# Use of remotely sensed environmental and meteorological data for mapping malaria and dengue entomological risk

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**Abstract.** Environment, climate and human activities play an important role in determining vector distribution and vector-borne diseases epidemiology. A better understanding of the contribution of those ecological factors on the spatio-temporal dynamics of mosquitoes may lead to improvement of controlling measures. In the present study, it is thought that the conceptual approach (CA) of Tele-epidemiology developed by the French Spatial Agency and its partners could be applied to spatio-temporal mapping of entomological malaria risk in urban settings and entomological dengue risk.

In Dakar, Senegal, a large amount of entomological data was collected (2007 - 2010). Appropriate satellite environmental and meteorological data were acquired in order to model the presence of water bodies, the presence of *Anopheles gambiae s.l.* larvae in those water bodies and the *An. gambiae s.l.* Human Biting Rates. In Tartane, Martinique, entomological field data consisted in the routine surveillance data collection. Very high spatial resolution data were used to map the environmental elements that may be associated with the presence and type of *Aedes aegypti* breeding sites in houses.

In Dakar, the first mapping level predicted the potential *An. gambiae s.l.* larval habitats (depending upon the predicted presence of water, the environmental and meteorological conditions). The second level was a map of the *An. gambiae s.l.* HBR (driven by surfaces and potential productivity of larval habitats, urbanization levels and rainfall amount). In Martinique, the basic information has been prepared in order to further apply the Tele-epidemiology CA to the mapping of dengue vectors.

**Keywords: R**emote Sensing, malaria, dengue, entomology, risk maps.

## 1. Introduction

Malaria is caused by a *Plasmodium* parasite transmitted among humans by the female mosquitoes/vectors of the *Anopheles* genus. Dengue is an infectious disease caused by one of the four serotypes (DEN-1 to DEN-4) of a dengue virus, transmitted to humans by the bites of infected female mosquitoes of the genus *Aedes*. The location of the vectors larval habitats and their dynamics are the primary determinants of the spatial and temporal distribution of malaria transmission. Transmission units are defined as the systems where the larval habitats are the sources for the pathogen transmission [Carter et al. (2000)]. Indeed, mosquitoes emerging from larval habitats have a somewhat limited flying range which depends on environmental conditions. Malaria and dengue risk is thus heterogeneous in space and time, as it is driven by the proximity and dynamics of the larval habitats. Risk is further weighted by the dispersion and survival rates of adult mosquitoes, the availability of reservoir and the human vulnerability (which depends on availability of protection and preventive devices as well as acquired individual immunity).

It is known that environment, climate (mainly rainfall amount and distribution, and temperature) and human activities play an important role in determining the vector distribution and vector-borne diseases epidemiology. A better understanding of the contribution of those ecological factors on the spatio-temporal dynamics of mosquitoes associated with malaria and dengue may lead to improvement of controlling measures. Indeed limited resources imply to focus the actions in places and time where they are the most useful. It has been argued that remote sensing technology has become a pre-requisite tool to assess the malaria burden, to model its spatio-temporal distribution, and plan effectively malaria control. The latter are key elements to implement within an operational system and thus to facilitate overall real-time monitoring of human health [Machault et al. (2011)].

Along the history of tropical medicine, maps had held different roles that depended on the era and the technical possibilities. Their objectives may be: communication, illustration, medical research or tool for public health policies. From the 90's, disease mapping strongly evolved with the introduction of the Geographic Information Systems (GIS) [Birchenall (2010)] that allow the collection, storage, integration, analysis, and display of spatially referenced data. Risk maps have been defined in [Kitron (2000)] as "outcomes of models of disease transmission based on spatial and temporal data", incorporating "to varying degrees, epidemiological, entomological, climatic and environmental information", and they have been applied to numerous diseases for mapping a current situation or even anticipating outbreaks with Early Warning Systems [Bergquist (2001)]. Numerous reviews have been published in the last years, attempting to describe spatial and/or temporal mapping and modeling of vector diseases using GIS and Remote Sensing (RS) information [Beck et al. (2000); Bergquist (2001); Hay et al. (2000); Machault et al. (2011)] with some inputs on the operational orientation of disease mapping.

