Mapping malaria risk using geographic information systems and remote sensing: The case of Bahir Dar City, Ethiopia

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Abstract

The main objective of this study was to develop a malaria risk map for Bahir Dar City, Amhara, which is situated south of Lake Tana on the Ethiopian plateau. Rainfall, temperature, altitude, slope and land use/land cover (LULC), as well as proximity measures to lake, river and health facilities, were investigated using remote sensing and geographical information systems. The LULC variable was derived from a 2012 SPOT satellite image by supervised classification, while 30-m spatial resolution measurements of altitude and slope came from the Shuttle Radar Topography Mission. Metrological data were collected from the National Meteorological Agency, Bahir Dar branch. These separate datasets, represented as layers in the computer, were combined using weighted, multi-criteria evaluations. The outcome shows that rainfall, temperature, slope, elevation, distance from the lake and distance from the river influenced the malaria hazard the study area by 35%, 15%, 10%, 7%, 5% and 3%, respectively, resulting in a map showing five areas with different levels of malaria hazard: very high (11.2%); high (14.5%); moderate (63.3%); low (6%); and none (5%). The malaria risk map, based on this hazard map plus additional information on proximity to health facilities and current LULC conditions, shows that Bahir Dar City has areas with very high (15%); high (65%); moderate (8%); and low (5%) levels of malaria risk, with only 2% of the land completely risk-free. Such risk maps are essential for planning, implementing, monitoring and evaluating disease control as well as for contemplating prevention and elimination of epidemiological hazards from endemic areas.

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Introduction

Malaria is a vector-borne disease caused by infection of red blood cells with protozoan parasites of the genus *Plasmodium*, where the parasites enter the human body through the bite of an infected female blood-feeding, anopheline mosquito (Cooke *et al.*, 2016). The most serious form of malaria is caused by *Plasmodium falciparum* which can be life-threatening. Due to the vector-dependent transmission of this disease, the environment plays an important role in determining its distribution and biodiversity (Guthmann *et al.*, 2002).According to the latest *World Malaria Report*, close to half of the world's population is at risk of malaria, while there are 216 million actual cases and the World Health Organization (WHO) estimates that sub-Saharan Africa's share of the global malaria burden exceeds 90%, including 91% of deaths (WHO, 2017). Children under five, pregnant women and patients with infections, such as the human immunodeficiency virus (HIV), are at a particularly high risk of contracting malaria, which continues to kill a child every two minutes (WHO, 2017).

According to the Federal Ministry of Health (FMoH) in Ethiopia and individual researchers, three regions make up the large majority of the national malaria case load, *i.e.* Amhara in the North (29%), Oromiya in the Centre South (13%) and the Southern Nations, Nationalities, and Peoples' Region (SNNPR) in the Southeast (47%) (Jima *et al.*, 2010; FMoH, 2014). Three quarters of the country, with about 60% of the population, consist of malaria-prone areas resulting in repeated waves of malaria epidemics (FMoH, 2014). For instance, 3 million people were affected by malaria in 1958 and 150,000 died (Fontaine *et al.*, 1961). Between 1986 and 1993, as many as 48 epidemic episodes were identified in various parts of the country, with a major epidemic in 1988 affecting the highlands (Abeku *et al.*, 2003). A peak case load was reported in June 1997 but the trend declined in the consecutive months, after which the situation improved with the Ethiopian National Malaria Control Programme scaling up prevention and control activities, demonstrating that strong progress is possible through political will and committed partnerships (Jima *et al.*, 2010).

Presence of malaria is strongly linked to environmental factors as they influence the abundance and survival of the mosquito vectors (Thomson *et al.*, 1996; Abeku *et al.*, 2003; Ceccato *et al.*, 2005; Abiodun, *et al.*, 2016). In warmer climates, the adult mosquito digests the blood meal faster and feeds more frequently, while the *Plasmodium* parasite completes the extrinsic incubation within its anopheline vector in a shorter time leading to increased transmission intensity as well as a higher proportion of infective mosquitoes

(Aster, 2010). According to Brhanie (2016), both vector and parasite multiply slowly at cool temperatures with 15°C and 18°C being the minimum, depending on species, which precludes transmission in areas with ambient temperatures below these levels. Based on modelling, Mordecai *et al*. (2013) predict optimal transmission at 25°C with a strong decrease at temperatures above 28°C.

