria cannot be defined purely on the basis of simple altitude cutoffs – nor can we necessarily assume that temperature is the sole factor determining the presence or absence of transmission (in many regions the upper level of transmission is far below that which we might expect). It may be more correct to define highland malaria as malaria occurring at the local altitudinal limits of

transmission, and whose epidemiological characteristics are typically unstable (*i.e.* the basic case reproduction rate fluctuates either side of one, changes in incidence are large and uneven, and the occurrence of outbreaks/epidemics is relatively common). Indeed it is these epidemiological facets, and particularly the occurrence of epidemics that perhaps best define highland malaria (especially in the lay sense), *even though altitude per se may not be a factor*.

It is also necessary to discount the notion of a simple altitude 'limit' to malaria transmission in highland areas. Clearly the changes in endemicity that occur with altitude will follow a continuum of increasing instability (or 'epidemicity'), from relatively endemic conditions through to a complete absence of malaria (given sufficient elevation). This continuum is inherently dynamic and reflects relative changes in both transmission intensity and the functional immunity of local populations. From a public health or malaria control perspective, it is the clinical outcomes of this trade-off that are of primary interest.

Defining highland malaria on this basis raises the question of how best to define unstable transmission – and specifically *epidemic* transmission. At the most basic level epidemics are 'acute exacerbation[s] of disease out of proportion to the normal to which the community is subject' (MacDonald 1957: 44). As Molineaux (1988) pointed out, such events are relatively easy to classify in areas previously free of malaria, but in areas where some degree of transmission is expected the definition of an epidemic is more problematical and depends to a certain degree on the magnitude of the excess of cases and on the rate at which this excess develops. These characteristics are partly a function of the degree of change in the transmission factor responsible for the epidemic. They also depend on the level of local endemicity: in some areas, minor changes in transmission conditions may bring about epidemics, while in others only the grossest changes bring about a tangible change (MacDonald 1957). Different 'types' of epidemics are likely to occur at different altitudes accordingly (*e.g.* Wilson 1949).[3]

MacDonald (1957) argued that epidemics can be caused by anything facilitating transmission above the normal level or, put another way, disturbing a previously existing equilibrium of the ecological system comprising human, parasite and vector populations in a particular environmental niche (Nàjera *et al.* 1998). A variety of factors could cause this type of disturbance and these essentially relate to the transmission factors already outlined in this section. Molineaux (1988) has provided a checklist of these factors, classified on the basis of which component in the transmission system is affected (vectors, infectives, susceptibles *etc.*) and according to whether the factor is man-made, natural, or both (Table 1.1).

Once disturbed, the malaria transmission system will either reach a new equilibrium or return to its original position, depending on the nature of the original disturbance and on the resilience of the system. On this basis Nàjera *et al.* (1998) distinguished between (1) epidemics brought about by temporary disturbances in the existing equilibrium, and (2) shifts towards an entirely new equilibrium caused by more persistent changes in the eco-epidemiological system. In the case of the African highlands it has most usually been assumed that epidemics reflect irregular, temporary disturbances to this equilibrium – most commonly associated with exceptional meteorological conditions.[4] However, a critical and outstanding issue in this context is the potential role of more systematic shifts in transmission dynamics which are likely to result from long term climate change, drug resistance and/or the breakdown of control activities. The epidemiological adjustments brought about by these changes are likely to be permanent, with epidemics heralding a shift to more endemic conditions. In the case of climate change this 'new' endemicity is likely to be unprecedented. In the case of drug resistance or the breakdown of control

Table 1.1 *Possible precipitating factors of malaria epidemics (after Molineaux 1988: 969)*

Factors	*Natural, man-made, mixed or either*	*Rating†*
1. *Increase in vectorial capacity through:*		
Importation of a more potent vector	man-made	+
Increased emergence through:		
increased availability of breeding sites through:		
abnormal rainfall (excess or deficit)	natural	+
errors in water management (irrigation, drainage, flooding)	man-made	+
deforestation	man-made	?
increased temperature (accelerated development)	natural	?
deteroration of larval control through:		
operation failure	man-made	?
resistance to larvicides	mixed	?
Increased survival of the adult vectors through:		
favourable meteorological conditions (humidity, temperature)	natural	+
deterioration of adult control through:		
operational failure	man-made	+
physiological insecticide resistance	mixed	+
behavioural insecticide resistance	mixed	?
increased feeding frequency through increased temperature	natural	?
increased man-vector contact through destruction of cattle and/or houses	either	+
decreased incubation period in the vector through increased temperature	natural	?
2. *Immigration of infective person*	man-made	+
3. *Immigration of non-immunes*	man-made	+
4. *Drug resistance*	mixed	?

† + = proven or very probable precipitating factor of some past epidemics; ? = possible factor, not clearly demonstrated

activities, it could be argued that epidemics preface a return to an equilibrium that preexisted before the widespread use of anti-malarials and insecticides.

1.5 The purpose of HIMAL

This discussion has argued that, in essence, highland malaria describes a stratum of highly unstable malaria at the local altitudinal limits of transmission. Furthermore, highland malaria is typified by acutely seasonal transmission with large inter-annual variations in intensity.

Arguably the real significance of this stratum lies in the problems that it poses for malaria control programmes: highland areas are often literally peripheral to routine control activities; outbreaks occur irregularly in time and space and cannot easily be detected using current approaches to surveillance; morbidity and mortality among local populations during epidemics can be extremely high; the political ramifications of epidemics are often significant.

The primary motivation in the development of HIMAL was to develop new tools for the control of epidemics in highland areas. Specifically, the project addresses the question of predicting 'when' and 'where' epidemics are likely to occur. The first phase of the project, described in this report, has been concerned largely with identifying zones of epidemic risk, in the geographical sense. This has involved the development of spatial stratifications of malaria risk based on climate parameters and on the known historical distribution of epidemics.

The modelling component of this exercise is described in the next section of this report, while Section 3 outlines the process of putting together a malaria database to validate the model and to explore alternative approaches to mapping epidemic risk. The results of this exercise are illustrated with reference to Kenya, Uganda, Ethiopia and Tanzania in Sections

4–7. Summary estimates of epidemic risk are also provided for Rwanda, Burundi and Madagascar in a separate appendix. Finally, in preparation for the second phase of the HIMAL project (HIMAL II), the summary report from a workshop addressing future strategies for epidemic early warning and detection in East Africa is attached as an annexe to this report.

Notes

[1]. The simplicity of this approach, which combines standard epidemiological equations with outputs from global climate models, has attracted a certain amount of criticism (*e.g.* Reiter 1996; Mouchet 1998), and a somewhat polarised debate over links between climate change and disease transmission has emerged (*e.g.* Epstein 1998; Haines 1998; Reiter 1998). In fact there may be more common ground in this debate that the main protagonists care to admit – in particular, both camps accept the potential significance of non-climatic risk factors in shaping present past (and future) patterns of malaria transmission. The problem is one of validation – as only a handful of studies (as distinct from reviews) have specifically addressed the issue of climate change and malaria transmission on the ground (Anon. 1996). These have tended to ignore or oversimplify the potential contribution of confounding factors.

[2]. Thus on Mount Kenya and Cameroun precipitation at 3000 m is only 10–30% of that at 1500 m. On Mount Kilimanjaro rainfall shows a similar pattern, but the rainfall maximum is significantly higher, at 2000 m. In Ethiopia there is a bimodal rainfall distribution with peaks at 2000–2500 m and at 3000–3500 m. These distributions apply at the general level, but at the local level rainfall patterns will be determined largely by aspect. On Mount Elgon and Mount Kenya, for example, rainfall is heaviest on western and south eastern slopes (Winiger 1981; Hamilton 1987).

[3]. From a pragmatic stand point, a more workable definition of an epidemic is any instance where health care resources are unable to cope with the number of malaria cases being presented. Hence epidemics can be the result of a breakdown in health care infrastructure or drug shortages and may not be indicative of an increase in disease transmission. Significantly, these epidemics may not be picked up by early warning approaches based only on the identification/monitoring of environmental transmission factors.

[4]. Such apparently irregular events in fact often recur within loosely-defined paraquinquennial cycles of 2–7 years (Gabaldón 1946) or, in the case of more intense abnormalities, in cycles of ten years or more (Nàjera *et al.* 1998). Links between these cycles and the El Niño Southern Oscillation (ENSO) have been explored in several regional studies (*e.g.* Bouma and van der Kaay 1996; Bouma and Dye 1997) and work is ongoing to examine ENSO-malaria relationships in specific highland settings (Bouma and Cox, unpublished).

2 Modelling malaria transmission risk in Africa (Phase 1A)

2.1 Mapping malaria

Previous attempts to map diseases have played an important role in disease monitoring and control (*e.g.* Lysenko and Semashko 1969; Doumenge *et al.* 1987). However, common to all attempts to map malaria risk is that they derive from a combination of expert opinion, limited data and the use of crude geographical and climate isolines. None has a clear and reproducible numerical definition: consequently their comparative value becomes limited. With the advent of affordable geographical information system (GIS) software the approach to mapping has changed. Increased availability of large global data sets (including climate, population, satellite imagery and topography) has prompted renewed interest in the mapping of vector-borne diseases, whose transmission and distribution are influenced mainly by environmental and climatic factors (*e.g.* Gesler 1986; Thomson *et al.* 1996; Macé *et al.* 1997; Malone *et al.* 1997).

Mathematical modelling of environmentally determined diseases has attracted much interest and has been reviewed more than once (Molineaux 1988; Martens 1997). Complex theoretical models aim to reconstruct the transmission cycle of the malaria parasites and predict the outcome in terms of the reproduction rate of the disease. Converting these mathematical models into geographical models, however, requires that the building blocks are available as continuous geographic data surfaces (or maps) – and in reality few of them are. Some parameters, for which the relationship with environmental factors is known, can be derived, but for others the relationships are either indirect, undefined or nonexistent.

2.2 A new approach using fuzzy logic

For the model used within this report (Craig *et al.* 1999) empirically demonstrated relationships between temperature and the transmission of the malaria parasite, *P. falciparum*, were employed. Climate was considered the most important factor influencing transmission and distribution of malaria at a large scale, and it was assumed that conditions are either able or unable to sustain transmission. This statement is essentially boolean, in that climate is deemed either suitable (one) or unsuitable (zero) for transmission. By defining simple thresholds, separating suitable from unsuitable (and hence malarious from non-malarious areas) would be possible, but would ignore natural gradients and inherent uncertainty.

Fuzzy logic (Zadeh 1965) is an extension of boolean logic that deals with the concept of partial truth or, put differently, the extent to which a statement is true (fractions between zero and one): climate is completely suitable, completely unsuitable, or in-between, 'semi-suitable'. The concept is discrete (*i.e.* suitable/unsuitable) and the application continuous (*i.e.* how suitable?). While probability sets are fuzzy (non-boolean), fuzzy sets themselves are not probabilities, because, unlike probabilities they do not have to add up to one. Thus any curve between 0 and 1 can be applied, with the type of curve chosen depending in part on how much is known about the uncertainty.

Continental monthly temperature and rainfall surfaces (Hutchinson *et al.* 1995) were used to provide climate data for the fuzzy model. These represent long-term mean monthly profiles (*i.e.* monthly means in the average year). Conceptually, regions can be defined as:

1 Perennial: conditions are always suitable for transmission

2 Seasonal: conditions become suitable for a short season every year

3 Epidemic: long-term variation in climate renders conditions suitable for transmission on an irregular basis (with a potential of epidemic malaria)

4 Malaria-free: conditions are always unsuitable

Since inter-annual variation is not reflected in these long-term mean climate data, epidemic zones are not readily detectable. Using these data to predict regions of annual transmission would lead to an exclusion, at the fringe, of rare epidemic zones, but inclusion of frequent epidemic zones. These issues are discussed with reference to the East African highlands in Sections 4–7.

2.3 Climatic determinants of malaria transmission

As outlined in Section 1.1, it has been demonstrated empirically that environmental temperature varies inversely with the duration of the sporogonic cycle (*n*). High temperatures also speed up mosquito development and reduce the interval between blood meals, which leads to more frequent host-vector contact (Gillies and de Meillon 1968). There is, however, a trade-off with the mosquito survival rate (*p*), which becomes progressively lower as temperatures rise above 22 °C (le Sueur 1991). Table 2.1 shows the impact of temperature on the duration of sporogony (*n*), on mosquito survival (*p*), the vector cohort survival after the required period for sporogony at that temperature (*pn*), and on larval duration.

At the lower end of the temperature scale the limiting factor is clearly the combined effect of *n* and *p*: below 18 °C transmission is unlikely because few adults (0.28%) survive the 56 days required for sporogony at that temperature, and because mosquito abundance is limited by long larval duration. At 22 °C sporogony is completed in less than three weeks and mosquito survival is sufficiently high (15%) for the transmission cycle to be completed. In this exercise temperatures below 18 °C were considered unsuitable for any transmission, while those above 22 °C were deemed suitable for stable transmission. At the upper end of the scale *p* is the limiting factor, since *n* is less than a week. The potential number of infective mosquitoes reaches a peak at 30.6 °C, after which it drops off rapidly. Temperatures higher than 32 °C have been reported to cause high vector population turnover but also weak individuals and high mortality survival (le Sueur 1991). Thermal death for mosquitoes occurs around 41–42 °C (*e.g.* Jepson *et al.* 1947), by which time *p* has also reached zero (at 40 °C). Thus in general, suitability begins to decline at 31 °C and reaches zero at 40 °C.

In addition to average temperature Leeson (1931) found that in Zimbabwe *An. gambiae s.l.* disappeared when absolute minimum air temperature in winter fell below 5 °C. Also, according to de Meillon (1934) vector distribution in former Transvaal province, South Africa, discontinued where areas experienced frost.

Many studies have demonstrated the association between *An. gambiae* abundance and rainfall (*e.g.* le Sueur 1991; Charlwood *et al.* 1995), but a direct, predictable relationship does not exist. *An. gambiae* can breed prolifically in temporary, turbid water bodies such as hoof prints or rain puddles, while *An. funestus* prefers permanent water bodies. However, both temporary and permanent water bodies are dependant on adequate rainfall. Rainfall is also related to saturation deficit, which affects mosquito survival (Molineaux 1988). There is, therefore, good reason for using rainfall to indicate the probable presence of vectors, their survival and the potential for malaria transmission. Although it is known that flooding often causes destruction of breeding sites (Molineaux 1988) and a temporary reduction of vectors, it never eliminates the vector, so that very high rainfall can still be considered

Table 2.1 *Temperature effects on sporogonic duration, daily vector survival, percentage cohort survival against sporogonic duration and larval development*

T (°C)	*Duration of sporogony (days)†*	*Daily vector survival (%)‡*	*Vector survival after period required for sporogony (%)*	*Larval development (days)¶*
16	—	89.3	0	47
17	111	89.7	0.001	37
18	56	90	0.28	31
20	28	90.3	5.9	23
22	19	90.4	15	18
30	7.9	88.1	37	10
35	5.8	80.8	29	7.9
39	4.8	38.9	1.1	6.7
40	4.6	0	0	6.5

† MacDonald (1957), Detinova(1962)
‡ Martens (1997)
¶ Jepson et al. (1947), le Sueur (1991)

optimal for transmission.

The rainfall patterns in known malaria and non-malaria regions indicated that the requirement for stable (regular) transmission was around 80 mm for 5 months. Neither 60 mm for 5 months, nor 80 mm for less than 5 months was sufficient to sustain endemic malaria. In north Africa, where high temperatures result in a particularly rapid growth rate in mosquito populations, three months of rain was sufficient, resulting in a short transmission season.

2.4 A fuzzy logic model of stable malaria distribution

The GIS raster software Idrisi and its fuzzy function was used to convert the climate data to climate suitability maps of fractions between zero, which means conditions are definitely unsuitable (*F*) and one, which means condition are definitely suitable (*T*). Initially a simple sigmoidal fuzzy membership curve was used, defined in Idrisi as:

$$y = \cos^2 [((x - F)/(T - F))\cdot (p/2)]$$

where *y* is the fuzzy membership value of climate value *x*. In the decreasing curve at the upper end of the range, fuzzy membership is equal to y, in the increasing curve at the lower end of the range it is (1–*y*). For rainfall, $F = 0$, $T = 80$ mm per month; for average temperature $F = 18$, $T = 22$ °C for the increasing curve and $T = 32$, $F = 40$ °C for the decreasing curve. For minimum temperature $F = 4$, $T = 6$ °C.

Because favourable temperature and rainfall conditions have to coincide for transmission to occur, the 12 monthly fuzzy rain and temperature images were overlaid month by month. The minimum suitability rating was calculated at each point, since overall suitability would be determined by whichever – rain or temperature – was more limiting at that point. Furthermore, suitable conditions have to occur for a certain time window, constituting a transmission season, long enough for vector populations to increase and for the transmission cycle to be completed. The highest value spanning any five consecutive months was calculated.[1] To adjust the model for the effect of frost, the fuzzy minimum winter temperature (mean daily minimum of the coldest month) was overlaid, again calculating the minimum.

The resulting model (Figure 2.1) shows the distribution of conditions more or less suitable for malaria transmission, lasting for at least five consecutive months (three in north Africa) in the average year. A value of 1 means that conditions in the average year are suitable, hence one could expect to find endemic malaria; a value of 0 means conditions are unsuitable in the average year, hence transmission should be absent or occur in rare epidemic episodes. To highlight the results for highland areas, Figure 2.2 shows only model results for areas above 1300 m.

Because we are looking at the distribution of *stable* malaria, the edge of the suitable zone must be regarded as the lowest level of endemic malaria (hypo-endemicity and/or strongly seasonal) where we expect to find substantial (but not necessarily high) levels of transmission occurring every year. The situation within the suitable zone (fuzzy value 1) varies from low to high transmission intensity and/or from highly seasonal to perennial, but this is not reflected in a distribution model. The situation outside the suitable zone (fuzzy values 0–0.9) reflects the gradient from stable to increasingly unstable malaria with lower and lower levels of transmission, until, at the outermost fringes, transmission becomes a sporadic, unpredictable event, subject to the chance influx of parasites in rare wet or warm years. In fact, in Botswana 13 years of incidence data[2] show that districts in the same fuzzy zone behave similarly from year to year in terms of actual numbers of cases recorded. There is a distinct decline of cases from the three endemic districts in the North, to extremely low numbers in the central district, where four out of 13 years had no recorded cases at all. In further five districts, cases are reported in extremely rare years (D. Rumisha, pers. com.).

It is remarkable how well this model, based on a simple sigmoidal fuzzy membership curve, and driven by an understanding of the situation on the ground, approximates the edge of malaria distribution across the continent. Comparing the model with historical maps and malaria case data in southern Africa and in Uganda, Kenya and Tanzania (Craig *et al*. 1999), the resemblance is striking. In southern Africa the edge of malaria distribution is well represented. The malaria-free east African highland regions are also clearly reflected in the model. In Kenya the coastal and southwestern endemic zones agree, as do the 'malaria near water' regions, too dry to register as 'suitable' in the model. The discrepancies in some large river valleys result because the model uses only rainfall to predict the presence of vectors, so while rainfall may be low, breeding sites are available and humidity is high along banks and flood plains of major rivers.

Notes

[1]. In the continental model, a 3 month window was used for areas of Africa >8° north.

[2]. Botswana malaria cases: district data 1982–94. Unpublished data.

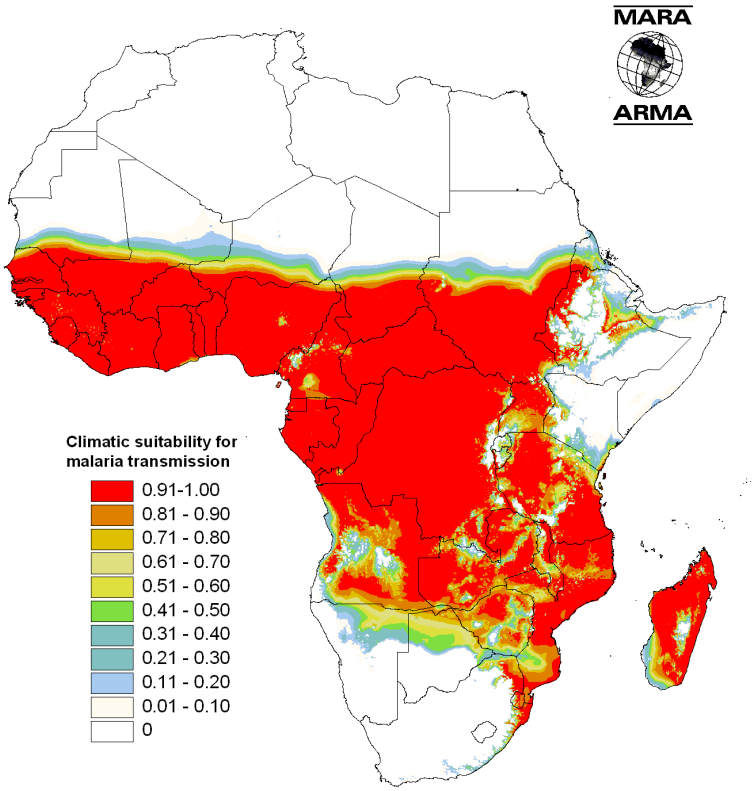


Figure 2.1 *The climatic malaria distribution model, showing fuzzy climate suitability for malaria transmission, where 0 = unsuitable (malaria transmission is most unlikely), 1 = suitable (stable malaria transmission is highly likely, 0 <> 1 = increasing climatic suitability (stable malaria transmission is increasingly likely)*

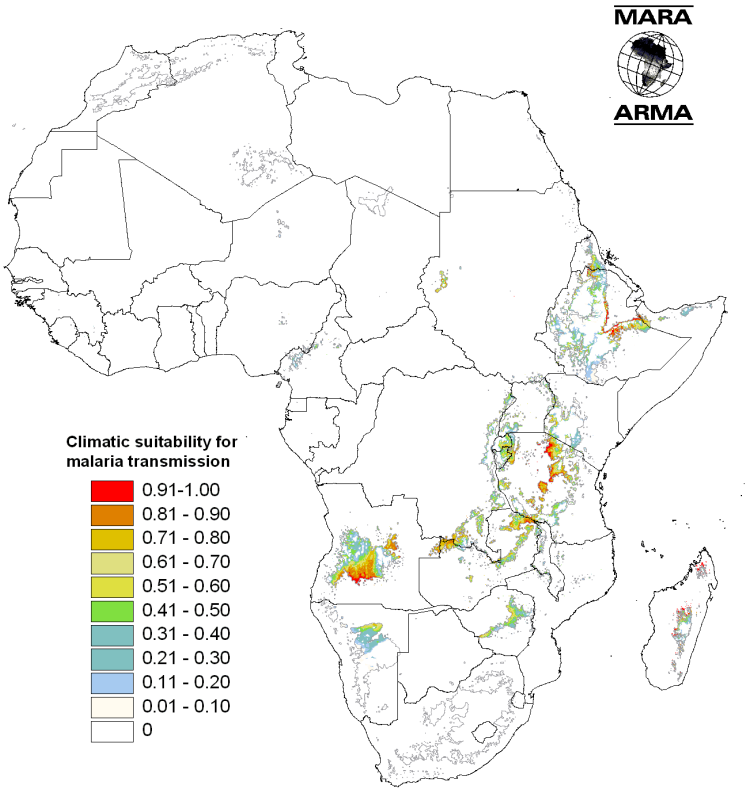


Figure 2.2 *Climatic malaria distribution model, showing fuzzy climate suitability in areas above 1300 m ASL. Grey lines represent the 1300 m contour*

3 Validation of spatial estimates of malaria risk in highland areas (Phase 1B)

3.1 Validation issues

The MARA model described in Section 2 is essentially a climatic stratification, indicating for any given locality the likelihood of conditions being suitable for malaria transmission. The principal approach used to validate this stratification is to compare predicted risk with available data for malaria transmission intensity. The following section outlines the approach adopted for this work as well as the methods used to create a database for highland malaria. Country-specific findings for East Africa are reported in Sections 4–7.

It is important to reiterate that the MARA model is a static model of risk. The climate surfaces used to develop the model represent mean values for rainfall and temperature over a number of years and as a result the model reflects malaria risk under 'expected' climatic conditions. The malariometric data used here to validate the model come from a variety of surveys, seasons and years which, taken together, also provide a representative picture of transmission risk over time (pooling the information in this way is necessary because of the general paucity of data for the highlands). The picture that emerges is therefore useful as a basic, static stratification, but temporal variations in transmission, either in the form of annual fluctuations or long term systematic changes, will be masked.[1]

3.2 Approach

3.2.1 Choice of data for model validation

Point prevalence

Point prevalence of malaria, expressed by the parasite rate, is by far the most commonly available measure of malaria endemicity. Although not strictly a measure of new infections in a population (unless measured in infants or adults previously cleared of infection), the parasite rate has been widely used as a proxy for transmission intensity over several decades, and was for this reason adopted as a marker of endemicity in MARA and HIMAL. The principal drawback to using parasite rates is that they are liable to vary significantly over time, particularly in areas of unstable malaria transmission (where the timing of the survey becomes critical and the representativeness of individual survey results uncertain). Small-area variations in parasite rates (*e.g.* Cattani *et al*. 1986; Jambulingham *et al*. 1991; Lindsay and Martens 1998) may also present problems from a spatial modelling perspective, particularly if the spatial resolution of explanatory variables (in this case gridded climate data) is relatively coarse.[2]

Some of variability associated with parasite rates can be avoided by using spleen rates (the prevalence of enlarged spleens). These reflect chronic and latent infections in partially immune hosts, and as such provide an indication of *prevailing* levels of malaria endemicity in the sample population (MacDonald 1957). The spleen index is admittedly crude and may be less reproducible than parasitological data, but its simplicity and ease of data collection has meant that it remains a popular measure of endemicity in many areas. In this study a significant amount of data came from this type of survey (see Table 3.2).

Data for epidemics

Point prevalence is used in this exercise to provide an indication of 'mean' conditions at a given location. This is based on the premise that prevalence surveys are randomly distributed over time. Where this is not the case, such as when surveys are specifically carried

out in epidemic situations, this assumption is untenable, and the data were not included in the analysis. Using the same logic, spleen rates and parasite rates from standard prevalence surveys are themselves poor indicators of the temporal and spatial occurrence of epidemics, and the assessment of epidemic risk can only be based on data for specific epidemic events.

Providing that sufficient data are available, it is possible to express epidemics in quantitative terms. However, indices such as Christophers' (1949) 'epidemic figure' (which compares total deaths in any given month to the 'normal' non-epidemic monthly number of deaths) rely on large sample populations and reliable records of mortality or morbidity. In Africa instances where this type of information is available are comparatively rare, and in most cases epidemic reports consist of isolated parasitological, clinical or entomological observations made by emergency teams some time after the onset of the epidemic. In other instances no data for the alleged epidemic, other than date and location, are available. In this exercise, given that it is the location of epidemics which is primary interest, all references to epidemics were extracted as 'epidemic locations', regardless of whether associated clinical or epidemiological data were available.

3.3 Identification of malaria data

Data for parasite rates, spleen rates and epidemic locations were obtained from a variety of published and unpublished sources. Table 3.1 shows the total number of reports used in the study and their origin. Table 3.2 provides a breakdown by country and the type of data contained in the reports. Figures for Rwanda and Burundi are combined because many of the older reports treat the countries as a single territory. Reports were accessed using three main approaches:

Searches for published journal articles and books. Various bibliographic databases were used to source journal articles containing malaria data, including Medline and Health Star (1983–; SilverPlatter International NV), EMBASE (1980–; Elsevier Science Publishers By), CAB Health (1972–; CAB International) and BIDS-ISI (1981–; Bath Information and Data Services). Older journal articles were traced through citations in recent papers, and through systematic searches of key journals. Searches for relevant book titles were made at the London School of Hygiene and Tropical Medicine library and the British Library (Science Reference and Information Service). A total of 115 papers and reports containing data for the highlands were collated in this way, constituting about 45% of the reports from all sources (Table 3.1).

Country visits. Given the relative paucity of published data for highland areas, country visits were important for locating old and grey material. The majority of these materials were obtained from Ministries of Health or government research institutions, although a significant amount of data were also made available by NGOs, independent scientific organisations and individuals. Overall, 76 reports were collected during the country visits, representing about 30% of the total collection. In Kenya, Tanzania and Zimbabwe this source of data was particularly important.

Specialist libraries and documentation centres. In addition to those libraries consulted in the UK and during the country visits, various documentation centres in Europe were visited as part of this study. Of particular importance was the Malaria Unit library at CTD/WHO, which houses a large amount of grey literature on malaria. Table 3.1 shows that 51 reports (20% of the total) came from this source. For some countries (notably Ethiopia, Cameroun and Rwanda/Burundi), WHO documents accounted for a high percentage of the total number consulted. In addition, the libraries of ORSTOM (Montpellier) and Institut Pasteur (Paris) provided a large proportion of the reports used for Madagascar.

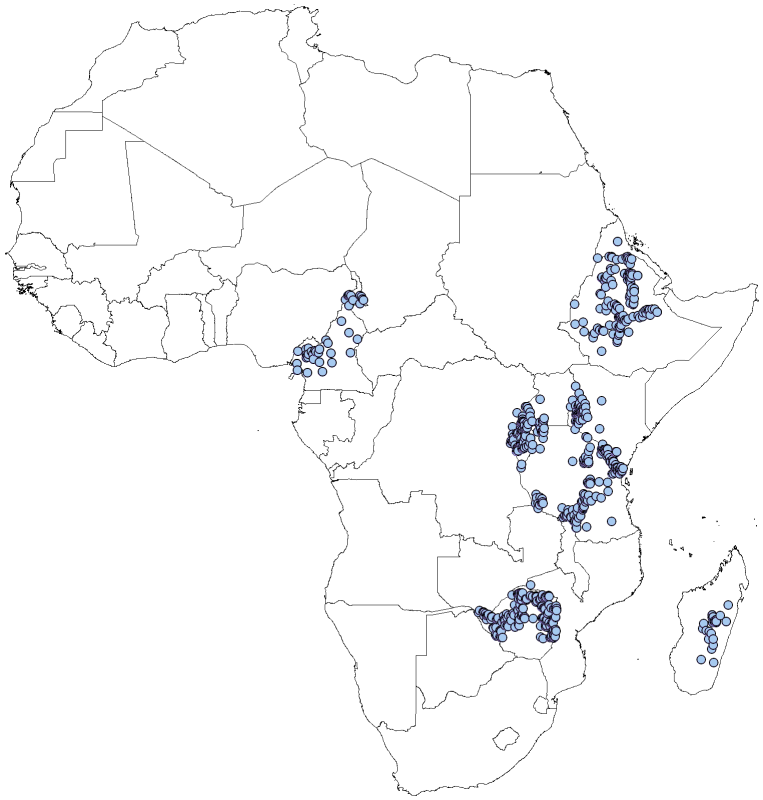


Figure 3.1 *Distribution of HIMAL data points*

In Cameroun, Ethiopia and Uganda the number of points representing parasite rates and spleen rates were evenly matched, while in Zimbabwe and Kenya, very few spleen rates were reported. The number of epidemic locations extracted for each country also varied considerably and ranged from 0 (Cameroun) to 147 (Ethiopia).

Sample points were geo-referenced using place name gazetteers (GeoName (GDE Systems, San Diego CA), GeoNet Names Server (NIMA, Bethesda MD)), or from digitised paper maps. A substantial number of survey points could not be located through these means, however (Table 3.2). The geographical distribution successfully geo-referenced points is shown in Figure 3.1.

3.4.2 Extraction of non-malaria attribute data for sample points

Once complete, spreadsheets for each country were imported into ArcView 3.0 (ESRI, Redlands, CA) in order to map their distribution and check consistency. The data point identifiers, latitude and longitude were then imported into Idrisi 2.0 (Clark Laboratories, Worcester, MA) and attribute data for each point were extracted using a range of gridded coverages for altitude and monthly precipitation and minimum/maximum temperature, as well as the MARA model predictions for each site. In subsequent analyses, spatial coverages of population density (Deichmann 1996) were also used to assess populations at risk of malaria epidemics.

Most of the datasets used have a nominal resolution of about 5 km. The CRES climate data, which were used for developing the MARA model and for examining the average climatic profiles of epidemic locations, mostly cover the period 1920–80 and are based on data from 1504 and 6051 meteorological stations for temperature and rainfall respectively. Quoted standard errors are ±0.50 °C for temperature surfaces and ±5–15% for rainfall, depending on data density and the spatial variability of the actual monthly mean

Table 3.1 *Numbers of documents used in the HIMAL study, by source*

	In-country	*Search*[†]	*WHO*	*Orstom/ Pasteur*
Kenya	19	19	0	0
Uganda	10	13	2	0
Tanzania	25	10	4	0
Ethiopia	11	23	14	0
Madagascar	2	13	7	15
Zimbabwe	10	10	5	0
Cameroon[‡]	0	7	9	2
Rwanda/Burundi[‡]	0	19	10	0
Total	**77**	**114**	**51**	**17**

[†] *Published journal articles and books from bibliographic databases*
[‡] *Not included in country visits*

3.4 Data extraction

3.4.1 Extraction of malaria data

Once the bibliographic database had been completed, data for parasite rates, spleen rates and epidemic locations were systematically extracted for each of the study countries. Each data point was given an unique identifier and the relevant malariometric information for each was entered into a spreadsheet. For parasite and spleen data additional information was extracted to describe the survey location, altitude (if available), type of survey, dates of the survey, survey size, age-specific groupings used[3], bibliographic source. In the same spreadsheet details of locations and dates of epidemics were also entered.

In all, 1713 individual sample points were extracted from the 259 reports in the HIMAL database (Table 3.1). Of these, parasite rates constituted just over half (55.8%) of the observations and spleen rates 22.6%. The remaining 21.6% comprise epidemic locations. The relative proportions for each category varied significantly from country to country.

Table 3.2 *Breakdown of HIMAL points by type and country*

	Data points	*Epidemic locations*	*Parasite rates*	*Spleen rates*	*% georef.*
Kenya	118	47	66	5	94.0
Uganda	442	15	214	213	59.5
Tanzania	301	29	213	59	93.7
Ethiopia	242	147	47	48	76.8
Madagascar	50	19	23	8	92.0
Zimbabwe	370	80	290	0	93.2
Cameroon	90	0	53	37	85.5
Rwanda/Burundi	100	33	50	17	92.1
Total	**1713**	**370**	**956**	**387**	

rainfall (Hutchinson *et al*. 1995). The CRES dataset does not include data for Madagascar. These were obtained using the Spatial Characterisation Tool developed at Texas A&M University (Corbett and O'Brien 1997), which has similar data characteristics to the CRES dataset.

The CRES dataset also includes a 5 km resolution DEM, although most of the analysis in this report used 1 km resolution data produced from contour and spot elevation data in the 1:1,000,000 scale Digital Chart of the World. The stated accuracy of the these data is 2000 m horizontal error and ±650 m vertical error at the 90% confidence interval.

3.4.3 Exploratory data analysis

Once attribute data for each sample point had been successfully extracted from the GIS database, values were exported into new spreadsheets and from there into Stata 6.0 (Stata Corporation, College Station, TX) for data analysis. These analyses focused on:

1. Relationships between malaria prevalence, MARA model values and altitude by highland region;
2. The distribution of malaria epidemics by region; identification of altitudinal and climatic 'niches' for epidemics
3. Assessment of the MARA model for delineating zones of epidemic risk; exploration of alternative approaches using climate parameters and altitude; quantification of populations at risk

Results of this exploratory analysis for the East African region are reported in Section 4–7. These sections also provide a rapid assessment of risk factors associated with highland malaria transmission, as presented in the literature and by expert opinion. These reviews are important in terms of validating the MARA model which, being solely climate-based, may over- or underestimate risk depending on the relative importance of non-climatic parameters. The premise that climate variables, on their own, may not always reliably predict malaria transmission has important implications for epidemic forecasting in general and the structuring of further phases of this study in particular.

Notes

[1]. In reality there are so few reliable time series of malaria data that this is rarely an issue. But notable exceptions do exist and provide an opportunity to relate inter-annual fluctuations in transmission to those of climate (and this has clear implications from an epidemic early warning point of view). To address this issue a series of climate surfaces, based on interpolated climate data for 1950–95 have been commissioned as part of the MARA project. These surfaces were designed to enable the temporal correlation of malaria transmission and climate variables, and in particular to evaluate climate conditions in known peak years for epidemics. Some preliminary analysis using these data is included in Section 4 (Kenya). On the whole, however, analysis at the general (national) scale proved problematical. More rigorous use of these surfaces will be made with reference to specific highland areas in the next phase of the HIMAL study.

[2]. In this study, the fact that the altitudes of most sample points were also derived from raster data (digital elevation models) meant that additional error was introduced.

[3]. A variety of age-specific groupings were encountered, but only rates reported for 1–10 year olds were used where possible. Slight variations around/within this age grouping (*e.g.* 1–9, 2–9 years) were also deemed permissible. (Experience within MARA suggests that minor variations in the age categories are not significant, provided infants and adults are excluded.)

4 Kenya

4.1 Principal features of the Kenyan highlands

The highlands of Kenya are concentrated in the south west corner of the country (see Map 1 in Appendix 1) and consist mainly of recent volcanic materials overlying ancient basement complex rocks. The Rift Valley system divides the highlands into two main units: highlands east of the Rift Valley (including Mount Kenya, the Laikipia plateau and the Machakos hills); and areas west of the valley (including the Uasin Gishu plateau and the Trans-Nzoia uplands). The physiology and geology of these areas have been described by Odingo (1971).

Population densities (Appendix 1) are generally high throughout the highlands, and particularly in the 1750–2000 m belt, which supports around 180 persons km^{-2} (of the countries included in this review only Rwanda, Burundi and parts of Uganda have higher population densities). In absolute terms about 13.3 million people (48.5% of the total population) live above 1500 m, which makes it second only to Ethiopia in the size of its highland population.

While rainfall patterns are primarily influenced by the ITCZ, the local effects of mountains, plateaux and lake basins are reflected in large variations in annual rainfall over relatively short distances (*e.g.* Davies *et al*. 1985). In the regional context, however, the Kenyan highlands are generally quite dry. The CRES data indicate that less than a third of the area above 1000 m receives more than 600 mm of rain in the wettest five months of the year, while only 5% receives more than 800 mm. The wettest areas are the western fringes of the central highlands in the vicinity of Kisii, Kericho, Kakamega and Mount Elgon. There is also a limited pocket of high rainfall around Mount Kenya, forming a rough triangle between Nairobi, Embu and Nakuru (Map 3, Appendix 1). Other parts of the highlands are significantly drier, especially in areas south and south west of Nairobi (Kajaido and parts of Narok) and west of Isiolo (Laikipia and Samburu).

There are two principal rainy seasons in the highlands; the short rains typically last from October to December and the long rains from March to May. In addition some parts of western Kenya (and especially around Mount Elgon) experience a third rainfall peak, usually in August. These patterns show up clearly in Figure 4.1, which shows long term monthly averages for temperature and rainfall in two altitude classes. The 'extra' rainy season is apparent at high altitudes (bottom figure), but is not detectable at lower elevations. In terms of temperature variations, conditions in both altitude classes[1] are warmest in March and coldest in July. Even in the 1900–2100 m class mean temperatures remain above 17 °C for the first five months of the year, and significantly this window coincides with the onset of the main rainy season.

To provide a better impression of the spatial distribution of limiting temperatures over the year, Figure 4.2 divides Kenya into three temperature classes by month. Yellow shading represents sites where mean monthly temperatures, at 19 °C or more, are unlikely to limit malaria transmission. Black areas show areas where the mean monthly temperature is below 17 °C, and where we would expect the extrinsic cycle (at >60 days) to be sufficiently long to make transmission unlikely. Red shading indicates intermediate areas (mean monthly temperature 17–19 °C), where the transmission status is less certain and where the potential for epidemics is likely to be highest. In Figure 4.2 black and red areas expand visibly in the coldest months from June to August. From September they begin to contract to a point where, in the warmest months (February to April) much of the highland zone

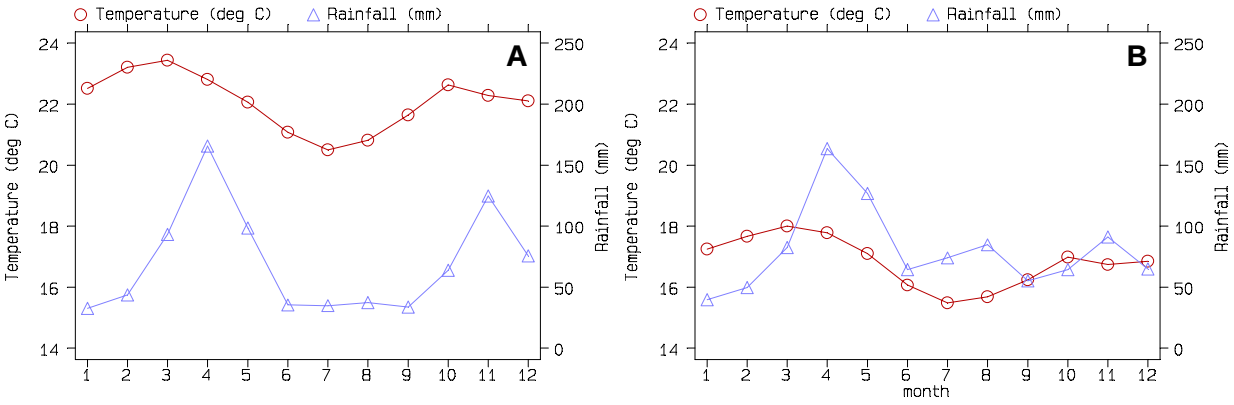


Figure 4.1 *Annual patterns of rainfall and mean monthly temperature for two altitude bands; (A) 1100–1300 m (B) 1900–2100 m.*

appears to experience temperatures suitable for vector breeding and sporogonic development. Admittedly this constitutes a short window and the extent to which transmission occurs will depend greatly on inter-annual variations in both temperature and rainfall (see below).