In the present study, it is thought that the conceptual approach (CA) of Tele-epidemiology [Marechal et al. (2008)] could be applied to spatio-temporal mapping of entomological malaria risk in urban settings and to dengue risk. This CA has been developed and patented by the French Spatial Agency (*Centre National d'Etudes* Spatiales - CNES) and its partners, and consists in monitoring and studying human and animal disease dynamics which are closely related to climate and environment variability: i) choice of appropriate satellite data and dynamical models are evaluated, ii) all results are assessed and double-checked with extensive in-situ measurements allowing for identification of key biological processes. The objective here concerning malaria was to develop a robust operational methodology to produce entomological malaria predictive risk maps. The whole methodology relied on predicted vector risk areas (obtained from Human Biting Rate, or HBR) which were centred in the vicinity of predicted *Anopheles gambiae s.l.* larval habitats. The objective concerning dengue was to start to investigate how the CA could provide information on the distribution and type of *Aedes aegypti* breeding sites in a dengue epidemic area.

## 2. Methodology

### 2.1 Malaria

The city of Dakar is the capital of Senegal and is located in the Cap-Vert Peninsula. The sahelian climate is modified by the proximity of the Atlantic Ocean, and the summer rainy season lasts from June to November, with average temperatures between 24°C and 30°C and average rainfalls of about 400 mm, while the cool and drier season lasts from December to May with average temperatures between 19°C and 25°C.

Entomological field studies have been undertaken during September-October of 2007 and during July 2008 to June 2010 and are detailed in [Gadiaga et al. (2011); Machault et al. (2009)]. Briefly, the monitoring study was conducted in Dakar, Pikine, Thiaroye and Guediawaye, in a total of 45 zones each covering a 200 x 200 m approximate area. Adult mosquitoes sampling was carried-out approximately in the centre of the 200 x 200 m zones, once every two weeks in each studied zone through human landing catch, for a grand total of 3,096 person-nights of capture, allowing to calculate the Human Biting Rate (HBR, number of *Anopheles* bites per person per night). Exhaustive search of all type of water bodies was undertaken every 10 days and for each zone. The latter were mapped using a Global Positioning System (GPS) device (5 m minimum precision) while physical, chemical and biological parameters (size, shade, floating and surrounding vegetation, water temperature, persistence along weeks) were recorded, including Anopheles larvae density.

SPOT-5 (Satellite Pour l'Observation de la Terre) images were programmed in order to be contemporary to the field work and were acquired during the three summer rainy seasons for the following dates: September 26, 2007, September 24, 2008, September 28, 2009, as well as during one dry season (May 11, 2009). A Digital Elevation Model (DEM) at 90 m spatial resolution was available from the Shuttle Radar Topography Mission (SRTM version 4.1). Decadal Moderate Resolution Imaging Spectroradiometer (MODIS-Terra) images were available at 1 km spatial resolution for the full duration of the field work. Ground measurements of daily rainfall event were available from the Senegalese weather agency for years 2007, 2008 and 2009.

A GIS was built in ArcGIS 9.2 (Environmental Research Systems Institute, Redlands, CA, USA) and statistical analyses were performed using Stata 11 (Stata Corporation, College Station, Texas). All ground information (water bodies and larval habitats, HBR, rainfall) was included in the GIS whilst processed images (indicators, LULC, LST, altitude) were added as georeferenced layers. Regressions between environmental and meteorological variables and presence of water or not (Step 1, logistic regression), presence of *Anopheles gambiae s.l.* larvae or not (Step 2, logistic regression) and *An. gambiae s.l.* HBR (Step 3, negative binomial regression), were fitted using all environmental and meteorological indicators as explanatory variables.

### 2.2 Dengue

The studied area for dengue work has been chosen in Tartane, a location of the Caravelle peninsula, in the North East of Martinique. The centre of the village is located by the seacoast but some houses have been built in the hills. Dengue epidemics that occurred in 2001 and 2010 have started in this area of the island. Dry season occurs from February to March while rainy season lasts from July to October. The study period was chosen from June 2009 to August 2011, as an extended period of the 2010 epidemics.

Entomological field data consisted in the routine surveillance data collection undertaken by the "*Centre de Démoustication/Lutte Anti-Vectorielle*" of Fort de France. Briefly, field workers repeatedly visited houses of the studied area and recorded the presence/absence of potential breeding sites that were filled with water, the number of water bodies that were positives with *Aedes* larvae and the type of water bodies.