The peak of malaria transmission follows the rainy season and its length is determined by the balance between precipitation and evaporation (Alemayehu, 2011; Amenu, 2014; FMoH, 2014). Rainfall, apart from supporting mosquito breeding, also affects malaria transmission through increased humidity which contributes to longevity of the adult vector, while altitudes above 2,500 m above the mean sea level (MSL) preclude transmission due to low temperatures (Aster, 2010; Alelign and Dejene, 2016). On the other hand, the Ethiopian lowlands below 1,500 m above MSL in the eastern and south-eastern parts of the country are prone to malaria infection, while the highlands, situated at 1500-2500 m above MSL (northern and central areas) experience malaria epidemics periodically depending on the climate (Abeku *et al*., 2003; Omukunda *et al*., 2013; Alelign and Dejene, 2016). Wind can be both negative and positive for the malaria cycle because strong winds decrease the mosquito biting frequency, while at the same time extending the length of its flight (Endo and Eltahir, 2018). Slope also has a variable impact, *e.g*., areas with high slopes are usually fragile, mountainous and unstable, while gentler elevation variations promote mosquito breeding through water retention (Clennon *et al*., 2010; Alemayehu, 2011). Land use/land cover (LULC) is associated with malaria transmission since vegetation provides a suitable environment for breeding with certain types of plant-cover playing an important role in determining vector abundance irrespective of a strong association with rainfall. It has, for example, been noted that rice irrigation schemes provide excellent breeding sites for *Anopheles* mosquitoes (Ceccato *et al*., 2005), while artificial irrigation aggravate control problems by increasing the number of aquatic larval habitats and extending the duration of the transmission season (Clennon *et al*., 2010; Ashenafi, 2013). The objective of this study was to assess and map malaria risk in the Bahir Dar area in the Amhara region of Ethiopia by an approach based on geographical information systems (GIS) with a remote sensing component. The former supplies the necessary infrastructure for identifying and combining environmental variables, while the latter continuously updates a broad range of environmental measurements and imagery making construction of up-to-date, large-scale risk maps possible (Ceccato *et al*., 2005; Dessalegne *et al*., 2016). This methodology should provide improved prediction capabilities leading to efficient allocation of resources for malaria control and significantly enhance the ability of local communities, government and non-governmental organizations to conduct contingency planning for malaria prevention and elimination.

Materials and Methods

The study area is one of the major malaria risk areas in northern Ethiopia, with different organizations trying to tackle the malaria problem together with the FMoH. However, there is no detailed indication where the most vulnerable areas are situated, which makes risk mapping a priority.

Study area

The Bahir Dar administration in the north-western part of Ethiopia, with a total area close to 370 km^2, is located 567 km from the capital Addis Ababa. It incorporates Bahir Dar City, the capital city of Amhara, located around the geographical coordinates of 11°35'34"N and 37°23'03"E, and three small urban centres (satellite towns), namely Zegie, Tis Abay and Meshenti and their rural vicinities (Figure 1). The whole area is situated on the Ethiopian high plateau at 1,800 m above MSL. Figure 2 shows the general altitudes in Ethiopia and the most pronounced slopes in the South-Eastern

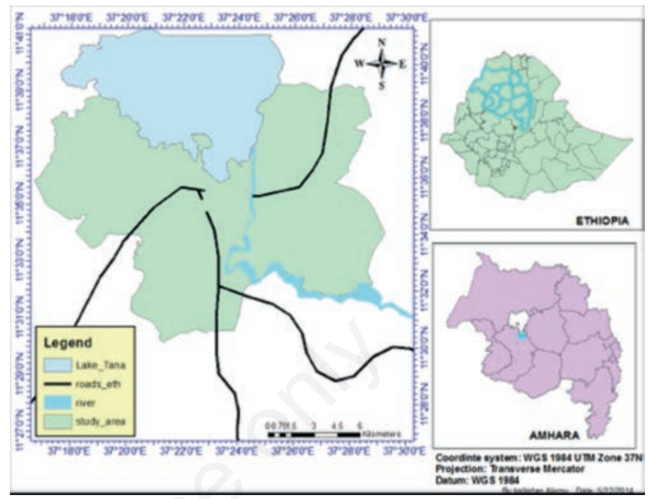

Figure 1. Map of the study area.