4.2 Malaria transmission in the highland zone

4.2.1 Previous studies

Historically, the issue of highland malaria in Kenya can be separated into three distinct phases. The first phase, roughly between the 1920s and 1940s, saw a huge increase in malaria transmission in highland areas, which continued more or less unchecked until DDT and antimalarial drugs became widely available after the Second World War. These developments facilitated a phase of intervention in the 1950s–60s which brought about the successful control of malaria in certain parts of the highlands and coincided with a period of relatively low levels of transmission. More recently however, the re-emergence of epidemics in many highland areas (1980s–), has led to renewed interest in developing new tools for epidemic prevention and control. At the same time there has been a search for 'new' explanations (*e.g.* global warming) for the increasing levels of transmission in the highlands. The following review aims, in part, to place these developments in an historical perspective and also to emphasise parallels between the pre- and post-intervention eras, both in terms of epidemiology and the need for reliable early warning systems for epidemic control.

4.2.2 The pre-intervention period

It is widely accepted that up until the First World War malaria was absent from most areas of Kenya above about 1500 m (Garnham 1948). After the war, however, malaria outbreaks in these areas became increasingly common, affecting first Nairobi and areas around Eldoret before spreading to other parts. In Trans-Nzoia and Uasin Gishu reports of malaria first appeared in the mid 1920s and were thought to be linked to an influx of infected hosts and a proliferation of new breeding sites brought about by railway construction. By the time of Anderson's (1929: 274) visit to Trans-Nzoia, malaria had become 'the most important disease amongst all communities living in the area.' Similar trends in malaria cases were observed in Nandi, where the return of infected troops enlisted in the First World War was believed to have caused a shift to more malarious conditions (Matson 1957). Outside the central highlands, Teesdale[2], expressed concern over the apparent spread of malaria to higher slopes in the Taita area of south east Kenya.

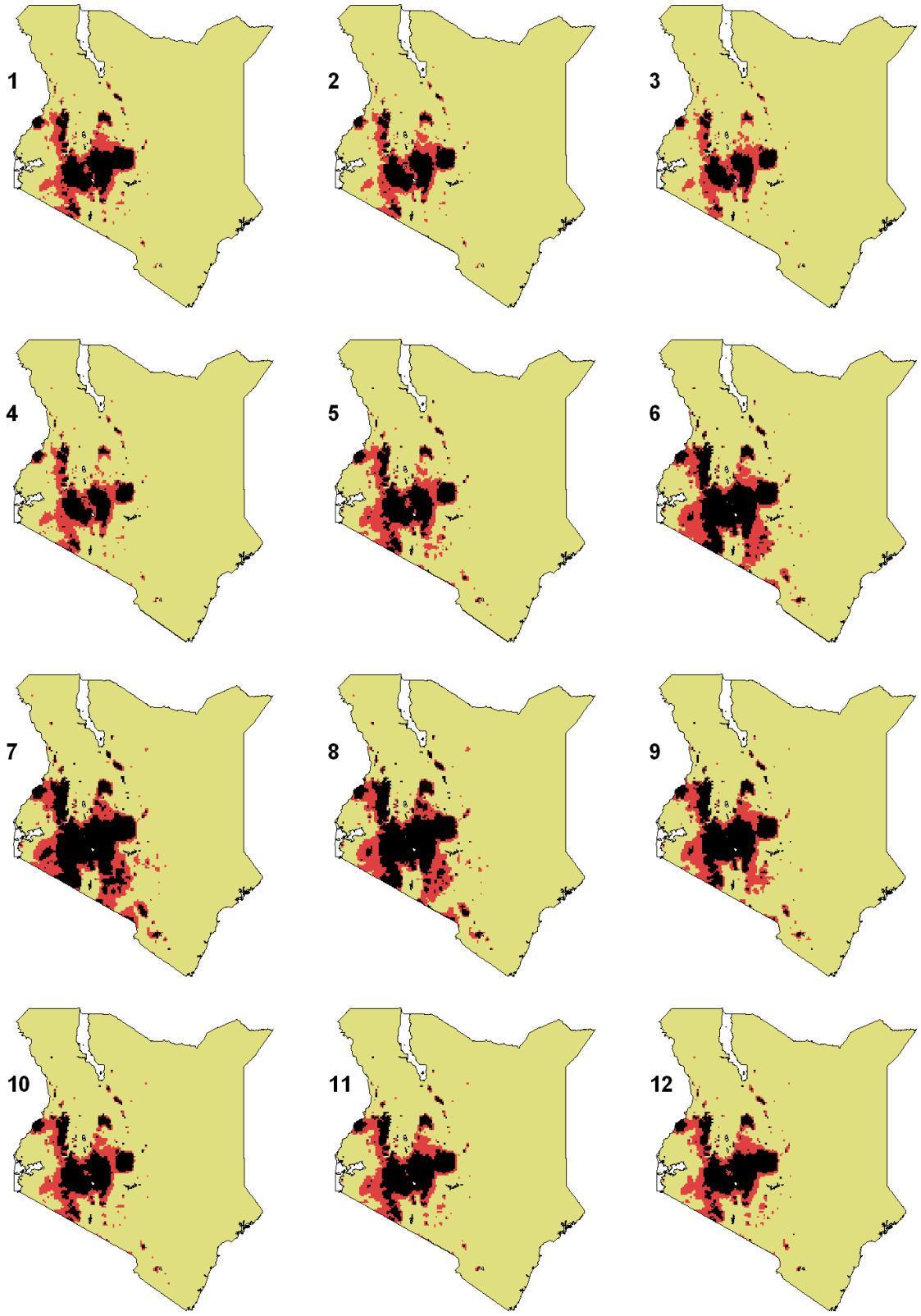


Figure 4.2 *Spatial variation in mean monthly temperatures in Kenya in a typical year. Yellow shading indicates areas where temperatures are likely to support malaria transmission in a particular month, while black shading signifies localities where temperatures are likely to be limiting. Red areas are intermediate and probably represent the altitudinal fringes of transmission (see Section 4.1)*

Records indicate that the first 'major' highland epidemics occurred in Uasin Gishu, Trans-Nzoia and Nandi in 1926 and 1928 (*e.g.* Chataway 1928; Anderson 1929). At the same time Campbell's (1929) analysis of rainfall and malaria data for Eldoret for the period provided the first clues of a linkage between rainfall variability and epidemics. Campbell (1929) placed particular emphasis on the fact that the 1928 epidemic was preceded by a period of drought and a 'state of physical and mental depression' among the local population. Such considerations later formed the basis of a crude early warning system (see Box 4.1). With hindsight, Campbell's (1929: 37) assertion that highland malaria was '"biding its time", always present' was accurate; further epidemics in Nandi were reported in 1931, 1932, 1934, 1937 and 1940. A particularly severe epidemic was reported in 1944, with high levels of transmission continuing in 1945–8 and 1951 (Roberts 1964a).

Evidence points to equally high levels of transmission elsewhere in the highlands. Heish and Harper (1949: 188), for example, maintained that by the end of the Second World War, 'the usual malaria picture' in Kericho and surrounding highlands was 'a severe annual epidemic.' Nairobi was also much affected by epidemics up to and including 1940 (*e.g.* Logan 1928[3]; Symes 1940; Haynes 1940; de Mello 1947), and the influence of climatic variation was again stressed in reports of the time. On the basis of slide positivity data for Nairobi (1938–44) Roberts (1949: 166), for example, found it 'safe to assume that the incidence of malaria at high altitudes is governed solely by *An. gambiae* and rainfall.'[4]

The importance of *An. gambiae* as a vector in highland areas was confirmed by subsequent entomological surveys – as was the small but significant presence of *An. funestus* (*e.g.* Heish and Harper 1949). Moreover, the occurrence of malaria transmission appeared to be strongly linked with the spatial distribution of these species, and hence to local ecology. Roberts (1964a) referred to focal swamps in which vectors were perennially present, and from which they would spread given suitable meteorological conditions. In these localities a situation somewhat similar to that of south west Uganda (see Section 5.2.1) appears to have existed in which spleen rates in the vicinity of swamps were typically 50% or more higher than those of surrounding areas (Roberts 1964a). Today it is likely that such foci still exist and that they act as seed beds for transmission in many highland areas (Sang, pers. comm.). Identification of these sites is likely to contribute to the early detection of epidemics by enabling surveillance activities to be focused on key areas.

Overall, despite the large amount of material written, there are few parasitological data available for this period, and the first major prevalence surveys in the highlands (in Nandi) were not carried out until 1951. They indicated that parasite rates among 1–10 year olds varied anywhere between 3 and 76% depending on the timing and location of the survey (Roberts 1956: 203). Details are also lacking with respect to the precise locations (and hence altitudes) of areas worst affected by epidemics. Garnham (1945) maintained that the general limit of malaria transmission occurred at around 7000 ft (2133 m), but also provided evidence of 'exceptional' epidemics at higher elevations. In June 1941 farms and military camps around Londiani (Kericho District; 2290–2390 m) experienced severe malaria outbreaks, with smaller outbreaks occurring annually in the following years. In the same year an epidemic was reported in Molo at 8600 ft (2620 m) which was thought to be the direct result of developments in communications and agriculture (Roberts 1964a). In 1944 an outbreak lasting only a fortnight was reported at a farm north of Londiani at 8300–8500 ft (2530–2590 m). Garnham's analysis of meteorological data for the area confirmed that local transmission was theoretically possible even at this altitude, with a very small window for vector breeding occurring around March. More generally, such occurrences demonstrate the high vectorial efficiency of *An. gambiae* even at the limits of its distribution (*e.g.* White 1972).

Box 4.1 Early epidemic warnings in Kenya

Following the experiences of 1926 and 1928 several epidemic warnings were issued by relevant government offices in Nairobi, most particularly in 1935 and 1944. The following excerpt from a circular letter to the principal highland districts is typical:

'I have the honour to invite your attention to the possibility of an occurrence of a serious and widespread outbreak of malaria in Kenya in the near future ... I am advised by the Director of Medical Services that the situation at the present time is so very similar to that which prevailed just prior to the very serious outbreaks of malaria experienced in 1926 and 1928 that it is desirable to issue the Local Authorities a most definite warning with regard to the possibility of a recrudescence of epidemic malaria in the near future.

The conditions which in view of the Director of Medical Services give cause for anxiety are firstly, the fact that we have had a prolonged drought succeeded now, in the Nairobi District at least by heavy showers, that the Native population is in many areas more or less debilitated from a shortage of food, and very especially a shortage of green food, and that in many places owing partly to the depression and partly to the fact that we have had some years of comparative immunity from malaria many simple but important precautionary measures may have been allowed to fall into abeyance as the need for such measures may have been forgotten.'

(From Circular letter (No. 2 of 1935) from WM Logan (Commissioner for Local Government, Lands and Resettlement, Nairobi to Town Clerks and Clerks of District Councils in Nairobi, Nakuru, Naivasha, Eldoret and Kitale), 21/2/1935.)

4.2.3 Intervention in the highlands

During the 1952 malaria epidemic in Nandi District, a one-off chemotherapeutic trial using pyrimethamine (Daraprim) produced significant reductions in malaria prevalence rates. Following this success, single doses of the drug were administered to around 120,000 people in Nandi at the beginning of the transmission season (one month after the onset of rains) in 1953 and 1954 (Roberts 1956). Subsequent reductions in parasite rates in the trial area led Roberts (1964b: 193) to conclude that 'mass chemoprophylaxis represents an effective and extremely cheap method of preventing epidemic malaria of short seasonal occurrence' (albeit in a trial situation with a dedicated cadre of staff). During these trials house catches of anophelines in Nandi and Turbo revealed that of 1911 specimens examined 98% were *An. gambiae* complex and only 2% *An. funestus* (Roberts 1956: 204). Roberts still thought it likely, however, that *An. funestus* was responsible for many localised malaria outbreaks.[5]

DDT was first used on a trial basis in 1946 in Kericho (Garnham 1948). Two spray rounds per year were carried out in 1946 and 1947, with parasite rates falling from 37% to 10% over the same period. Over the longer term, Roberts (1974), asserted that the operation virtually eliminated transmission in the area until at least the early 1970s. In Nandi, the trials with pyrimethamine were followed up in 1955–1957 with Dieldrin spraying in around 6000 homes. The spraying had dramatic effects in the trial area and supposedly also had knock-on effects in surrounding areas, including the control site. While the three spray

rounds did not eradicate malaria, they did obtain 'an extremely high degree of malaria control' (Roberts 1964b: 195), with the remaining low but persistent levels of infection being attributed to population movement. Vector surveys indicated that *An. gambiae* populations had been reduced 'almost to the point of extinction' (p.196).

The combined effects of the pyrimethamine and Dieldrin interventions on parasite rates in Nandi are shown in Figure 4.3, in which 'CP' indicates the timing of pyrimethamine administration and 'RS' that of Dieldrin spray rounds. As the graph suggests, transmission, as detected by surveillance systems implemented after the campaign, remained low well after the final round of residual spraying. Localised malaria outbreaks were reported from 1963 onwards, most notably in highlands adjacent to hyperendemic areas (Roberts 1964c). By 1964, Roberts concluded that conditions in Nandi were once again conducive to epidemics, given suitable meteorological conditions. It was not, however, until the 1980s that severe epidemics began to affect the area.

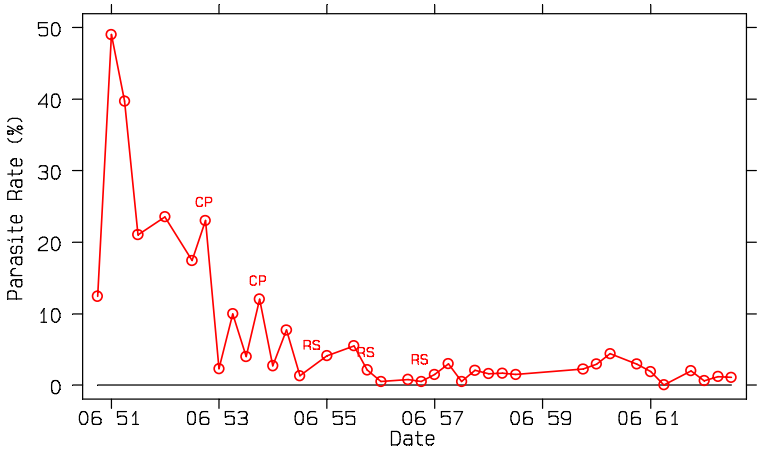


Figure 4.3 *Parasite rates in Nandi after intervention trials using chemoprophylaxis (CP) and residual spraying (RS) (data from Roberts 1964b,c)*

4.2.4 Post-intervention epidemics

Although Some (1994) referred to an 'undetected' epidemic in Uasin Gishu in 1985, the first documented epidemic to occur in the highlands since the 1940s appeared in Uasin Gishu in June 1988. The epidemic followed a period of heavy rainfall which had been preceded by two years of relatively dry conditions (Ngindu *et al.* 1988). These were precisely the high risk conditions that concerned district officials in the 1920s–40s, and which had previously given rise to official epidemic warnings (Box 4.1). From 1988 onwards, epidemics were reported on an almost yearly basis, but most notably in 1990, 1994 and 1998.

The epidemics in 1990 first affected Uasin Gishu (in May), and subsequently spread to the northern Rift Valley districts of Nandi, Kericho, Trans-Nzoia and parts of Elgeyo Marakwet (Some 1994). Some obtained data for Uasin Gishu from hospital registers in Eldoret (2050 m ASL) and health centre records in Turbo (1500 m). The data from Eldoret hospital indicated 146 inpatient deaths due to malaria in the first three quarters of 1990, and a substantial increase in both inpatient and outpatient malaria cases over the epidemic period (although case fatality rates remained more or less constant). Outpatient data for Turbo, which represents a highland fringe area, also demonstrated a marked peak in 1990, mirroring similar peaks in 1988 and 1985.

Although many researchers refer to 'annual' epidemics in the highlands during the 1990s, the next widespread epidemic did not appear until 1994. Information on this epidemic is fragmentary, but it seems that the worst affected districts were in the southern parts of the highlands, and especially in Kisii, Nyamira and Kuria. According to Hill (1994) over 1600 patients were admitted to Tabaka Mission Hospital (Kisii) with severe malaria infections in May 1994 alone. Of these 167 died. The scale of the epidemic is also well illustrated by data for Nyamira District Hospital (also in Hill 1994) which show that at the peak of the epidemic in May–June 1994, inpatient malaria cases and malaria deaths were 4 and 10 times higher, respectively, than corresponding figures for the previous transmission peak in August 1993. Experience in the 1994 epidemics confirmed concerns first raised by Khan *et al*. (1992) about the efficacy of chloroquine for case management in epidemic situations. Khan *et al.*'s results indicated that sensitivities of a number of drugs (and chloroquine and amodiaquine in particular) were highly variable over small distances, and should be evaluated as part of emergency control measures.

Information on the more recent epidemics in 1997 and 1998 come mainly from statements made in press reports.[6] It appears that in the third quarter of 1997 severe epidemics affected West Pokot, Uasin Gishu and surrounding areas (Kigotho 1997). In press statements at least, DVBD staff highlighted drug resistance as a major underlying factor in the severity of these outbreaks. Later in the year the short rains were particularly heavy and prolonged, as had been widely predicted on the basis of the size of the developing El Niño event. The first indications of an epidemic were apparent as early as February (epidemics occur more usually in July and August after the long rains), which led to mobilisation campaigns throughout the western highlands.[7] Although all indications suggest that the 1998 epidemics were as widespread and severe as those of 1990 and 1994, few details were available at the time this report was prepared.

4.2.5 Longitudinal trends in highland transmission

Despite the lack of reliable time series data for malaria, the widely held view that malaria transmission (and specifically epidemic malaria) in the highlands has become more widespread over the past ten years is probably accurate. The underlying mechanisms behind this trend are, however, less clear and are likely to remain moot until more reliable data for the highlands become available.

One commonly held view is that epidemics have followed a gradual re-colonisation of highland areas by malaria vectors (notably *An. gambiae* at high altitudes and *An. funestus* in the intermediate zone) since the cessation of active control measures (*e.g.* Oloo *et al.* 1996). This view probably assumes that intervention in the highlands was more widespread than it actually was and, while doubtless relevant in some specific cases, may not be universally applicable. It also rests on the assumption that the lack of epidemic reports for the 1950s–70s reflects the disease pattern of the time, rather than any change in the way information on outbreaks was collected or reported.

Another common hypothesis is that increases in transmission reflect shifts in vector efficiency brought about by climate change – and in particular by increasing environmental temperatures. This itself is not a new concept: Matson (1957), for example, speculated that a shift to warmer conditions in the first half of the century was a prime factor behind the initial spread of vectors and parasites to higher parts of Nandi. Today, however, the idea that climate change may have modified malaria transmission patterns in the highlands appears grounded largely on results of studies conducted *outside* Kenya, while existing climate series provide little evidence to support the existence of monotonic climate changes within Kenya itself.

There is, however, some evidence that climate cycles exist which may, in the short term, produce signals which are analogous to climate change. Tiffen *et al.* (1994), for example, analysed meteorological data from six stations in Machakos (1957–90) and found evidence of a cycle of 9–11 years in the long rains, with peaks in 1967–8 and 1977–9 and troughs in 1973 and 1982–5. Data for the short rains revealed a longer cycle of 16–22 years, declining from a peak in 1962–3 to a trough in 1970–4 and rising again to a peak in 1984 (1988 in one station) (Tiffen *et al.* 1994). It is conceivable, therefore, given the clear link between annual rainfall and malaria transmission in the highlands, that the relatively low levels of malaria transmission in the 1970s was related to the prevailing drought conditions of the time (although we would expect some transmission to have occurred in the late 1970s). Nor may it be merely coincidental that the rise in epidemics from 1988 has come at the 'top ends' of the short and long rain cycles.

As has already been noted, the paucity of reliable data for the highlands has meant few opportunities to examine rigorously links between climate and malaria transmission over time. A notable exception is the recent analysis by Malakooti *et al.* (1998) of malaria records from the central hospital of the Brooke Bond tea estates near Kericho (1780–2225 m). Their analysis of malaria data for the period 1991–7 indicated that the area is subject to highly unstable transmission in which the inter-annual fluctuations in cases appear to be correlated with patterns of rainfall (Figure 4.7). The authors concluded that rainfall in excess of 150 mm per month was the principal risk factor for epidemics, while transmission generally ceased once mean monthly temperatures fell below 18 °C (which usually occurs in July). Given the lack of evidence to support either changes in climate or the increased movement of people between the estates and hyperendemic areas, the authors considered it likely that the worsening malaria situation (observed over the longer term) could be linked to treatment failures associated with the use of chloroquine or misuse of other drugs.

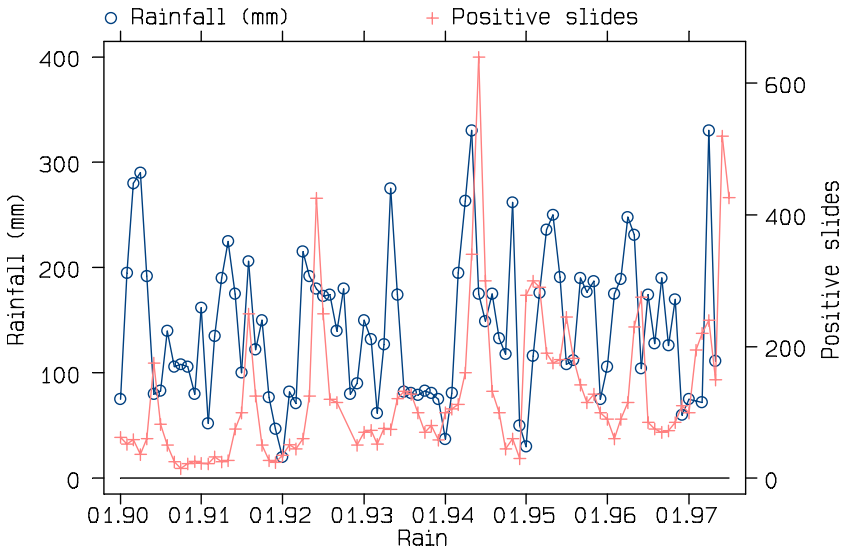


Figure 4.4 *Relationship between rainfall and positive malaria slides from Kericho tea estates 1990–7 (after Malakooti et al. 1998)*

4.3 Analysis of the HIMAL dataset

4.3.1 Data collected for HIMAL

Despite the prominence of highland malaria as an issue in Kenya, and the wealth of malaria data available for the country as a whole (*e.g.* Omumbo *et al*. 1997), a search of the literature revealed very little information specific to the highlands, either in the form of research papers or prevalence survey results. This is likely to be due in part to the various successful interventions implemented in the highlands in the 1950s–70s, and it has only been with the apparent re-emergence of malaria transmission in the highlands since the late 1980s that research papers on the subject have themselves re-emerged. These, however, tend to focus on the clinical characteristics of specific epidemics and contain little in the way of detailed parasitological data. In all, out of 38 reports sourced for Kenya only eight provided cross sectional data for parasite rates (generating 66 data points in total). Only two reports were found to contain data on spleen rates (5 data points), and consequently there is no analysis of spleen rate data in this section.

Data for epidemics are also scarce, and although a large number of sources refer to epidemics in specific years, few provide precise details of epidemic locations (more often only the affected district is named). Thus out of 47 'reports' of epidemics, only 22 could be geo-referenced with any confidence. To ensure that these were highland epidemics as distinct from desert fringe epidemics, only locations higher than 1000 m were considered (thereby excluding from the analysis epidemic prone areas in the north and north east of the country).

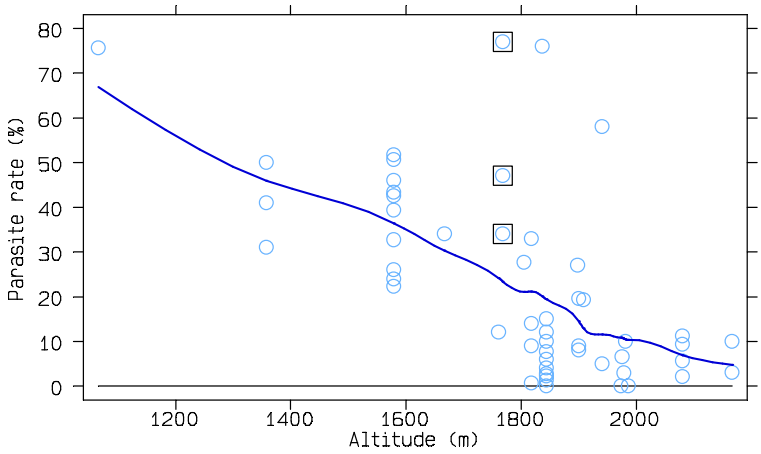
The geographical distribution of data points for Kenya is shown in Map 5 in Appendix 1, which indicates that the majority of parasite survey data come from the vicinity of Eldoret and Kakamega (*i.e.* Uasin Gishu, Nandi and Kakamega Districts). Epidemic locations are also principally spread around the western fringes of the central highlands.

4.3.2 Effects of altitude on malaria transmission intensity

To examine the relationship between transmission intensity and altitude, a dataset for Kenya comprising parasite rates and altitudes of survey sites was compiled. Where possible, the altitudes given within the survey description were used — although in most cases only the name of the survey location was provided. Altitudes for these sites were extracted from the USGS DEM once survey locations had been successfully geo-referenced. The resultant plot (Figure 4.5) shows that while altitude and parasite rates are clearly correlated ($p < 0.001$), the relationship is quite variable. This is not surprising, given that the dataset includes survey data taken over a number of years. It is also probable that the considerable spread of parasite rates at individual sites reflects seasonal variations in transmission intensity. To illustrate this, the three boxed observations in Figure 4.5 are parasite rates recorded at a single site in April, October and November of the same year (corresponding to the highest to lowest values respectively) (Roberts 1964a: 166). Given a larger sample it would have been optimal to standardise for this source of variation.

From Figure 4.5 it is difficult to determine any absolute altitudinal limits for transmission. Seasonal parasite rates of zero are encountered from about 1800 m upwards, but no surveys in the HIMAL dataset indicated absence of transmission throughout the year. This is likely to be, at least in part, a function of the geographical distribution of the survey data, with observations coming mainly from highlands bordering hyperendemic areas. Sites in the (higher) central highlands, on the other hand, are not represented in available records, nor are they commonly available from unpublished DVBD sources.

Figure 4.5 *Variation in parasite rates with altitude, Kenya*



4.3.3 Effects of altitude on the MARA model

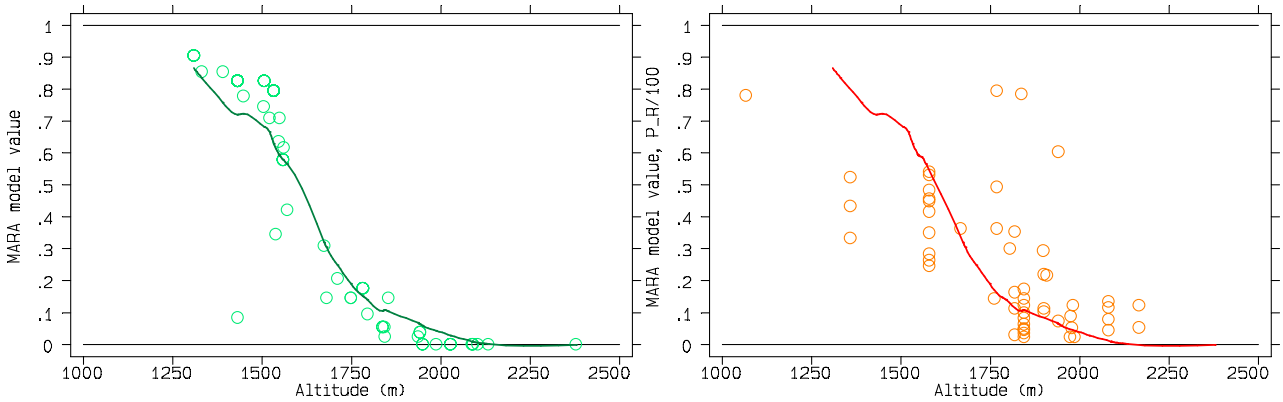
Figure 4.6a, shows the MARA model plotted against altitude for all Kenyan survey points. The strong correlation between model results and altitude indicates the sensitivity of the temperature component of the model, while the small degree of scatter is likely to reflect spatial variations in rainfall (the most obvious outlier, at around 1400 m ASL, represents a relatively dry site in Samburu). The pattern in Figure 4.6a implies that transmission (at least in a typical year) is unlikely at altitudes above about 1800 m, and this is largely consistent with available expert opinion. According to Oloo *et al.* (1996), for example, areas between 1300 and 1700 m correspond to areas of seasonal, but stable, transmission (typically 30–40% child prevalence rates in the wet seasons), while areas between 1700 and 2300 m are generally epidemic prone.

We can get a more direct assessment of the MARA model by comparing prevalence rates with corresponding model predictions for the same sites. The results of this exercise (Figure 4.6b) are encouraging, and suggest that the model provides an excellent basis for stratifying risk in relation to altitude, and for extrapolating this risk geographically (see below), although it would be unrealistic to use the MARA model to predict parasite rates at the level of the individual locality.

Figure 4.6

(a) Relationship between the MARA model and altitude for Kenyan survey sites

(b) The MARA model (line) and parasite rates (circles, re-scaled) against altitude



4.3.4 The MARA model as a geographical stratification of risk

Map 4 in Appendix 1 shows the MARA model for East Africa. In contrast to neighbouring Uganda and Tanzania much of Kenya is characterised by low model predictions, with only relatively small areas having values above about 0.5. These tend to be lowland areas (<1300 m) in Coast, Nyanza and Western provinces, where transmission is generally considered to be stable/hyperendemic. Outside these areas transmission is typically unstable, being limited either by insufficient rainfall (principally in areas north and east of Isiolo) or by low temperatures in the highlands and highland fringes. Of these, the highland zone is by far the more significant in terms of the size of population at risk from epidemics (see below).

Given that there is no way of knowing the true pattern of malaria endemicity in Kenya, it is not possible to evaluate the spatial distribution of the MARA model in any formal or rigorous way. However, we can validate the model in a broad and qualitative sense on the basis of existing malaria stratifications, which usually reflect a mixture of prevalence survey results and expert opinion. For this purpose the map of malaria transmission intensity that appears in the National Atlas of Kenya (Nelson 1959) was digitised and registered to existing MARA coverages (Figure 4.7).

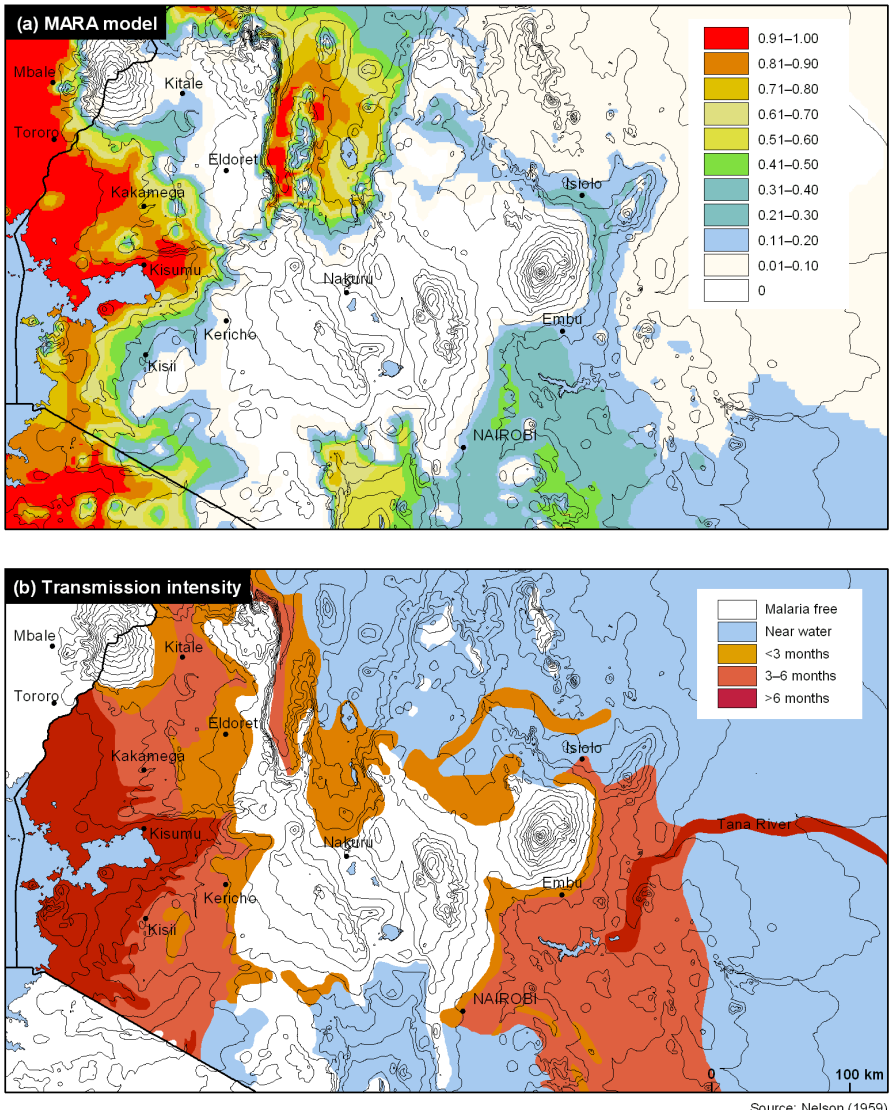


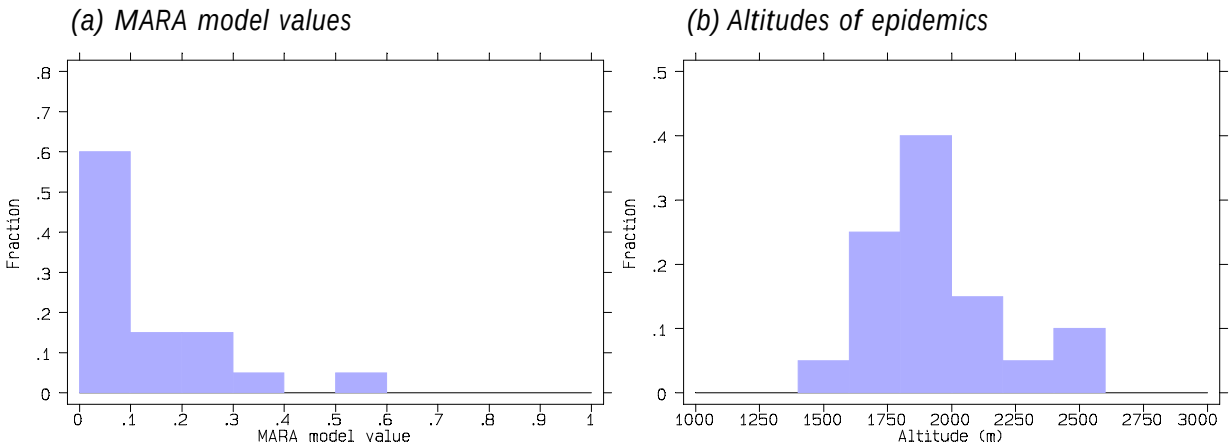
Figure 4.7 *The MARA model and standard malaria stratification map for south west Kenya*

On the whole there is good general agreement between the MARA model and the standard malaria stratification. High model values correspond with areas of more than six months transmission (principally around Lake Victoria), while zero model values generally match those areas classed as malaria-free. There are, however, specific areas where the two maps are not consistent. The model predicts relatively low transmission risk in highland/fringe areas between Kitale and Kakamega and also in areas around Kisii and Kericho (in Nelson's map it appears that a cut-off of 2250 m was used to distinguish malaria-free areas from those with less than three months transmission). Other areas of disagreement are in the Rift Valley immediately east of Eldoret, where the model predicts relatively high risk of transmission, and in the heavily populated areas east of Embu where the model predicts relatively low transmission risk. The Tana river valley, which stands out as an area of relatively stable transmission in Nelson's map does not feature in the MARA risk map as the MARA model only incorporates climate variables.

4.3.5 The MARA model as a means of delineating epidemic-prone areas

Extraction of model values for epidemic prone areas indicated that the majority of epidemics occur in areas where model values are within the range 0–0.1 (Figure 4.8a) and suggests that around 60% of epidemics should fall in the white or light blue areas in Figure 4.7. In epidemiological terms, therefore, the model has a reasonable level of sensitivity. The specificity of the model is less certain, however, given that localities which are clearly too high to ever support malaria transmission will also register as zero in the MARA model. On the basis of the current model output it is not possible to separate out these regions from sites which also score zero, but which are in fact epidemic prone. Consequently it would appear essential to incorporate information on the known altitudinal range of epidemics in order to produce meaningful delineations of risk, and in particular to define the upper limits of epidemic occurrence.

Figure 4.8 *Histograms for altitude and MARA model values for epidemic locations in Kenya*



4.3.6 Alternative strategies for mapping epidemic risk: altitude based estimates

Using the USGS DEM data, altitudes were extracted for localities known to have experienced epidemics in the past. These data, which at best can be seen as a representative sample of the total 'population' of Kenyan epidemics, indicate that in highland areas epidemics occur within a broad altitude range of 1510–2572 m. The mean altitude at which epidemics occur is 1947 m and the spread around the mean approximates a normal distri-

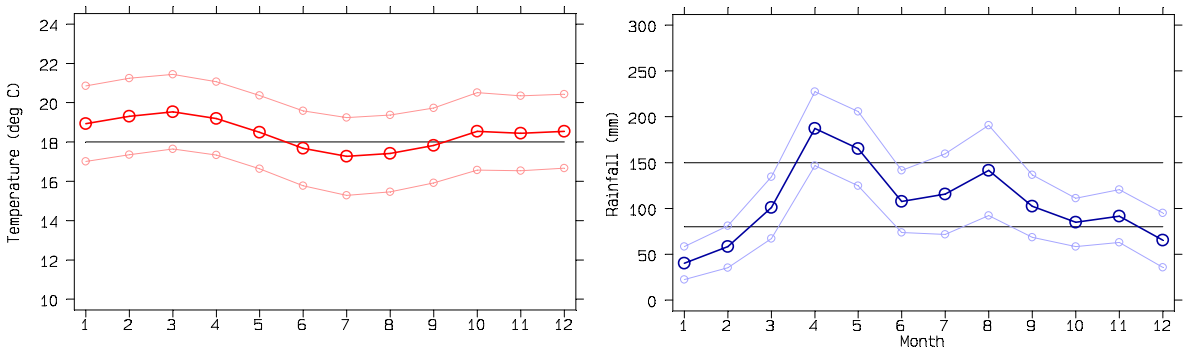
bution with some positive skew (Figure 4.8b). The relative probability of epidemics occurring within a specified altitude range can be defined statistically on the basis of this distribution and as such it is possible to estimate risk on the basis of altitude alone. In the Kenyan case we would expect roughly two-thirds of (highland) malaria epidemics to occur within one standard deviation of the mean epidemic altitude, and most of the remaining third to fall between one and two standard deviations of the mean. Nominally we can define these areas as 'high' and 'moderate' risk respectively. Only 5% of epidemics should occur in areas outside these zones.

Using available DEMs it is possible to map out these epidemic risk zones (Figure 4.10a). For comparison, the risk model is overlaid with known epidemic locations. Figure 4.10a shows that predicted risk is reasonably sensitive in areas which we know to be epidemic prone. However, extensive areas outside this zone (and which have no history of epidemics) are also classed as high risk, suggesting a general overestimation of risk in these areas. This discrepancy demonstrates one of the potential weaknesses of this approach: that we are likely to get spurious results when extrapolating epidemic risk to areas where environmental conditions are significantly different to those used in the initial definition of the altitudinal thresholds. In this case it would appear, judging from Map 3 in Appendix 1, that the spatial variability of rainfall may explain much of this discrepancy, although local factors may also play a role.

4.3.7 Alternative strategies for mapping epidemic risk: estimates using climate profiles

To examine the possibility of mapping epidemic risk by determining a typical climatology for epidemic prone areas, long term monthly average temperatures and rainfall were extracted from the CRES dataset for all highland localities with a history of epidemics (Figure 4.9). In the plots mean annual profiles for rainfall and mean temperature are shown by the middle curves, while the outer lines show ±2 standard deviations from each monthly value.