Regarding the known ecology of *Aedes aegypti* which is the dengue vector in Martinique and that is mainly defined by small breeding sites and low dispersal, the experimental study unit has been chosen as: the house and its close environment (garden, yard, neighbors). Indeed, even the highest spatial resolution image could not allow to directly map the *Aedes* larval habitats. In consequence, remotely-sensed data has been acquired and treated in order to characterize this study unit and further investigate the environmental and meteorological determinants of the presence of breeding sites. The exact size of this study unit will further be refined using the results of the statistical analysis and several scales are expected to play a role in the presence of the vector (*e.g.* fine scale = type of house, trees in the garden, and large scale = density of houses in the neighborhood, presence of nearby vegetation).

As the size of the experimental study unit was small, a very high resolution image was chosen. A Goe-Eye-1 image at 0.5 m spatial resolution has been acquired from archive images for 13/03/2011. It has been orthorectified using the 50 m Digital Elevation Model of IGN (*Institut National de l'Information Géographique et Forestière*). Pixel-based and object based classification were undertaken, as well as calculation of several environmental (vegetation, humidity, soil) indices.

Meteorological data were available from two ground stations located nearby the studies zone. They provided daily precipitation and temperature data. In addition, radar data was available at 1km spatial resolution and hourly rainfall information. The latter is of particular interest as it allows taking into account the spatial heterogeneity of rainfall.

## 3. Results and discussion

### 2.1 Malaria

First step was for detection of water bodies in Dakar. Each observation included in the logistic regression (n=48,858) corresponded to the presence/absence of water, based on the maximum water area recorded on the ground in the 45 studied zones during the 3 studied years, at 10 m resolution. In the global univariate and multivariate analysis, the SPOT-5 Modified Normalized Difference Water Index (NDWI) of the rainy season and the SPOT-5 NDVI of the dry season were positively associated with the presence of water while the SPOT-5 built-up area and the altitude from DEM were negatively associated. The inversion and extrapolation of the model allowed drawing one map for the water bodies for each year, at 10 m spatial resolution.

Step 2 highlighted the environmental and meteorological determinants of the presence of *An. gambiae s.l* larvae or not, recorded during the field work. In the global univariate and multivariate analysis, the SPOT-5 NDWI Mc Feeters and the SPOT-5 Soil Brightness Index (BI) of the dry season, as well as the current night MODIS LST and the total ground rainfall in the preceding 30 days were positively associated with the presence of *Anopheles* larvae in the water bodies. The NDWI Mc Feeters and the Soil BI, as both environmental explanatory variables for the presence of larvae, were computed, using GIS, in and around each water body predicted during the first step. For every single day of the full duration of the study, including daily LST and rainfalls, the inversion of the multivariate global model allowed drawing daily maps of the probabilities of presence of *An.gambiae s.l.* larvae in water bodies. Figure 1 provides zoom images of the predicted probability of presence of *An. gambiae s.l.* in three districts of Dakar, calculated at the level of the water bodies predicted at step 1.