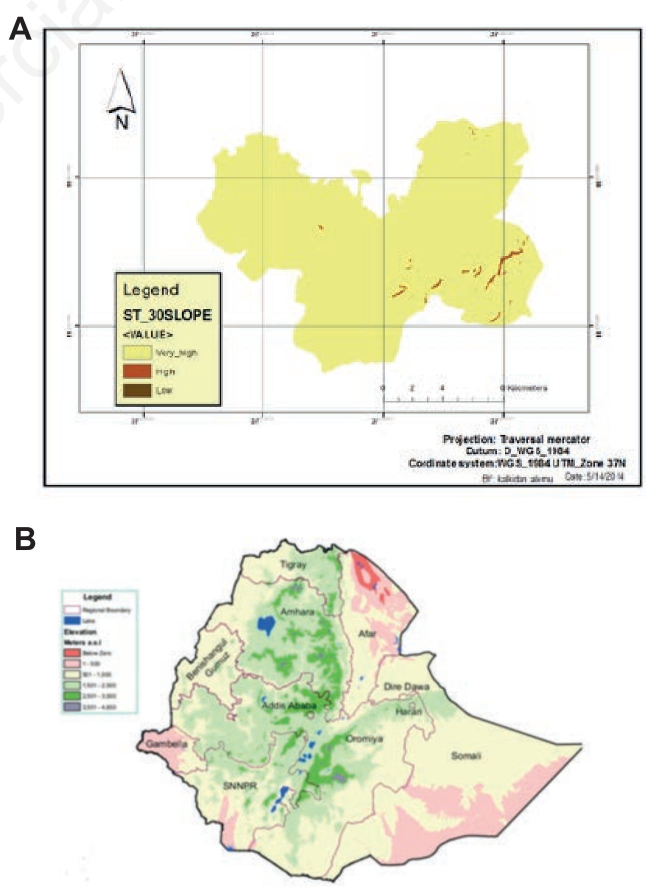

Figure 2. Terrain characteristics. A) Slopes in Bar Dar City; B) Altitudes in Ethiopia.

part of the study area. There are significant seasonal variations of rainfall with around 60% of the annual rains in July and August, the highest temperatures in April (up to 30°C), the lowest in July and August (22-23°C) and wind speeds that can reach 1.8 km. per sec (Amare and Kameswara, 2011). The study area is of highland type and characterized by one international waterway (Abbey River) and Lake Tana, the largest lake in Ethiopia (>3,000 km^2), which is the source of the Blue Nile. Based on the Bahir Dar administration estimation in 2012, the total population of the city was about 277,566, with 135,441 males and 142,125 females. The area included a total of 40,893 households with an average of 4.47 persons per household distributed between 40,097 building units. The population density was 753 persons per km^2.

Data and approach

We examined the relative effect on malaria transmission by temperature, rainfall, terrain (altitude and slope), proximity-related factors (distance from lake, river and health facilities) and LULC. The National Metrological Service Agency, Bahir Dar branch, provided the climatic data, while elevations and other topographic data, collected by the Shuttle Radar Topography Mission, were downloaded from the server of the United States Geological Survey (http://dds.cr.usgs.gov/srtm/). This information, together with shape files from the Ethiopian Mapping Agency, information from the FMoH (2008, 2014) and ancillary data obtained from field surveys, observations and focus group discussions with malaria control experts, allowed us to represent the extent of malaria prevalence over the study area.

The mean temperature and rainfall for each month for the latest 30 years were calculated by regression analysis carried out on Excel 2007. These values were utilized for surface interpolation of temperature and rainfall values over the study area creating layers of inverse distance weight using ArcGIS v.10.2 (ESRI, Redlands, CA, USA) applying the *Spatial Analyst* tool. For proximity-related malaria risk factors, such as distance from the lake, distance from the river and distance to health facilities, the same procedure was followed. Global positioning system (GPS) classification of ground control points, previously used to classify LULC in Bahir Dar, was used to identify distances and to pinpoint locations of the health facilities within the study area.

The values assigned for each variable was based on its estimated level of influence on malaria prevalence identified from prior research and discussions held with malaria experts working in the area. Importantly, influence levels vary from place to place so local conditions needed to be carefully considered before deciding on their relative influence. Since each risk factor has a separate degree of influence there was a need to determine the weight of each of the malaria risk factors chosen. Pair-wise comparison along with the Analytical Hierarchical Process (AHP) introduced by Saaty (1980) was used as a first step in the weighting process. This is a multi-criteria decision method that adopts hierarchical structures to first reduce complex decisions into a series of pair-wise comparisons and then produces the result as a synthesis. The AHP approach captures both subjective and objective aspects assisting judgments based on expert opinion. It also incorporates a technique for checking the consistency of the decision maker's evaluations, thus reducing the bias after decision-makers and experts had filled the comparison matrix. The weight computed for each factor are given in Tables 1 and 2.