Figure 4.9 *Average annual profiles for mean monthly temperature and rainfall for known epidemic locations in Kenya*



The graphs show that in areas known to be epidemic prone, temperatures in the period January to April are generally well above 18 °C and are therefore unlikely to limit malaria transmission. At the same time, data in the lower graph suggest that rainfall in these months is modest in relation to monthly thresholds which have been applied previously in Kenya.[8] It also appears that the main rainfall peak occurs towards the end of the window of suitable temperatures. These characteristics suggest that in a 'typical' year, rainfall rather than temperature is most likely to determine the extent to which epidemics occur. It follows that the risk of epidemics is likely to be greatest in years where total rainfall in the

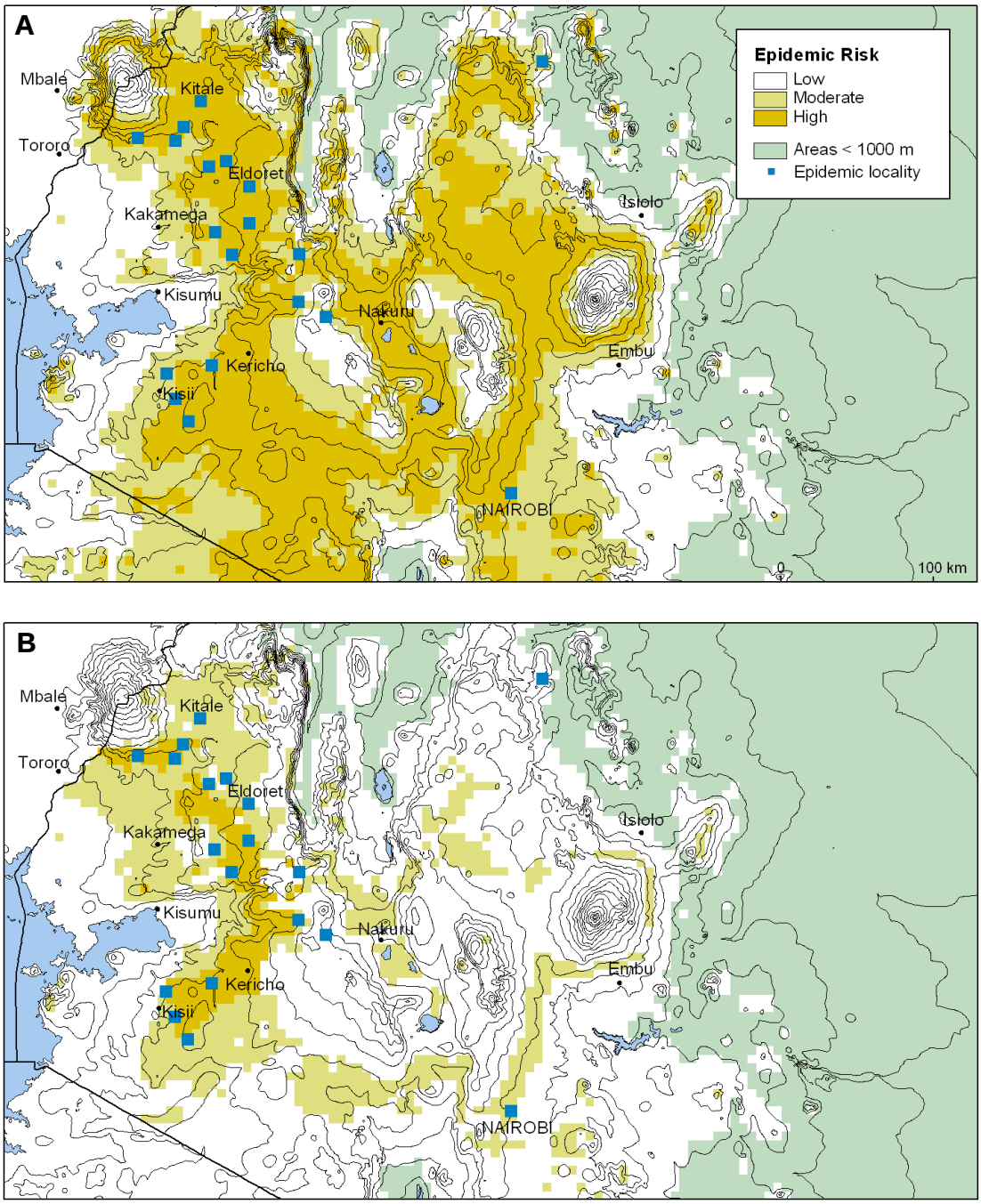


Figure 4.10 *Models of epidemic risk for south west Kenya based on altitude (A) and typical climate profiles (B)*

period December to March is unusually high, or where the precipitation peak occurs relatively early in the season (the ENSO-related epidemics of 1997/8 are a case in point here). This conclusion is not novel, but does reaffirm the findings of previous studies which have highlighted the association between malaria epidemics and rainfall. Moreover, the results imply that direct or indirect monitoring of rainfall is a prerequisite for effective epidemic early warning.

Adopting a similar mapping approach to the altitude-based risk assessment in Section 4.3.6, it is possible to delineate areas with typical climate profiles within ±1 or 2 standard deviations of the mean profiles shown in Figure 4.9. The results of this exercise are shown in Figure 4.10b, in which a mask has been applied to exclude sparsely populated areas (population density less than 10 persons km^{-2}). Given what we already know about the

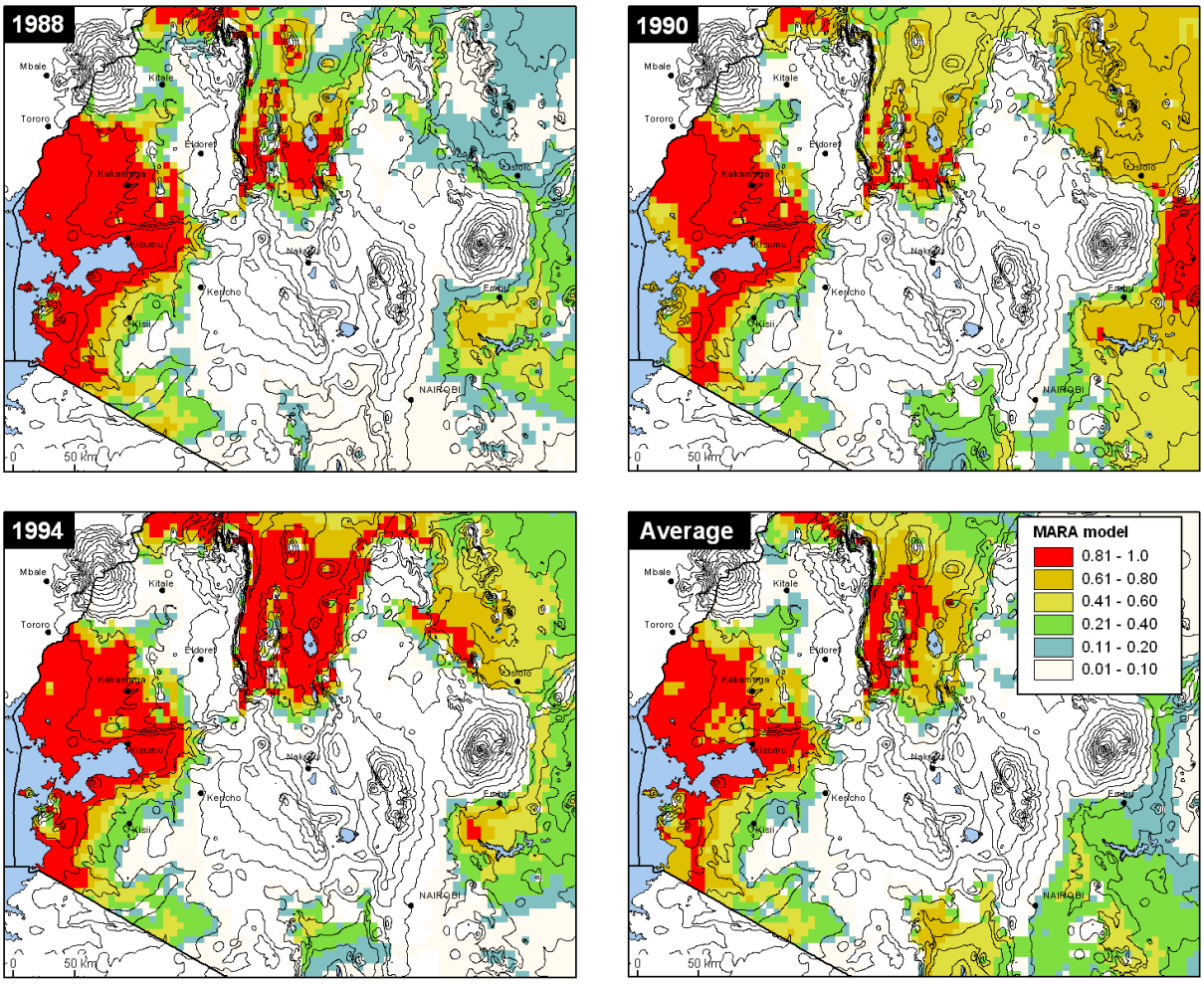


Figure 4.11 *The MARA model for south west Kenya determined using climate data for known epidemic years (1988, 1990, 1994) and using long term climate averages (average)*

distribution of epidemics in Kenya we can see that this approach provides a relatively conservative, but realistic, estimate of epidemic risk. Although risk is focused on a relatively small geographical areas, population densities in these parts of the highlands are high (Map 3, Appendix 1) and this translates into large populations at risk (Table 4.1). From the table just over 8 million people inhabit parts of the country considered to be at high or moderate risk from epidemics. In comparison Snow *et al.*(1998) estimated that 13,460,105 live in 'unstable' or 'low transmission' settings in Kenya as a whole (*i.e.* including non-highland areas).

4.3.5 Inter-annual climate variability and the occurrence of epidemics

As was discussed in Section 3, the standard MARA model, which is based on long term climate means, does not reflect the potential effect of inter-annual climate variability on malaria transmission in 'marginal' highland areas. To address this issue a series of climate surfaces, based on interpolated climate data for 1950–95, were developed by the Climate Research Unit (University of East Anglia, UK) for the MARA project. These surfaces are designed to enable the temporal correlation of malaria transmission and climate variables, and in particular to evaluate climate conditions in known peak years for epidemics.

MARA models for the known epidemic years of 1988, 1990 and 1994, together with the 'standard' long term model, are plotted for south west Kenya in Figure 4.11. These show that, at least visually, the model fluctuates only slightly from year to year in the central

Table 4.1 *Land area and population at risk from epidemics in the Kenyan highlands*

Risk zone	*Average population density (persons km^{-2})*	*Land area in risk zone (km^2)*	*Total population at risk*
Moderate	231	27 903	6 445 593
High	282	5 618	1 584 276
Total		33 521	8 029 869

highland areas. Although the fringe areas around Nandi and Uasin Gishu (between Eldoret and Kakamega) appear to have had relatively high model values in 1988, 1990 and 1994 (in relation to the long term average), elsewhere the pattern is less consistent, and on the whole visual interpretation is difficult. An alternative approach is to extract model values for each year for all known epidemic locations and to plot these graphically. The results of this exercise are shown in Figure 4.12, which suggests that epidemics in 1988 and 1990 corresponded with relatively high model values for those years. However, model peaks in 1983, 1987 and 1995 do not appear to have been accompanied by high transmission levels, while model values for the epidemic year of 1994 were actually below average.

It is not clear at this stage whether these discrepancies are a product of an incomplete historical record of epidemics, errors in the inter-annual surfaces, or an artefact of generalising spatial risk for all epidemic localities. Alternatively it may be that producing model estimates for individual calendar years is artificial and that it may be more informative to examine the original climate data on a seasonal basis. Unfortunately it is not possible within the time constraints of the current project to explore these issues further. (This analysis, which yielded similar results in other country-scale analyses is not repeated in this report, but will be followed up for specific highland areas in Phase II of the project).

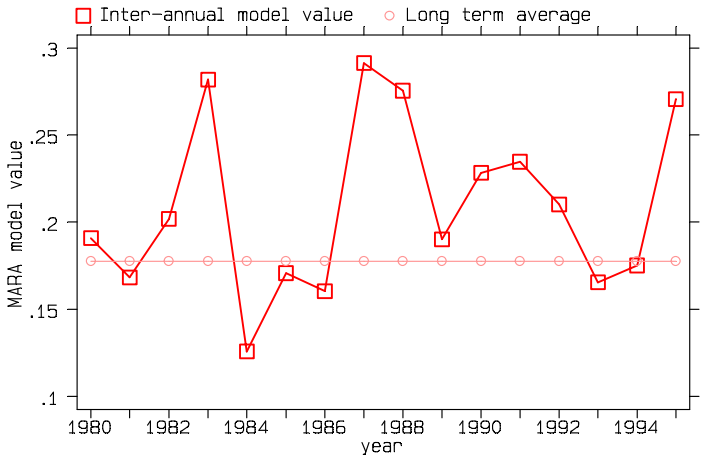


Figure 4.12 *Long term and annual values of the MARA model for known epidemic localities (1980–95)*

Notes

[1]. Results from the CRES dataset correspond almost exactly to a formula linking average annual temperature and altitude developed for the Kenyan highlands by the East African Meteorological Department (cited in Braun *et al*. 1997: 9):

T *mean* (°C) = 30.2 – 0.00650 × altitude (in metres)

According to the formula, average annual temperature increases by 0.65 °C for every 100 m rise in elevation.

[2]. 'Report by Mr Teesdale on mosquitoes and malaria in Teita District' in letter to the Director of Medical Services, Nairobi (14/9/1936).

[3]. Logan, W.M. (unpublished) Anti-malarial works in Nairobi. 23/8/1928. 5p.

[4]. Although closer examination of data for the 1940 epidemic revealed that malaria cases had started to rise in advance of the main rains. This pattern, together with the fact that subsequent heavy rains in 1941 and 1942 were not accompanied by epidemics, led Roberts and others to the conclusion that the relationship between rainfall and epidemics was confounded by variations in the immunological status of local populations.

[5]. In more recent epidemics in Kericho (1991) and Kisii (1994), *An. gambiae s.l.* and *An. funestus* were both found in significant numbers (Githeko, unpublished). Less is known about malaria vectors in Nandi, where borrow pits, swamps, domestic wells, dams, spillways and seepages have all been found to contain *An. gambiae* larvae, but not those of *An. funestus* (Githeko, *op. cit*).

[6]. *e.g.* Anon. (1997), 'Malaria - Kenya, Uganda' All Africa Press Service, 21 July 1997; Macharia, J. (1997), 'Problems of drugs in malaria epidemics' East African, 29 July 1997.

[7]. Mwaura, J. (1998) 'Kenya reports increase in malaria cases' Pan African News Agency, 25 February. It is also worth noting that the 1998 malaria epidemics were not restricted to the highlands. Following heavy rain between September and December 1997 severe epidemics also occurred in semi-arid north east Kenya between January and May 1998 (Brown *et al*. 1998). The official response to these and other epidemics was later criticised in an editorial in the East African Medical Journal (Anon. 1998a).

[8]. The two thresholds on this graph correspond to: (1) 150 mm, which Malakooti *et al*. (1998) considered to be the minimum monthly rainfall required for transmission in the Kericho area; (2) 80 mm, which has been used as a threshold in the MARA model (this threshold needs to be exceeded in five consecutive months for stable malaria transmission to occur, although unstable transmission is still likely when the rainfall window is considerably shorter than this).

5 Uganda

5.1 Principal features of the Ugandan highlands

Much of Uganda constitutes a plateau of between 1000 and 1500 m, with volcanic intrusions in the east (around Mbale) and the south west (around Kabale), along with the uplifted massif of the Ruwenzori (around Kasese), forming relatively localised highland areas (see Map 1 in Appendix 1). The physical distribution of highlands in Uganda is thus quite different to that of neighbouring Kenya and Rwanda, with only 8 and 2.4% of the land surface being above 1500 m and 2000 m respectively. Land over 2250 m, which is mainly forested, tends to be sparsely settled and cultivation at this altitude is difficult. In contrast, areas between 1500 and 2000 m (principally around Rukungiri, Kabale and in strips flanking Mount Elgon and the Ruwenzori) are intensively farmed and support population densities in excess of 150 persons km^{-2} (see Map 2, Appendix 1).

In a regional context the Ugandan highlands are relatively arid (Map 3 in Appendix 1). Less than 3% of the land area receives more than 800 mm of rainfall in the five wettest consecutive months of the year. These areas form isolated pockets in the north of the country and around Mount Elgon. The south western highlands are significantly drier, with areas around Kabale receiving only 400 mm of rain in the wettest five months of the year.

Seasonal variations in climate are less extreme in Uganda than in many other highland areas. Figure 5.1 shows the seasonal profiles for rainfall and temperature over two altitude ranges, chosen to represent highland and highland fringe areas. The graphs show Uganda's two principal rainy seasons from March to May and from August to December, with the highest peak occurring in April. Rainfall totals in the two altitude classes are broadly similar. Mean monthly temperatures are highest in February and lowest in July. As in Kenya, mean monthly temperatures at 1900–2100 m typically remain above 17 °C for the period January to April, indicating a potential for malaria transmission in these months. Significantly, this period also coincides with the onset of the first rainy season.

To illustrate the spatio-temporal distribution of temperatures in Uganda, Figure 5.2 maps out three temperature classes by month (see Section 4.1 for a full explanation of these classes). In the figure the three principal highland areas stand out as areas where temperatures are limiting throughout the year, and only very small areas show up as red 'intermediate' areas. There is minimal seasonal variation in this pattern (in contrast to the other countries included in this review). This reflects both the relatively stability of temperatures over the year and the steepness of slopes in many highland fringe areas.

5.2 Malaria transmission in the highland zone

5.2.1 Previous studies

Most of the malaria studies carried out in Uganda since the Second World War have concentrated on areas of hyperendemic transmission and relatively few data relate specifically to highland areas. Official health records are also extremely scarce; a situation due largely to the collapse of malaria control activities and basic health services during the political unrest of the 1970s. Although this situation has recently improved with the establishment of the Malaria Control Unit in July 1995, a continuing reliance on clinical diagnosis limits the value of official records.

The first significant parasitological surveys in the highland zone were carried out by Garnham *et al.* (1948) in Kigezi (now Rukungiri, Kabale and Kisoro Districts). Their results revealed

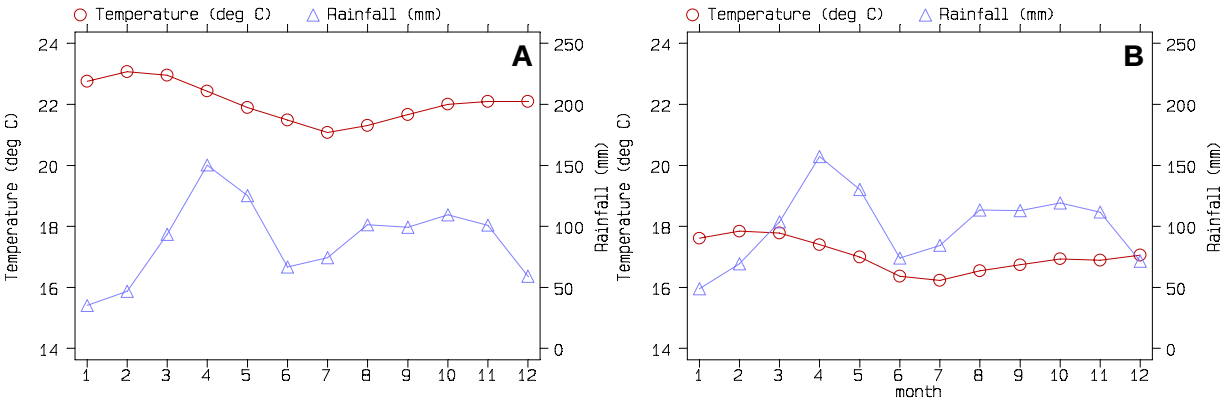


Figure 5.1 *Annual patterns of rainfall and mean monthly temperature for two altitude bands; (A) 1100–1300 m (B) 1900–2100 m*

unexpectedly high levels of endemicity around Lake Bunyonyi (1900 m), where spleen rates in adults and children were around 80%. Rates were much lower (10–20%) in areas not immediately adjacent to the lake. *An. funestus* was identified as the principal vector in the lake area, with *An. gambiae* being the main vector elsewhere.

More surveys were carried out in North Kigezi (Rukungiri) in the 1950s, following a scheme to resettle much of the Bakiga population from Kabale District (de Rook and Cullen 1957). Results (Figure 5.3) suggested an absence of transmission above 1500 m, below which levels of endemicity rose sharply (the spleen rate being especially sensitive to elevation). De Rook and Cullen concluded that areas between 4300 and 5000 feet (1311–1524 m) experienced only very low levels of transmission, while areas between 4000 and 4300 feet (1220–1311 m) and below 4000 feet (1220 m) were mesoendemic and hyperendemic respectively. Transmission above 1220 m appeared to be limited largely by a shortage of breeding sites for malaria vectors, with the seasonal pattern of transmission generally mirroring that of rainfall. The authors speculated that the creation of new breeding sites (*e.g.* through valley bottom cultivation) would lead to malaria epidemics, given suitable meteorological conditions – a point echoed throughout the Ugandan literature.

Subsequent surveys carried out in Rukungiri between April and May 1960 (de Zulueta *et al.* 1961) provided more data on the relationship between altitude and malaria transmission. De Zulueta *et al.* divided their survey results into two altitude classes; *viz*. areas <1128 m and 1128–1372 m. Parasite rates among children aged 2–9 were 33.8 and 22.3% respectively, while spleen rates were 72.1 and 23.9%. Surveys carried out further south in Kabale District showed essentially similar results to Rukungiri. Here, de Zulueta *et al.* (1964) estimated that the 1120 and 1370 m contours represented the limits of mesoendemic conditions and found no evidence of permanent foci of transmission above this level, with the exception of Lakes Bunyoni (1920 m), Mutanda (1800 m) and Kimbuga (1600 m). In these areas malaria was hyperendemic, with *An. funestus* the principal vector present. Other surveys carried out at about this time showed very low levels of infection (typically below 1.5%) in non-lake areas of Kabale (Jelliffe and Jelliffe 1963; Onori 1967; Brown *et al.* 1970).

More recent malariometric data for Rukungiri have been collected as part of a situation analysis in four districts carried out in 1992 by the Ministry of Health and UNICEF (Langi and Lalobo 1994). Summary data from the Rukungiri survey indicated a parasite rate in 1–9 year olds of just 2.7% and a spleen rate for all ages of 5.5%.

Further north, in Kabarole and Bundibugyo Districts a series of parasitological and entomological surveys at a range of altitudes were carried out as part of a joint study by GTZ,

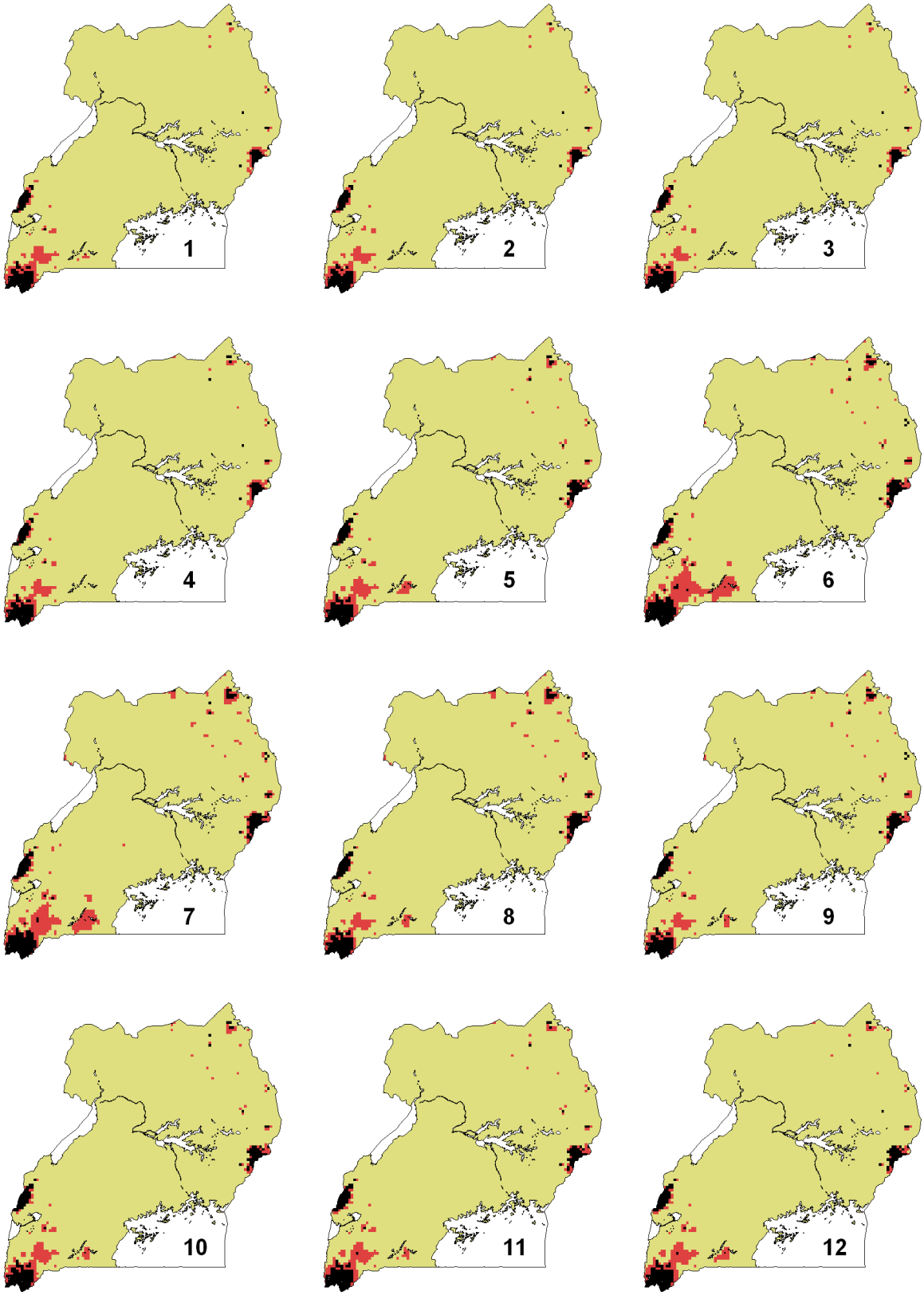


Figure 5.2 *Spatial variation in mean monthly temperatures in Uganda in a typical year. Yellow shading indicates areas where temperatures are likely to support malaria transmission in a particular month, while black shading signifies localities where temperatures are likely to be limiting. Red areas are intermediate and probably represent the altitudinal fringes of transmission (see Section 4.1)*

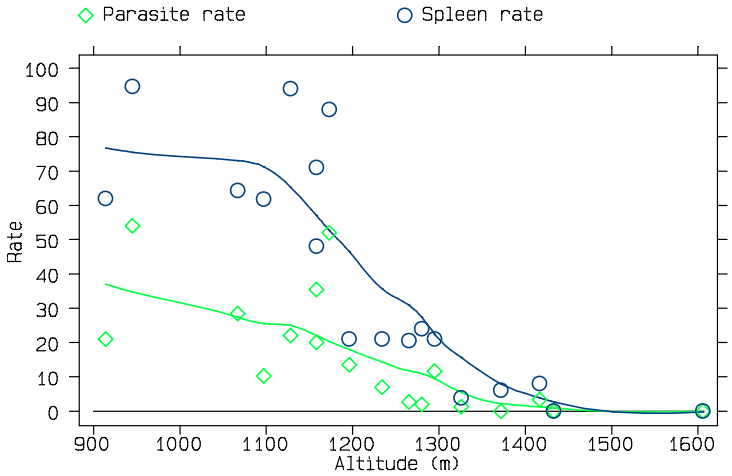


Figure 5.3 *Variation in parasite and spleen rates with altitude, Rukungiri (de Rook and Cullen 1957: 3)*

the University of Munich and the Ministry of Health (Kilian 1995). The main results from this work (summarised in Table 5.1) illustrated the sensitivity of various malariometric parameters to relatively small changes in altitude. Kilian (1995) concluded that in Kabarole 1500 m represented a threshold between hypo- and mesoendemic conditions, while areas below 1300 m were holoendemic. Surveys, repeated five times between June 1993 and June 1994, revealed little seasonal variation in malariometric parameters, even in hypoendemic areas. Kilian attributed this to the limited variability of temperature and humidity over the year, which is in part a function of the steepness the highland fringe. Entomological surveys showed that *An. gambiae s.l.* and *An. funestus* were present at all four sites, although their relative proportions varied. In the hypoendemic site (Kicwamba) *An. gambiae s.l.* was the dominant vector (98.5%), while *An. funestus* was more significant elsewhere. Subsequent PCR analyses indicated that samples of *An. gambiae s.l.* consisted primarily of *An. gambiae s.s.* (97.3%) with some *An. arabiensis* (1.7%).

Perhaps the most interesting finding of the GTZ study was the degree to which the general relationship between altitude and endemicity, as outlined above, could be modified by 'micro-epidemiological' factors at the local level, particularly in the meso- and hypoendemic sites. Part of this could be explained by localised variations in altitude, with results from a single village indicating that parasite and spleen rates among 2–9 year olds varied within the ranges 20–40% and 10–30% depending on where in the village they lived. In other cases Kilian found large variations in parasite rates between nearby villages with similar altitudes, socioeconomic status, housing *etc*. These he put down to the presence or absence of breeding sites, a factor deemed capable of creating 'islands' where endemicity differed from that which would be expected on the basis of altitude alone (Kilian 1995).

Kilian's findings suggest that altitude, on its own, may be a poor guide to endemicity and (by implication) that low environmental temperatures may not be the primary factor limiting transmission in these areas. Thus it is possible, as Garnham, de Zulueta and McCrae have described, that isolated but permanent pockets of endemic malaria can exist at relatively high elevations (around 2000 m), given the presence of suitable vectors. By logical extension, the naturally low levels of malaria transmission over much of the rest of the south western highlands seem likely to be a function of a shortage of breeding sites for efficient vectors. In Uganda this may have as much to do with the unsuitability of existing sources as with an absence of surface water *per se*. The entomological results of Steyn (1946), Goma (1948) and others, indicated that in its natural condition much of the per-

Table 5.1 *Summary results from Kilian's (1995) surveys in Kabarole and Bundibugyo*

	Site			
	Bundibugyo	*Kamwenge*	*Ruteete*	*Kicwamba*
Maximum altitude (m)	910	1290	1530	1680
Parasite rate (%)	89.0	84.6	27.8	6.7
Spleen rate (%)	72.1	86.4	19.5	5.3
Gametocytemia (%)	17.8	16.4	6.8	2.2
Incidence of clinical malaria†				
0-4 years	0.79	0.44	0.22	0.11
5-10 years	0.32	0.12	0.33	0.11
Vector density‡	5.2	6.9	0.6	0.1

† Attacks/child/year
‡ Vectors/house/day

manent swamp in south west Uganda was unsuitable for vector breeding — although modification through the removal of the natural vegetation may change this picture entirely. Steyn (1946), for example, demonstrated that drainage operations in valleys around Kabale from 1942 were accompanied by large increases in both the number of malaria vectors and malaria incidence.

Work is currently ongoing in Kabale to reassess links between swamp drainage, cultivation and malaria transmission.[1] The project is focusing primarily on entomological variables and the hypothesis that the removal of native swamp vegetation, followed by drainage and cultivation, modifies vectorial capacity through its effect on mosquito density, species distribution and/or by altering the local climate. Preliminary results suggest that minimum temperatures in areas bordering cultivated swamps are 0.5–1 °C higher than those adjacent to natural swamps. Work to determine whether this is sufficient to affect sporozoite rates is ongoing.

5.2.2 The occurrence of epidemics

Although clinical and parasitological data are often lacking, there is plenty of anecdotal evidence of epidemics in highland areas of Uganda. These are not necessarily a recent phenomenon (*e.g.* Onori 1967), although most available information is from this decade. On the whole the most affected areas seem to have been the south west highlands. Epidemics in the cultivated valleys of Kabale and Rukungiri Districts were reported in the early 1990s (Onapa and Mouchet 1996), with hospital and DMO records indicating that the worst affected areas were Kifunjo (in Kanungu Sub-District) and Bwanga, Bunono, Burora, Kisizi, Ndago, Nyabushenyi and Ibanda in Rukungiri District.

Epidemics were also reported in the Bukinda, Mparo, Muko, Rubaya and Kamwezi areas of Kabale District. Onapa and Mouchet are not specific regarding dates for these epidemics, but do indicate that further serious epidemics occurred in the open valleys of Kabale and Rukungiri between June and August 1994, with the most serious outbreaks affecting the valley bottoms around Kisizi (Rukungiri) and Kamwezi (Kabale). In July 1994 over 90% of the 1140 inpatients registered at Kisizi Hospital were diagnosed with malaria, but otherwise few data are available on the extent of the epidemic or the associated mortality. What is known, however, is that the epidemic was preceded by heavy rainfall in the first half of 1994, with 1000 mm of rain being recorded at Kisizi between January and June, as compared with figures of 245, 353 and 503 mm for corresponding periods in 1992, 1993 and 1995 respectively (Onapa and Mouchet 1996: 5). Outpatient figures for Kigezi hospital (Figure 5.4) showed a large peak in cases in the middle of 1994, following less serious

peaks in 1992 and 1993. The graph also shows clearly the preceding peak in rainfall in early 1994 (2–3 months before the epidemic peak). It would appear that the high number of malaria cases in 1993 could also be linked to antecedent rainfall conditions.

Many parts of the south west again reported malaria epidemics in the first quarter of 1998. The indications are that ten districts (Kabale, Ntungamo, Bushenyi, Kasese, Rukungiri, Bundibugyo, Mbarara, Kisoro, Kabarole and Kibale) were affected (Malaria Consortium 1998). As in the 1994 epidemic, available data suggest a strong climatological link; rainfall

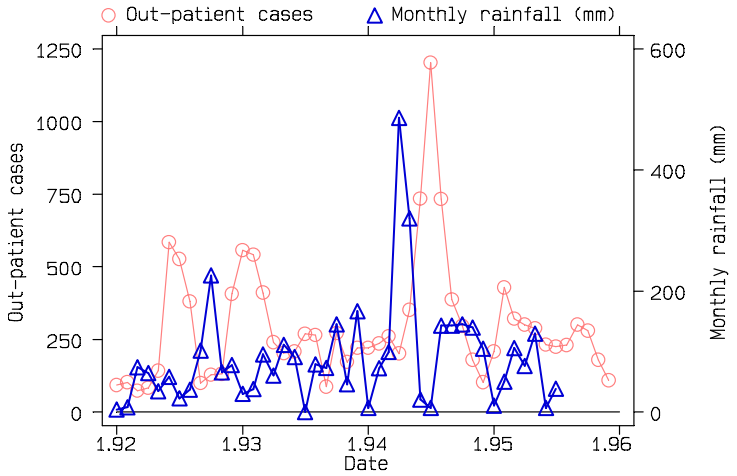


Figure 5.4 *Out-patient cases and rainfall by month for Kisizi mission hospital, 1992–6 (Onapa and Mouchet 1996)*

for November, December and January was 58, 68% and 148% higher than the five-year averages for those months. In addition, average daily minimum temperatures for November, December and January were 1.4, 1.5 and 1.7 °C higher than respective five-year averages. At the same time, entomological monitoring around Kabale, which began in January 1998, showed a sharp increase in indoor resting densities of anophelines during February (Lindblade *op. cit.*). The average IRD for the first half of February (2.08), was three times higher than that recorded in January, with IRDs dropping off quickly in the second half of the month. Most of the anophelines caught were identified as *An. gambiae s.l.*

Epidemics in 1998 appear to have been more geographically widespread than previous outbreaks, with Kabarole and Bundibugyo being severely affected. Again, the epidemics in these areas have been attributed to heavy and prolonged rains between October and December 1997 (and hence to ENSO). Data recently analysed by Kilian (1999) show that average mean monthly rainfall in this period of 1997 was 209 mm, compared with 157 mm for 1994–1996. Kilian compared rainfall figures to those for reported clinical cases (0–4 year olds) from health facilities in Kabarole, deriving an index of 'standard cases' in which monthly malaria cases for each unit were expressed as a fraction of the annual average. These were then averaged for each month to derive district-wide mean relative incidence. The results of this exercise are presented in Figure 5.5, which shows a strong temporal correlation between peaks in monthly rainfall and peaks in malaria incidence, with a time lag of 2–3 months (cf. Figure 5.4).

Historically there are fewer reports of epidemics in Uganda's eastern highlands, which are substantially wetter than the south western highlands. Mouchet *et al.* (1997) do refer to an epidemic which allegedly occurred in 1993 around Kapchorwa (2000 m ASL) in the vicinity of Mount Elgon, but the extent to which the outbreak could be explained by local

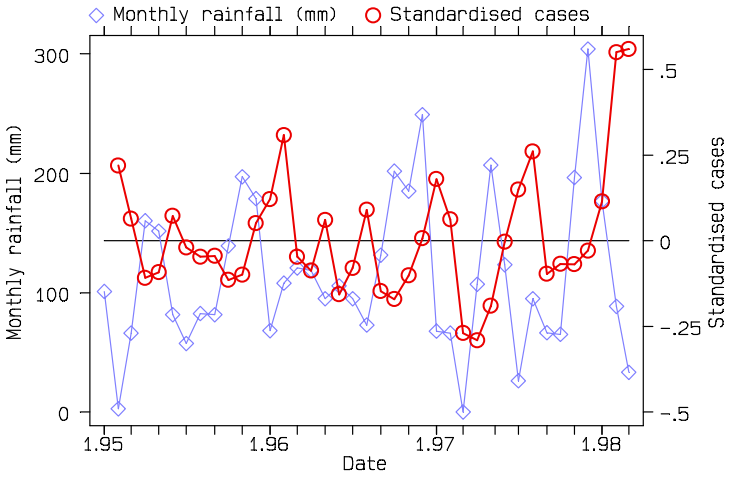


Figure 5.5 *Temporal distribution of rainfall and malaria cases in Kabarole District, 1995–8 (Kilian 1999)*

transmission is not clear. In the first half of 1997 the All Africa Press Service also referred to a malaria epidemic at Kapchorwa in which 150 deaths were recorded, but no other information is available.[2]

Finally, Mouchet *et al*. (1997) have also described outbreaks linked to human activities rather than climatic variation. An example is an epidemic around the village of Kanunga in Rukungiri, which began in 1989 and reached a peak in 1990 before tailing off in 1991 (with a recrudescence in 1992). The authors strongly suspected that the epidemic was linked with the creation of breeding sites through gold prospecting. By working at night miners put themselves at maximum risk of infection, which may explain why 80% of cases were in adult men. In 1990 an epidemic at Kiziba in Rutenga Sub-County (1800 m ASL) also appeared to be connected with gold prospecting (Mouchet *et al.* 1997).

5.2.3 Temporal trends in highland malaria transmission

The paucity of malaria data for the Ugandan highlands makes it difficult to place recent epidemics within a longer time frame. Most available facility-based data consist of clinical diagnoses, and in most cases only a few (rarely continuous) years of data are available. One notable exception is that of the previously mentioned Kisizi mission hospital, near the Rukungiri-Kabale border, where almost all diagnoses are confirmed by microscopic examination (Onapa and Mouchet 1996). Malaria case data are available from 1968 to present, and although there are large gaps in the data series, data for 1982–1992 are complete.[3]

Although the evidence is patchy, Mouchet *et al.*'s (1997) examination of the Kisizi data led them to conclude that there had been a general increase malaria endemicity since residual spray campaigns ended in the late 1960s. At the same time, risk of epidemics in the area was also apparently on the increase, creating what Mouchet *et al.* termed 'paludisme à deux vitesses' (Mouchet *et al*. 1997: 54). Onapa and Mouchet (1996) put these apparent increases within the general context of the worsening malaria situation throughout the country, citing as possible reasons the 'collapse of health and other social services; mismanagement of malaria cases and antimalarial drugs ..; breakdown of malaria vector research and control ..; and ecological changes' (Onapa and Mouchet 1997: 1).

Whether recent increases in transmission can also be linked to long term climatic change is moot. While it seems clear from the preceding discussion that rainfall is a significant factor in creating suitable conditions for epidemics, available data show no real evidence

for any long term shifts in rainfall patterns (either in terms of variability or absolute amounts). The situation regarding temperatures is also far from clear cut. Superficial analysis of temperature data from the meteorological station at Kabale (1870 m ASL) has shown that the observed increase in the number of local malaria cases between 1969 and 1974 coincided with a period of relatively stable temperatures (Mouchet *et al*. 1997). Temperatures rose slightly between 1979 and 1984, and this warming may have precipitated a small malaria outbreak in the area in 1982 (although there is no direct evidence of this). Records for Kabale also suggest that temperatures rose steadily between 1992 and 1994 (mean temperatures being 17.3, 17.7 and 17.8 °C for the three years respectively, as compared to a thirty year average of 17.1 °C — Mouchet *et al.* 1997: 56). These anomalies may have been connected with malaria epidemics in the Kabale area in 1994, although this cannot be proven with existing data. Similarly, Kim Lindblade's work has shown that epidemics in 1998 coincided with above average temperatures (as well as with abnormally high rainfall), although again it is not possible to directly implicate these anomalies in terms of the occurrence of outbreaks. There is a need to design specific prospective studies to address this issue more rigorously.