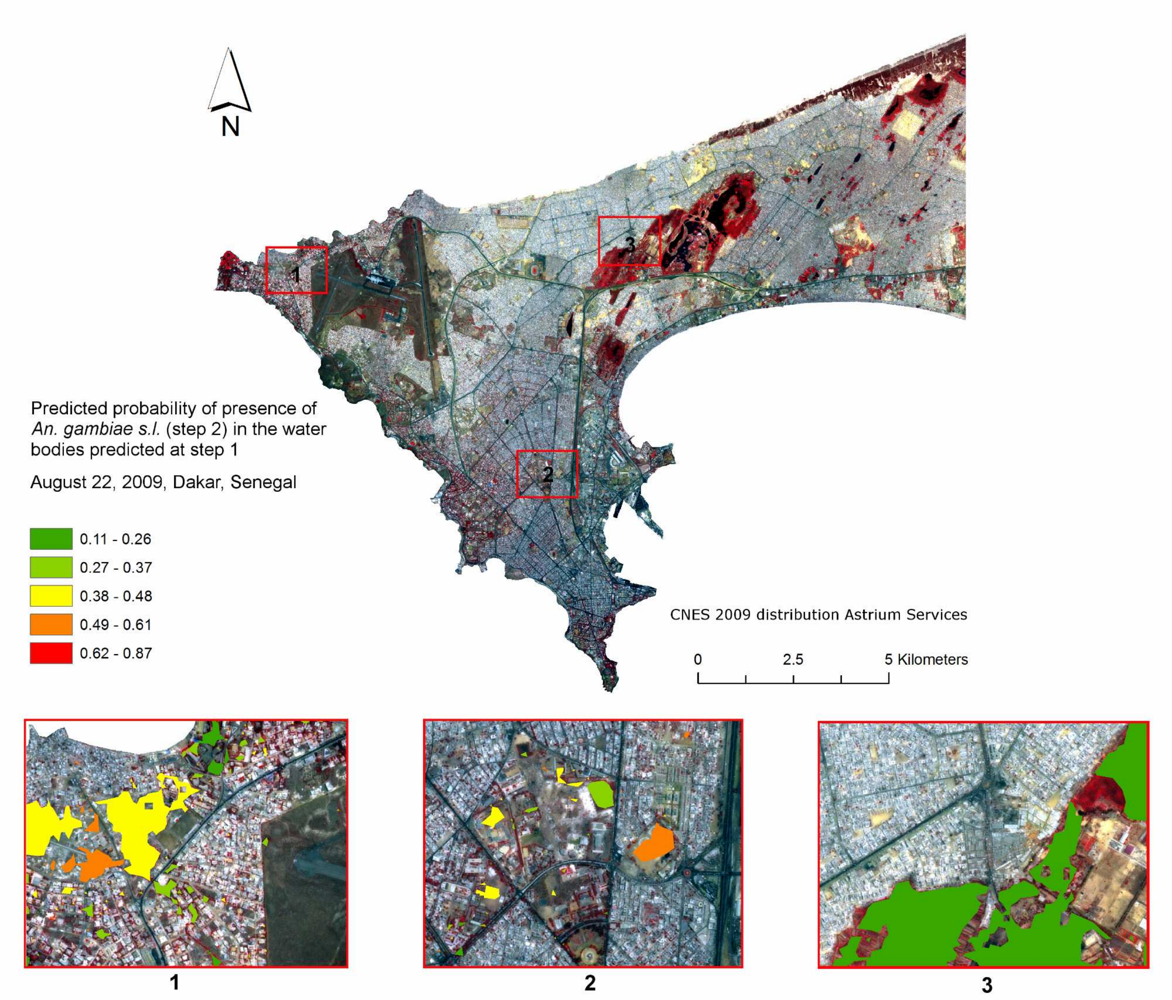


Figure 1. Predicted probability of presence of *An. gambiae s.l.* larvae (step 2) for August 22, 2009 in the water bodies predicted at step 1.

Step 3 allowed defining the relationship between the predicted larval productivity surrogate and the field measured HBR, in order to generate *An.gambiae s.l.* HBR maps . In the global univariate and multivariate analysis, the *Anopheles* larval productivity surrogate (sum of the probability of presence of larvae calculated at step 2 from 30 to 1 days before the actual adult catching night, since the daily vector survival rate is estimated at 82% in the Dakar peninsula [Vercruysse (1985)], summed-up in 200 m buffers and rings going from 300 m to 1,000 m of the catching points, the weight decreasing with distance) and the ground rainfall in the preceding 7 days were positively associated with the HRB whereas the SPOT-5 built-up and asphalt surface were a protective factor. The inversion of the global model allowed the daily prediction of the *An.gambiae s.l.* HBR at any location in Dakar with 10 m spatial resolution (Figure 2).