Table 1. Environmental factors and their comparative weight.

Factor	Category	Vulnerability	Reference	Weight
Annual rainfall	<800 mm >800 mm	High Very high	Aster, 2010 FMoH, 2009	35%
Ambient temperature (°C)	<15 20-23 23-25 25-27 >30	None Moderate High Very high None	Haque, 2007 Mordecai *et al*., 2013 Brhanie, 2016	15%
Slope (°C)	0-7 7-15 15-20 >20	Very high High Moderate Low	Food and Agriculture Organization (FAO)	10%
Altitude (above MSL)	<2000 m 2,000-2,200 m 2,200-2,400 m 2,400-2500 m >2,500 m	Very high High Moderate Low None	Meron, 2011 Alemayehu, 2011	7%
Distance from water source (lake)	0-500 m 500-1,000 m 1,000-1,5000 m 1,500-2,000 m >2,000 m	Very high High Moderate Low None	Aster, 2010 Arega, 2009	5%
Distance from water source (river)	0-500 m 500-1,000 m 1,000-1,500 m 1,500-2,000 m >2,000 m	Very high High Moderate Low None	Aster, 2010 Arega, 2009	3%

Variables investigated

Although anopheline mosquitoes can fly 10 km, and be carried by wind much larger distances, dispersal studies have shown that 95% of these insects do not move further than around 2 km after breeding (Thomas *et al*., 2013). Since mosquitoes prefer humid breeding places, distance zones of <500, 500-1000, 1000-1500, 1500-2000 and >2000 m from the lake and from the river were drawn up (Figure 3A and B) and ranked (Table 1). Counting from the water source, they were labelled as very high, high, moderate and low regarding malaria hazard with distances exceeding 2000 m counted as malaria-free in principle. With malaria prevention declining in line with the distance from a health facility, we ranked areas from 5-1 if situated within 1000 m, between 1000-1500 m, between 1500-2000 m, between 2000-3000 m or further away than 3000 m, respectively. (Figure 3C; Table 1).

For LULC data (Figure 4), we relied on the French high-resolution, Earth-observation system *Satellite Pour l'Observation de la Terre* (SPOT) (http://eoedu.belspo.be/en/satellites/spot.htm) based on supervised classification using the Earth Resource Dynamic Analysis System (ERDAS) (https://www.dataone.org/software-tools/erdas-imagine). The SPOT imagery was selected for this study because of its high optical resolution and its link to ERDAS image processing software package that allows users to process geospatial and other imagery as well as vector data. The various land covers making up the LULC pattern were ranked based on the importance with regard to malaria as follows: water body fringes and wetlands (5), forest (4), settlements and agricultural land (3) and scrubland (2) where a higher figure infers more importance effect than a lower. GPS data were collected from the field and used as ground truth in the classification process.

When estimating the malaria risk, we emulated the calculations by Shook (1997) who originally applied his formula to express the risk with respect to natural disasters as follows:

$$R = H \times E \times V$$

where R is risk, H hazard, E the degree of exposure and V vulnerability. In Shook's work, H represents a potentially damaging, natural phenomenon of a given magnitude threatening a given area, while R is the probability of H actually occurring within a specified period of time. E refers to the degree at which threatened ele-

Table 2. Base for the calculation of malaria risk based on hazard, distance to health facility and land cover.

Factor	Weight	Category	Rank
Hazard	56%	Very high	5
		High	4
		Moderate	3
		Low	2
		Very low	1
Distance to health facility	26%	0-1,000 m	5
		1,000-1,500 m	4
		1,500-2,000 m	3
		2,000-3,000 m	2
		>3,000 m	1
LULC*	13%	Water body	5
		Wetlands	5
		Forest	4
		Agricultural land	3
		Settlement	3
		Scrubland	2

*Land use/land cover.