5.3 Analysis of HIMAL dataset

5.3.1 Data collected for HIMAL

From the literature search, 25 documents provided relevant data, of which six included information on epidemic locations and 22 contained suitable data for spleen and parasite rates. Together these yielded 442 data points; 15 epidemic locations and 214 and 213 points for parasite and spleen rates respectively. The majority of parasite and spleen data came from the annual reports of the Malaria Eradication Pilot Project for 1959 and 1960 (de Zulueta 1959a-d, 1960). The geographical distribution of these data points, which is shown in Map 5 in Appendix 1, is strongly weighted towards the south western highlands, and particularly to Rukungiri and Kabale Districts. Of the 442 data points, around 40% could not be geo-referenced.

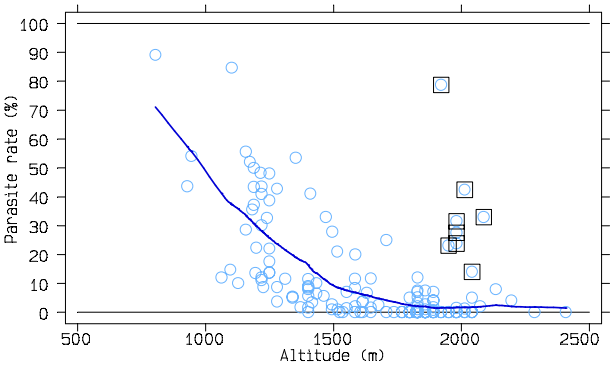
5.3.2 Effects of altitude on malaria transmission intensity

Figure 5.6 shows parasite and spleen rates for geo-referenced survey locations plotted against altitude. Both graphs show a clear relationship between altitude and transmission intensity ($p<0.001$), although there is considerable scatter. The obvious outliers within this relationship appear on the extreme right hand side of the graphs and are boxed. These represent the surveys of Garnham *et al*. (1948) and de Zulueta *et al*. (1964) in the Lake Bunyonyi area of south west Uganda. The outliers demonstrate that the general relation between transmission intensity and altitude can be altered significantly by the presence of suitable breeding sites and efficient malaria vectors, as has already been discussed. Elsewhere it appears that parasite rates of zero are encountered from about 1400 m upwards (slightly higher for spleen rates), although populations above this altitude do often demonstrate a degree of parasitaemia (parasite rates are typically below 10%, although there is no way of knowing the extent to which these are local infections).

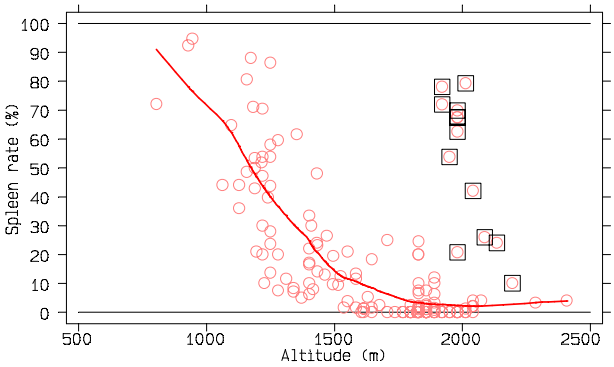
Because this dataset principally comprises data collected in the 1950s and 1960s, the question remains as to how applicable these graphs are to today's conditions. The truth is that, on the whole, we do not have sufficient contemporaneous data to evaluate this. The exception is in Kabarole, where a comparison of survey results from the 1950s and 1990s has revealed a remarkably consistent pattern of parasite rates in relation to altitude (Kilian, unpublished data). Analysis of these data is ongoing.

Figure 5.6 *Variation in parasite and spleen rates with altitude, Uganda*

(a) Parasite rates



(b) Spleen rates



5.3.3 The MARA model as a means of stratification in highland areas

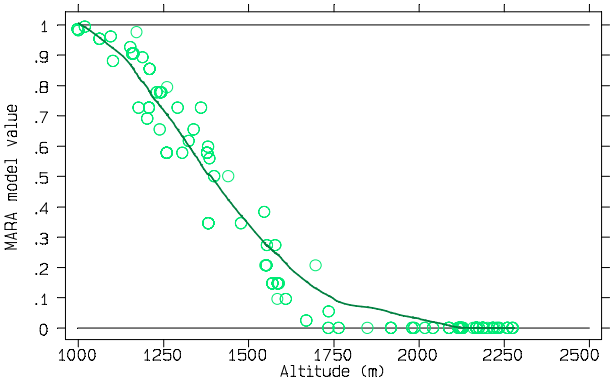
MARA model values were extracted for the geo-referenced sites and, as in the case of Kenya, proved to be highly correlated with altitude (Figure 5.7a). The model suggests that endemic conditions are unlikely above 1750 m ASL and that areas between 1500 and 1750 m (with typical model values <0.2) probably represent the fringes of stable transmission. This appears to be generally consistent with expert opinion and with existing data for parasite and spleen rates (Figure 5.7b). It also suggests that the MARA model provides a good basis for assessing and extrapolating the effects of altitude on transmission risk (see below). Significantly, however, the MARA model cannot predict the high levels of transmission in the Lake Bunyonyi sites, which are largely the product of non-climatic risk factors.

The MARA model for East Africa is presented geographically in Map 4 in Appendix 1. Much of Uganda has model values of 0.9–1 (red shading) indicating that average conditions are almost certainly suitable for transmission and that malaria is likely to be endemic. In contrast, the principal highland areas of the west, south west and east stand out as zones of low risk (model = 0–0.1), where conditions in average years are almost certainly unsuitable for transmission, but where we might expect the possibility of epidemics in some 'non-average' years. Much of the rest of the south west quarter shows 'intermediate' risk somewhere between the two extremes. Patches of low-intermediate risk are also a feature of the eastern part of the country adjacent to the Kenyan border, where it is likely that rainfall has some influence on model results.

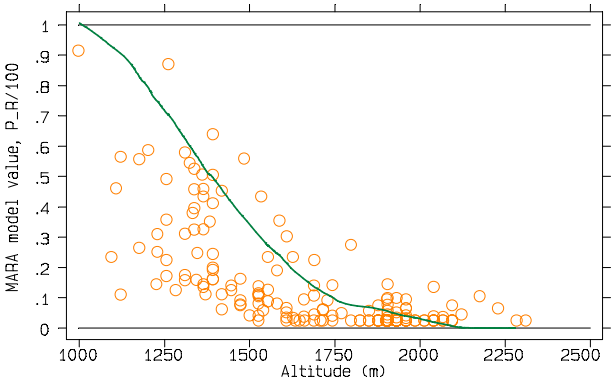
For purposes of comparison, two standard stratifications for southern Uganda are shown in Figure 5.8. The top map shows the malaria stratification which appears in the first

Figure 5.7

(a) Relationship between the MARA model and altitude for Ugandan survey sites



(b) The MARA model (line) and parasite rates (circles, re-scaled) against altitude



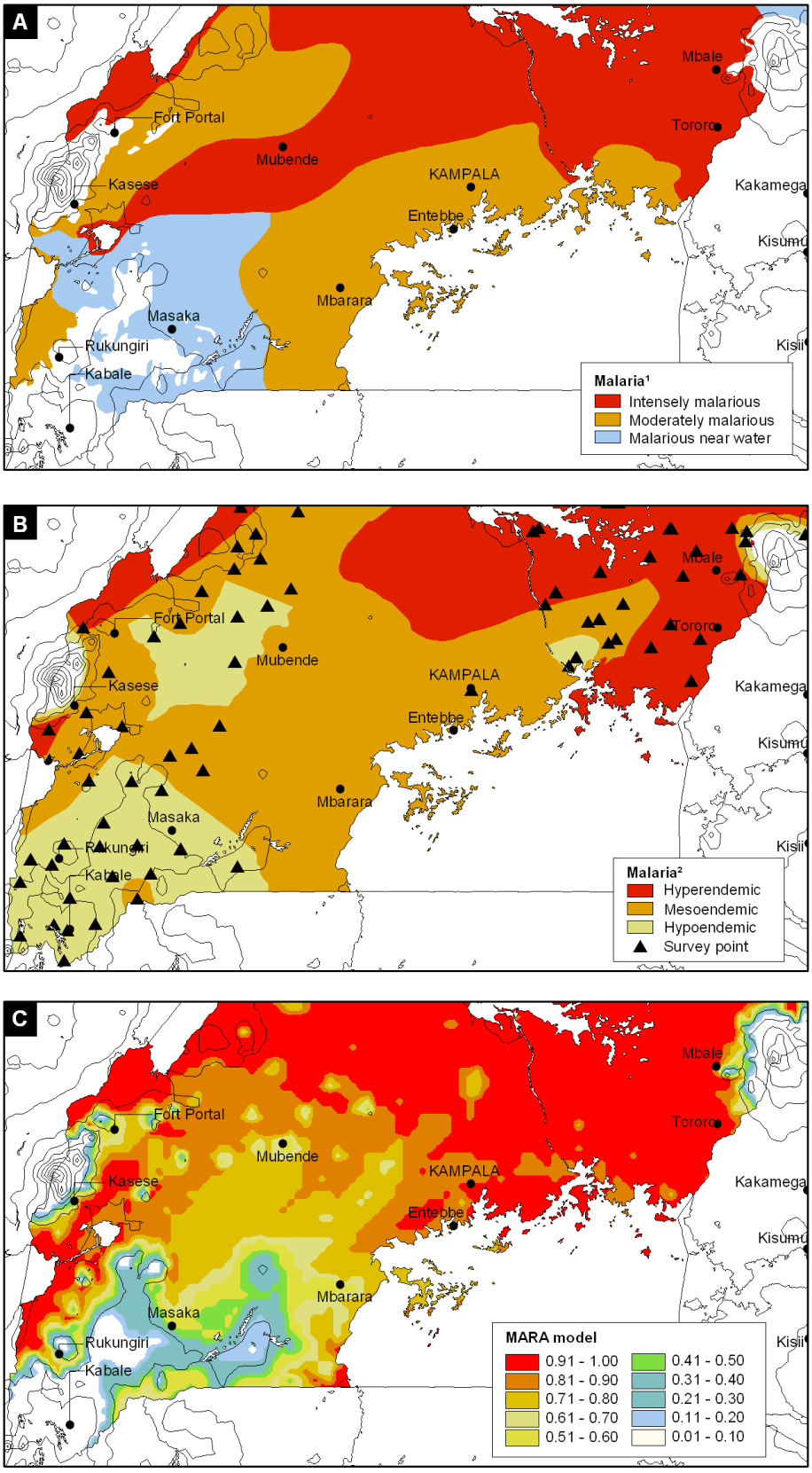


Figure 5.8 *The MARA model and standard malaria stratification maps for southern Uganda (source: Republic of Uganda [1]1962; [2]1967)*

edition of the Atlas of Uganda (Government of Uganda 1962). Below it is an alternative stratification from the second edition of the Atlas (Government of Uganda 1967), based on the results of prevalence surveys conducted by the WHO/Uganda Government Malaria

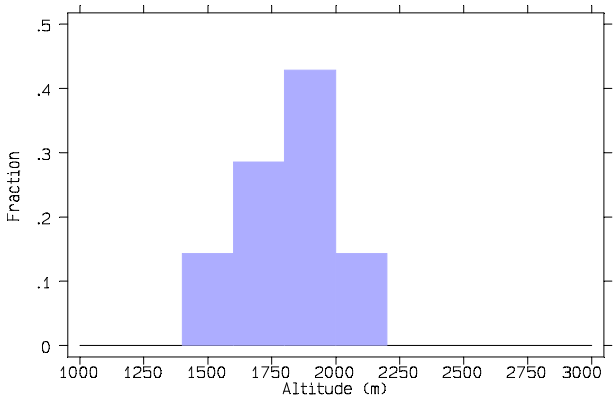
Pre-eradication Programme between 1965 and 1967. Both maps indicate malaria-free or hypoendemic areas around Mount Elgon (Mbale), the Ruwenzori (Kasese) and in the Rukungiri/Kabale area, although the precise boundaries of these strata differ, as do the means of their classification. In the 1967 stratification malaria free areas (which are left blank) are restricted to the immediate vicinities of Mount Elgon and the high Ruwenzori, while all other highland areas, including those around Kabale and Rukungiri, are seen as having some transmission potential. The 1962 map is somewhat different in that it uses the 5000 feet (1524 m) contour to define malaria free areas. Generally, Figure 5.8 demonstrates good agreement between these stratifications and the MARA model – with the model performing well in both rainfall and temperature limiting situations.

5.3.4 The distribution of epidemics and epidemic risk

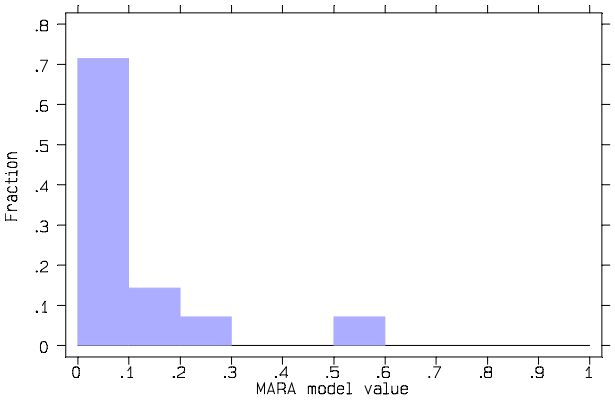
Using the USGS 1 km DEM data, altitudes were extracted for localities which have historically experienced epidemics. It was found that highland epidemics occur within an altitude range of 1572–2131 m. The mean altitude at which epidemics occur is 1809 m and the spread around the mean roughly takes the form of a normal distribution (Figure 5.9a). Examination of the MARA model values for epidemic locations indicated that the majority fall within a model value range of 0–0.1 (Figure 5.9b).

Figure 5.9 *Histograms for altitude and MARA model values of epidemic locations in Uganda*

(a) Altitudes of epidemics

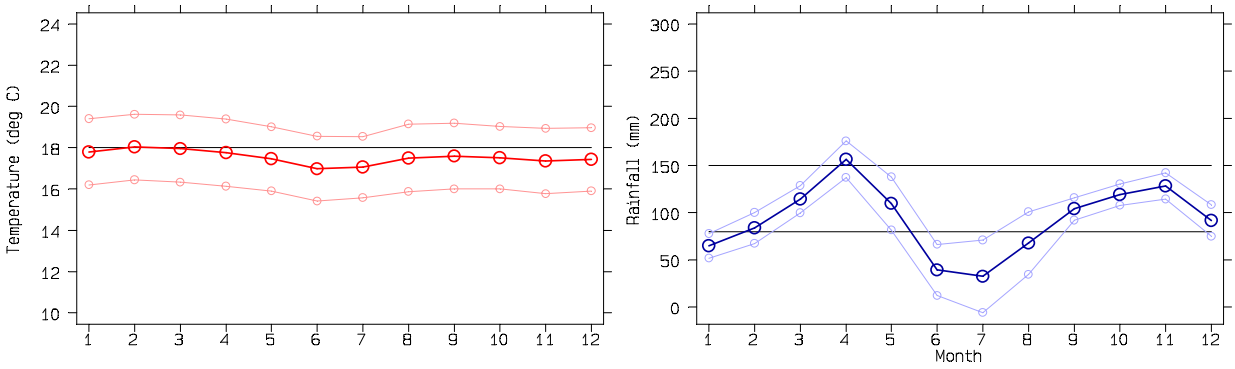


(b) MARA model values



To determine the typical climatological profiles of epidemic prone areas, monthly data for temperature and rainfall from the CRES dataset were extracted for known epidemic locations. In Figure 5.10a the average climate profiles over all epidemic locations (indicated by the centre curves) show somewhat different patterns to those presented for Kenya (Section 4.3.7). In Kenya a window of suitable temperatures for transmission (mean monthly temperature > 18 °C) exists in the first few months of the year, while temperatures in Uganda, being more stable, remain marginal throughout the year (with the warmest period occurring in January–March). Much, therefore, may depend on corresponding rainfall conditions, with the lower graph indicating relatively modest monthly totals in epidemic prone areas during the main rainy seasons. For the Kenyan highlands, Malakooti *et al*. (1998) suggested that a minimum of 150 mm of rainfall per month was required for malaria to occur. If this threshold were applied to Uganda (Figure 5.10b), transmission in a typical year would be unlikely. It is therefore probable that the occurrence of epidemics is dependent on the occurrence of above average rainfall, especially in the first rainy season. In Uganda recent epidemics in 1994 and 1998 have been shown to correspond with unusually high rainfall events, and the wider association between transmission and rainfall has been well demonstrated by Kilian (1999). As in the case of Kenya, it would appear likely

Figure 5.10 *Average annual profiles for mean monthly temperature and rainfall for known epidemic locations in Uganda*



that the provision of timely information on rainfall and temperatures would provide a sound basis for epidemic early warning.

The previous analysis of Kenyan epidemics (Section 4.3.7) showed that it is possible to use these climate profiles to extrapolate epidemic risk. Using this approach, areas of high and moderate risk were mapped out for Uganda and the results are shown in Figure 5.11. Orange shading in the figure signifies areas most at risk from malaria epidemics and these are concentrated primarily in the south west, and in pockets along the slopes of the western highlands. Population densities in these areas are relatively high (Table 5.2), with results obtained from Deichmann's (1996) population data suggesting that around 15% of Uganda's population live in areas of high or moderate risk.

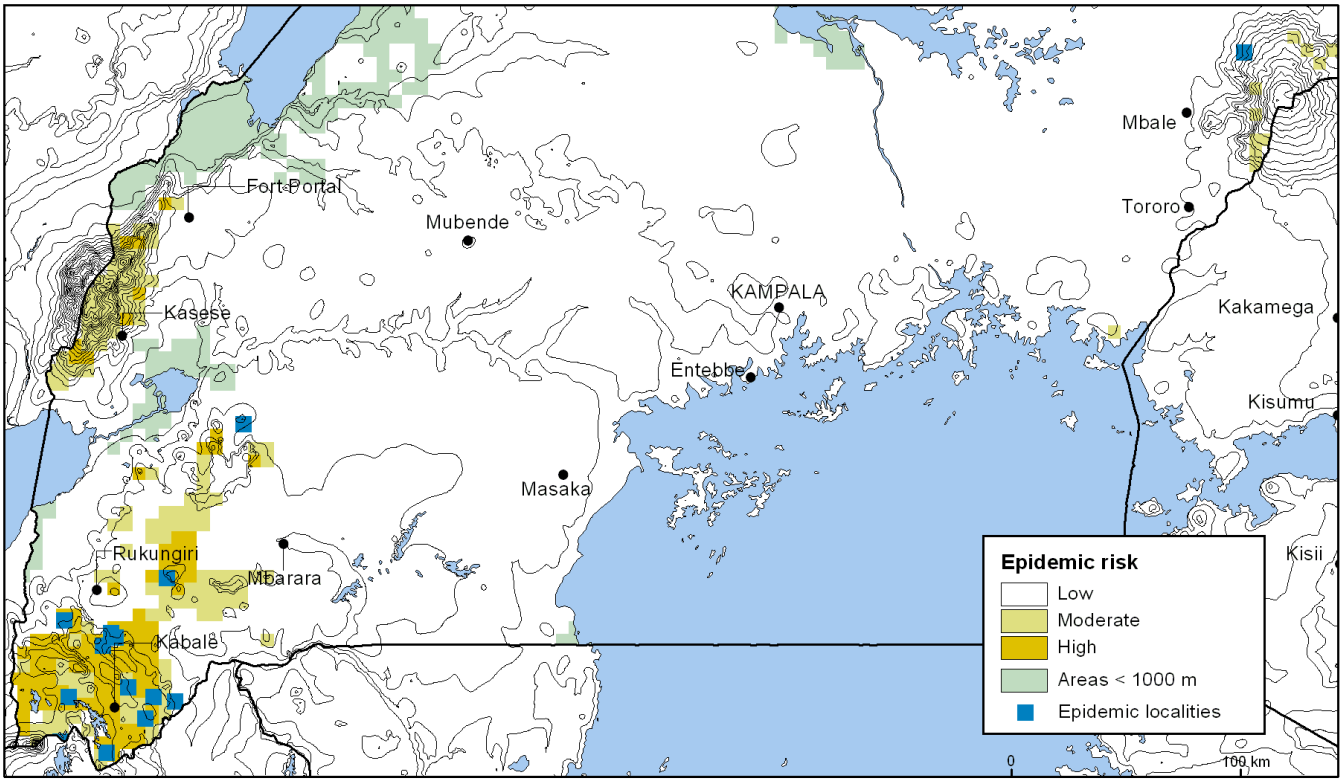


Figure 5.11 *Distribution of epidemic risk in the Ugandan highlands*

Table 5.2 *Land area and population at risk from epidemics in the Ugandan highlands*

Risk zone	*Average population density (persons km^{-2})*	*Land area in risk zone (km^2)*	*Total population at risk*
Moderate	248	9 476	2 347 205
High	189	3 117	588 858
Total		**12 593**	**2 936 063**

Notes

[1]. Lindblade, K.A., Katungu, J., Onapa, A., Walker, E.D. and M.L. Wilson (1998), 'land use change and malaria transmission in a highland area of Uganda' (unpublished manuscript).

[2]. Africa News Online (http://www.africanews.org), 21/7/1997.

[3]. There are no data for the period 1976–1981 and for 1992–1995 only outpatient returns are available. Work to complete the dataset is, however, ongoing (Onapa pers. com.).

6 Ethiopia

6.1 Principal features of the Ethiopian highlands

The Ethiopian highlands constitute one half of an uplifted dome (the other half being centred in southern Yemen), where the three rift systems of the Great Rift Valley meet. The Ethiopian section is further divided into northern and southern massifs by the upper reaches of the Eastern Rift Valley (Map 1, Appendix 1). Of these, the northern massif (commonly called the Ethiopian Plateau) is the larger and more elevated, with the Simien range (north of Gonder) reaching altitudes of about 4600 m. The southern massif (Somali or Eastern Plateau), which forms a tilted block sloping gently south eastwards towards the Indian Ocean, is generally lower-lying and being highly dissected does not demonstrate the classical plateau features of the northern massif. Taken together, the sheer scale of the northern and southern massifs makes the Ethiopian highlands unique in an African context. Roughly a third of the country (376,000 km^2) lies above 1500 m, of which 45% (168,135 km^2) is higher than 2000 m (Table 3, Appendix 1).

Within the highlands annual rainfall totals generally increase with altitude, at least up to around 2500 m (Figure 6.1, cf. Section 1.3.1), although the distribution of rainfall at the national scale (Map 3, Appendix 1) also reflects the direction of moisture-bearing winds. The wettest areas are concentrated in the western highlands (West and East Gojjam, West and East Welega, Illubador and Jima), while the northern and eastern sections of the highlands (including Tigray, Wello, Shewa and Hararge) are relatively dry. Inter-annual variation in rainfall is relatively high throughout the highlands, with part of this variability being linked to ENSO (El Niño years being associated with warm, dry conditions, *e.g.* Beltrando and Camberlin (1993), Seleshi and Demarée (1995)).

Seasonal rainfall patterns are strongly influenced by the relative movements of the ITCZ, the north east trade winds and the south west monsoon. In January, when the ITCZ is in its most southerly position, most of Ethiopia comes under the influence of north east trade winds, resulting in a pronounced dry season (Figure 6.1). The northward movement of the ITCZ between March and June is associated with relatively humid south west monsoon air, which is responsible for the main rainy season (*krempt*) in July and August. Malaria transmission typically rises rapidly in September following the main rains, before tailing off in November as mean temperatures and humidity fall and breeding sites dry up.

As would be expected, mean monthly temperatures are strongly correlated with altitude (*e.g.* FAO 1984), although in a regional context, temperatures at high altitudes (Figure 6.1b) are relatively warm, and remain above 18 °C much of the time. Temperatures are relatively stable over the year, but are generally highest in the period March to June, and lowest in July to September, during and immediately after the main rainy season. This is illustrated in Figure 6.2, in which areas that are unlikely to support malaria transmission on a month by month basis (black shading) shrink significantly in months 3–4, before expanding again in subsequent cooler months.

Human population densities are high throughout the Ethiopian highlands (Table 1 and Map 2, Appendix 1), and particularly in areas above 1750 m. Given that the land area of the highlands is also relatively large, this translates into large absolute populations – with roughly 45 million people living at 1500 m ASL or above (Table 2, Appendix 1). This clearly has implications for the size of population at risk from malaria epidemics (see below).

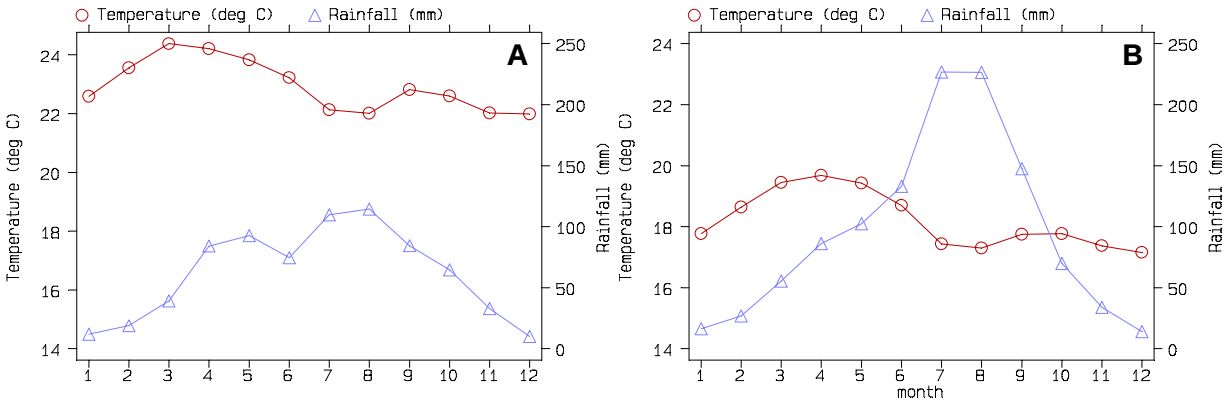


Figure 6.1 *Annual patterns of rainfall and mean monthly temperature for two altitude bands; (A) 1100–1300 m (B) 1900–2100 m*

6.2 Malaria transmission in the highland zone

6.2.1 Previous studies

Some of the earliest malariological studies in Ethiopia were carried out by Italian scientists, mostly during the period of Italian occupation (1936–41). These included a number of entomological surveys (Giaquinto-Mira 1938, 1950; Brambilla 1940; Corradetti 1938a) which showed *An. gambiae s.l.* to be the most important vector in both lowland and highland areas (up to 2100 m), with *An. funestus* being generally limited to areas below 1500 m. In addition *An. d'thali*, *An. praetoriensis* and *An. pharoensis* were identified as likely secondary vectors.

A number of parasitological surveys were also conducted in this period. Lega *et al.* (1937) carried out a series of rapid surveys between Eritrea and Dese and also further south between Addis Ababa and Harar in 1936–7. Corradetti (1938b, 1940) conducted more detailed surveys around Dese (Wello) between 1938 and 1940, the results of which illustrated both the seasonal nature of transmission and the particular significance of rainfall (Figure 6.3). Corradetti's results also demonstrated a clear association between altitude and malaria transmission intensity. In areas below 1000 m he found intense perennial transmission only in the vicinity of permanent water bodies. Away from these areas transmission was highly seasonal, with peak transmission occurring during and immediately after the rainy season. This seasonality became more pronounced with increasing elevation: between 1000 and 1500 m transmission was widespread in the wet season, but only isolated cases appeared in the dry season (Corradetti described this zone as an area of 'scarce diffusion' of *An. gambiae*).[1] Between 1500 and 1900 m transmission was completely absent during the dry season and rose gradually after the onset of the wet season, 'reaching its altitude limits at the end of the rainy season.' This limit appeared to be 2000 m.

The British army occupied Ethiopia briefly during the Second World War and a number of parasitological surveys were carried out by the East African Army Medical Corps during 1941–2. As reported by Melville *et al.* (1945), these surveys revealed 'moderate' hyperendemicity between 1500 m and 1800 m, below which rainfall tended to be limiting and the extent of transmission depended on relative proximity to streams. Above 1500 m, the length of the transmission season became progressively shorter with increasing altitude and transmission generally ceased at 2000 m. There were notable exceptions to this rule, however. In particular, local transmission was reported at Akaki, immediately south east of Addis Ababa, and also in the city itself (see also Martin 1942; Giaquinto-Mira 1950).[2] As in earlier Italian studies, *An. gambiae* was found at all surveyed sites, with *An. pharoensis*, *An. funestus*, and *An. d'thali* being identified as possible secondary vectors (Melville *et al.* 1945).

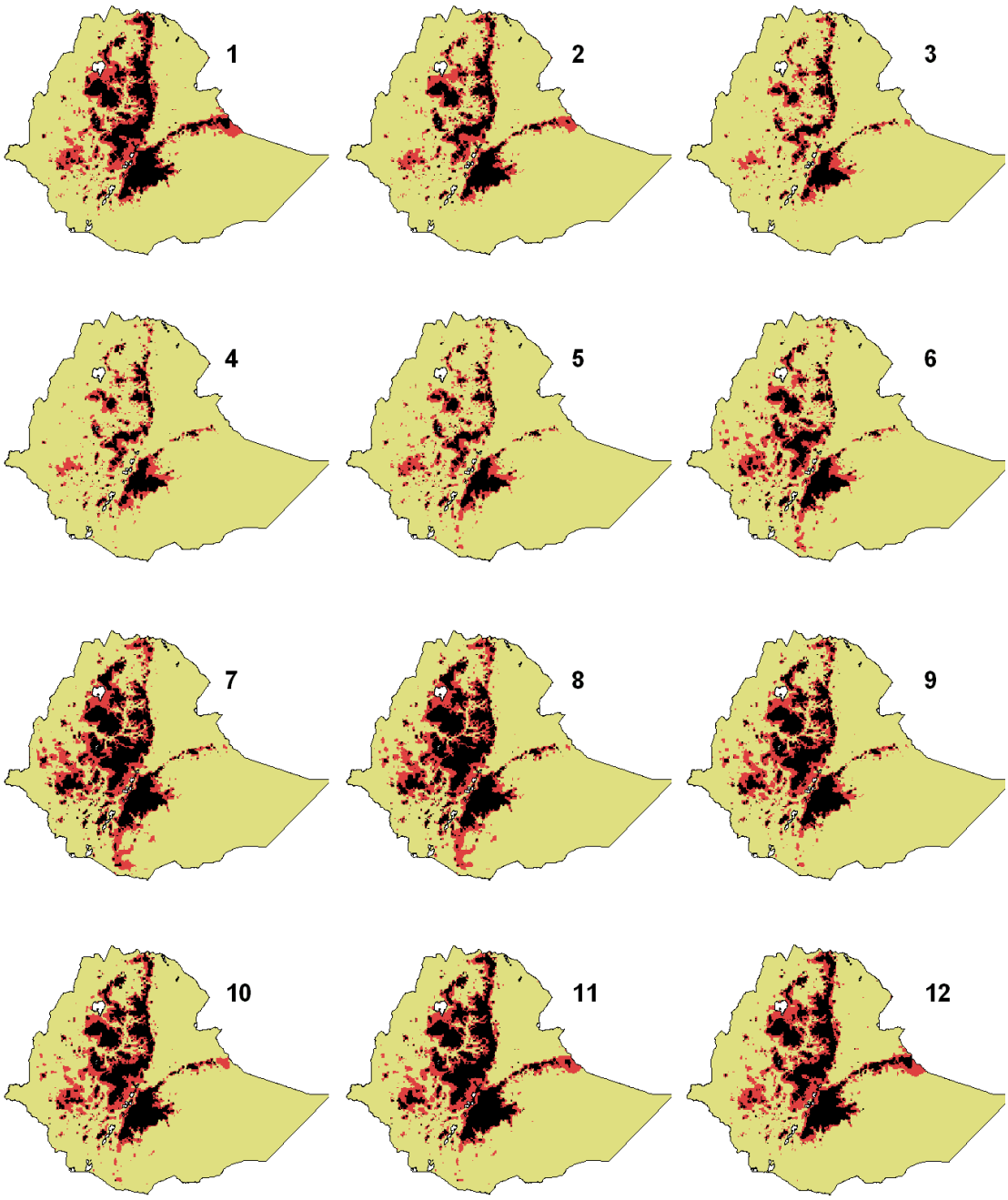


Figure 6.2 *Spatial variation in mean monthly temperatures in Ethiopia in a typical year. Yellow shading indicates areas where temperatures are likely to support malaria transmission in a particular month, while black shading signifies localities where temperatures are likely to be limiting. Red areas are intermediate and probably represent the altitudinal fringes of transmission (see Section 4.1)*

In 1952 Covell investigated the malaria situation around Bahir Dar and carried out surveys in other areas in 1955, the results of which underlined the general importance of altitude, and the more focal significance of water bodies in determining local levels of transmission intensity (Covell 1957). Partly as a result of Covell's recommendations, demonstration malaria control projects were set up in Kobo Chercher (1955), the Upper Awash Valley (1956), Dembia Plain (1957) and around Gambela (1959) in order to test the effectiveness of residual house spraying in a range of transmission settings. While none of the projects achieved complete interruption of transmission (*e.g.* Najjar and Fontaine 1959),

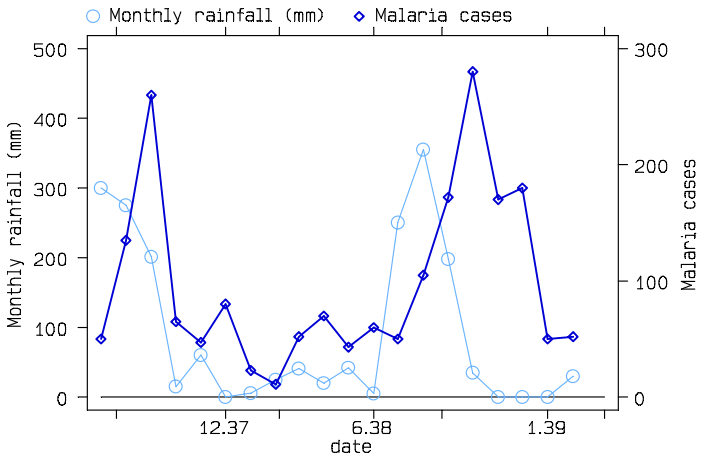


Figure 6.3 *Seasonal variation in rainfall and malaria cases around Dese, Ethiopia, 1937–9 (data from Corradetti 1940)*

residual spraying was generally considered a success and this fact, together with concern generated by a widespread malaria epidemic in 1958 (see below) led to the establishment of the National Malaria Eradication Service. This became fully functional in 1959 and after initially following an *ad hoc* spraying strategy centred on the original demonstration sites and other areas of economic significance, a comprehensive spraying programme was initiated in 1966. Baseline data were collected in reconnaissance studies (*e.g.* Turner 1972) and through six monthly parasite surveys in ecologically stratified, homogenous areas (*e.g.* Cowper 1967; Mekuria and Wolde Tsadik 1970). A system of active case detection was also initiated in 1968, although this proved so laborious that by 1971 it had been discontinued completely. By this time the strategy of blanket spraying had also been replaced with selective spraying, with a 5% prevalence rate being used as a tolerable (critical) level of control (Gabre Mariam 1984).[3]

Following the realignment from eradication to control, annual blood surveys covering 3–4% of the population were conducted in representative localities during the peak transmission season. These were sufficiently sensitive to detect epidemics in 1980/81 but it appears no data are available after 1987 (Tulu 1996) and with the exception of a handful of isolated studies few parasitological data are available for the highlands after this period. Yohannes and Petros (1996) carried out prevalence surveys in and around Nazret in 1988/9, and historical data for the Nazret-Debre Zeit area were collated by Tulu (1996). These data (Figure 6.4), taken from seasonal blood surveys (1974–87), showed very low rates of *P. falciparum* above 1900 m and were consistent with surveys carried out in the area several decades previously (*e.g.* Lega *et al*. 1937; Giaquinto-Mira 1938; Melville *et al*. 1945).[4] More recently a number of parasitological data have been collected as a part of an ongoing project to assess impacts of small-scale irrigation dams in Tigray (Ghebreyesus *et al*. 1998). Although irrigation dams have been shown to increase levels of malaria transmission in lowland parts of Ethiopia (*e.g.* Meskal and Kloos 1989), less is known about their potential impacts in highland settings. Preliminary data from Tigray, where hundreds of such dams are planned, suggest that parasite rates in the vicinity of dams are significantly higher than those in outlying areas.

6.2.2 The occurrence of epidemics

While many early accounts allude to the epidemic-prone nature of the Ethiopian highlands, little information is available for epidemics prior to the 1950s. Melville *et al.* (1945),

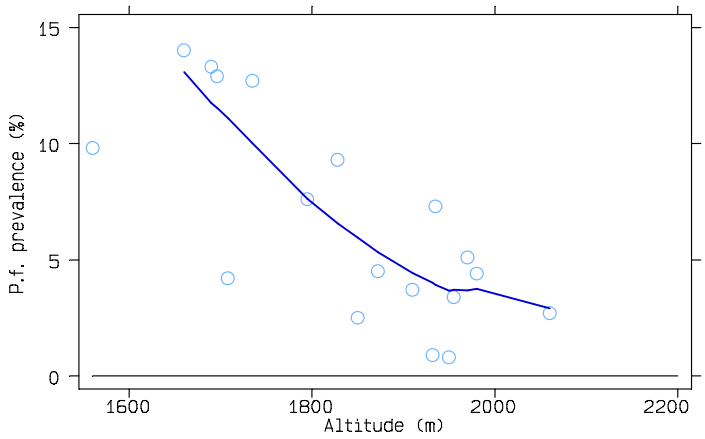


Figure 6.4 *Relationship between altitude and prevalence of P. falciparum in Debre Zeit Sector, Ethiopia (data from Tulu 1996)*

for example, refer to epidemics in Batie (Wello) and Ada (Shewa) in 1941, following a prolonged period of rainfall, but no other information is given.

In 1953 an epidemic was reported in the Dembia plain area between Gonder and Lake Tana, with an estimated 7,000 deaths (Covell 1957). Covell surmised that although transmission occurred on an annual basis in the area, the brevity of the transmission season (typically limited to October and November) was such that levels of functional immunity in local populations were very low (a fact later confirmed by Collins *et al.*'s (1971) serological surveys in the area). Cowper went on to argue that 'in years when conditions are particularly favourable to the production and longevity of the vector species, this region is liable to be visited by severe epidemics of malaria attended by a high mortality' (Covell 1957: 11). The accuracy of this statement became evident only three years after Covell's visit, with an intense and widespread epidemic affecting the Dembia plain and other areas in 1958. Significantly, the epidemic followed a period of exceptional meteorological conditions in which unusually heavy and prolonged rains combined with abnormally high temperatures and humidity to create conditions conducive to very high vector concentrations.

The early stages of the 1958 epidemic were first noticed in June, when a routine survey near Bahir Dar (1800 m ASL) revealed unexpectedly high levels of *P. falciparum* infection in the local population. The epidemic went on to affect more or less the whole of the Lake Tana region as well as most highland areas of Shoa, Gojam, Wollo and various parts of Wollega, Arussi, Harar, Sidamo and Tigray. Within these infected regions, epidemics occurred anywhere between 1200 and 2200 m, with the only areas not being unduly affected being the malaria control pilot sites on the Dembia Plain and in the Upper Awash valley. Addis Ababa, at 2350 m, was itself not directly affected by epidemics, although outbreaks did occur in many surrounding localities up to altitudes of about 2100 m (*e.g.* at Akaki and along the Addis-Jima road).

Estimates of morbidity and mortality associated with the 1958 epidemic, based largely on expert opinion, are contained in various unpublished reports cited by Fontaine *et al.* (1961). From these Fontaine *et al.* estimated that case fatality rates during the epidemic were generally in the region of 5–10%, but could have been as high as 20% in areas where food shortages existed. Given an estimated 3 million clinical cases of malaria during the 1958 epidemic, Fontaine *et al.* concluded that even using a conservative case fatality rate of 5%, the number of deaths would probably have exceeded 150,000.

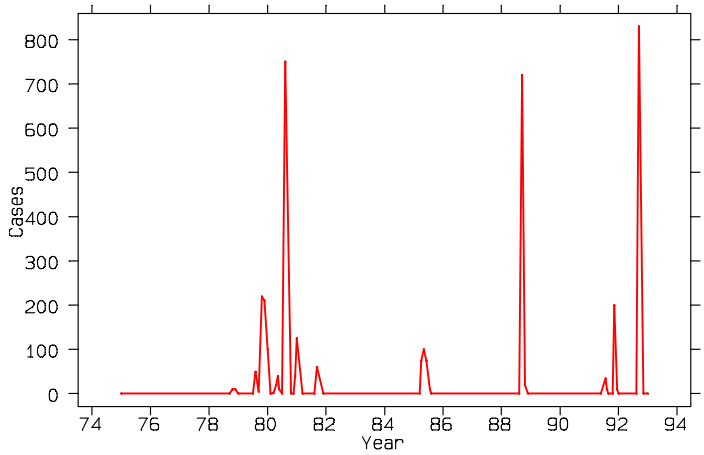


Figure 6.5 *Malaria cases diagnosed during malaria outbreaks in Debre Zeit Sector, Ethiopia, 1975–93 (data from Tulu 1996)*

Extensive epidemics showing similar but less intensive characteristics to the 1958 epidemic, occurred in many parts of Ethiopia in 1965, 1973 and 1981–2 (Gabre Mariam 1988). There are few data on the extent of these or later epidemics, nor is there a comprehensive list of localities affected. Instead, available data for epidemics tend to come from individual studies of specific geographical areas. Tulu (1996), for example, examined epidemic reports from the Debre Zeit area for the period 1973–1993 and extracted information on the number of cases diagnosed (and confirmed) in each outbreak (Figure 6.5). Major outbreaks occurred in 1980/81, 1988 and 1992; smaller outbreaks also occurred in 1985 and 1991. The outbreaks in 1988, 1991 and 1992 coincided with large increases in hospital admissions (data from Debre Zeit hospital; Tulu 1996: 64). In these years inpatient mortality due to malaria was consistently high, peaking at 21.5% for *P. falciparum* infections in 1992. It also appears that outbreaks in these years affected relatively high-lying areas, including localities at around 2200 m.