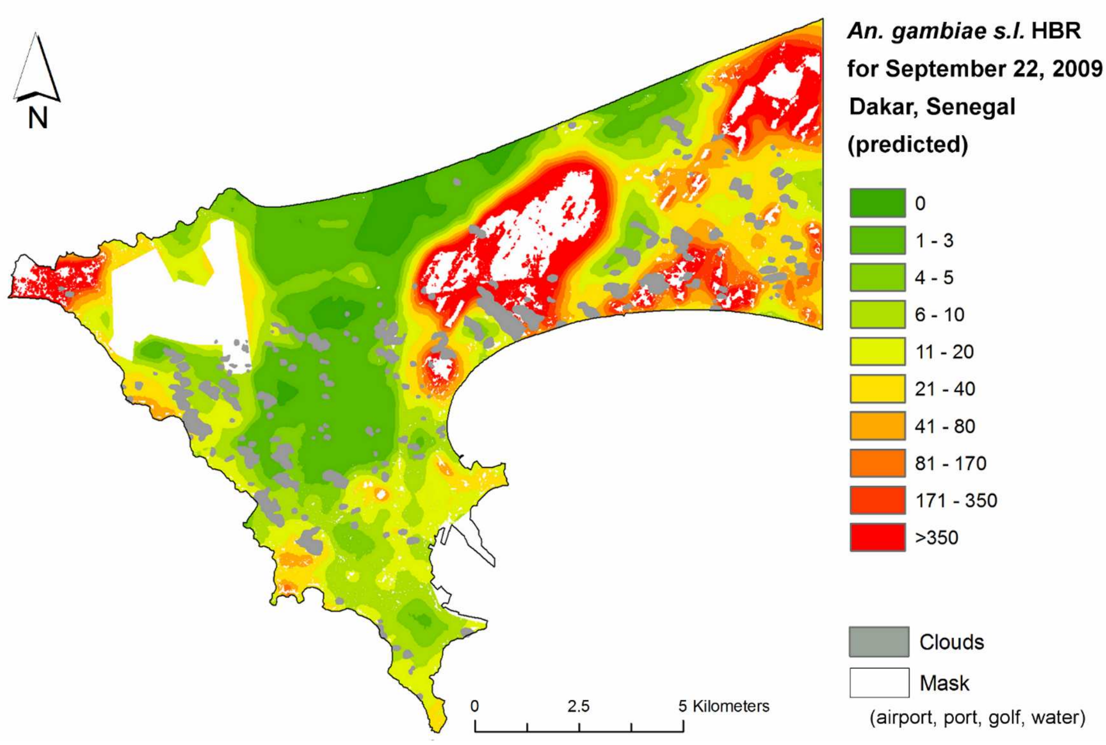


Figure 2. Predicted *An.gambiae s.l.* HBR (step 3, number of bites per person per night) for September 22, 2009.

Modelling malaria risk requires as a first step, to model the entomological risk. In the present study, a step-by-step mapping approach has been followed in order to closely relate modelling and the biological and physical mechanisms of the presence of water bodies, the larval development and of the adult survival and dispersion. The temporal resolution of larvae and adult *Anopheles* mapping was daily, allowing weekly, monthly and/or yearly maps production that could help in mosquitoes control within Dakar.

### 2.2 Dengue

Photo-interpretation of the results of pixel-based and object-based classifications and calculation of kappa coefficients allowed identifying the strengths and weaknesses of both techniques, in the context of the present study. Indeed, some elements of the land cover had to be particularly well classified in the aim of characterizing the experimental study units (*e.g.* building, gardens, and trees). The buildings were better mapped using the object-based method while the accuracy of the classification of the vegetation, trees, and bare soils was higher using the pixel-based method. The creation of a composite classification image allowed improving the global accuracy of the land cover classification. This layer has been added in a GIS containing the entomological data in order to further apply the Tele-epidemiology CA.

## 4. Conclusion

The Tele-epidemiology CA has been successfully applied for mapping entomological malaria risk in sub-Saharan urban setting. Remotely-sensed environmental and meteorological data, associated with a large amount of ground entomological data collected specifically, allowed setting-up a robust operational methodology to draw different levels of malaria entomological dynamic risk maps that could be of interest for planning and targeting malaria control in urban settings. The first mapping level predicted the potential *An. gambiae s.l.* larval habitats in Dakar (depending upon the predicted presence of water, as well as environmental and meteorological conditions) that could guide local larval management. The second level was a map of the *An. gambiae s.l.* HBR (driven by surfaces and potential productivity of larval habitats as well as urbanization levels and rainfall amount) which could guide adult mosquitoes control activities and could help concentrating and reinforcing awareness and information messages to local inhabitants. The results of the present study could be seen as providing the basic elements for real-time monitoring of human health.

Basic information has been prepared in order to apply the Tele-epidemiology CA to the mapping of dengue vectors. The expected results should allow to better understand the impact of environmental and meteorological determinants on the spatial and temporal distribution of *Aedes*.

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