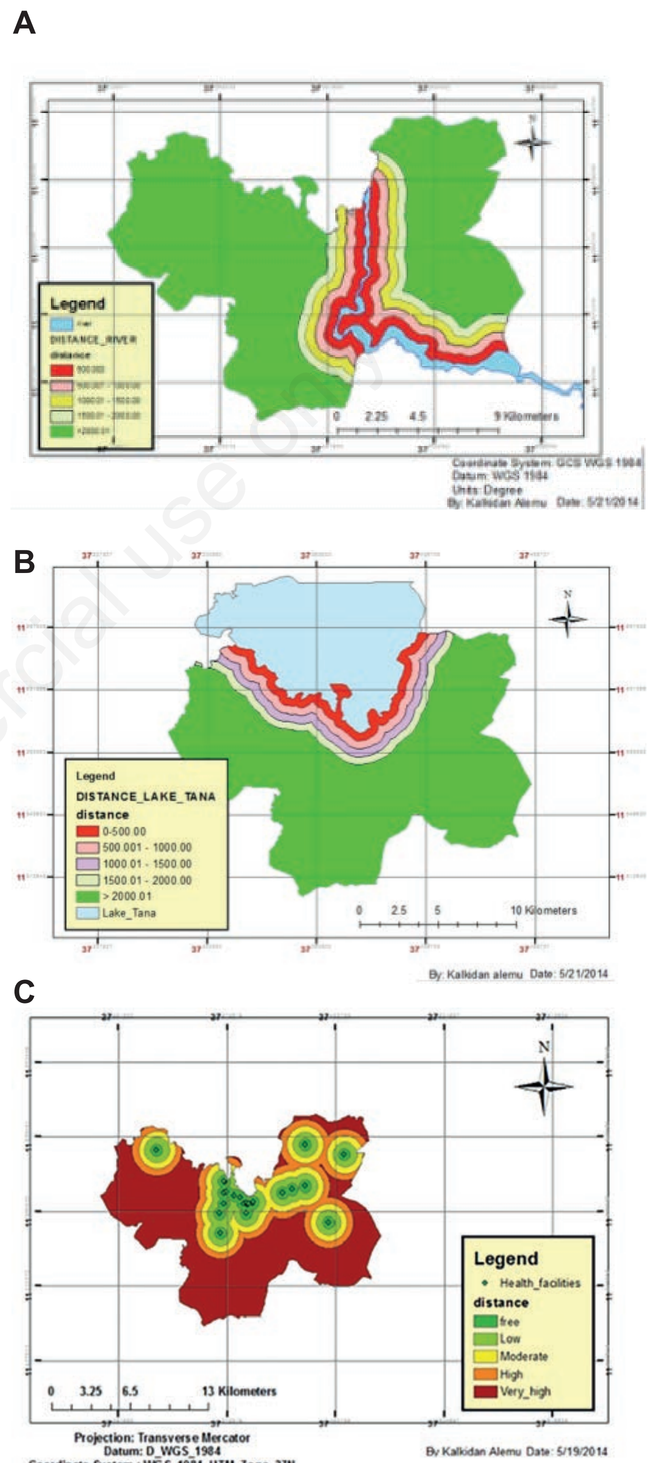

Figure 3. Proximity-related parameters in Bar Dar City. A) Proximity to River; B) Proximity to Lake Tana; C) Proximity to a health facility.

ments, such as populations, property, economic activity, infrastructures, etc., would be directly affected should H actually occur (*i.e.* exposure), while V expresses E's degree of susceptibility to H.

Shook's equation can also be utilized to estimate the risk of an epidemic occurring in a specified geographical area, where H would be the simultaneous presence of a case of malaria together with capable anopheline vectors ready to spread the infection into the wider population (E). The vulnerability can be quite complicated as it depends on the degree of immunity and general health of the population in question as well as its access to care and treatment. We mapped the malaria hazard using the ArcGIS *raster calculator* taking into account related previous work, national malaria guidelines, available reports (FMoH, 2008, 2014) and the different environmental factors as these factors would modulate the core hazard (presence of a malaria case together with capable vectors). Special reference was paid to the temperature as it not only governs vector capability, but also the parasite's requirement inside the vector (Mordecai, 2013; Brhanie, 2016).