An extensive malaria epidemic affected the northern highlands of Ethiopia in 1990. Epidemics were reported in the Lake Tana area, around Bahir Dar, Debre Tabor and Addis Zemen although no data are available for these outbreaks. Severe epidemics also occurred in the north central parts of Tigray Autonomous Region, with 16,456 cases and 246 deaths being reported (Ghebreyesus *et al.* 1996). Here the situation was worsened by the inability of the National Organisation for the Control of Malaria and other Vector-borne Diseases (NOCMVD) to implement any control measures (although it was still active in other parts of the highlands). Tigray had previously experienced a large epidemic in Shire Province in 1987, which was reportedly responsible for 142,317 clinical cases and 349 deaths (Teklehaimanot 1991b). Epidemics returned in June and July 1991 and although much of the country was affected (over 317,000 cases were reported), the situation in Tigray proved once again to be particularly serious. By September and October 1991 NOCMVD had received reports of epidemics in 177 villages – principally in Tigray, around Lake Tana and in highland areas of Shewa, south and south west of Addis Ababa (Teklehaimanot 1991b).

Severe epidemics reappeared in the Ziway (1680–2020 m) area of Shewa Region in 1992. NOCMVD data from seven localities indicated that mortality rates were in the range 0.91–11.92%. In Ziway zone as a whole, around 450 localities were affected by the epidemic and the total number of deaths put at around 10,000 (Bosman *et al.* 1993) Although all age-groups were affected, mortality was especially high among the under fours. Entomological surveys carried out during the main transmission seasons indicated a

preponderance of *An. pharoensis* adults and larvae over those of *An. gambiae s.l.*, *An. squamosus* and *An. coustani*. Follow-up retrospective surveys in individual villages suggested somewhat higher mortality rates than those estimated by NOCMVD (11.4–31.6%) and indicated that 95% of the deaths occurred between July and November 1992.

As had been the case for the 1958 epidemic, meteorological data for the Ziway area revealed that climatic conditions preceding the 1992 epidemic had been particularly conducive to malaria transmission. Bosman *et al.* (1993) showed that temperatures in 1990–2 were consistently above the long term average for the area, with exceptionally high temperatures being recorded in April and November 1990, January, February and May 1991, and March to May 1992. Rainfall at the end of the cold seasons in 1990 and 1991 was also well above average. In 1992 rainfall in February and March was somewhat below average, but increased to well above normal in July and August and October.

A number of epidemics were again reported during the main transmission season of 1994, with Wollo (Amhara) and Shiraro being especially affected. Epidemics also reappeared in central areas (Zwai, Butajira, Alaba, Nazret and Metahara) during this period and following the short rains of January and February 1995. This last wave also affected the Lake Tana area and the vicinity of Jimma and was believed to be the result of intermittent rain coupled with above average temperatures (Anon. 1997). Focal epidemics again hit these areas in 1996.

6.2.3 Temporal trends in highland malaria transmission

The 1980s saw a huge number of reported malaria cases in Ethiopia, rising from an average of 43,545 p.a. in 1980–85 to 235,992 p.a. in 1985–90 (Tulu 1993b: 347). While a large portion of this national rise may have reflected the combined effects of conflict, resettlement and emerging drug resistance in lowlands areas, the trend was also evident within the highland zone. Tulu's (1996) study of the malaria history at Debre Zeit near Addis Ababa (1900 m ASL), for example, showed that the reported mean annual malaria cases rose from 1058 to 3905 between the periods 1980–85 and 1985–90, while malaria incidence rose from 1.1 to 65 per thousand between 1980 and 1989. Hospital admissions and malaria deaths also increased markedly in this period.

Tulu's analysis revealed that these changes in transmission intensity had been accompanied by a gradual shift towards warmer (and dryer) conditions in the Debre Zeit area. In particular, he found a positive correlation between minimum night time temperatures and malaria incidence on a monthly basis. This was particularly apparent between 1988 and 1993. Tulu took this to be a causal relationship, although, by his own admission it proved impossible to separate out the effects of climate from those of potentially confounding factors. The contribution of drug resistance, for example, to the increased incidence of clinical malaria may have been particularly significant, with Tulu's study of 142 *P. falciparum* infected patients indicating a significant level of chloroquine resistance *in vivo* (RI/S in 14%, RII in 62% and RIII in 24%; Tulu *et al.* 1996). Such levels of chloroquine resistance had previously been thought to be restricted to border areas of Ethiopia (*e.g.* Teklehaimanot 1986) and early surveys in the Debre Zeit area (Gabre Mariam 1982) showed no evidence of resistance. However more recent findings both in Debre Zeit and elsewhere (Wolde *et al.* 1994; Alene and Bennett 1996) indicate significant levels of chloroquine resistance nationwide. This has important implications in terms of the selection of appropriate drugs for epidemic control.

Data for Debre Zeit also highlight the fact that shifts in the level of malaria transmission during the 1980s coincided with a period of disruption and general decline in control

activities. Data presented by Tulu show that at the peak of control operations in the early 1970s around 120,000 houses in Debre Zeit sector were sprayed annually. This figure declined rapidly and steadily from the mid 1970s: by 1985 it had been reduced to just over 8,000.

6.3 Analysis of the HIMAL dataset

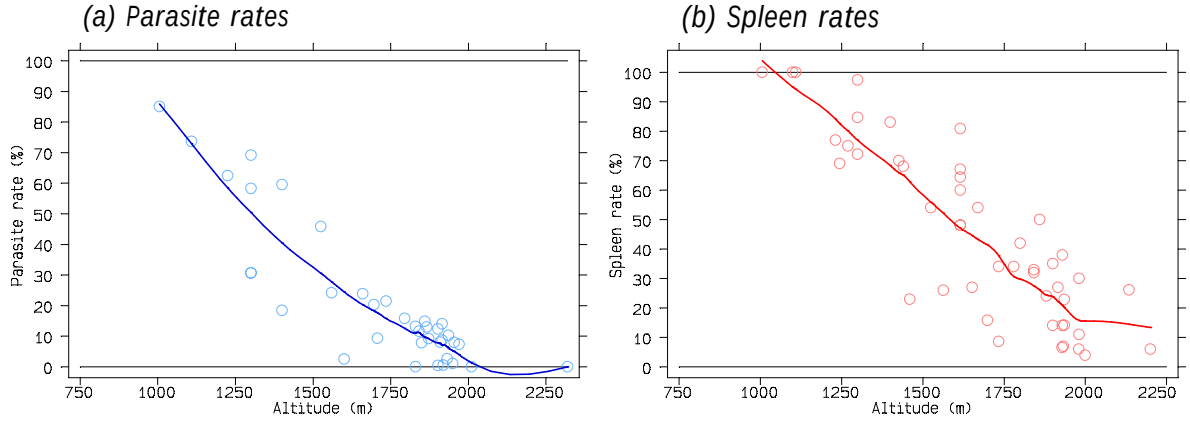
6.3.1 Data collected

From the literature search, 48 documents provided relevant data for parasite and spleen rates and/or epidemic locations. These yielded at total of 242 data points: 147 epidemic locations and 47 and 48 points for parasite and spleen rates respectively. The majority of data for epidemic locations came from the reports of Teklehaimanot (1991a, b). Data for parasite and spleen rates come from a wider range of reports, some of which date back as far as the 1930s. The geographical distribution of data points is shown in Map 5 in Appendix 1, which indicates that the majority of prevalence data come from Tigray, the Lake Tana area and from the southern highlands of Shewa and Hararge. Of the 242 data points for Ethiopia, around 23% (mainly epidemic localities in Tigray) could not be geo-referenced.

6.3.2 Effects of altitude on malaria transmission intensity

Figure 6.6 shows parasite and spleen rates for geo-referenced survey locations plotted against altitude. Both variables demonstrate strong correlations with altitude, with a slightly higher degree of scatter in the case of spleen rates. Figure 6.6a bears out the strong effect of altitude on transmission intensity, as first described by Corradetti and others in the 1930s, with parasite rates declining rapidly as altitude increases above 1000 m. Within the altitude range 1750–2000 m, parasite rates are somewhat variable, but generally lie in the range 0–15%. On the evidence of parasite rates there is no suggestion of transmission above 2000 m (although there are relatively few data points at this altitude). The data for spleens, however, suggest that parasite surveys may underestimate the degree of transmission at these altitudes.

Figure 6.6 *Variation in parasite and spleen rates with altitude, Ethiopia*



6.3.3 The MARA model as a means of stratifying risk in highland areas

MARA model values were extracted for the geo-referenced sites and plotted against similarly extracted DEM values (Figure 6.7a). In contrast to findings for Kenya and Uganda, there is considerable scatter in the relationship between the MARA model and altitude. Leaving aside the possibility of errors in the elevation data or in the climate surfaces used

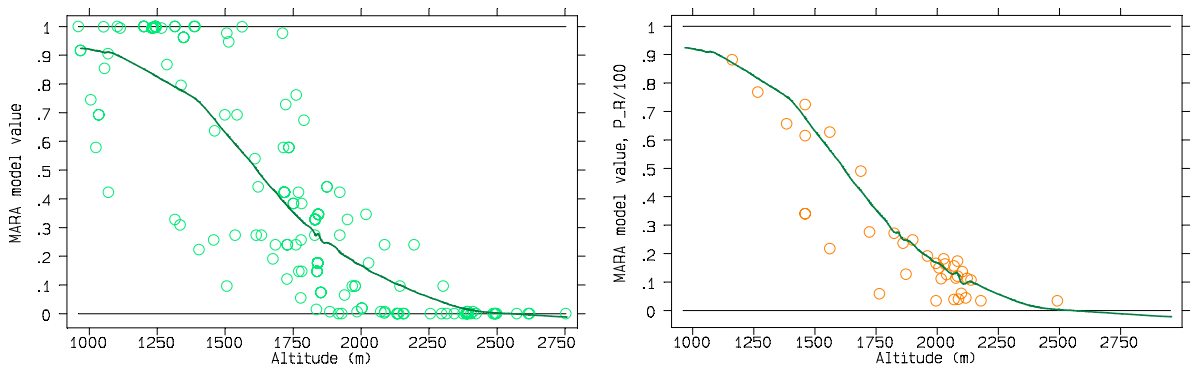
in the analysis, it is likely that this scatter reflects the relative importance of rainfall in determining the MARA model values at some Ethiopian sites (unlike temperature, rainfall cannot be correlated with altitude in a straightforward way). Hence the majority of outliers which fall below the smoothed line in Figure 6.6a can be traced to sites in relatively dry sections of the Ethiopian highlands, and specifically to areas of Tigray (Raya and Azebo), Shewa (Yere and Kereyn) and relatively dry parts of Gojjam and Welega.

Arguably, this logic is confounded by the fact that available prevalence data for Ethiopia (Figure 6.7b) strongly suggest that a clear correlation between transmission intensity and altitude does exist. Two possible explanations may account for this apparent discrepancy: the first is that an (unknown) portion of the scatter in Figure 6.7a is likely to reflect errors

Figure 6.7

(a) Relationship between the MARA model and altitude for Ethiopian survey sites

(b) The MARA model (line) and parasite rates (circles, re-scaled) against altitude



in the estimation of altitude for individual sites, resulting both from internal error in the DEM and from inexact geo-referencing of localities; the second is that the plot in Figure 6.7a includes *all* geo-referenced localities for Ethiopia in the HIMAL dataset – *i.e.* it includes epidemic locations, many of which are in the drier parts of the highlands referred to above. These sites are not represented in Figures 6.6 and 6.7b.

The MARA model for Ethiopia is presented geographically in Figure 6.8. The main highland areas of the northern and southern massifs stand out as areas where the model value is zero (white shading), indicating that conditions in an average year are almost certainly unsuitable for transmission. Similarly low levels of transmission are predicted in the lowlands in the south east of the country and in the north east (bordering Eritrea), where transmission is limited by the availability of surface water. In contrast, the relatively wet highland fringes to the west and south of the Ethiopian plateau appear as areas of endemic transmission (model values 0.9–1), as do highland fringe areas in the vicinity of Dese, Nazret, Dire Dawa and Harar. Within the plateau area itself, relatively low-lying valley areas are characterised by low model values, typically below 0.2.

As a crude method of validating the MARA model, Figure 6.8 also shows a map of malaria transmission intensity (shown by periods of transmission) as presented by Schaller and Kuls (1972) and which has been informally adopted, with some slight modifications, as a standard stratification for Ethiopia.[5] In broad terms, the pattern of transmission intensity in Schaller and Kuls' map is similar to that indicated by the MARA model. Central parts of the highlands stand out as malaria free, while the arid lowlands (outside the main river valleys) are malarious only near water. Within the highland fringes the two maps also

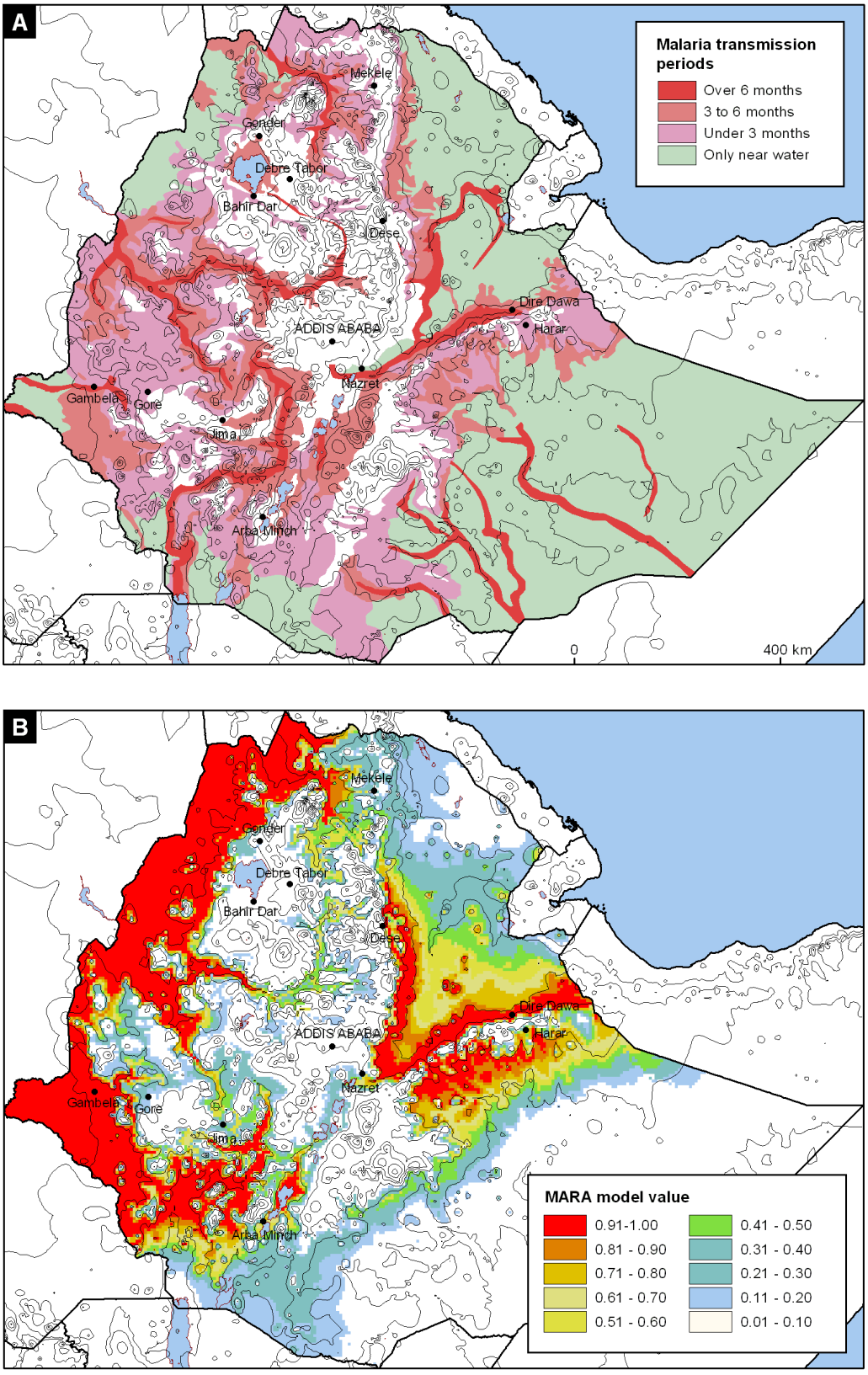


Figure 6.8 *The MARA model and standard malaria stratification map for Ethiopia (source: Schaller and Kuls 1972)*

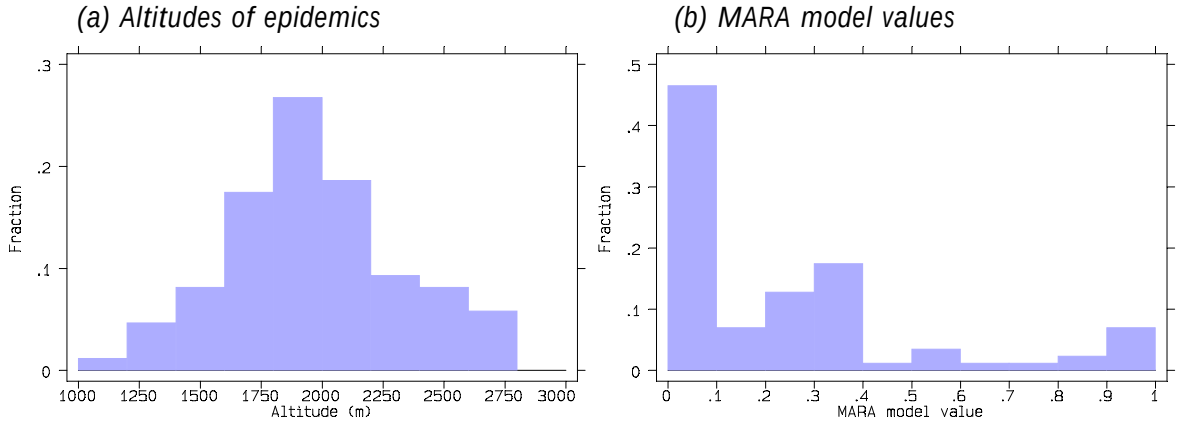
correspond well – the only significant discrepancies being on the northern slopes of the Somali plateau (south of Nazret) and in areas surrounding Lake Tana, where the MARA model predicts relatively low levels of transmission. In reality both these areas are highly epidemic prone.

6.3.4 The distribution of epidemics and epidemic risk

As for Kenya and Uganda, DEM values were extracted for localities which have historically experienced epidemics. Results indicated that the average altitude at which epidemics occur is 1977 m, which is similar to the corresponding figure for Kenya (1947 m) and somewhat higher than that for Uganda (1809 m). However, Figure 5.9 also suggests that the altitude range within which epidemics occur (1172–2777 m) is much broader than is the case in either Kenya or Uganda (1510–2572 m and 1572–2131 m respectively). This may well reflect the fact that Kenyan and Ugandan epidemics are focused in relatively small geographical areas, while in Ethiopia epidemics occur over a wider range of localities. This is an important consideration when producing estimates of epidemic risk based on either altitude or climate, and for this reason subsequent analyses were carried out using (smaller) contiguous regions (see below).

Examination of the MARA model values for epidemic locations indicated that, in contrast to Kenyan and Ugandan epidemics, more than half of the locations fell outside a model value range of 0–0.1 (Figure 6.8b). These sites were found to be located outside the main plateaux areas and typically represent fringe areas in the drier, eastern sections of the highlands: Agame, Raya and Azebo, Raya and Kobo (Tigray); Yeju, Ambasel (Wello); Yifat and Timnga (Shewa); Chercher Adal, Webera (Hararge); Jima, Limu (Kefa). This suggests that

Figure 6.9 *Histograms for altitude and MARA model values of epidemic locations in Ethiopia*



the MARA model may generally overestimate suitability for transmission (and thereby underestimate epidemic risk) in relatively dry highland sites.

To determine the typical climatological profiles of epidemic prone areas, monthly data for temperature and rainfall from the CRES dataset were extracted for known epidemic locations. As previously mentioned, this analysis was downscaled to four contiguous sub-regions:

Region A (including northern Tigray): 34.45 °E, 13.5 °N/42.55 °E, 14.9 °N

Region B (including the L. Tana area, Gojjam): 34.45 °E, 8.9 °N/39.10 °E, 13.5 °N

Region C (including S. Tigray, Wello, Hararge): 39.10 °E, 8.9 °N/42.55 °E, 13.5 °N

Region D (including highlands S. of Addis Ababa, E. Shewa, Jima): 34.45 °E, 5.8 °N/42.55 °E, 8.9 °N

In Figure 6.10 average profiles for rainfall and temperature for epidemic locations (indicated by the centre curve) are presented for each of the these regions (for a full explanation

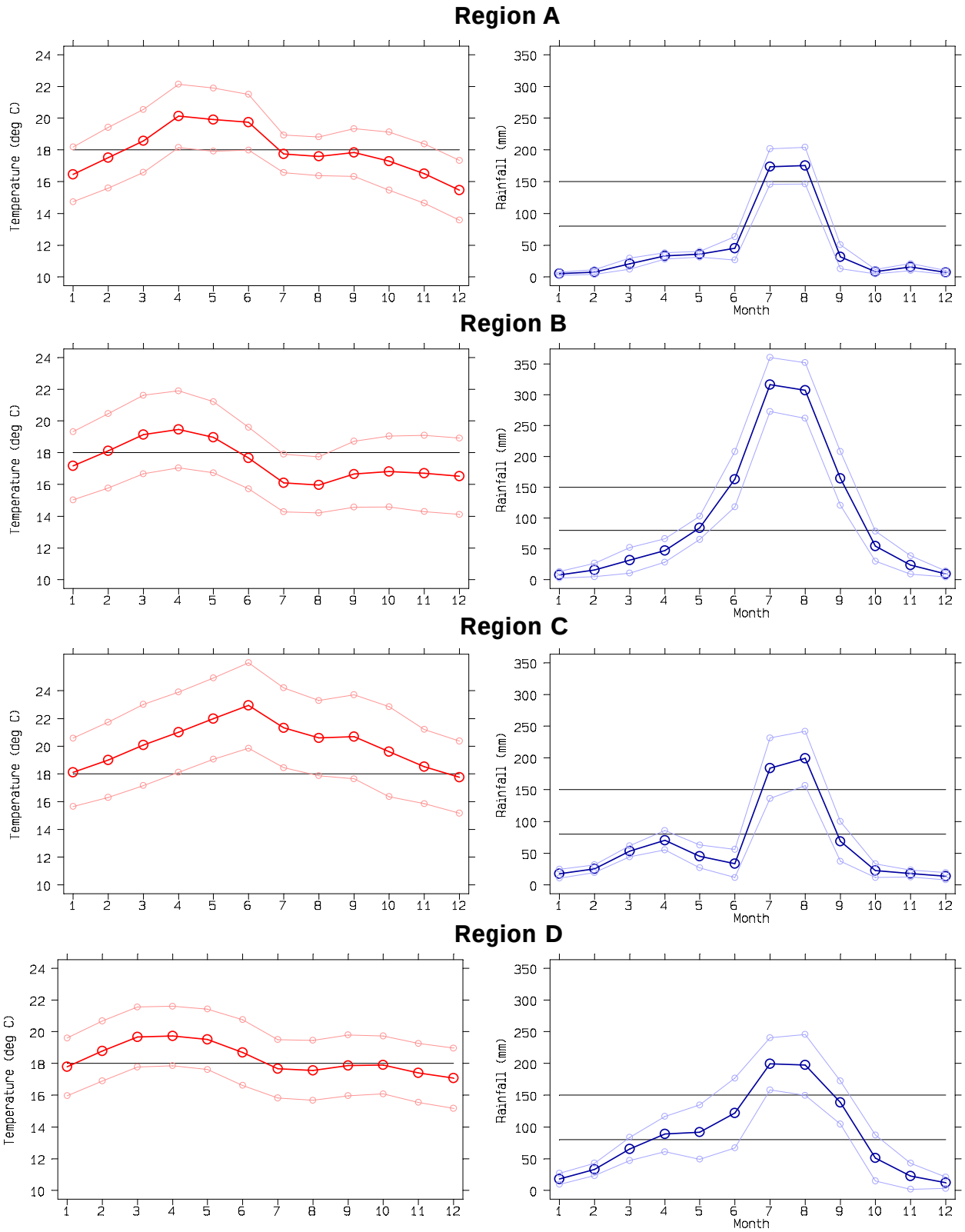


Figure 6.10 *Average annual profiles for mean monthly temperature and rainfall for known epidemic locations in Ethiopia, separated by region*

of these curves and the thresholds shown, see Section 4.3.7). These suggest that climatic risk factors associated with epidemics probably differ between regions. In the dryer sections of the eastern highlands (Region C), for example, temperatures are relatively high year round and may only become critical, from the point of view of malaria transmission,

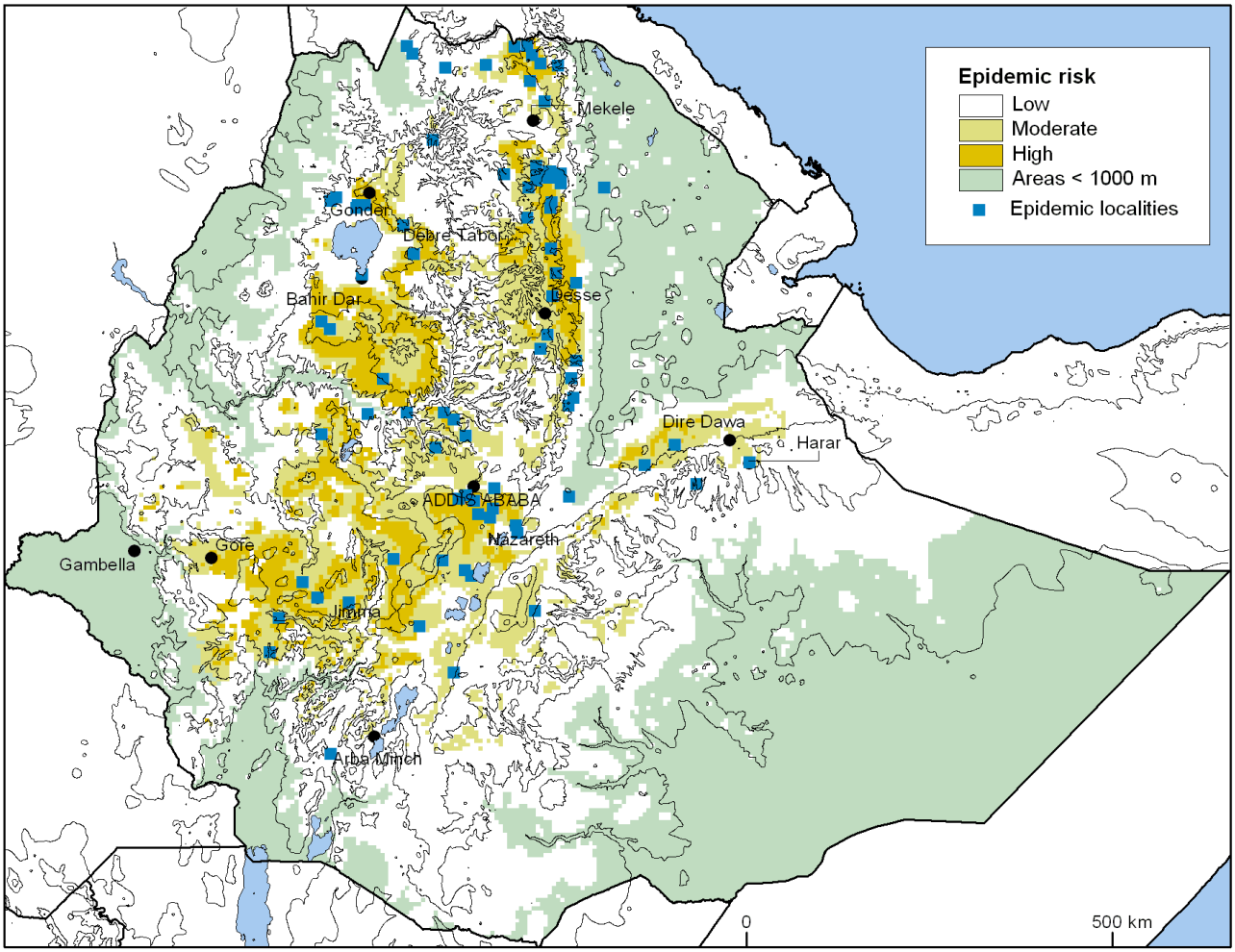


Figure 6.11 *Distribution of epidemic risk in the Ethiopian highlands*

well after the main rainy season – if at all. Corresponding rainfall totals are, however, relatively modest and it is therefore likely that excess rainfall is the primary risk factor for epidemics. This may well be the case in Regions A and C, also – although here average temperatures during the rainy season are more borderline and may be an additional limiting factor in terms of transmission. In Region B, which comprises much of the high plateau of the northern massif, rainfall totals are much higher during the rainy season compared with Regions A, C and D. Corresponding temperatures are, however, generally far below 18 °C during the main rains and transmission may therefore be dependent upon above average temperatures. In this context, it is perhaps worth reiterating that the epidemics that affected this area in 1958 followed a period of unusually warm (and wet) weather.

As for Kenya and Uganda we can use the climate profiles in Figure 6.10 as a means to geographically extrapolate epidemic risk (see Section 4.3.7). Following this approach, areas of high and moderate epidemic risk were mapped out and are presented in Figure 6.11. Orange areas in the figure signify areas of high epidemic risk and predominate in highland areas of Gojjam (south of Bahir Dar), Jima and Tigray/Wello. As in Kenya and Uganda, these epidemic risk zones correspond to areas of relatively high population densities. On the basis of Deichmann's (1996) population data it is likely that around 23 million people are subject to some degree of epidemic risk (Table 6.1).

Table 6.1 *Land area and population at risk from epidemics in the Ethiopian highlands*

Risk zone	*Average population density (persons km^{-2})*	*Land area in risk zone (km^2)*	*Total population at risk*
Moderate	115	130 175	14 914 150
High	124	66 413	8 263 105
Total		**196 588**	**23 177 255**

Notes

[1]. Subsequent work by White *et al.* (1980) illustrated the extent of such "vector population upsurges" (p.684). Their data for Jimma indicated that densities of *An. gambiae s.l.* rose from an average house index of <1 in the period January–March 1973 to >100 in July–October.

[2]. It seems that in recent years, the annual occurrence of malaria transmission at Akaki (2100 m ASL), now effectively a suburb of Addis Ababa, has been interpreted as evidence of a general increase in the altitudinal limits of transmission in Ethiopia (Umunna pers. comm.). However, historical reports suggest that malaria vectors and local transmission have been present at Akaki at least since the early 1950s when a hydro-electrical plant was constructed there (*e.g.* Ovassa and Neri 1959). Incidently, Martin's (1942) discovery of autochthonous malaria within Addis Ababa was at Filoha, famous for its thermal springs.

[3]. The eradication effort, while unsuccessful in its effort to interrupt malaria transmission, did have the effect of reducing the occurrence of epidemics in highland areas (Delfini and Shidrawi 1977, cited in Gish 1992) – although whether an eradication programme, as opposed to specific, focussed control measures, was necessary to achieve this goal is questionable (Gish 1992).

[4]. The somewhat variable relationship between altitude and prevalence reflects (a) that a single altitude is used here to represent a number of observations from one cluster; and (b) the effect of inter-annual variability.

[5]. This standard stratification is largely based upon the classification on localities into one of the following climatic categories:

(1) The cold zone (*dega*) which includes areas above 2500 m (mean monthly temperatures typically about 15 °C, annual rainfall around 1600 mm).

(2) The temperate zone (*weyna dega*) which extends from 1500 to 2500 m (mean monthly temperatures around 20 °C, annual rainfall anywhere between about 400 and 2,400 mm). This includes much of the highland zone and constitutes the principal area of epidemic risk.

(3) The warm zone below 1500 m (*kolla*), where rainfall is highly variable (except in the west) but temperatures are invariably high. While malaria is endemic in much of this zone, population densities are typically low (see Map 2, Appendix 1).

7 Tanzania

7.1 Principal features of the Tanzanian highlands

Although isolated volcanic peaks occur in western parts of Tanzania and also in the north (Kilimanjaro and Meru), much of the highland zone constitutes a chain of isolated blocks of crystalline Precambrian rock, which stretches from the Pares and Usambaras in the north to the Uzungwa range in the south. To the east of this range is the Tanzanian coastal plain, while areas to the west and north constitute an extensive elevated plateau (*c.* 1200 m ASL; see Map 1 Appendix 1).

Annual rainfall in the highlands varies between 750 and 1750 mm and, at least in the southern half of the country, is spread over about six months of the year. Many highland fringe areas receive significantly less rain than this, however, and in areas south of Moshi and north of Iringa the number of rainy days per year can be as little as 50 (annual totals <500 mm). The dry season generally lasts from May to October (Figure 7.1) but even in the wetter months (November to April) rainfall is unpredictable. The timing of these rains is also somewhat erratic and may vary geographically. The malaria transmission season tends to vary accordingly; in northern Tanzania the main season is centred around May–June in the east and April–June in the west. In central and southern parts of Tanzania it occurs slightly earlier, in March–May (Clyde 1967).

Environmental temperatures are highest in the period October–April and lowest during the dry months of June–August (Figure 7.1). During the latter period, malaria transmission is likely to be interrupted over quite large areas (Figure 7.2). During the warm months only isolated sections of the highlands are likely to experience temperatures sufficiently low to limit transmission.

Population density is moderate (by East African standards) in most highland areas and reaches 100+ persons km^{-2} only in fringe areas around Mbeya and in the vicinity of Moshi and Arusha (Map 2 Appendix 1).

7.2 Malaria transmission in the highland zone

7.2.1 Previous studies

Bagster Wilson described Tanzania as consisting of a few 'islands' in which malaria is slight or absent, set in a sea of intense transmission. Clyde (1967) concurred but added that there are extensive areas outside these islands where transmission is highly seasonal (including most of the central region and parts of the eastern and southern regions), 'with all that this connotes in respect of susceptibility in the indigenous population and liability to annual epidemics of greater or less severity' (Clyde 1967: 1).

For historical reasons, much of the highland malaria research carried out in Tanzania has focused on the Eastern Usambara mountains and particularly areas around Amani. These hills range from 600 to 1200 m but the local climate is atypical for this altitude range – annual rainfall totals being relatively high (*c.* 2500 mm) and environmental temperatures relatively low. The malaria picture is complicated by high mobility within local populations and those of workers in local tea estates, as well as by environmental change in the form of deforestation and agricultural development. It may not be surprising, therefore, that results from previous studies fail to provide a particularly clear or consistent picture of malaria transmission in the area.

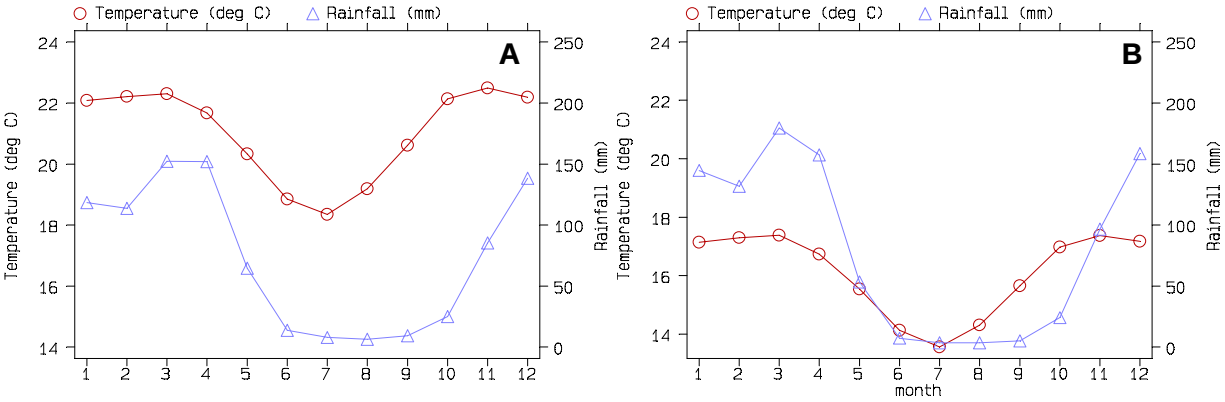


Figure 7.1 *Annual patterns of rainfall and mean monthly temperature for two altitude bands; (A) 1100–1300 m (B) 1900–2100 m*

Early studies around Amani reported relatively high rates of infection in local populations, but entomological surveys revealed few anophelines. Wilson and Wilson (1937: 438) reported parasite rates of 75 and 76% among 1–5 and 6–10 year olds respectively, but considered most, if not all, of the infections to be imported from lowland areas. Surveys carried out by the Malaria Service in 1958–9 substantiated this view, indicating that the highest rates of infection occurred in children living at the edge of the highland area and maintaining close contact with the plains below (Clyde 1967: 60).

Subsequent research around Amani in the early 1970s indicated lower infection rates than those demonstrated by earlier workers. Lelijveld's (1971) surveys before and after the main rains of 1970 showed parasite rates of 17 and 11% respectively in the 2–9 year range. Voller *et al.*'s (1971) surveys at three localities in the Eastern Usambaras indicated an average parasite rate of 19.6% among 2–9 year olds – although like Wilson, the authors considered few, if any, of these to be autochthonous cases. The main factor constraining malaria transmission, in their view, was a shortage of breeding sites for anophelines, rather than unsuitable temperatures.

According to Matola *et al.* (1987), levels of malaria infection around Amani increased markedly from the late 1970s, and at a rate that could not easily be explained by the 'importation' theory. Their own parasitological data (from 1980–2) suggested a significant increase in local transmission when compared to findings from the early 1970s. In addition, vector studies in 1980 indicated that populations of *An. gambiae* and *An. funestus* had risen substantially since previous studies in the 1960s and that vector infectivity rates were sufficiently high to support local transmission (sporozoite rates for *An. gambiae* and *An. funestus* were 11.8 and 11.1%, albeit in relatively small samples). The authors thought it likely that these changes were linked to the creation of breeding sites brought about by forest clearance and agricultural development, as well as with an influx of labour to local tea estates. In their view, rising environmental temperatures in the general area may also have contributed to these changes in transmission intensity.

More recent data for the Eastern Usambaras have been reported by Ellman *et al.* (1998), who carried out parasitological surveys in the vicinity of Amani and at lower altitudes near Muheza. Their results showed that despite relatively low EIRs at the highland sites (the average EIR (at 34) was less than a tenth of that of the lowland site), parasite rates were substantial – with age-standardised prevalence rates in four highland villages varying between 33.3 and 75.6%. From these findings the authors concluded that malaria was 'firmly established in the highlands of Tanzania' and that the 'rarity of malaria in the past was probably exaggerated' (p. 749).