Results

As can be seen in Figure 5A, four areas with different levels of malaria hazard were found, *i.e.* very high (11.2%); high (14.5%); moderate (63.3%); low (6%); and one zone free of hazard (5%). The three highest categories (moderate to high) in Bahir Dar City showed a higher hazard (89% of the whole area) than that reported from the Awassa Zuria Woreda in SNNPR which was estimated at 68% by Arega (2009) confirming that the malaria hazard of Bahir Dar City is considerably higher in spite of its higher altitude.

The map of malaria risk, *i.e.* the probability that malaria would spread in the population and the expected degree of loss due to malaria infection, was based on the equation formulated by Shook (1997) where E and H represented the population and the hazard, respectively, with V being the population's vulnerability based on proximity of health stations and LULC (Table 2). The outcome showed that most of the study area is at risk for malaria (Figure 5B), with a majority of the kebeles (small administrative units) subject to high or very high risk of malaria. Four areas with different levels of malaria risk were found, *i.e.* very high (65%); high (15%); moderate (8%); low (5%); with only 2% of the area without risk (Figure 5B). Hence, it can be concluded that the great majority of Bahir Dar City (around 80%t) is at high to very high risk for malaria.

Discussion

As everywhere else, the malaria transmission intensity in Ethiopia, along with its temporal and spatial distribution, is determined by climatic conditions (Thomson *et al*., 1996; Abeku *et al*., 2003; Ceccato *et al*., 2005; Abiodun *et al*., 2016). A large part of the country is situated on a plateau, varying between 1500 and 2000 m above MSL, where the higher levels due to cooler temperatures experience malaria as occasional epidemics rather than through constant transmission (Bautista *et al*., 2006; Patz *et al*., 2008). The Ethiopian plateau forms the largest continuous high-altitude in Africa making altitude prominent among the variables affecting malaria transmission at these latitudes. Bahir Dar City at

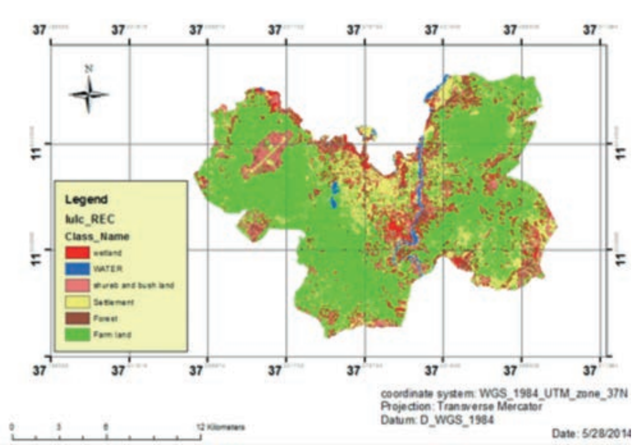

Figure 4. Land use and land cover.

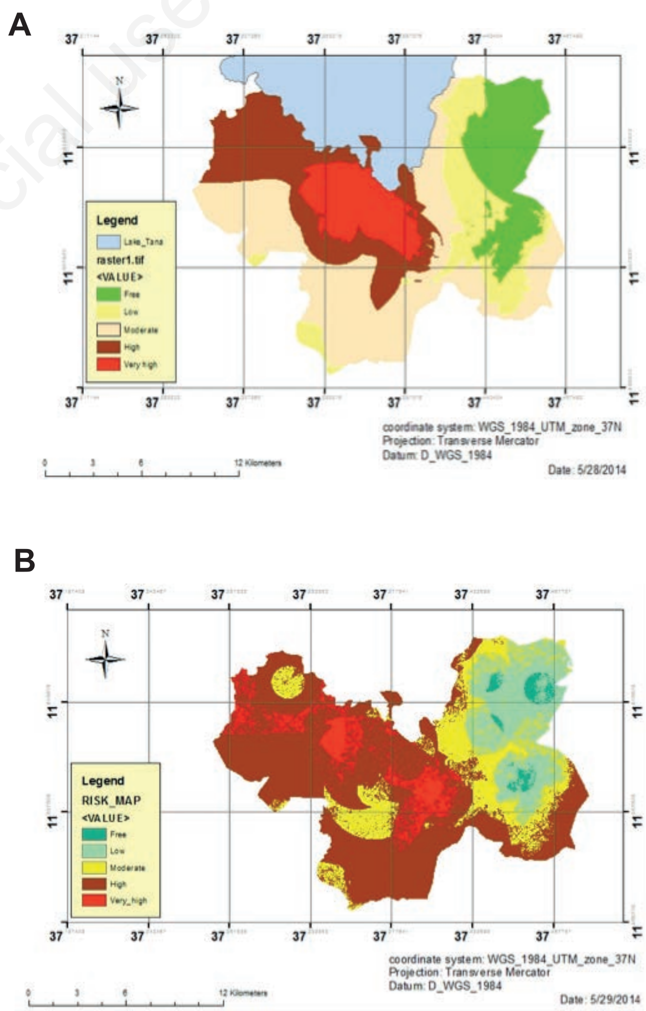

Figure 5. Variability of malaria risk in Bar Dar City. A) Malaria hazard map; B) Malaria risk map.