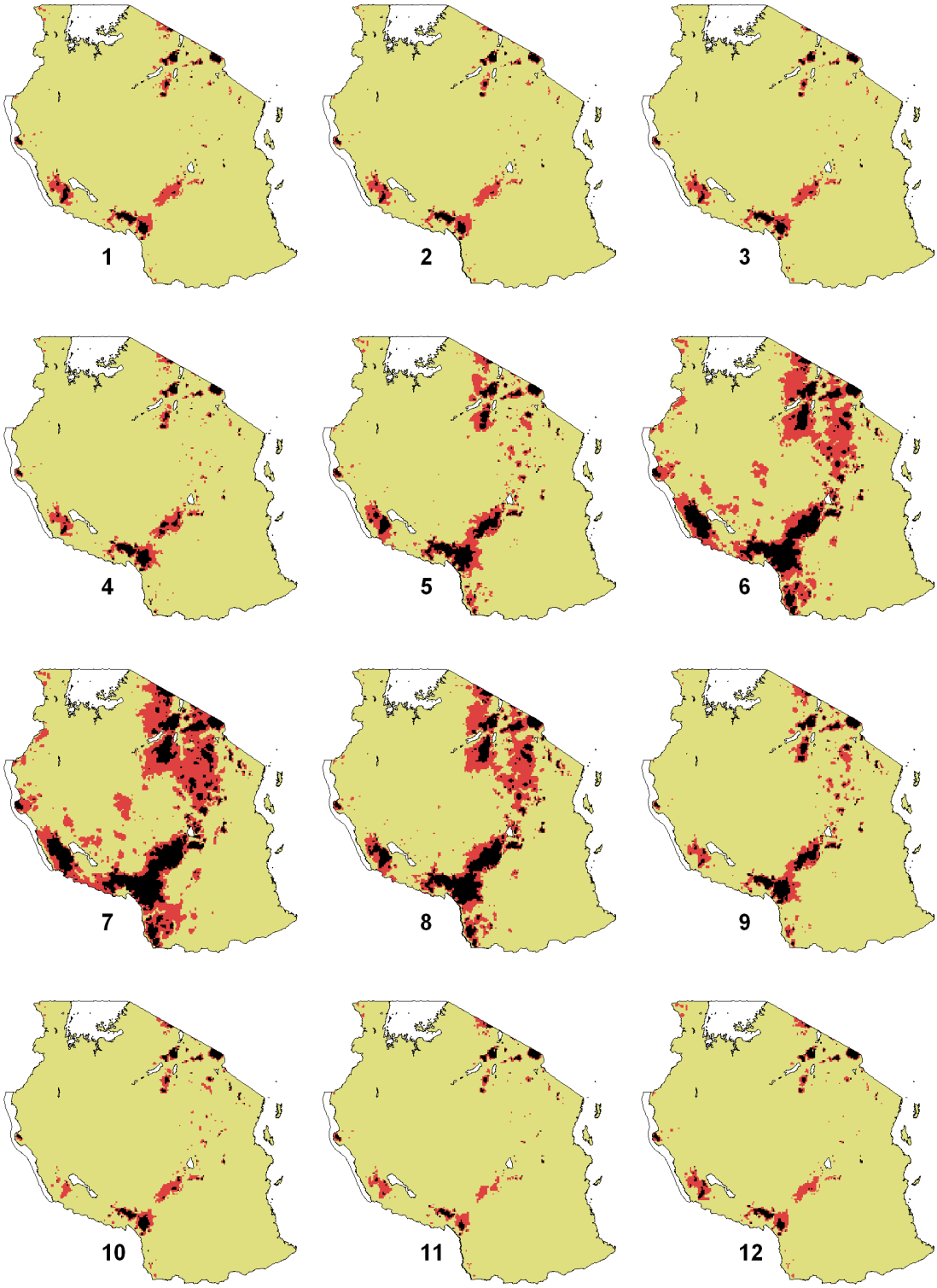


Figure 7.2 *Spatial variation in mean monthly temperatures in Tanzania in a typical year. Yellow shading indicates areas where temperatures are likely to support malaria transmission in a particular month, while black shading signifies localities where temperatures are likely to be limiting. Red areas are intermediate and probably represent the altitudinal fringes of transmission (see Section 4.1)*

Few highland areas of Tanzania have been studied to the same extent as the Eastern Usambaras. Recent studies are especially rare and much of the data available today were published in the 1960s or earlier (see Clyde (1967) for a review).

The **Western Usambaras**, which are somewhat higher and cooler than the Eastern Usambaras, are generally considered malaria-free – although epidemics have been reported at some sites (see below) and parasite rates are likely to vary as a function of the mobility of local populations and the existence of local breeding sites. As reported by Clyde (1967), survey results from the Mlalo Basin (1341–1829 m) in 1948 indicated that more than a quarter of 1–5 year olds were carrying malaria parasites, while subsequent surveys in 1959–60 showed no infections in children in Funta, Bumbuli and Lushoto Town. The latter were consistent with results of previous surveys carried out by the Tanga Malaria Unit in the mid 1930s (Wilson 1936).

Historical data from **Kilimanjaro** suggest that malaria is 'marginally' endemic at 4000 ft (1220 m) on the south western slopes of the mountain, and that areas above 4500 ft (1372 m) are malaria-free (Wilson 1938; Clyde 1967). On the eastern flanks Voller *et al*. (1971, 1972) found no infections among 153 2–9 year olds at Marangu and Usseri and also considered 4500 ft to be the general limit for transmission. Lelijveld (1971) working at slightly higher altitudes (*c*. 1700 m) found no evidence of local transmission either before or after the main rains in 1970.

Almost all data available for the **Pare mountains**, which extend between the Usambaras and Kilimanjaro, come from the Pare-Taveta Malaria Scheme, in which highland villages in the South Pare Mountains were included in some routine surveys (Bradley 1991). While the survey teams found no malaria in these areas, entomological surveys revealed the presence of *An. gambiae* and *An. funestus* in significant numbers, particularly in May. Smith (1959) speculated that the presence of these vectors was the result of direct infestation from the lower plains (vectors disappeared from higher areas during the insecticide trial even though only the lower villages were sprayed). The only other surveys in the South Pares were carried out by Lelijveld (1971) in the Mamba/Bwamba area. Of 365 2–9 year olds examined, none proved to be carrying malaria parasites.

In **central Tanzania**, around Mbulu and Babati, Clyde (1967: 103) considered malaria to be 'variably' endemic between 4500 and 5000 ft (1220–1524 m) and epidemic up to 5500 ft (1676 m). This variability (over space and time) has been more recently illustrated by the survey results of Irare *et al*. (1986).

Other areas which have been shown to be largely free from malaria transmission include small parts of the **Uluguru Mountains** (south of Morogoro) above 1500 m, in isolated pockets around **Sumbawanga** and in the **Kipengere** highlands between Tukuyu and Njombe. Clyde (1967) also considered the higher parts of **Kagera** Region in north west Tanzania to be malaria-free, although the mobility of local populations meant that this was difficult to demonstrate on the basis of prevalence survey results.

6.2.2 The occurrence of epidemics

The Usambaras

The first documented malaria epidemic in Tanzania occurred in 1915 at Bungu in the Western Usambaras (Taute 1919, cited in Clyde 1967). To what extent this constituted a 'true' highland epidemic is, however, uncertain, as most infections were probably acquired by highlanders guarding the railway line at the foot of the mountain. Further malaria epidemics were reported in the Western Usambaras between December 1941 and February 1942, affecting areas around Lushoto, Vuga/Bungu and Bumbuli up to an altitude of around 4500 ft (1372 m). Around 1500 clinical cases were recorded in these areas, and the number of deaths was estimated to be 240 (Clyde 1967: 62). The reasons for the epidemic appear to have been meteorological, with the rainy season being unusually prolonged. In the Eastern

Usambaras an epidemic occurred at Derema (near Amani) in 1954, and appeared linked to very large numbers of *An. funestus* and by an unusually high sporozoite rate, peaking at 9.6% in February 1954 (Clyde *et al*. 1958).

Although in recent decades the Usambaras (particularly the Western range) have generally been considered to be epidemic prone, few details exist of individual outbreaks. According to National Malaria Control Programme records, an epidemic at Ubiri (Lushoto) was reported in March/April 1986, and may have been linked to local quarry activity (Table 7.1). The following year a much larger outbreak affected the villages of Tewe, Mpale and Mali in Bungu Division, north east Korogwe in February and March, killing around 40 people (Egwaga 1997). Altitudes of these villages are not provided in Egwaga's report, but using DEMs we can surmise they are situated at about 1300 m.

In 1998 outbreaks were reported for several localities in Korogwe and Lushoto Districts, following an abnormally long rainy season (data from Communicable Disease Surveillance and Response, WHO). No other details of these outbreaks are available at present.

Central Tanzania

Before 1936, Mbulu and surrounding areas above 5500 ft (1676 m) were considered malaria free, and although it is thought likely that some transmission at this altitude occurred in the period 1936–40, it was not until the war years that evidence of malaria vectors was found (Clyde 1967). Following food shortages in 1946, a widespread malaria epidemic affected Mbulu District in March and April 1947, and was particularly severe in southern parts of the district around Dongobesh. Epidemics also occurred at Endasak, near Mount Hanang, in February 1948. After this period, malaria transmission appeared to decline to a point where by 1963 it had disappeared completely (despite the absence of any intervention measures), only for epidemics to reappear in the early 1980s. The first of these occurred in 1983, when Dareda district hospital saw 5465 inpatient cases of malaria, with 495 deaths being attributed to malaria or severe anaemia (Irare *et al.* 1984). This was followed by an epidemic centred on Babati District in the first half of 1987, in which over 70,000 cases and 63 deaths were recorded (Table 7.1). Since then the area has experienced a general increase in malaria cases, although epidemics have not been reported (Wakibara *et al.* 1997).

In 1987 epidemics also hit parts of Dodoma Region between March and April. The area around Mvumi appears to have been most severely affected, with 93 deaths being attributed to malaria (Table 7.1). Few other data are available, however.

Other epidemic-prone areas

Although the Usambaras and central Tanzania are usually considered the most significant areas of epidemic risk, malaria outbreaks have also been reported in the north west and south west of the country. According to Carlstedt (1997), for example, a widespread malaria epidemic affected parts of north west Tanzania including Kigoma and Kagera regions in 1997. A Ministry of Health mission to Muleba examined hospital records and concluded that the epidemic had started in May and that poor rainfall in the previous wet season may have been responsible for the outbreak (with drought conditions leading to the beading of streams and accounting for 'low food and economic situations' in the local population) (Egwaga *et al.* 1997).

Kagera was subject to further epidemics in the first months of 1998 following very high rainfall (>300 mm month^{-1}) in October to December 1997. Bukoba and Muleba districts appeared to be most severely affected. A subsequent epidemiological assessment carried out by MSF-Tanzania in Nshamba division (Muleba: 1200–1500 m ASL) indicated that ma-

Table 7.1 *Recent epidemics in Tanzania (Dr W Mwita, National Malaria Control Programme)*

Place	*Period*	*Cases*	*Deaths*	*Predisposing factors*	*Action taken*
ARUSHA (Hanang and Babati Districts)	Nov 1982 to Jun 1983	108, 243	334	1 Drought 2 Movement of non-immune population from high to low altitude areas for cultivation and employment	1 Case Management 2 Vector control; larviciding in urban/rural settlements, general sanitation 3 Health Education on malaria preventative measures 4 Survey by MoH and study by NIMR
DODOMA (Mvumi)	Mar 1987 to Apr 1987	713	93	1 Unusually heavy and prolonged rainfall with a peak in Jan. of 330 mm	1 Case management 2 Vector control: residual spraying in 600 houses 3 Health Education on malaria preventative measures 4 Survey by NIMR
ARUSHA (Babati District)	Jan 1987 to Aug 1987	70,721	63	1 Lack of anti-malarial drugs in health facilities during transmission season	1 Case management 2 Vector control: larviciding in urban/rural settlements 3 Health Education on malaria preventative measures 4 Survey by MoH and study by NIMR
TANGA (Lushoto District at Ubiri)	Mar 1986 to April 1986	67	27	1 Highland: potential breeding sites created out of limestone quarries	1 Case management 2 Residual spraying 3 Health education
TANGA (Korogwe District)	Feb 1987 to Mar 1987	1122	40	1 Movement of population to malaria holoendemic areas for rice irrigation	1 Case management 2 Health education
ARUSHA (Babati District)	Jan 1997 to Jun 1997	?	227	1 Unusually heavy rains 2 Lack of anti-malarial drugs	1 Case management 2 ITNs
KAGERA (Muleba District)	Oct 1997 to Mar 1998	133,866	1740	1 Unusually heavy ENSO rains 2 Lack of anti-malarial drugs 3 Ineffective drugs (chloroquine)	1 Case management 2 Health education 3 Survey by MSF - Spain

laria admissions for January–March had risen four fold on the previous year's figures, while malaria specific mortality had risen almost 12 fold (Garay 1998). Verbal autopsy data from 36 villages indicated a monthly mortality rate of 5.5 per thousand (a total of 1740 deaths over the three month course of the epidemic), with case fatality rates estimated at 13 per thousand (confirmed) malaria episodes. Mortality rates varied substantially by ward, but this could not be linked either to altitude or access to health care facilities.

Elsewhere, isolated epidemics have also been reported in highland areas around Lake Malawi. At Mwakaleli, near Tukuyu (1520 m) a small outbreak was discovered in March 1954 during a routine parsitological survey (results indicating a rate of *P. falciparum* infection among 6–10 year olds of 62.5% – Clyde 1967: 95). Since that time no reports exist which refer to specific epidemic events in these areas, although Kyela and Njombe have been included in the Tanzanian Malaria Control Programme's list of key epidemic-prone areas.[1] In addition, parts of Sumbawanga region reported malaria epidemics in 1997/8 (it is thought) for the first time. Data from the Regional Health Authority suggest that outbreaks have been most severe in Matai, Sopa and Katete wards.[2]

7.3 Analysis of the HIMAL dataset

7.3.1 Data collected

A search of the literature revealed 39 documents containing relevant data for highland areas of Tanzania. Over half of these were unpublished reports obtained in-country (see Table 3.1). The reports generated 301 data points, the majority of which (213) were parasite rate data. The remainder comprised 59 data points for spleen rates and 29 for epidemic locations. Geographically, data are weighted towards the northern highlands (and the Usambaras and Kilimanjaro in particular), although highland areas around Iringa,

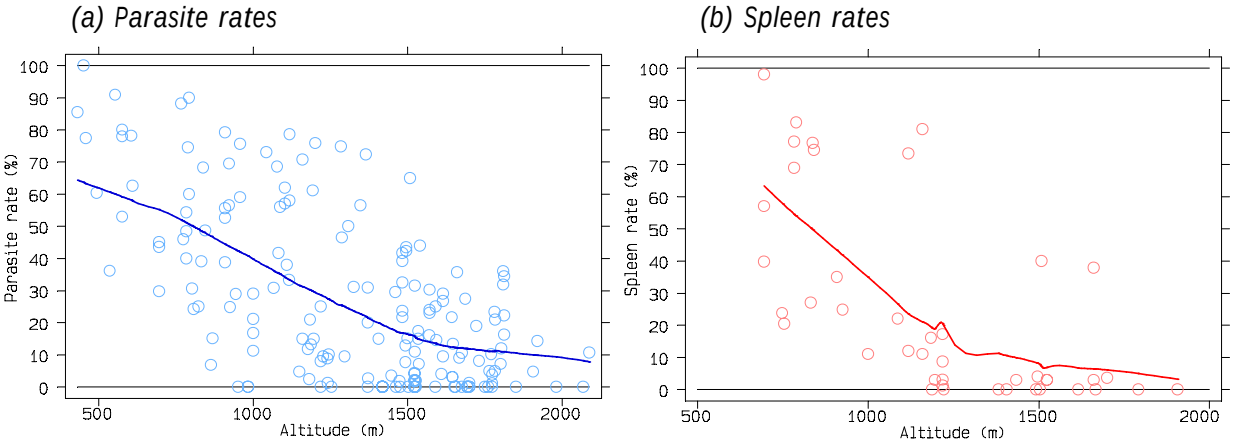
Mbeya and Sumbawanga are reasonably well represented (Map 5, Appendix 1). Around 6% of Tanzanian data points could not be geo-referenced.

7.3.2 Effects of altitude on malaria transmission intensity

Figure 7.3 shows parasite and spleen rates plotted against altitude for all geo-referenced positions. In both cases a general trend of decreasing ratios of infection with altitude is evident, although this relationship is much more variable than has been the case for other countries in this review. At 1000–1250 m parasite rates vary between 0 and 80%, depending on locality, and even at 1750 m this range is 0–40%. Clearly altitude is not a reliable predictor of transmission intensity, with the most obvious implication being that temperature itself may not always be a significant transmission factor, even at relatively high altitudes. As in Uganda, secondary sources for Tanzania suggest that (at least in some localities) malaria transmission is limited by the availability of breeding sites for malaria vectors, which itself may reflect local ecological and topographical characteristics and/or the aridity of much of the highland zone (see below).

It is also possible that much of the apparent variability in Figure 7.3 reflects regional variations in the relationship between transmission intensity and altitude. To test this, survey data from specific highland zones were plotted against the general regression curve obtained for all sites (Figure 7.4). Visual inspection suggests that the 'national' regression line tends to overestimate rates of infection in elevated parts of the northern highlands (Kilimanjaro and the Usambaras) and underestimate infection rates in Sumbawanga.

Figure 7.3 *Variation in parasite and spleen rates with altitude, Tanzania*



7.3.3 The MARA model as a means of stratifying risk

MARA model values were extracted for geo-referenced sites and plotted against altitudes derived from DEMs (Figure 7.5a) and against parasite rates for geo-referenced sites (Figure 7.5b). As with Ethiopia there is considerable scatter within this relationship, most likely reflecting the importance of local ecological factors and also rainfall, which at these altitudes is not directly affected by elevation. As in the Ethiopian case, the most obvious outliers (*i.e.* those points with model values <0.7 below 1250 m) can be traced to relatively dry highland fringe areas, particularly in low-lying parts of Iringa, Dodoma, Monduli, Mbulu and Hanang.

To evaluate the performance of the MARA model as a geographical stratification of risk, the map of malaria endemicity produced by Wilson (1956) was digitised and registered to

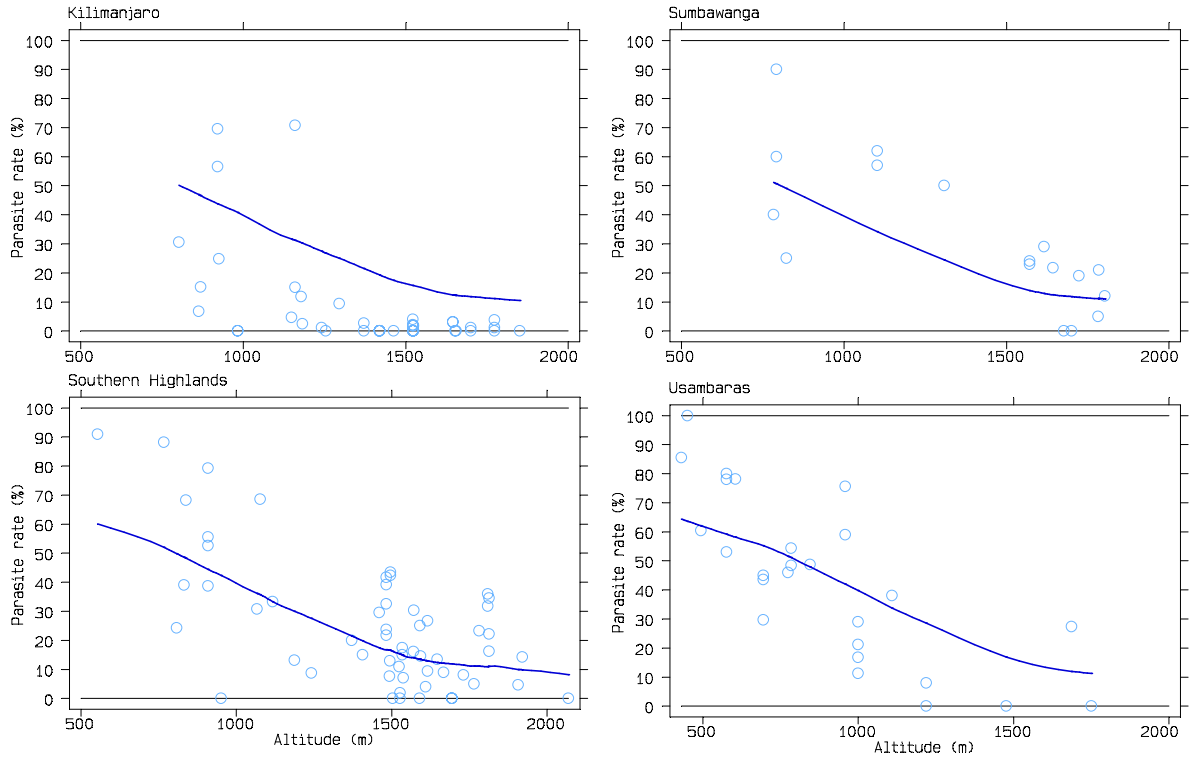


Figure 7.4 *Variation in parasite rates with altitude for specific highland zones in Tanzania*

the MARA model coverage for Tanzania (Figure 7.6). The coverages correspond closely, particularly in the main highland areas, with the only significant area of discrepancy being in the highland fringe areas south and east of Babati (mainly Kiteto District). Wilson classified this an area of low endemicity, where transmission is dependent on the availability of breeding sites. By comparison, the MARA model appears to overestimate the likelihood of transmission in these areas. Outside the highlands, the model appears to under-predict the likelihood of malaria transmission in coastal areas south of Tanga and in areas to the north of Iringa.

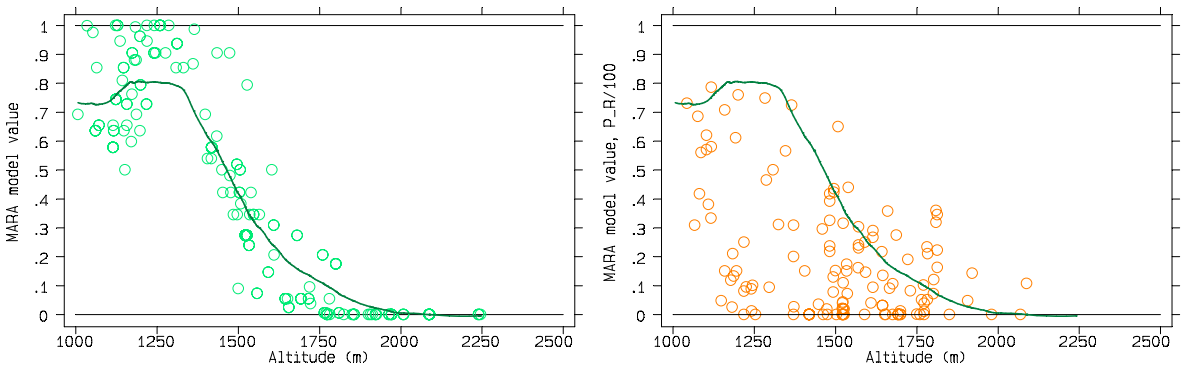
7.3.4 The distribution of epidemics and epidemic risk

DEM values for epidemic localities indicated that, at 1455 m, the mean altitude at which epidemics occur in Tanzania is significantly lower than corresponding altitudes for other

Figure 7.5

(a) Relationship between the MARA model and altitude for Tanzanian survey sites

(b) The MARA model (line) and parasite rates (circles, re-scaled) against altitude



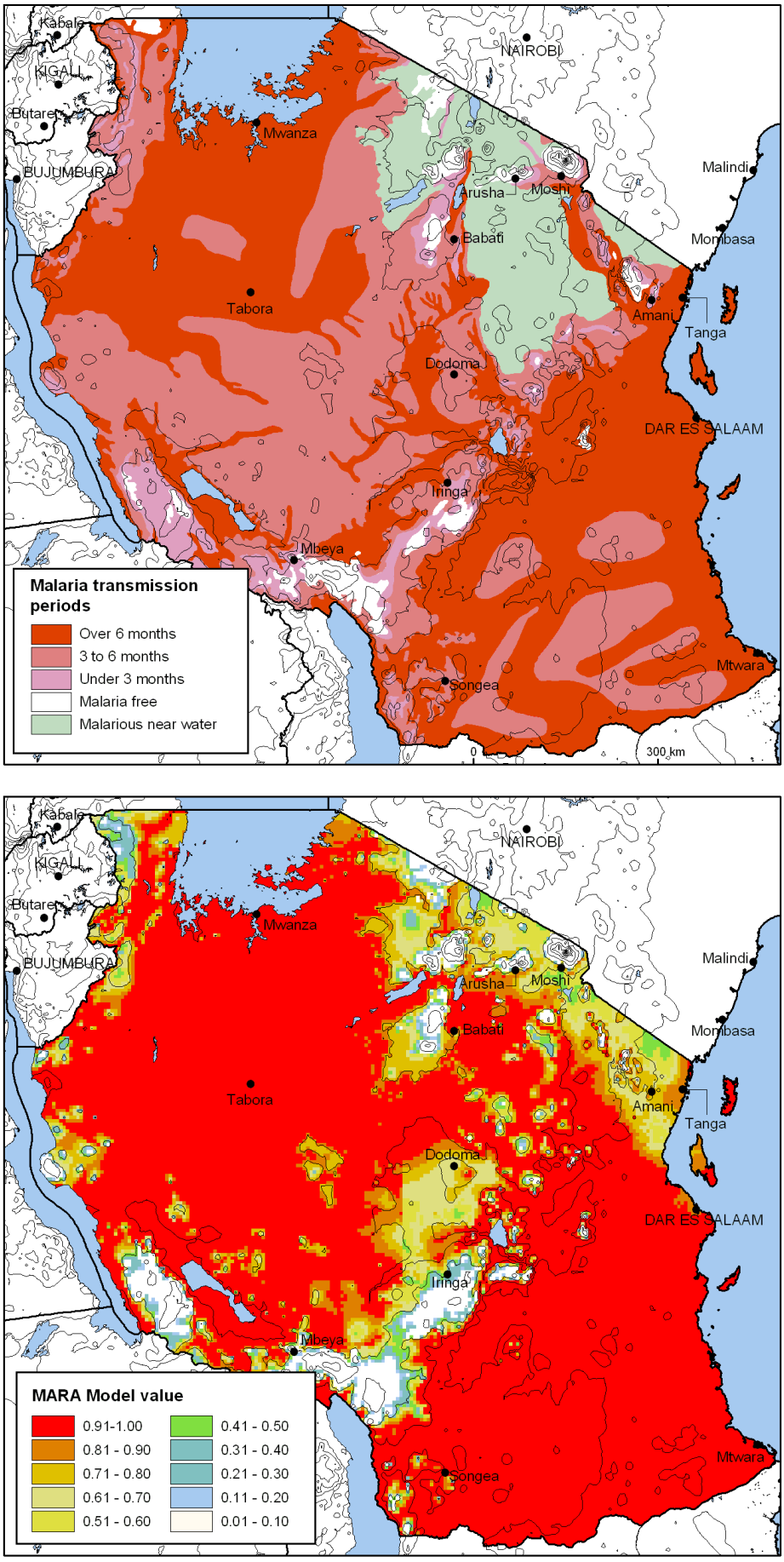
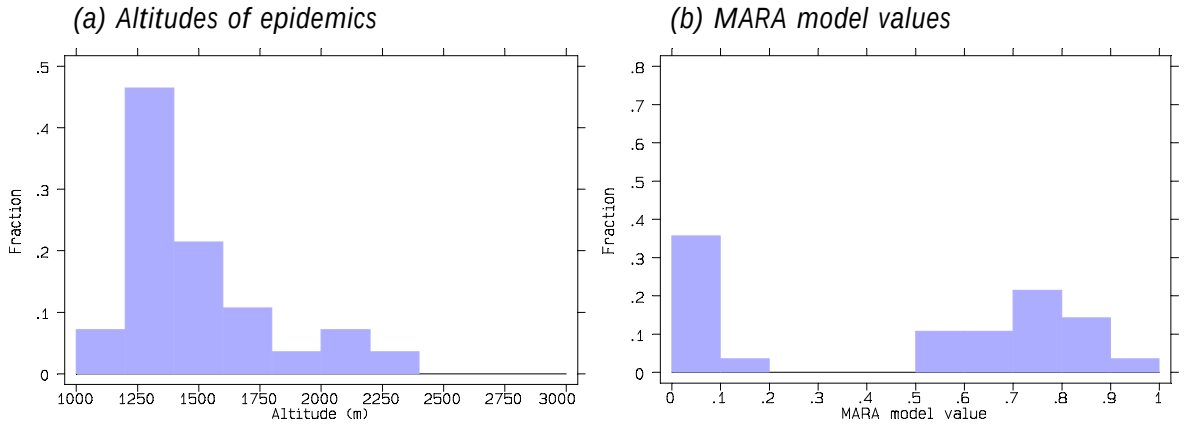


Figure 7.6 *The MARA model and standard malaria stratification map for Tanzania (source: Wilson 1956)*

Figure 7.7 *Histograms for altitude and MARA model values of epidemic locations in Tanzania*



countries reviewed in this report. The distribution of epidemics is, however, positively skewed (median altitude = 1502 m), and the overall range of epidemic altitudes is relatively wide (Figure 7.7a). This fact probably reflects the heterogeneity of environmental conditions in the Tanzanian highlands (a feature underlined by the pattern of parasite rates in Figure 7.4), and it is likely that altitudes at which epidemics occur vary geographically within the country. In view of this, subsequent mapping of epidemic risk zones was carried out using contiguous sub-regions of the highlands rather than the highland zone as a whole (see below).

Examination of MARA model values for epidemic localities indicated that a large number of epidemics have occurred in areas where model values are above 0.5 – *i.e.* at locations where transmission is expected to be endemic rather than epidemic. Closer scrutiny of these sites revealed that all of them are located in relatively steep parts of the highland fringe. It is probable, therefore, that these discrepancies represent errors resulting from inaccurate geo-referencing and/or generalisation from the use of climate surfaces with a relatively coarse spatial resolution. Spatial estimates of epidemic risk are also likely to suffer as a result of this source of error (see below).

To determine the typical climate profiles of epidemic prone areas, rainfall and temperature series for individual epidemic localities were extracted from the CRES database. This was carried out for three sub-regions:

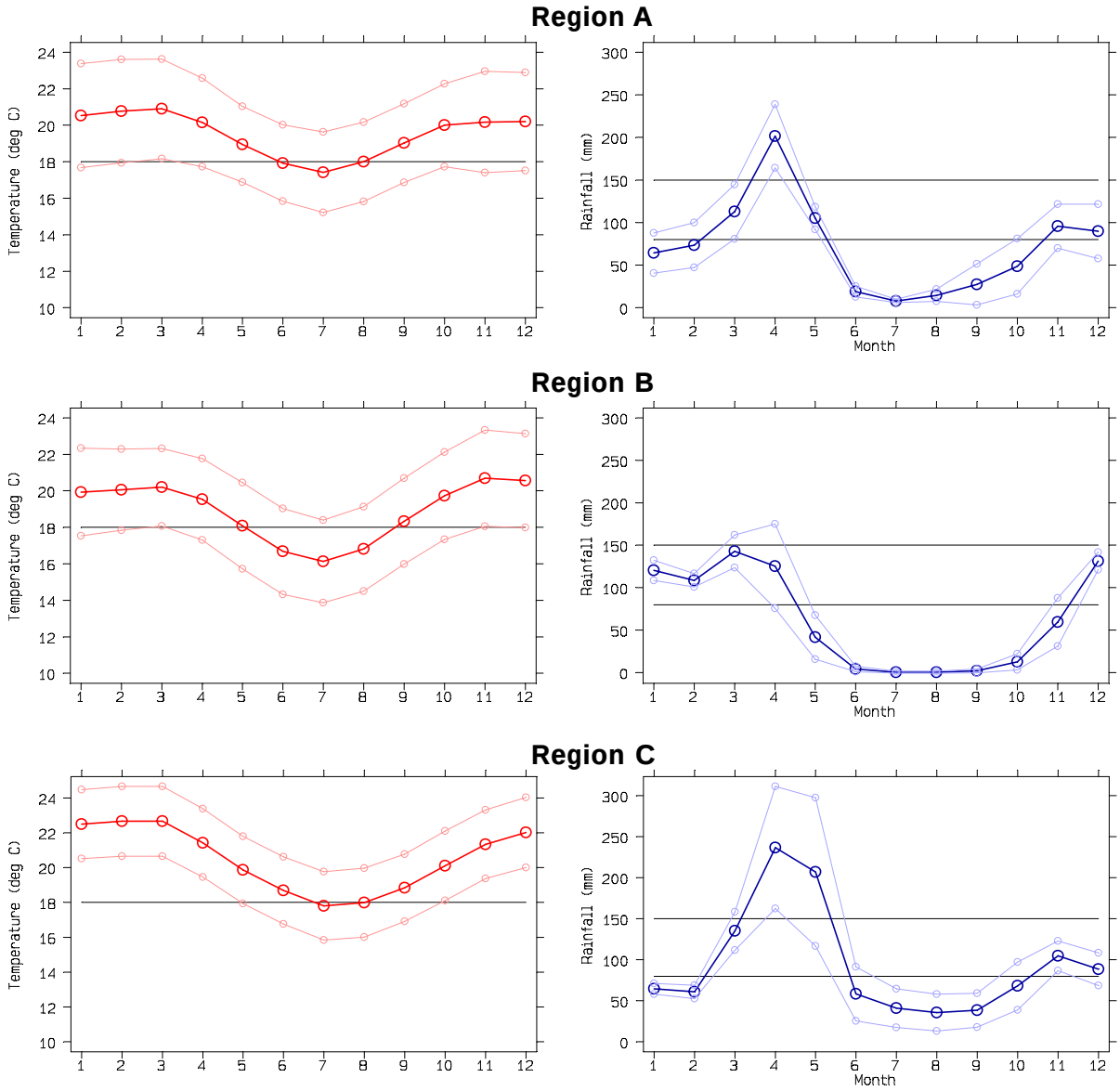
Region A: 29.2 °E, 0.8 °S/40.5 °E, 3.61 °S (including Kagera, Kilimanjaro)

Region B: 34.5 °E, 3.61 °S/36.6 °E, 6.8 °S (including Babati and the central highlands)

Region C: 36.6 °E, 3.61 °S/40.5 °E, 6.8 °S (including the Pare and Usambara mountains)

In Figure 7.7 average profiles for rainfall and temperature for epidemic locations (indicated by the centre curve) are presented for each of the these regions (for a full explanation of these curves and the thresholds shown, see Section 4.3.7). The graphs suggest that, at least in the case of Areas A and C, temperatures rarely, if ever, fall to a level where they are likely to limit malaria transmission. On the other hand, monthly rainfall totals remain modest by regional standards, even during the wet season. Conditions are particularly dry in Area B (the central highlands and Babati), where it is likely that malaria epidemics will only occur after exceptional rainfall events.

Figure 7.8 *Average annual profiles for mean monthly temperature and rainfall for known epidemic locations in Tanzania, separated by region*



As for Kenya, Uganda and Ethiopia, we can use the climate profiles in Figure 7.7 as a means to geographically extrapolate epidemic risk (see Section 4.3.7). Following this approach, areas of high and moderate epidemic risk were mapped out and are presented in Figure 6.11. Orange areas in the figure signify areas of high epidemic risk and are focused in the western Usambaras and the southern and eastern flanks of Kilimanjaro, as well as in areas south and west of Babati. These areas correspond with moderately high population densities, and calculations on the basis of Deichmann's (1996) population density surface for Africa suggest that around 3.3 million people live in a moderate or high epidemic risk zone (Table 7.2).

Notes

[1]. 'National Malaria Control Programme of Tanzania – Summary of activities carried out up to December 1997' (Unpublished document)

[2]. Epidemic risk mapping for Tanzania (this chapter) was carried out before this information was received. As such epidemic risk maps do not cover areas around Mbeya and Sumbawanga.

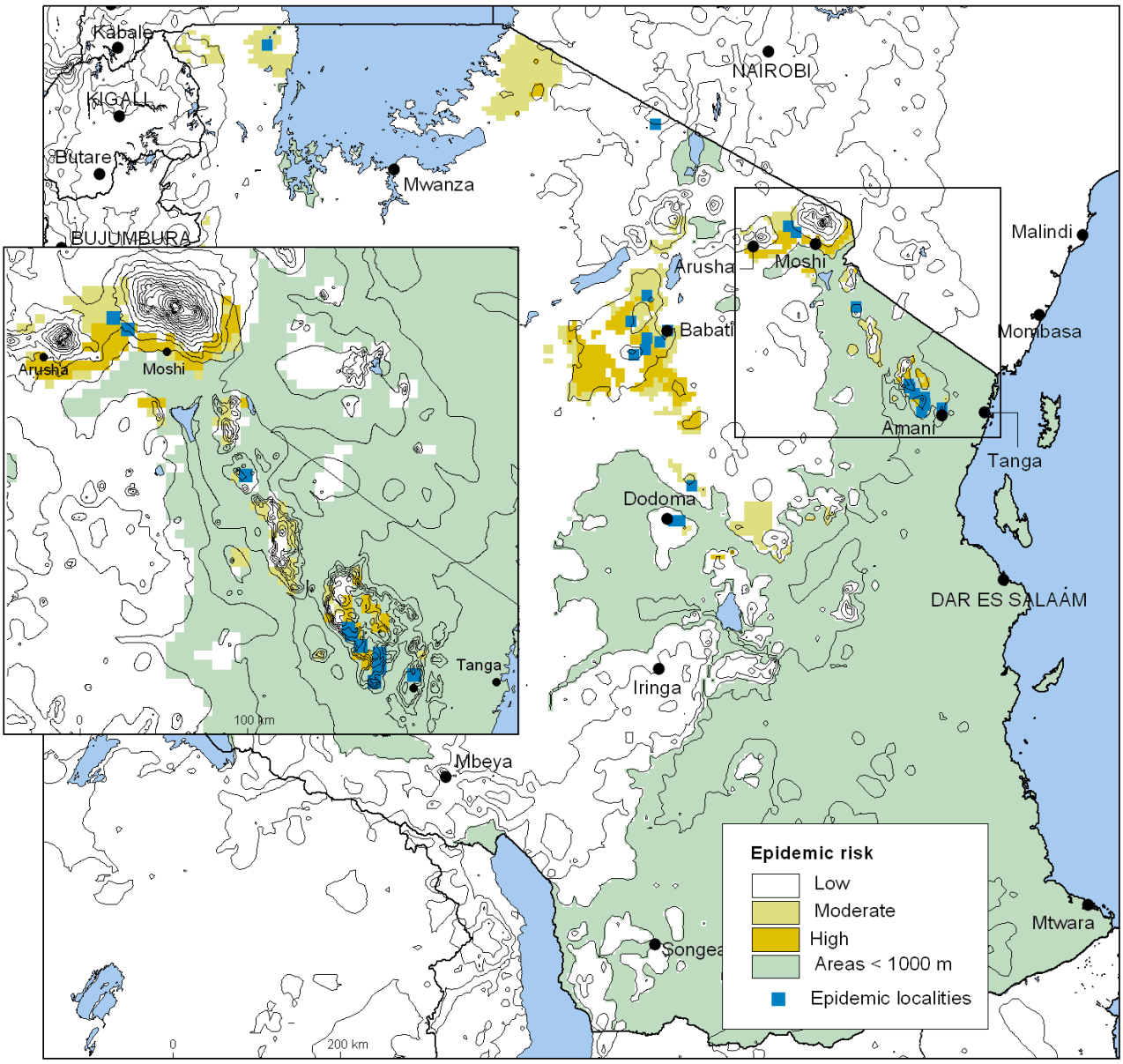


Figure 7.9 *Distribution of epidemic risk in the Tanzanian highlands*

Table 7.2 *Land area and population at risk from epidemics in the Tanzanian highlands*

Risk zone	*Average population density (persons km^{-2})*	*Land area in risk zone (km^2)*	*Total population at risk*
Moderate	87	27 677	2 405 131
High	92	10 344	947 096
Total		38 021	3 352 227

8 Summary

8.1 The significance of highland malaria

Highlands have traditionally been regarded as areas of little or no malaria transmission, primarily because of the negative impacts of low temperatures on parasite sporogony and vector development. Some reports have suggested that this picture is changing, and that malaria epidemics now occur more often and over larger areas than was previously the case. Other reports have been sceptical of this view, arguing that highland malaria is not a new phenomenon and that recent epidemics do not necessarily represent a shift to more malarious conditions.

It could be argued that the ensuing debate has tended to overlook a significant point: that from a public health perspective highland malaria probably poses a greater challenge to national malaria control programmes today than it ever has previously. Whether this can be attributed to 'real' increases in malaria transmission, or to the fact that control programmes and the tools available to them have become less effective is debatable. The fact remains that in terms of identifying and responding to epidemics, the recent record of national malaria control programmes has been poor.

The primary motivation behind HIMAL is to explore new tools for predicting malaria transmission in highland areas, and in particular to address the issue of 'when' and 'where' epidemics are likely to occur. The first phase of the project, described in this report, has been concerned largely with stratifying risk of highland malaria transmission and mapping zones of epidemic risk from a geographical perspective. This has involved the development of spatial models of malaria risk based on climate parameters and on the known historical distribution of epidemics. The main findings of this phase of work are summarised below.

8.2 The distribution of malaria in the highlands

Historical data show that parasite and spleen rates are strongly correlated with altitude (and thereby temperature) in highland areas of East Africa, and in the past various authors have used these relationships as a basis for stratifying transmission intensity. However, while this approach may be viable in some instances, elevation is not always a reliable guide to endemicity, primarily because many transmission factors are not directly related to altitude. At the national scale, rainfall patterns may have a significant effect on geographical patterns of transmission, with levels of endemicity being relatively low in more arid areas of the highland fringe. In parts of northwest Ethiopia, northern Tanzania and southwest Uganda, for example, the upper limits of malaria transmission are far below what would be expected on the basis of temperature alone.