1,800 m above MSL supports malaria transmission annually since the annual temperature there seldom sinks below 22°C.

A rise in temperature enhances the survival chances of both *Anopheles* mosquitoes and malaria plasmodia and can thus accelerate transmission dynamics. However, an increase in temperatures does not mean an increase in malaria transmission if accompanied by a decrease in rainfall, since lack of water prevents development of the vector. At low temperatures, the vector needs to survive longer for the saprogenic cycle to take place, while temperatures above 30°C counteracts mosquito survival (Mordecai *et al*., 2013; Brhanie, 2016) (Table 1).

Rainfall creates favourable conditions for the mosquito malaria vectors (Rogerson, 2006; Omukunda *et al*., 2013; Abiodun *et al*., 2016). Although the mean annual rainfall in the study area is limited to about 800 mm annually, it is sufficient to support malaria transmission. Indeed, a study conducted in Boricha Woreda of Ethiopia at just a slightly lower altitude than Bahir Dar where the rains vary between 700 and 1200 mm per year has shown that this level of rainfall is sufficient for malaria transmission (Aster, 2010).

The study area contains strongly climbing slopes (>20°) which do not support anopheline vectors, but it also have many lower slope associated with very high (0-7°), high (7-15°), moderate (15-20°) of malaria hazard, respectively (Aster, 2010) (Figure 2). Such conditions accelerate chances for water stagnation creating waterlogged areas favourable for both mosquito breeding and mosquito survival (Thomson *et al.*, 1999; Hailegiorgis *et al*., 2010).

Mosquitoes require motionless or slow-moving water to lay its eggs and to complete its life cycle. Rivers are therefore not conducive for this (Bekele *et al*., 2014), but the neighbourhood areas support mosquito breeding thanks to the increased humidity. Thus, proximity to water bodies is one of the factors associated with the malaria hazard. Another factor that also depends on proximity are those surrounding health facilities, which are not only important for treatment of patients, but also influence the prevalence of disease in the locality by the creation of awareness through its staff who knows the malaria situation in the immediately surrounding area, which translates into people living near health institutions are safer than those living further away (Aster, 2010, Hailegiorgis *et al*., 2010, Meron, 2010) (Figure 3).

Mosquito habitats differ according to the nature of local environment, *e.g*., with regard to vegetation. LULC classes with plantations have a strong association with malaria (Hailegiorgis *et al*., 2010), which was confirmed in the study area where a high incidence of malaria coincided with the prevalence of farms and vegetation lands. Special types of vegetation not only provide excellent breeding sites, but are also ideal sites for resting for adult mosquitoes as well as protection from adverse climatic conditions (Aster, 2010). Wetlands and agro-forestry areas accentuate the malaria hazard from that point of view (Haque, 2007). This study underlines the risk due to the fact that majority of the area is covered by farm lands and open vegetation (Figure 4).

Highlands should be recognized as areas of concern with respect to malaria and other vector-dependent infections. Recent evidence for an increase in the altitude of malaria distribution in Africa and South America (Siraj *et al*., 2014; Alelign and Dejene, 2016) confirms an earlier mathematical model identifying epidemic-prone regions in the African highlands (Lindsay and Martens, 1998). This implies that the malaria burden in the highlands of the tropics will grow if the global warming trend continues. Indeed, even a minor change in areas where malaria transmission is unstable could precipitate serious epidemics.

Conclusions

Malaria is a disease with high mortality that causes much suffering in the world. Various variables govern the level of risk with respect to this disease and GIS provide the necessary technology for identifying and combining these different variables, while RS plays the important role of providing the necessary environmental information. Planners and decision-makers should use these technologies to generate their information for further decisions. The malaria risk map is essential for this work and should contribute to the establishment of reliable early warning systems.

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