While the effects of temperature and rainfall appear to dominate at the national/regional scale (see Section 2 on modelling malaria transmission risk), they can be confounded significantly at the local level by non-climatic factors, and especially by those factors which determine the presence or absence of malaria vectors. In Uganda, for example, the discovery of very high parasite and spleen rates in populations living at 1900 m ASL around Lake Bunyonyi (*e.g.* Garnham 1948) demonstrated the local significance of the distribution of suitable breeding sites for efficient malaria vectors (in this case *An. funestus*). Similar foci of endemic malaria have been reported in the highlands of Kenya, Ethiopia, Rwanda and Burundi (*e.g.* Ovassa and Neri 1959; Meyus *et al*. 1962; Roberts 1964a). It has long

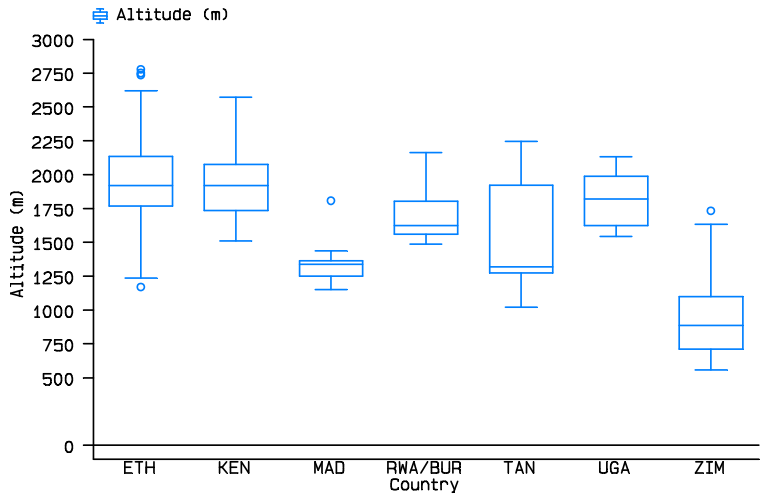
been recognised that vectors can spread outwards from these locales, given suitable meteorological conditions, so that the sites act as 'seed beds' for malaria epidemics in surrounding areas. Identifying these sites is likely to contribute to the early detection of epidemics by enabling surveillance activities to be focused on key areas (see below).

The effect of local risk factors means that general models of malaria risk based on climate parameters are unlikely to predict reliably rates of transmission at the level of the individual locality. The model of transmission risk described in this report (Section 2) represents a reliable stratification at the general level (applicable at the national scale and as judged against existing stratifications and expert opinion), but is less consistent when compared with data from individual localities. To be applicable at a larger scale, additional risk factors need to be incorporated within more comprehensive estimates of risk.

8.3 The distribution of epidemics

Information extracted for epidemic localities suggests that highland epidemics tend to occur within defined altitudinal ranges, which vary by country primarily as a function of latitude (Figure 8.1). However, efforts to map epidemic risk on the basis of these ranges proved unsuccessful and demonstrated that, on its own, altitude is a poor indicator of the likelihood of epidemics. Instead, risk maps were developed by identifying representative climatological profiles for epidemic-prone localities in each country and by classifying risk on a 5 km × 5 km pixel basis, according to how closely annual climate patterns matched those of known epidemic prone areas (Section 4.3.7). Results suggested that epidemic risk was in most cases (with the exception of the Ethiopian highlands) limited to relatively small, discrete areas (Figure 8.2). However, population densities in these parts of the highlands are relatively high (Map 3, Appendix 1) and absolute populations at risk of epidemics large (Table 8.1).

Figure 8.1 *Altitude ranges of highland malaria epidemics by country (standard box and whisker plot)*



Developing typical climate profiles for epidemic areas provided strong clues regarding climatological risk factors for epidemics. In Kenya, for example, most epidemic prone regions experience a window of relatively warm temperatures (daily average > 18 °C) from January to April. Rainfall in this period is relatively modest and usually does not peak until April (*i.e.* towards the end of the period of suitable temperatures), suggesting that the

Table 8.1 *Land area and populations at high or moderate risk of highland* malaria epidemics (*excludes areas < 1000 m ASL)*

Country	*Average population density (persons km^{-2})*	*Land area in risk zone (km^2)*	*Total population at risk*
Ethiopia	118	196 588	23 177 255
Kenya	239	33 521	8 029 869
Rwanda & Burundi	291	23 646	6 885 558
Madagascar	117	29 425	3 432 638
Tanzania	88	38 021	3 352 227
Uganda	233	12 593	2 936 063

risk of epidemics is likely to be greatest in years where total rainfall in the period December to March is unusually high, or where the precipitation peak occurs relatively early in the season. This concords with previous experience in Kenya, where epidemics have frequently been linked with abnormal rainfall conditions.[1] Elsewhere in East Africa the balance between rainfall and temperature may be different. In drier parts of Tanzania and Ethiopia, for example, temperatures may be sufficient to support transmission all year – but rainfall totals are such that any transmission under typical conditions is unlikely. In other highland areas (*e.g.* Uganda and northwest Ethiopia), it is probable that above-average temperatures are required for transmission to occur and it is probably not coincidence that previous epidemics in these areas have been associated with abnormally warm as well as with abnormally wet conditions.

It is clear that not all highland epidemics can be related to meteorological factors. Historically, outbreaks have been associated with various environmental modifications including swamp clearance (*e.g.* Steyn 1946), dam construction (*e.g.* Meyus *et al*. 1962) and rice irrigation (*e.g.* Lepers *et al*. 1991). In other instances, suitable climate conditions on their own have not always been sufficient to bring about epidemics, and transmission has depended upon importation of parasites and/or vectors into the highland area. However, evidence from this report suggests that the most significant and widespread epidemics in the region have occurred during and/or after abnormal weather events. This suggests that relatively simple early warning systems based on direct or indirect monitoring of meteorological variables are plausible. Ideally these should form part of more comprehensive warning systems which include the early detection of malaria cases (see below).

8.4 Changes in malaria transmission patterns in the highlands

Although the evidence is patchy, data for certain highland localities suggest that malaria transmission has become progressively more intense since the 1960s. To what extent this is a reflection of a more general, regional or continental trend is unclear. The role of climate change is also uncertain – for while epidemics have clearly been associated with abnormal weather events, there is little evidence (*yet*) that these are a feature of longer term shifts in climate conditions. (It would, however, be unwise to assume that because anticipated changes in the climate/malaria system have not yet happened that the danger has passed.)

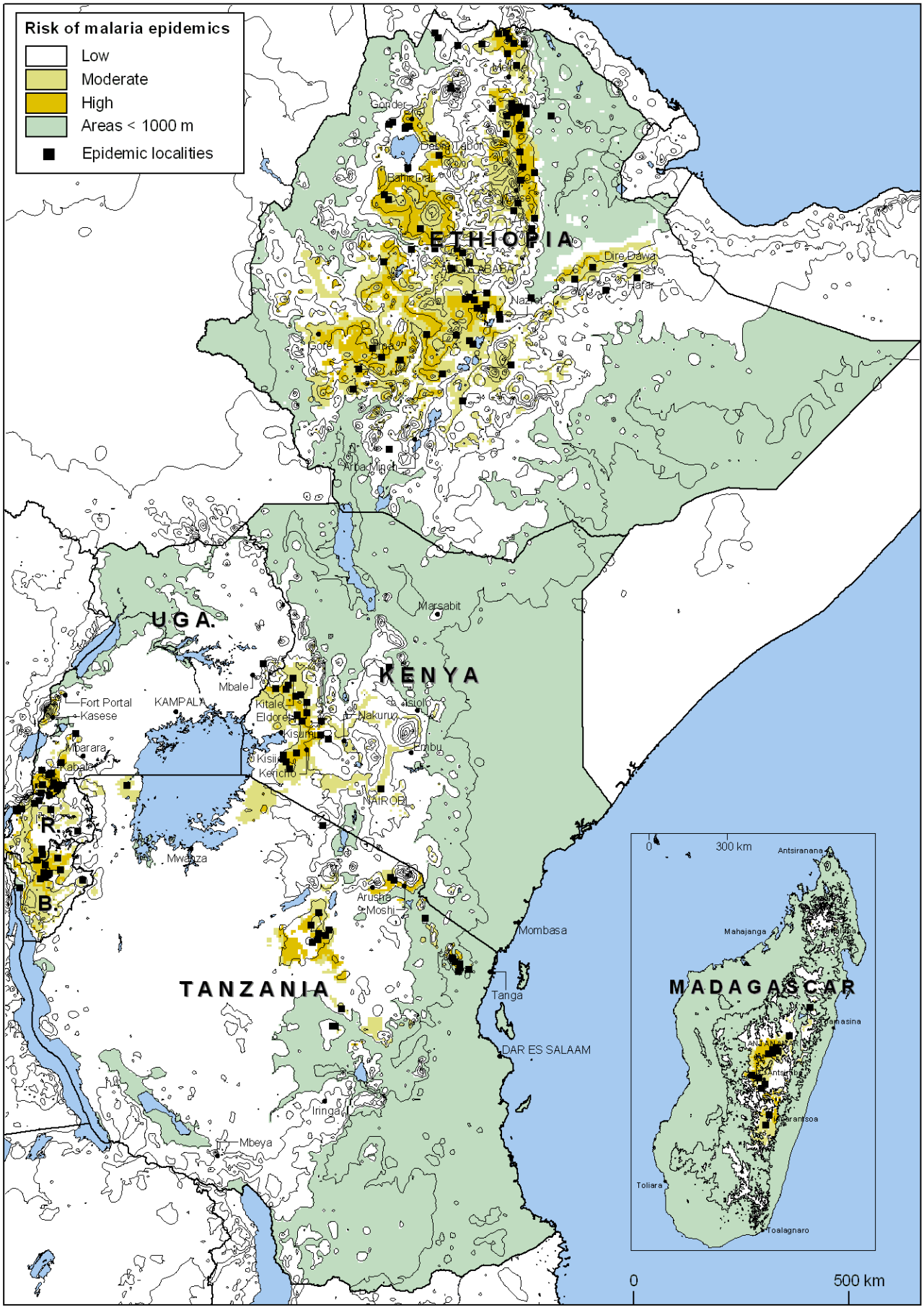


Figure 8.2 *Distribution of epidemic risk in highland areas of East Africa and Madagascar*

In the rare instances where changes in malaria transmission intensity have been correlated with climate change, it has proved difficult to evaluate the contribution of confounding (non-climatic) factors. Several authors, for example, have noted that observed increases in highland malaria transmission have occurred at a time when, for one reason or another, basic health services and malaria control activities have been in decline. It is likely that this problem is being compounded by an emerging drug resistance problem, and in certain instances by uncertain drug supplies. Under these conditions, a rise in observed morbidity and mortality may not necessarily reflect an increase in malaria transmission, but nevertheless represents a significant problem for national malaria control programmes.

8.5 Implications for malaria control in highland areas

The products of HIMAL Phase I give a good overview of epidemic risk and are a useful starting point for more detailed studies. However, given that they are based on pooled retrospective data, this approach can at best provide a highly aggregated and static picture of risk. While this may be useful for focusing control activities on sensitive areas, from an operational standpoint control programmes also require more detailed information on when and where epidemics are likely to strike in future. At the design stage of HIMAL it was envisaged that this need could best be addressed through a collaborative network of sentinel sites at which malaria cases and likely risk factors could be monitored simultaneously, and where various approaches to epidemic early warning and control could be evaluated (HIMAL Phase II). It was recognised that this work should be designed specifically to feed into existing approaches to epidemic control and as such should be planned and carried out in tandem with control programmes.

These issues were the subject of a workshop on 'developing new approaches for the surveillance and control of malaria epidemics in East Africa', organised as part of HIMAL (see Annexe). The meeting brought together researchers and control programme managers in an effort to identify opportunities and constraints for developing appropriate warning systems in East Africa. The workshop recommended that a system of 'nested' surveillance be developed, in which long-range forecasts, early warning and early detection could provide warning signals as a series of 'flags' (Figure 8.3). Each flag is triggered by a specific set of indicators and in turn sets off a predefined set of responses. The workshop discussed current impediments to such a system and outlined a strategy for future regional cooperation and a set of priority areas for further research. These will form a focus for the second phase of the HIMAL project.

Notes

[1]. It should be recognised that the link between climatological anomalies and highland epidemics is not a recent discovery. Early workers in Kenya and Ethiopia (*e.g.* Campbell 1929; Corradetti 1938b) described associations between rainfall and malaria transmission, and in Kenya climate forecasts formed the basis of simple early warning systems in the 1920s and 1930s (see Section 4.2.1).

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Appendix 1 Contextual information for the East African highlands

Table 1 *Average population densities (persons km^{-2}) for various altitude ranges by country**

Altitude (m)	*Ethiopia*	*Tanzania*	*Madagascar*	*Kenya*	*Cameroun*	*Zimbabwe*	*Uganda*	*Rwanda*	*Burundi*
<1000	8.9	32.1	18.9	10.8	24.9	18.2	44.1		248.6
1000-1250	26.4	35.2	23.9	91.1	34.0	28.9	102.2	380.8	177.9
1250-1500	52.7	27.9	98.6	171.6	89.5	72.9	107.4	214.4	190.8
1500-1750	85.9	33.2	80.7	173.7	133.0	84.5	134.1	357.4	294.6
1750-2000	116.8	47.8	78.7	180.7	114.8	36.2	155.4	354.8	270.3
2000-2250	129.3	51.3	78.9	112.3	138.8	24.5	210.2	380.9	260.6
2250-2500	145.0	45.2	72.2	77.6	144.9	60.3	189.1	299.8	246.0
>2500	144.6	30.8	2.5	72.3	168.6		120.3	297.0	146.4

Table 2 *Total population by altitude class* (figures in thousands, percentages of national totals in parentheses)*

Altitude (m)	*Ethiopia*	*Tanzania*	*Madagascar*	*Kenya*	*Cameroun*	*Zimbabwe*	*Uganda*	*Rwanda*	*Burundi*
1000-1500	9,708 (17.0)	14,875 (48.8)	4,187 (27.4)	9,334 (33.9)	2,122 (15.2)	213 (1.8)	14,837 (75.9)	1,010 (13.0)	1,618 (24.9)
1500-2000	20,378 (35.7)	3,221 (10.6)	1,679 (11.0)	10,079 (36.6)	744 (5.6)	9 (0.1)	1,615 (8.3)	4,845 (61.2)	3,859 (59.4)
2000-2500	16,559 (29.0)	554 (1.8)	95 (0.6)	2,725 (9.9)	35 (1.0)		769 (3.9)	1,751 (22.6)	444 (6.8)
>2500	6,495 (11.4)	63 (0.2)		545 (2.0)	25 (0.2)		141 (0.7)	248 (3.2)	13 (0.2)
Total	53,140 (93.0)	18,683 (61.4)	5,961 (39.0)	22,683 (82.5)	3,026 (21.9)	222 (1.9)	17,362 (88.8)	7,854 (100)	5,934 (91.3)

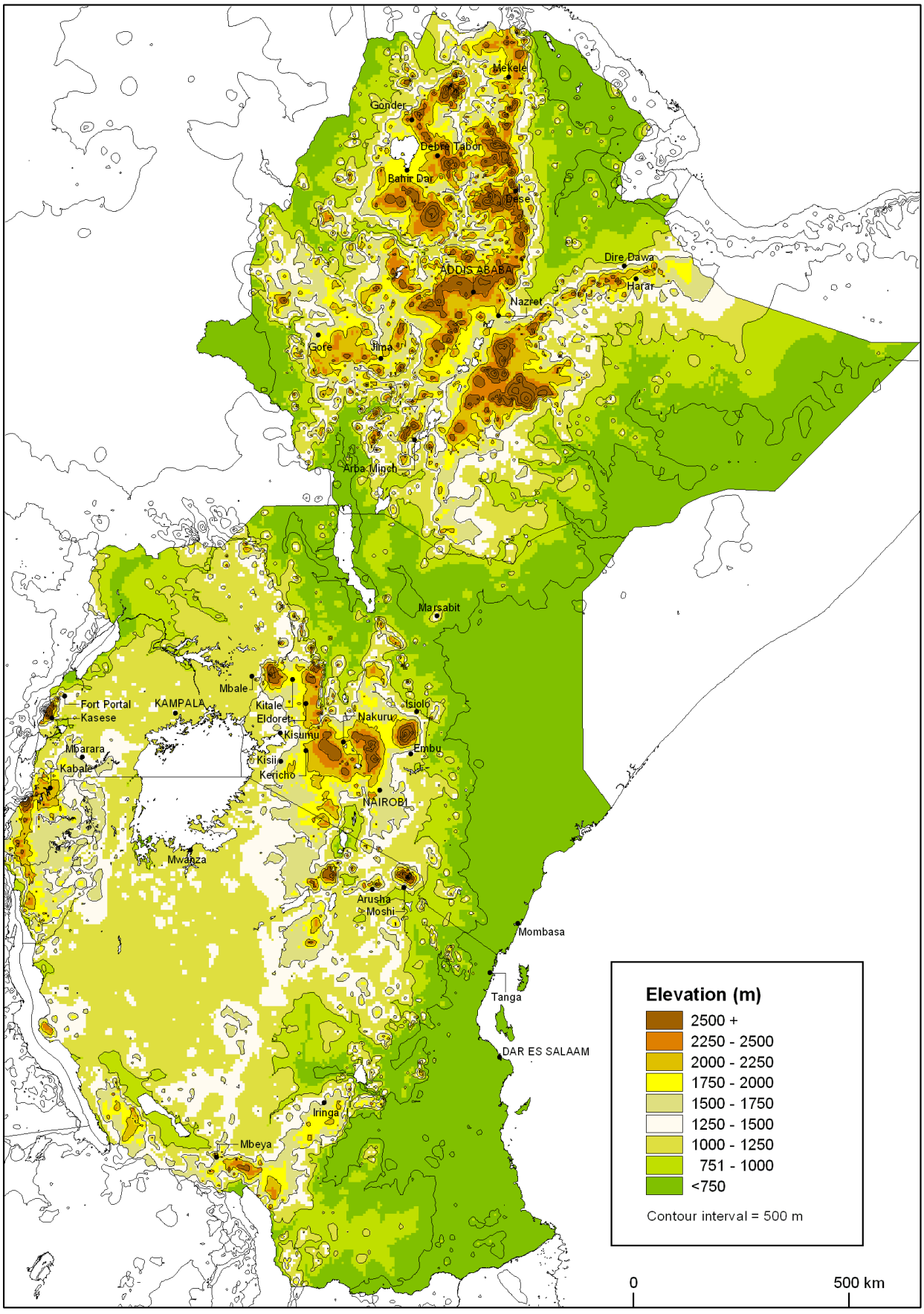
* *Population estimates are derived from Deichmann's (1994) data for Africa, and adjusted to 1998 values using national population growth rates (1990-96) published in World Bank Development Indicators, 1996.*

Table 3 *Total land area for three alternative definitions of highland (percentages of national totals in parentheses)*

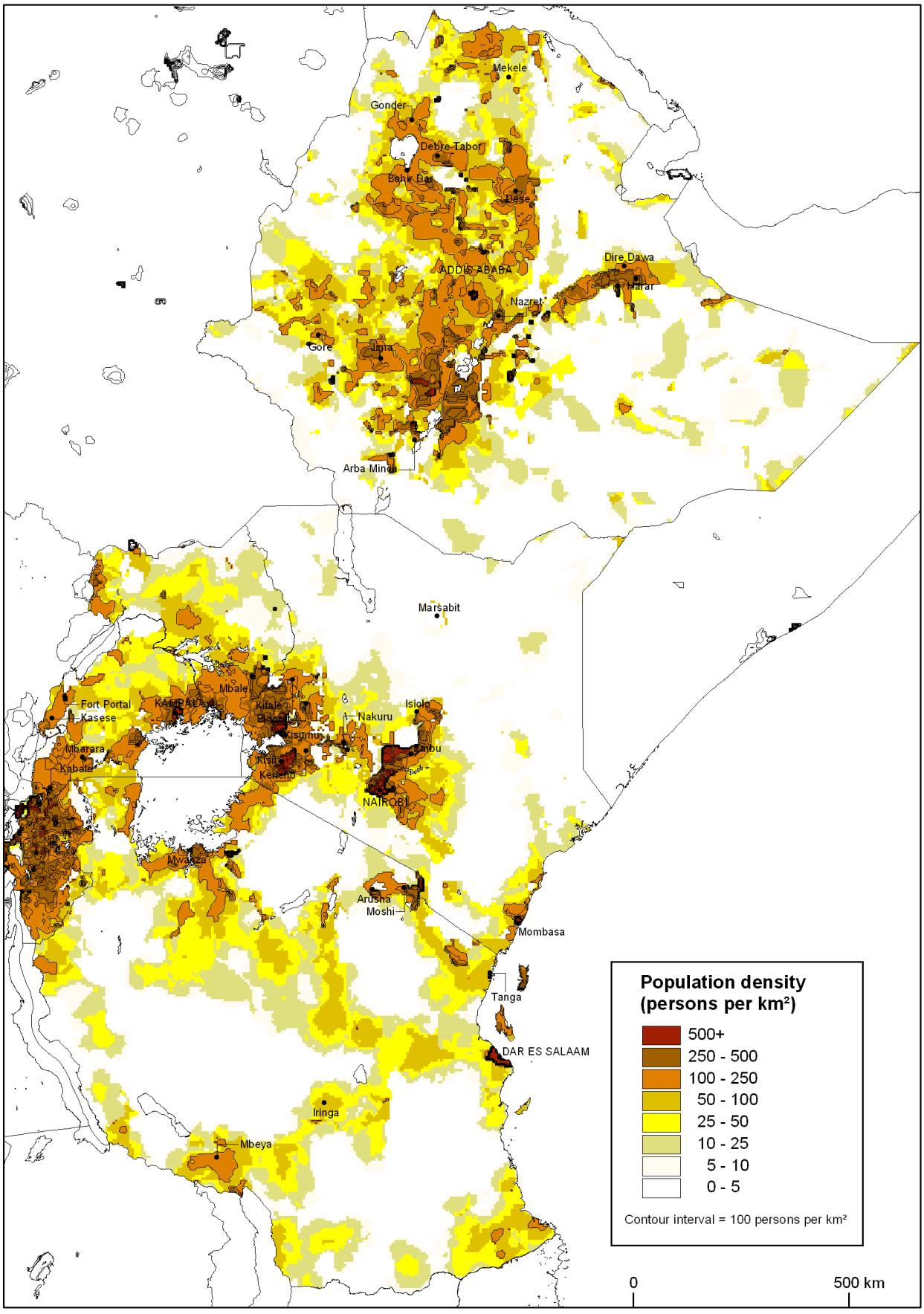
	Total land area (km^2)	*Area > 1000 m*	*Area > 1500 m*	*Areas > 2000 m*
Ethiopia	1,127,924	631,141 (56.0)	375,962 (33.3)	168,135 (14.9)
Tanzania	890,682	561,348 (63.0)	101,538 (11.4)	13,271 (1.5)
Madagascar	588,319	110,276 (18.7)	22,164 (3.8)	1,240 (0.2)
Kenya	573,942	168,029 (29.3)	91,604 (16.0)	34,539 (6.0)
Cameroun	468,013	47,776 (10.2)	7,150 (1.5)	1,105 (0.2)
Zimbabwe	387,440	179,929 (46.4)	7,176 (1.9)	322 (0.1)
Uganda	205,643	162,661 (79.1)	16,507 (8.0)	4,907 (2.4)
Rwanda	25,297	25,297 (100.0)	20,576 (81.3)	5,615 (22.2)
Burundi	25,116	24,006 (95.6)	15,286 (60.9)	1,818 (7.2)

Table 4 *Land areas for different altitude zones (figures in km^2; those in parentheses indicate percentage of total area > 1000 m)*

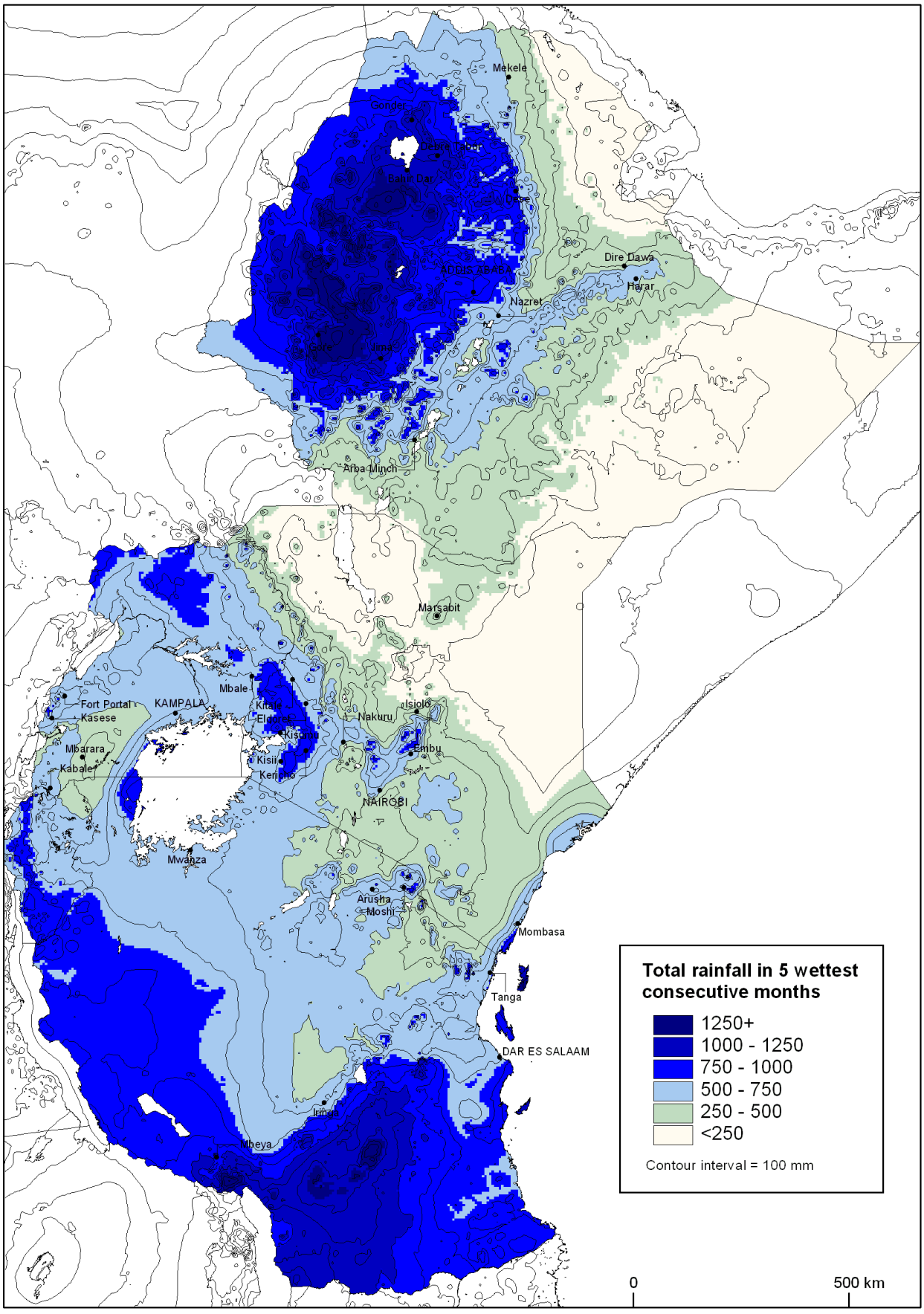
Altitude (m)	*Ethiopia*	*Tanzania*	*Madagascar*	*Kenya*	*Cameroun*	*Zimbabwe*	*Uganda*	*Rwanda*	*Burundi*
1000-1250	139703 (22.1)	304636 (54.3)	60324 (54.7)	45876 (27.3)	27315 (57.2)	114442 (63.6)	118200 (72.7)	154 (0.6)	2649 (11.0)
1250-1500	115476 (18.3)	155174 (27.6)	27788 (25.2)	30549 (18.8)	13311 (27.9)	58311 (32.4)	27954 (17.2)	4566 (18.1)	6071 (25.3)
1500-1750	111587 (17.7)	66709 (11.9)	16230 (14.7)	31046 (18.5)	4388 (9.2)	6386 (3.5)	8484 (5.2)	11414 (45.1)	9401 (39.2)
1750-2000	96250 (15.2)	21559 (3.8)	4694 (4.3)	26019 (15.5)	1657 (3.5)	468 (0.6)	3116 (1.9)	3548 (14.0)	4067 (16.9)
2000-2250	78552 (12.4)	8301 (1.5)	1058 (1.0)	18426 (11.0)	614 (1.3)	293 (0.2)	2962 (1.8)	3918 (15.5)	1356 (5.6)
2250-2500	44617 (7.1)	2909 (0.5)	159 (0.1)	8581 (5.1)	337 (0.7)	29 (0.0)	771 (0.5)	864 (3.4)	370 (1.5)
>2500	44966 (7.1)	2061 (0.4)	23 (0.0)	7532 (4.5)	154 (0.3)		1173 (0.7)	833 (3.3)	92 (0.4)


Mekele
Gonder
Debre Tabor
Bahir Dar
Dese
Dire Dawa
ADDIS ABABA
Harar
Nazret
Gore
Jima
Arba Minch
Marsabit
Mbale
Fort Portal
Kasese
KAMPALA
Kitale
Eldoret
Kisumu
Nakuru
Isiolo
Embu
Mbarara
Kabale
Kisii
Kericho
NAIROBI
Mwanza
Arusha
Moshi
Mombasa
Tanga
DAR ES SALAAM
Iringa
Mbeya
Elevation (m)
2500 +
2250 - 2500
2000 - 2250
1750 - 2000
1500 - 1750
1250 - 1500
1000 - 1250
751 - 1000
<750
Contour interval = 500 m
0
500 km

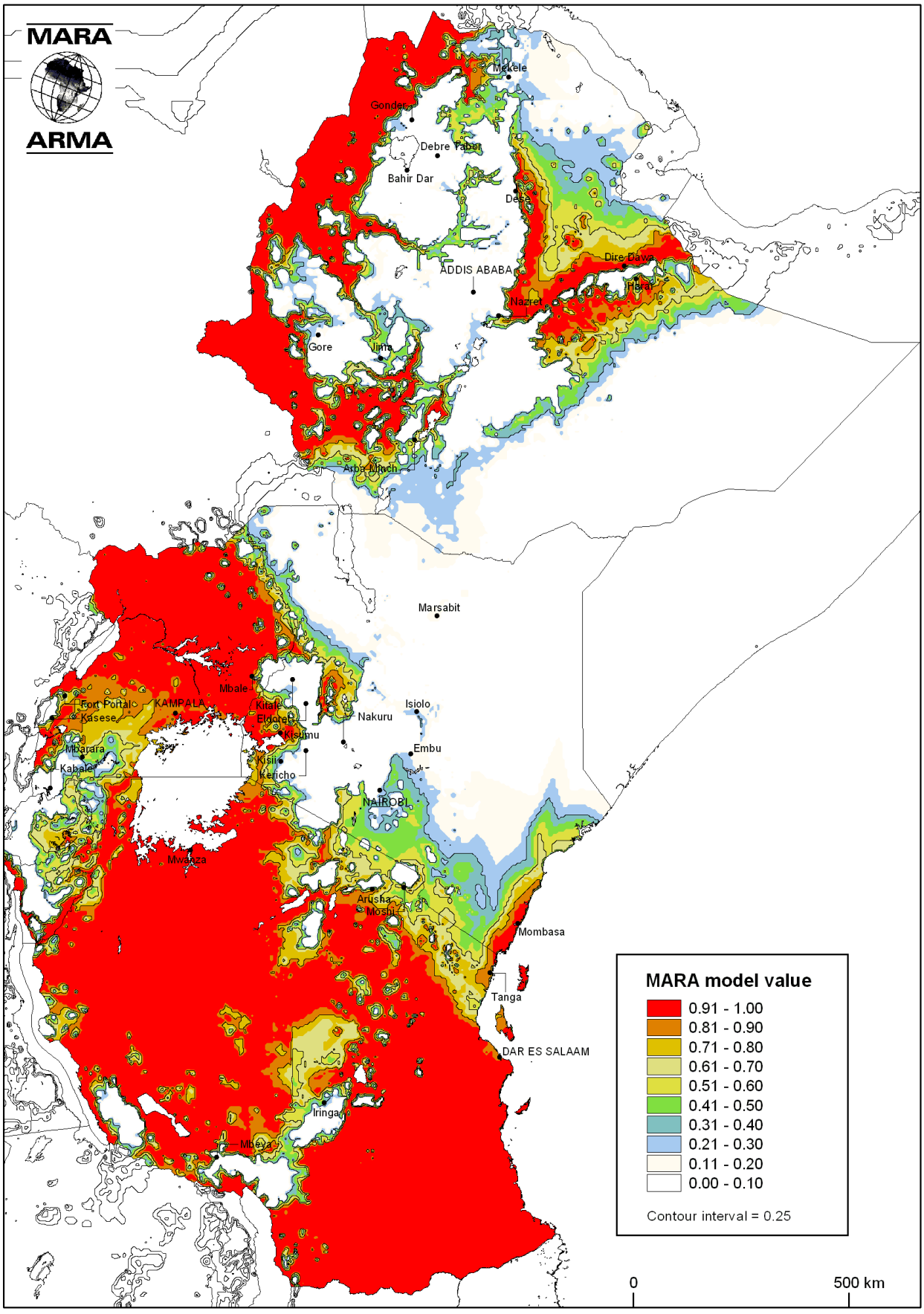
Map 1 *Relief*



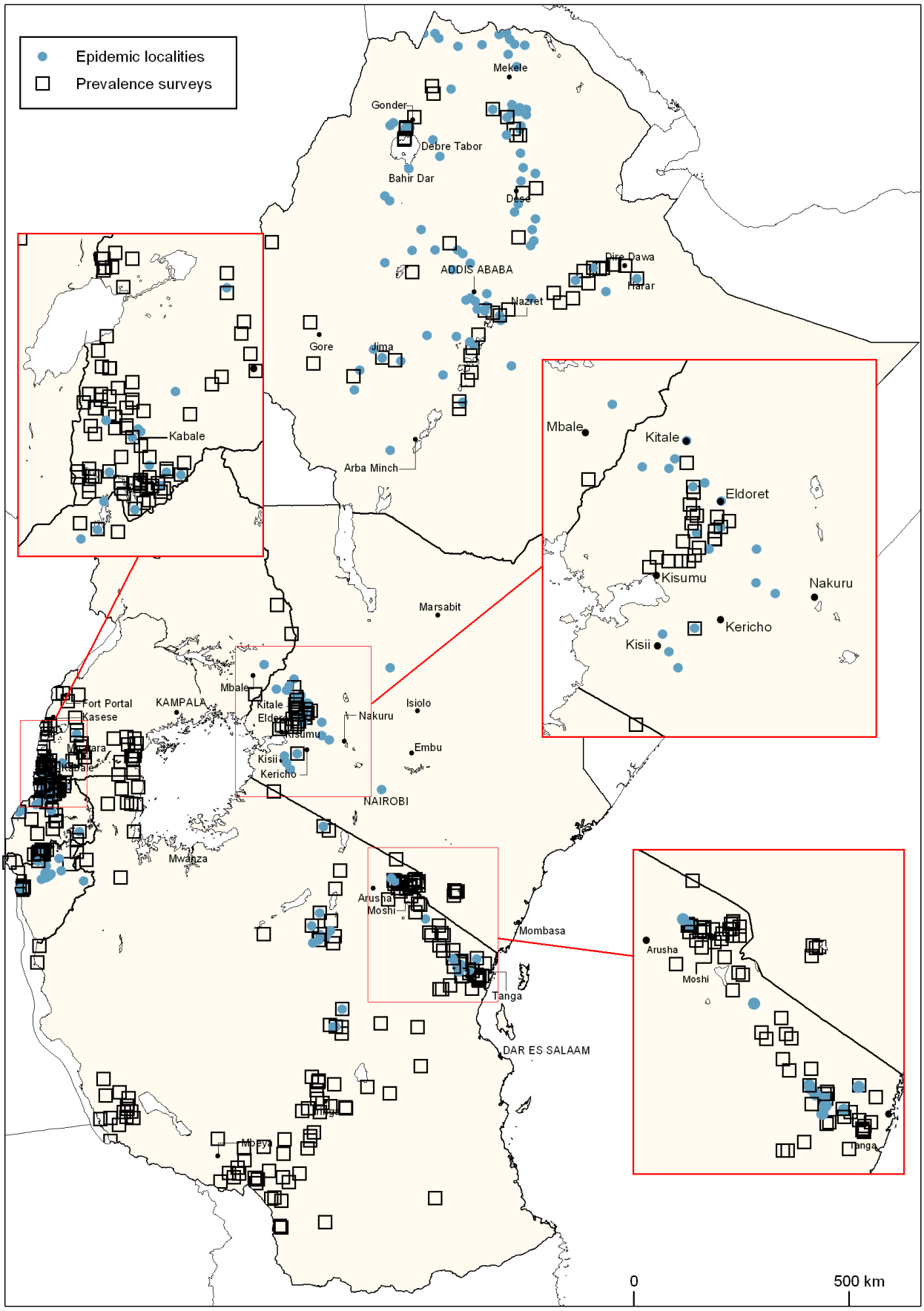
Map 2 *Population density*



Map 3 *Wet season rainfall*



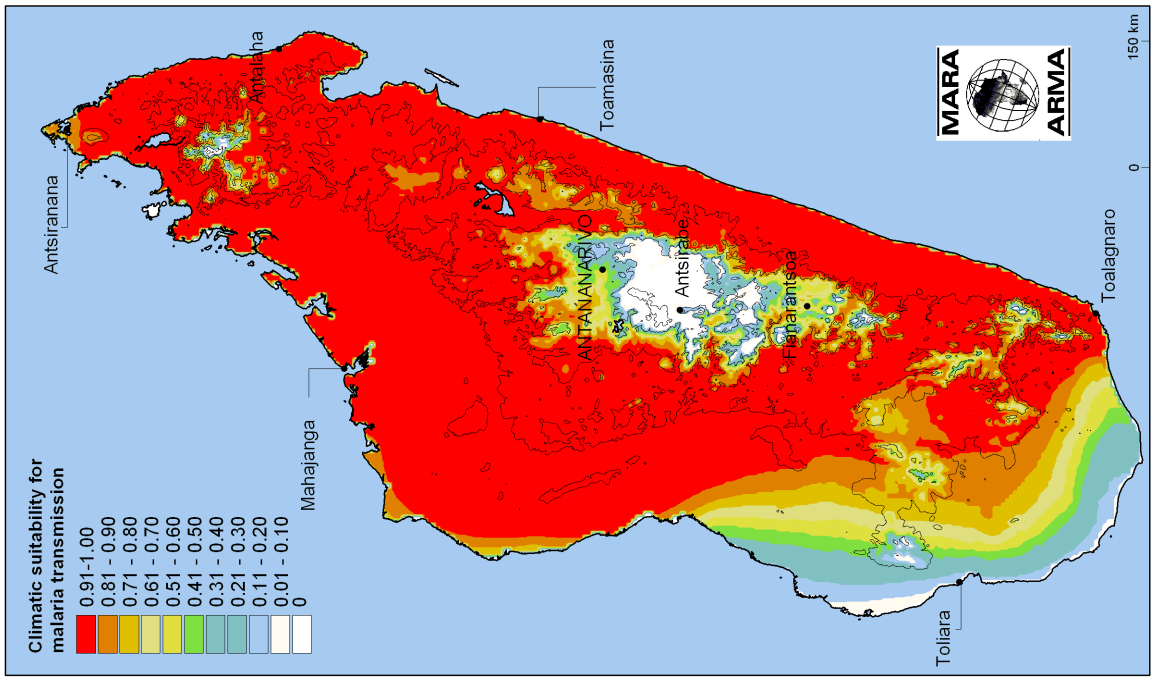
Map 4 *The MARA malaria distribution model*



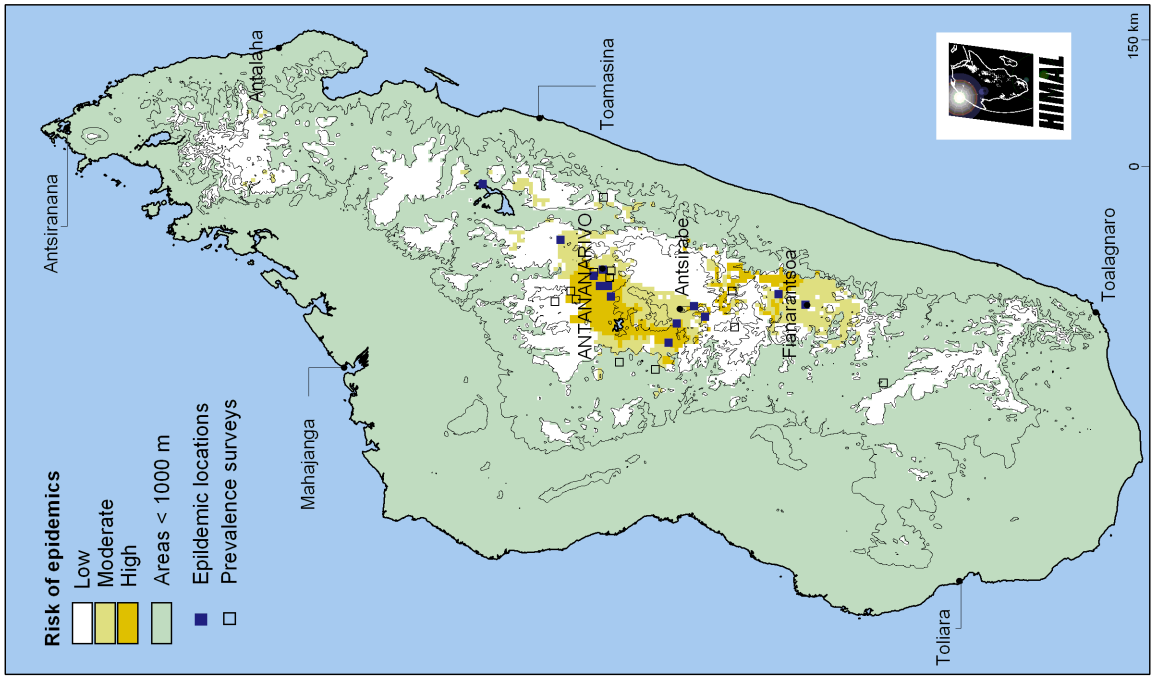
Map 5 *HIMAL data points*

Appendix 2 Contextual information for Madagascar, Rwanda and Burundi

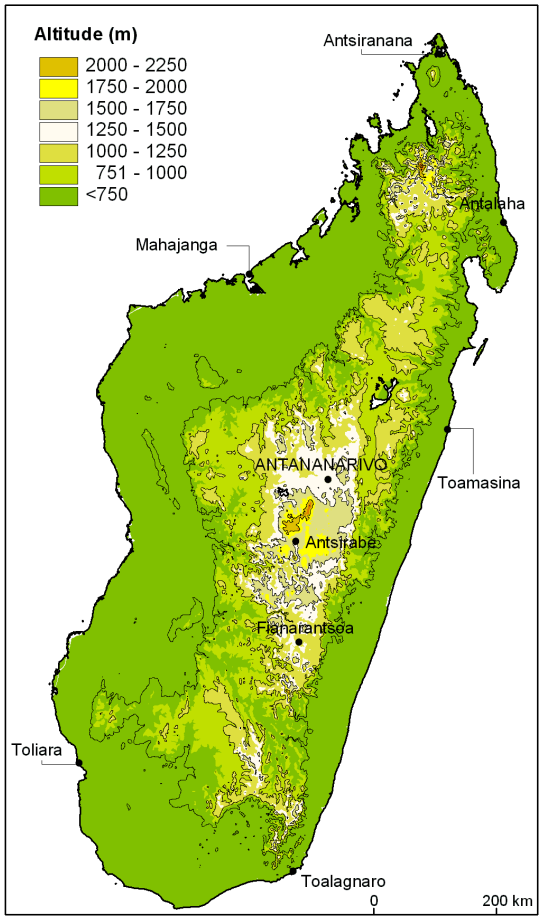
Madagascar: MARA model



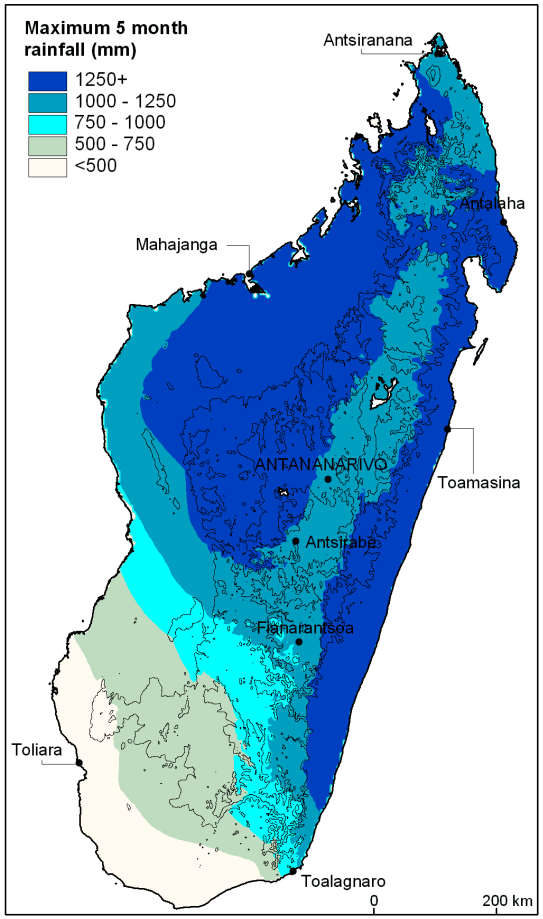
Madagascar: risk of epidemics



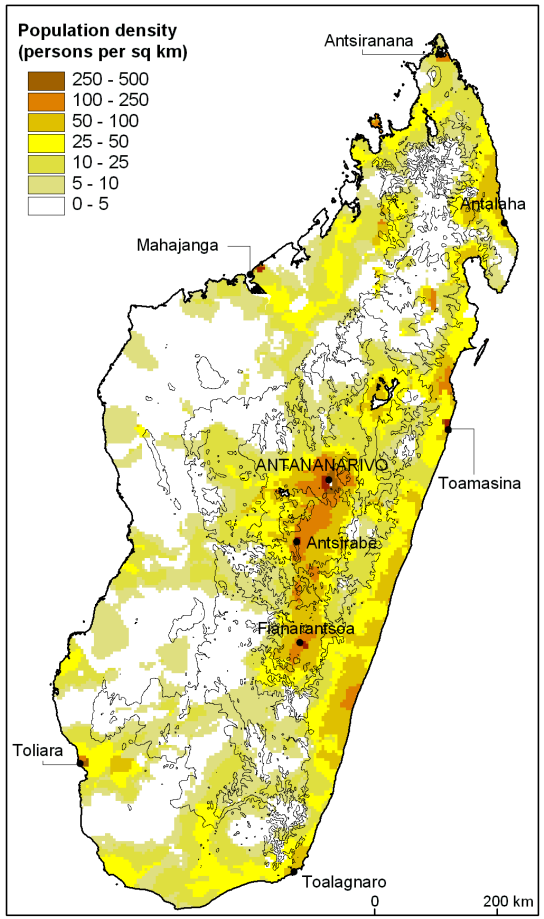
Madagascar: relief



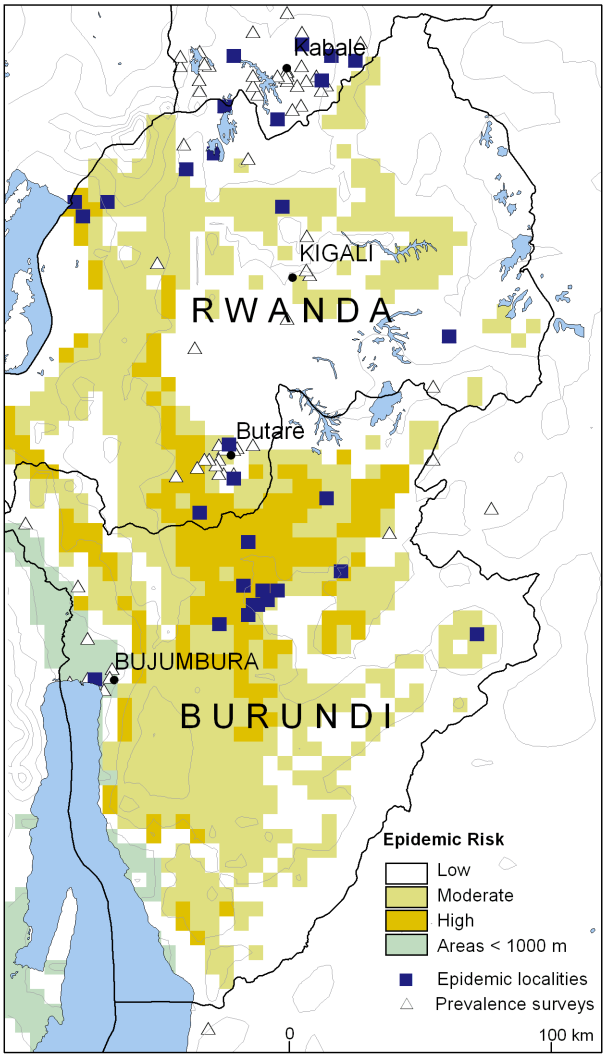
Madagascar: wet season rainfall



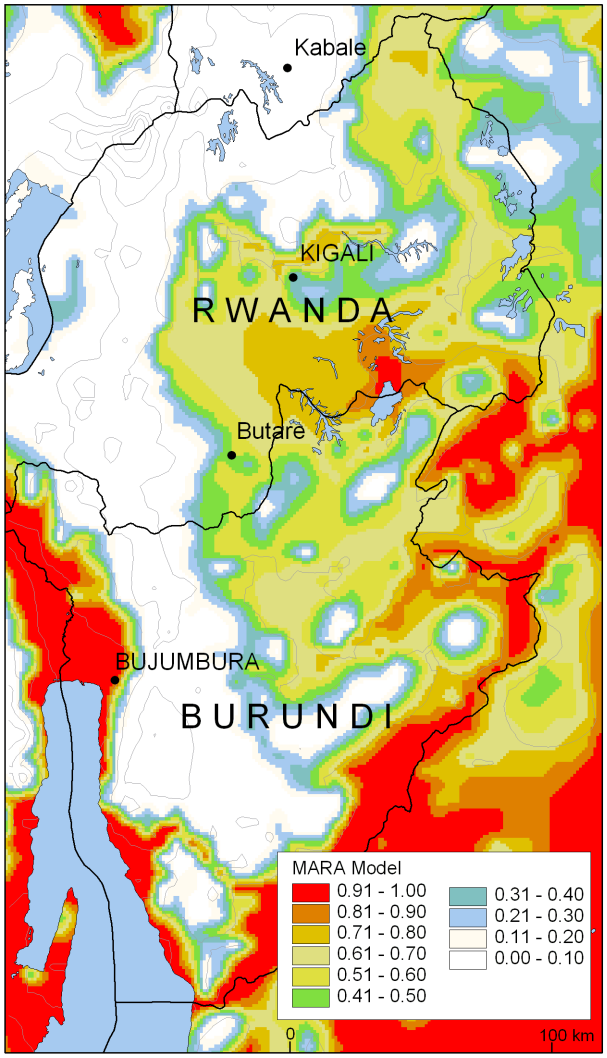
Madagascar: population density



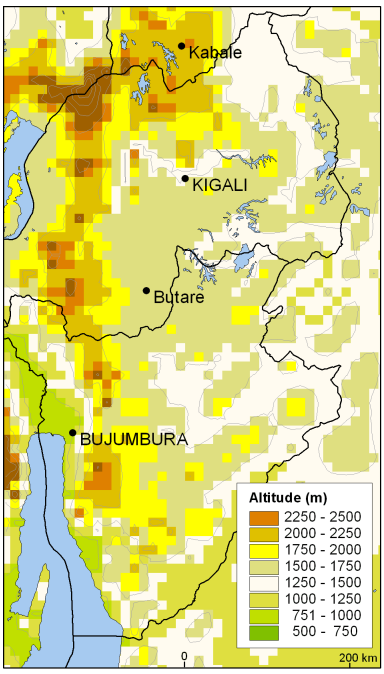
Rwanda and Burundi: risk of epidemics



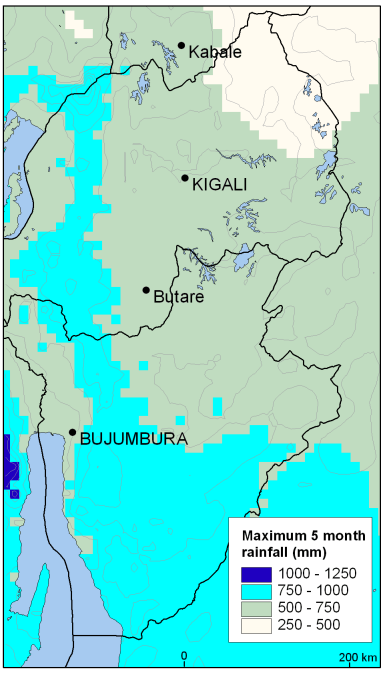
Rwanda and Burundi: MARA model



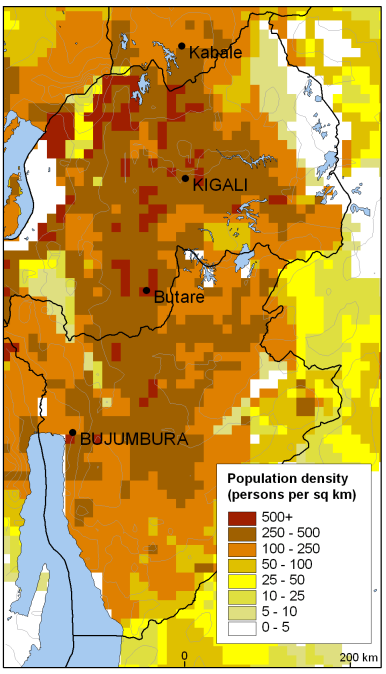
Rwanda and Burundi: relief



Rwanda and Burundi: wet season rainfall



Rwanda and Burundi: population density



A N N E X E

Summary Workshop Report

Developing new approaches for the surveillance and control of malaria epidemics in the highlands of East Africa

Salt Rock, South Africa, 20–21 March 1999

Highland Malaria Project

Mapping Malaria Risk in Africa

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1 Introduction

1.1 The Highland Malaria Project

The African highlands have traditionally been regarded as areas of little or no malaria transmission, due mainly to the negative effects of low environmental temperatures on parasite and vector development. But this picture appears to be changing, with studies in Ethiopia, Kenya, Rwanda and elsewhere suggesting that malaria epidemics are becoming increasingly common in areas where risk was previously considered minimal, and where local populations have little immunity to the disease. The possible factors underlying this trend have been widely debated, and those implicating climate and ecological change have been most prominent. Unfortunately the lack of reliable malaria data for most highland areas has made analysis of these issues difficult and the subject has often been oversimplified.

While it is likely that the relatively high mortality rates characteristic of highland epidemics could be greatly reduced through prompt intervention, most national malaria control programmes are poorly equipped for identifying and responding to epidemics. There is, therefore, a dual need for increased scientific understanding of the epidemiology of highland malaria on one hand, as well as greater local capacity in epidemic forecasting, surveillance and response on the other.

These issues were raised at the TDR/WHO/IDRC co-sponsored Task Force Meeting on "Highland Malaria in Africa", held in Addis Ababa in May 1996, at which a general framework for future research was proposed. In particular, the workshop recognised the need for mapping epidemic prone areas in order to target surveillance activities and response mechanisms.

The Highland Malaria Project (HIMAL), that came out of the Addis Ababa workshop was designed to address this issue in particular. To date HIMAL Phase I activities have focused on the use of Geographical Information Systems (GIS) to stratify epidemic risk on the basis of climate and altitude. Various modelling approaches have been explored and outputs validated using historical data for malaria prevalence (parasite and spleen surveys) and past epidemics in nine African countries. Risk maps are currently being circulated to control programmes and a detailed report is in the final stages of preparation.

The products of HIMAL Phase I give a good overview of epidemic risk and are a useful starting point for more detailed studies. However, given that they are based on pooled retrospective data, this approach can at best provide a highly aggregated and static picture of risk. While this may be useful for focusing control activities on key risk areas, from an operational point of view control programmes also require more detailed information on when and where epidemics are likely to strike in future. At the design stage of HIMAL it was envisaged that this need could best be addressed through a collaborative network of sentinel sites at which malaria cases and likely risk factors could be monitored simultaneously, and where various approaches to epidemic early warning and control could be evaluated (HIMAL Phase II). It was recognised that this work should be designed specifically to feed into existing approaches to epidemic control and as such should be planned and carried out in tandem with control programmes. Moreover future research in this area should respond directly to the stated needs of these programmes. The principal motivation for this workshop, therefore, was to bring together control programme managers and researchers to explore these issues and develop a framework for a future work in the highlands.

1.2 Objectives of the meeting

The general purpose of this workshop was to bring together control programme managers and local and international researchers to address operational issues of epidemic forecasting, early warning, detection and control. Specifically, the meeting aimed to:

- Review existing approaches for forecasting and detecting epidemics in Kenya, Tanzania and Uganda
- Identify priorities for strengthening ongoing activities in these areas
- Define an agenda for future collaboration between control programmes and researchers
- Identify priority research areas for HIMAL phase II

The plan for the meeting was to explore these issues with reference to epidemics in highland areas, as distinct from malaria epidemics in general (and most notably desert-fringe epidemics). This distinction was adopted in part for historical reasons (reflecting the focus of HIMAL), and in part because it was recognised that there are basic differences between highland and non-highland epidemics both in terms of their epidemiology and in terms of how we might approach prediction and intervention. That said, this meeting revealed a demand for new epidemic tools, regardless of the 'type' of epidemic, and it is hoped that the themes discussed here will be relevant within this wider context.

1.3 Scope of this report

This document represents a synthesis summary. Given the informal nature of the meeting the report does not attempt to provide a detailed account of proceedings or the presentations given. Instead, it attempts to draw out and summarise the main themes of the meeting, particularly regarding immediate priorities for improving epidemic detection.

2 Main themes of the meeting

2.1 A framework for epidemic forecasting, early warning and early detection

Although the terms have sometimes been used interchangeably, the workshop emphasised basic distinctions between the concepts of epidemic forecasting, early warning and early detection. These strategies differ in approach, specificity and the lead times they provide. The following definitions were agreed:

Forecasting and early warning are both intended to warn of environmental conditions that are suitable for the occurrence of an epidemic. It is not yet clear exactly how such conditions can be defined. Presumably factors such as rainfall and temperature are likely to be important, but other factors such as migration may also be involved, and precise definitions are likely to vary from place to place. Epidemic **forecasting** consists of predicting that such conditions are likely to appear at some place and time in the future, and will normally depend on medium-range weather forecasts. **Early warning**, on the other hand, consists of monitoring these environmental risk factors directly and locally, in order to detect when conditions suitable for an epidemic have appeared at a given time and place. **Early detection** is the monitoring of epidemiological data in order to detect the actual occurrence of an epidemic as soon as it begins.

Each of these functions has an important role in an integrated strategy. Epidemic forecasting provides the longest lead times, but is likely to be the least specific and reliable. It will allow heightened surveillance and some initial precautionary measures in the danger areas. Early warning should provide greater reliability and local specificity, and therefore a lower frequency of false alarms, but will allow less time to prepare a response. Early detection will be even more reliable and geographically specific, but at the cost of much reduced lead times.

In an integrated epidemic prevention strategy, therefore, long-range forecasting, early warning and early detection would provide warning signals that can be thought of as a series of "flags". Successive flags correspond to increasing degrees of alarm, and trigger activities of increasing degrees of urgency. Each flag is triggered by a specific set of indicators, and in turn triggers a specific set of responses (Figure 1). These responses follow pre-defined procedures with detailed algorithms, and are likely to include not only measures related to prevention or intervention, but also intensified surveillance and sensitivity to the next level of indicators. As suggested by the Figure, successive flags carry increasing weight and, from a planning perspective, it is important that the higher weight flags are implemented first (it is likely that flags 2 and 3 would provide sufficient warning, even if flag 1 never went up).

A general framework for an integrated epidemic warning system in Kenya, Tanzania and Uganda can therefore be described as follows:-

At the most general level, **forecasting** would provide very early, long range assessments of epidemic risk over a wide area (*e.g.* at the national or international scale). The information provided would not be specific but would indicate the likelihood of future conditions being generally suitable for epidemics (*e.g.* medium range weather forecasts, rainfall predictions based on the El Niño/Southern Oscillation). In terms of malaria control such forecasts would raise a first, low weight plausibility flag. This flag would trigger activities of two kinds. First, checks would made that early warning and early detection activities in known epidemic prone areas are fully alert. This may involve an intensified level of monitoring. Second, it would initiate the preparation, at a central or provincial level, of the additional resources that might be needed in one district or another if an epidemic did appear. For example, stocks of anti-malarial drugs might be built up in regional stores. In order to be useful for these purposes, the forecast would have to precede the actual epidemic by 3 to 6 months.

Epidemic **early warning** would involve the collection of real time data for known epidemic risk factors (*e.g.* rainfall) from within the epidemic risk zone. This information would need to be collected and analysed frequently by district authorities. When the local environmental indicators suggest that conditions have become suitable for an epidemic, a second warning flag would be raised (Figure 1) at district level. Districts in turn would then ensure that epidemiological monitoring for early detection is being carried out properly at the sentinel health facility level within the delineated zones. (This may involve all the local health facilities, or a predetermined subset of "sentinel" facilities.) Districts would also ensure that local epidemic response reserves were well prepared. In some cases, pre-emptive intervention (*e.g.* by house-spraying) may be possible at this stage. Depending on the candidate variable(s) used for early warning, a lead time of several weeks could be achievable.

Within the epidemic-prone zone, a simple framework for **detecting** outbreaks would be based on a weekly or monthly assessment of facility data. In selected health facilities within this zone, historical malaria data (*e.g.* outpatient attendance, or severe malaria admissions) would be summarised in simple graphical form. This would show, for each week or month, the mean or median figures over recent years (*e.g.* the last five years), together with an estimate of the upper

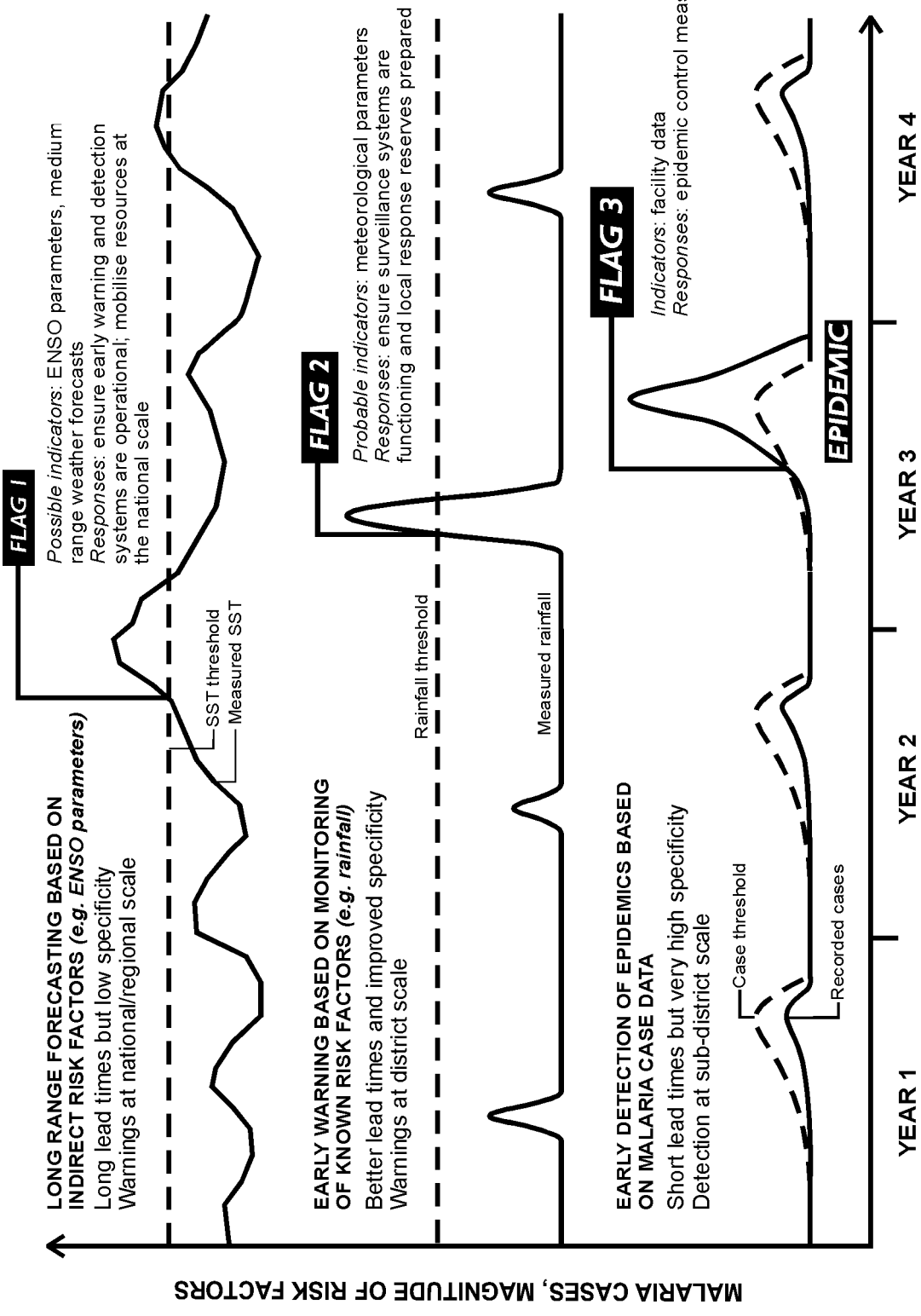

Figure 1. A three-tiered approach for epidemic forecasting, early warning and detection. Each tier is associated with specific indicators and responses. In this simplified example a first warning flag is raised at the regional level after sea-surface temperature (SST) anomolies suggest an impending El Niño event. Subsequent excess rainfall is monitored directly as part of an early warning system and Flag 2 is raised. Malaria cases are monitored at the individual facility level and an epidemic declared once a defined threshold has been exceeded.

limit of the "normal range" (*e.g.* the 75th percentile) over this period. Current data would be plotted into the graph as they are collected. Figures in excess of the historical "normal range" would trigger the process of declaring an epidemic in the local area (*i.e.* the third warning flag in Figure 1). District authorities would then launch a pre-planned series of epidemic control measures, in an attempt to attenuate the incipient epidemic. The monitoring process could be adjusted in various ways, for example by using different indicators, different time intervals, a moving average, or by requiring current data to exceed the threshold for several successive time intervals. However, it must be remembered that once an epidemic has already begun, an immediate response is necessary. Experience suggests that intervention may be useless if it is delayed until there is no doubt in anyone's mind that an epidemic is under way. In previous cases, delays at this stage of the process have sometimes allowed local epidemics to proceed entirely unchecked, or at least until the national press had drawn attention to the problem.

Within East Africa, various elements of this strategy are already being explored, either in a research context (in the case of forecasting and early warning), or in an operational context (in the case of early detection — see below).

The success of a system of this kind is contingent on being able to adequately define the "normal" case profile for the locality in question. Whilst it is a relatively straightforward exercise to provide this information using historical morbidity data, care should be taken to use a sufficiently long series.

Given that it is possible to define the "normal range", an arbitrary choice must still be made of an "epidemic threshold". In Uganda, a threshold of one quartile above the long term average number of cases (per month) is used as a basic indicator (see below). Elsewhere a threshold of two standard deviations above a moving average has been commonly used. An alternative way of defining an epidemic is in relation to the capacity of local services: an epidemic is said to occur when the case load exceeds the local capacity of health services to cope. It would perhaps therefore be possible to define a less arbitrary case threshold by studying details of historical epidemics and corresponding facility indicators (see Section 2.2.1).

It was agreed that whatever threshold is used, its applicability should be validated and evaluated on a regular basis. A critical feature of any system of this kind is that it should be "self-correcting". In other words, it should be gradually adjusted in the light of experience so as to improve its sensitivity and specificity in predicting and detecting epidemics, and to improve the sequence of responses that are triggered at each stage.

2.2 Existing epidemic forecasting/detection systems in East Africa

A breakaway session was held by control programme managers in order to discuss ongoing and planned activities that could feed into an integrated strategy for epidemic prevention. The main findings and recommendations of this session, together with the ensuing discussion with the main group, are summarised in the following sections.

Kenya already has a weekly reporting system from sentinel sites for a variety of diseases, including malaria, although as yet no use has been made of a threshold term for identifying epidemics. However, following a specialist workshop on epidemic malaria (held in February 1999), the National Malaria Control Programme is actively developing its own system for early detection using weekly morbidity data from peripheral health centres. A limited number of health units have so far been selected as sentinel sites.

While there is currently no system of sentinel sites in **Tanzania**, data are routinely available from the existing health management information system and could, in principle, be used as part of an early detection system. However, the success of this approach would depend on the timely collection and reporting of data, and it is not clear that such intense surveillance could be sustained throughout all epidemic-prone areas. Recently the Malaria Control Programme has prepared a manual on epidemic preparedness and containment. It has also organised a workshop with district Medical Officers from key epidemic-prone districts to discuss practical aspects of epidemic control.

A rather more developed system exists in **Uganda**. It relies on a number of sentinel sites in epidemic prone areas, chosen on the basis of altitude, stratification maps (including MARA products) and expert opinion. For these sites, time series of malaria morbidity data from health centre records over the last 3 to 5 years are used to define median and quartile values for malaria incidence on a monthly basis. District Health Management Teams are assisted in this exercise by the Malaria Control Unit. Health workers are trained to plot malaria cases onto this graph on a weekly basis. When cases are in excess of the median ("expected"), a report is made to the District Medical Officer and from there to the Ministry of Health, where preparations for epidemic control are made (*e.g.* ensuring adequate drug supplies through the Medical Stores Department, mobilising local personnel, setting up blood banks *etc.*). If cases plotted rise above the third quartile an epidemic is declared, and the local DMO, Ministry and DMOs in other epidemic prone districts are notified immediately.

The Malaria Control Unit in Uganda has also recently explored the possibility of using non-malariometric variables to provide some early warning of malaria outbreaks. Preceding rainfall conditions and the demand for blood for transfusions have both been found to be significantly correlated with malaria cases, and may in future provide a viable basis for operational early warning. There have also been attempts to correlate rainfall and malaria outbreaks in Kenya and Tanzania, but in both cases efforts have been hampered by limited availability of meteorological data (see Section 2.3.3).

As a result of these discussions, the control programmes of the three countries agreed to act immediately to (a) set up early warning systems modelled on the current system in Uganda, and (b) to create a regional network to share experience and coordinate activities relating to epidemics. It was also agreed that forthcoming RBM National Situation Analyses in the three countries would be made aware of this initiative and be used to help mobilise resources.

2.3 Priorities for improving epidemic detection, forecasting and early warning

2.3.1 Requirements for better detection of epidemics

In general, control programmes were most interested in predicting, with reasonable specificity, where and when an epidemic is starting, as well as having some indication of the likely scale of the epidemic. To date Kenya, Tanzania and Uganda have been developing their own separate plans for early detection systems and it was agreed that a standardised strategy for East Africa would be advantageous. Programme managers felt that this system should be based on the existing Ugandan approach but that special consideration should be given to the following:

Appropriate siting of sentinel facilities

There was general agreement that the appropriate siting of sentinel facilities is a prerequisite for successful epidemic detection and that current estimates of epidemic risk should be taken

into account when designing sentinel systems. It was noted that the provision of stratification maps is within the remit of MARA and HIMAL, and that these products should be made available to control programmes as soon as possible. Given the potential significance of these products in terms of decision making it is important that they are updated and validated as more secondary data become available. In this context the Resource Network on the Prevention and Control of Malaria Epidemics (Roll Back Malaria Project) has recently provided funds for collecting historical data on epidemics in Uganda. The general view in the meeting was that the collection of historical data on epidemics is a priority and should be encouraged.

Several participants felt that sentinel sites should be sited so as to represent a range of endemic (and epidemic) conditions and should not be restricted to very low transmission settings.

Refinement of tools for defining epidemics

The sentinel site system is based on a number of assumptions which require testing. At the most basic level, given that sentinel sites are likely to be health centres, the assumption that their catchments reach up to epidemic prone areas in the highlands should be evaluated. In some instances it may be necessary to include dispensaries at higher altitudes. In addition some basic work on health seeking behaviour is required to determine the extent to which local populations use the sentinel facility when they have a fever.

It was also recognised that input from researchers would be required to develop the health facility analysis of historical attendance data and the graphical instrument on which to record current attendances. Facilities with very low historical attendance may need a different threshold to avoid false alarms. There may also be a need to weight recent years more highly for the median, or have a correction for areas which have experienced recent epidemics.

In terms of planning remedial measures, control programmes highlighted the need for information on the likely scale of the impending epidemic, as well as timing and location. It was suggested that retrospective analysis of previous epidemics should be carried out to provide data with which early season case numbers could be compared to known epidemic situations.

Reducing delays brought about by poor communications

A successful early detection system relies on good communication between sentinel sites and DMOs and between DMOs and the Ministry of Health. While channels between the districts and the centre are often effective, the experience of the control programmes (particularly in Uganda) was that communication with peripheral health centres was problematical and undermined the usefulness of the detection system. It was recommended that appropriate solutions be sought. The Tanzanian Essential Health Intervention study (TEHIP), for example, has been using solar powered Codan radios to connect health centres to each other and to the DMO/ District Health Management Teams in the district capital.

The issue of communications between districts/health centres and local people was also raised. At present it is unclear whether any official mechanism exists for alerting the community of epidemic warnings, and it was recommended that the possibility of involving local community organisations and health committees in disseminating this information should be explored.

Methods of confirmation

However the signs of the onset of an epidemic are defined, there will be occasions when such signs are observed, but no epidemic follows. In order to justify allocating resources to one district rather than another, central health authorities will sometimes need some method of

confirming that the alarm is genuine – even if this confirmation is retrospective. One possible means of confirmation is to send a team to investigate. This would also help to document events, and to improve coordination between district and Ministry, during these critical early stages.

Training requirements for local health personnel

All control programmes felt that human resource strengthening at the district level was required to implement an early detection system. Training of this kind is already being carried out in Uganda and could work as a model for Kenya and Tanzania. In the Ugandan case WHO has sponsored the training of senior medical officers and researchers in epidemic preparedness by a national core team on epidemics, using mainly WHO materials. This team has subsequently trained DHMTs and health workers at the health centre level. It was suggested that Kenya and Tanzania could benefit from adopting a similar approach. Given the current pressures on control programme staff time, it was also suggested that each country consider applying for an Associate Professional Officer appointment (or similar), specifically to help handle the extra work load necessary to get an epidemic detection system in place.

2.3.2 Requirements for improved early warning and forecasting

There are limits to the amount of lead time that can be provided through an early detection system and it was widely accepted that new research is needed to explore the use of non-malariometric variables for early warning and forecasting.

Selection of appropriate candidate variables for early warning/forecasting

It was widely agreed that a suite of potential candidate variables for early warning need to be evaluated. These should be investigated in the next phase of HIMAL.

Entomological monitoring

Some participants proposed that entomological monitoring could be useful as part of an early warning or early detection system. Others, however, expressed doubt that such labour-intensive methods could be sustained with an adequate degree of intensity over sufficiently wide areas. It was agreed that further research is needed into systems for disseminated long term entomological monitoring, and into the choice of entomological indicators.

Focusing on key geographical areas for monitoring candidate variables

In the experience of the Kenyan control programme, there are known 'sensitive' sites from which highland epidemics spread in the first instance. Where these hot-spots are known, they should be used as geographical foci for early warning activities. In other cases it may be possible to get some indication of where hot-spots exist by reviewing historical facility data in which patient records include information on village.

Sourcing of data for candidate variables

For early warning/forecasting to be viable as an operational tool, data for candidate variables must be freely available to control programmes. However, the evidence in this meeting was that control programmes have already had difficulty in obtaining data free of charge. It was agreed that in the short term there is a need to carry out a stakeholder analysis of potential data partners (meteorological departments, HMIS *etc.*). In the longer term these partners need

to be incorporated in future proposals and activities and mechanisms by which all data can be made available to control programmes set out.

2.4 Response to epidemic warnings

As already noted, **timeliness** is a critical requirement for an effective response. The key need is to minimise the delay between the detection of an epidemic and the decision to intervene, as well as the delay between this decision and active implementation on the ground.

Intervention must also be **effective**. When an epidemic has been recognised, a critical issue for health managers at all levels (national, provincial and district) is to decide what measures to take, given the prevailing logistical and financial constraints. Recent epidemics in all three countries have led to new plans. Kenya is trying to develop its capacity for immediate response; drug supplies were adequate in most areas and mortality was much lower than usual despite increased levels of morbidity. The specific needs and issues that were stressed by participants included:

- In Uganda, districts lack basic spray equipment
- Vector profiles are needed
- Information is also needed on drug sensitivity; chloroquine is still effective in Uganda, but this is less certain elsewhere
- Stocks of anti-malarial drug packs exist in Kenya, but not in Tanzania or Uganda; the possibility of decentralised stores was suggested
- There is a need in Kenya for better intersectoral collaboration and better community awareness
- Ideas like the use of specialist teams for parasitological confirmation are not currently in control programme budgets. There is a need for costs analysis

3 Agreed research priorities

The meeting started its discussion of this subject by listing important topics for research:

Better descriptive studies:

- Burden of disease; documenting incidence rates, mortality rates *etc.*
- Better knowledge of vectors
- HIV in relation to malaria
- Population movement and its role in precipitating epidemics
- Transect sampling during an epidemic, and if possible beforehand as well, could be very informative as to the importance and role of altitude in the development an epidemic

Forecasting - including "what is an epidemic?"

- Rapid tools and thresholds

- Basic epidemiology: a lot is known in stable areas, but very little known in highlands (further research should build on recent work by Bødker, Salum, Kilian, *etc.*)
- Disease patterns and infection reservoirs
- Climate, ecology and land use, detailed data on altitude
- Changes in vector abundance, longevity and infection rates
- Human behaviour (response to epidemics), including community awareness, drug usage
- Migration and mobility
- Drug resistance patterns

Monitoring for early warning

- Census, cluster surveys
- Longitudinal parasite surveys (especially in schools)
- Health centre data
- Entomological monitoring
- Ecological monitoring
- Case control studies during epidemics

Impact of intervention

- House-spraying *vs.* ITBN
- Methods of evaluation
- Drug supplies and national policies
- Community awareness
- Inter-sectoral collaboration

In the subsequent discussion of these research topics, the following points were made:

- Each country should generate baseline retrospective data on malaria cases in the sentinel sites
- Efforts should be made to identify easily measurable surrogate markers; work in Uganda, for example, has shown a good correlation between demand for blood and the occurrence of malaria epidemics
- At present, there is no work on early warning. Research is needed on the correlation of meteorological variables with the early warning system, and on other micro-epidemiological indicators (*e.g.* entomological parameters, immunology, drug sensitivity)

- Cost analysis: operational research should address issues of human resource capability and the flow of information from the periphery to the centre and vice-versa. Once systems are in place, research should also be carried out to assess how the health system responds to the epidemics and the reaction of policy makers to the early warning

Later, in the concluding discussions, the following research priorities were noted:

- Resistance
- Baseline micro-epidemiology
- Vectors
- Health seeking behaviour – this determines what proportion of cases are seen at formal health facilities, before and during an epidemic
- Health systems' responses – this means reconstructing, from records and testimony, the behaviour of health systems during previous epidemics
- HMIS - information systems and communications – how should they fit in to an integrated system?
- Immuno-epidemiology – is it a useful indicator, as a means of warning, as a measure of vulnerability, or as a means of investigating epidemic history?

4 Summary of group recommendations

(i) An Epidemic Malaria Network

The control programmes of Uganda, Tanzania and Kenya agreed to act collectively to set up a network on epidemic malaria. The structure and constitution for this network could be similar to that of EANMAT, the network which has recently been created to coordinate information and policy on drug resistance. It would have a "core" of members from the national control programmes, with additional members drawn from the research community. The initial activities of this network could include developing and coordinating a unified early detection system, based on the current system in Uganda (see Section 2.2). This is primarily an activity for control programme managers, but Dr Cox could assist in negotiating and drafting a constitution.

(ii) Consider the incorporation of arid-area epidemics into the scope of the network, and into the next phase of the project.

It was felt strongly by the control programme managers that arid-area epidemics present many of the same operational problems as highland epidemics, even if the limiting environmental factors are rather different. They therefore wished to expand the scope of the network, and if possible the HIMAL project, to include arid-area epidemics. This will require further negotiation with donors (by Dr Cox).

(iii) A unified surveillance system for early detection

As explained in Section 2.2, the three national control programmes agreed to set up a system for early detection using routine data, based on the system currently operating in Uganda.

(iv) Select sentinel sites

This should use experience from different countries, with the existing selection system in Uganda as a basic model.

(v) Review data sources and surveillance systems

The potential should be investigated of using data from the CDC surveillance system, and from the AMMP (Adult Morbidity and Mortality Project) in Tanzania, either for routine epidemic surveillance, or for more detailed analysis of the epidemiology of epidemics. More generally, a review should be conducted of the GIS resources and systems available in each country.

(vi) Development of the concept of staged indicators and responses

The stratified system illustrated in Figure 1 could include a wide variety of possible indicators and responses. The next stage should be to draw up a checklist of these, and, together with control programme staff, to make a short-list of those that are likely to be useful in the short or medium term, together with provisional links between the indicators and the responses. This short-list should then be re-examined in the light of retrospective data on previous epidemics, which may be helpful in determining which indicators are the most sensitive and specific. The meeting hoped that Dr Cox would undertake this task in conjunction with control programme managers.

(vii) Development of Forecasting Indicators

Dr Cox and Dr Hay will collaborate in exploring the problems of handling remote sensing data and using it to generate medium-range forecasts of epidemic potential. It is anticipated that parallel initiatives outside the East African region (*e.g.* MALSAT in Southern Africa, LSHTM in India, NASA) could provide useful inputs into this exercise.

(viii) Research Components

Important topics for research are listed in Section 3. It would be helpful to review the relevant institutional capacity for research available within each country, by broad subject area and by location. This could be carried out by national programmes.

Following further negotiation, a proposal-writing workshop could be held to develop the research component of the project.

(ix) Case studies and recruitment of an 'APO'

It would be useful to investigate in depth one or more epidemics from the recent past, including not only data of various types describing the epidemiological course of the epidemic, but also how the data available at the time was monitored, and what responses were made at each stage. The aim would be to describe the history of the epidemic from its origins to its aftermath, including a wide variety of viewpoints and paying particular attention to the flow of information. This would be a suitable task for a junior researcher (*e.g.* an APO or associate professional officer). Perhaps DANIDA or DFID might be interested in funding such a post.

Annexe: Participants

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