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Application of GIS and remote sensing in the identification of environmental determinants of the spatial distribution of *Anopheles gambiae* sl and *Anopheles funestus* in the health district Ouidah-Kpomassè-Tori Bossito

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Abstract

Every year in the world, more than 3 billion people are exposed to therisk of malaria and there are more than 500 million acute cases resulting in more than one million deaths. This work aims to describe the area's risk of malaria due to the species *An. gambiae* and *An. funestus* in the Ouidah-Kpomassè-Tori Bossito health area. The scientific approach is based on the collection, evaluation and processing of climatological data (temperature, precipitation, number of rainy days, relative humidity, wind, visibility and vapor pressure);geographical data (hydrography, relief, and localities); biotic data (human presence and vegetation) and entomological data (nocturnal catches of mosquitoes on human bait and larval surveys). This study shows a spatial dependence and the fact that space (absolute) is insufficient to explain the observed distribution.Wind, visibility, rainfall, temperature, and distance from localities to watercourses are the determinants of the spatial distribution of *An. gambiae* and *An. funestus*. From these results, two models were developed and were used to develop distribution maps of the two malaria vector species. Thus, *An. funestus* species prefers the southeastern regions where swamps and aquatic meadows predominate, whereas *An. gambiae* has a wider distribution.

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Introduction

Each year worldwide, more than 3 billion people are at risk of malaria and there are more than 500 million acute cases resulting in more than one million deaths (NMCP, 2011). According to the same source, in endemic African countries, 25-35% of consultations, 20-45% of hospitalizations and 15%-35% of deaths in hospitals are due to malaria, which is a considerable burden on already fragile health care systems.

In Benin, malaria is the most common disease and accounts for 35% of the reasons for attendance and hospitalization recorded in health centers nationwide (SNIGS/MS, 2009). In the Ouidah Kpomassè -Tori Bossito health zone, despite the efforts of the various actors involved in the fight against this disease, malaria is and remains omnipresent. Why malaria has continued to be a major public health problem for several decades, and it is now widely accepted that vector control will only be effective in the long term if there is a thorough knowledge of vector transmission cycles, biology and ecology. The failure to take into account the behavioural heterogeneity of the vectors involved in the transmission system, i.e., the lack of knowledge of the biology and ecology of the vectors, has undoubtedly been at the root of the failures recorded in the eradication of malaria in Africa (Chauvet *et al.*, 1969). The current state of knowledge on the ecology of anopheles remains insufficient to allow effective vector control measures to be put in place. For example, the causes of spatial heterogeneity observed in the abundance and distribution of members of the *Anopheles gambiae* complex are still unknown (Somé, 2010). The application of GIS and remote sensing is a prerequisite for taking into account this spatial heterogeneity in vector control programs.Since Earth observation satellites have been in orbit, they have been widely used to answer health questions. Much work has benefited from the environmental information provided by space platforms for the study of infectious diseases, using image processing techniques, GIS and GPS (Bio-Bangana, 2013). Among these diseases, malaria has been the subject of much research and risk maps and models have been developed at all levels of the transmission cycle to assess or predict different malaria indicators. In addition, remote sensing data have made it possible to obtain maps of human populations, which is an essential point in assessing the number of people at risk of malaria and the burden of the disease (Machault, 2010). Keeping the devastating effects of this disease in mind, this study aims to apply GIS and Remote Sensing to identify the environmental determinants of the spatial distribution of *Anopheles gambiae sl* and *Anopheles funestus* in the Ouidah-Kpomasse-Tori Bossito health district in the Republic of Benin.

Materials and methods

Study area

The Ouidah-Kpomassè-Tori Bossito health district is located in southwest Benin, between 1°56' 30'' and 2°16' 20'' east Longitude and between 6°18' 30'' and 6°38' 20'' north Latitude (Fig. 1). It is bordered to the north by the municipality of Allada, to the east by the municipality of Zè and the municipality of Abomey-Calavi, to the west by the municipalities of Bopa, Comé and Grand-Popo and, finally, to the south by the Atlantic Ocean. Its surface area is 783,763 km^2. The relief is flat, almost monotonous. The highest locality in the area, reaches a height of more than 78 meters. The average altitude is 39.62 m. More than 75% of the area is between 12 and 101 meters (Bio-Bangana, 2013). The soils are very diverse. The mineralogical composition of the soil can promote mosquito breeding, especially when combined with high humidity (Assoko, 2005).

Collection methods

The methodology used is essentially based on the collection and processing of entomological and environmental data. Entomological data can be used to account for people's exposure to malaria transmission, which is essential for studying the geography of malaria. These data were collected through nocturnal catches of mosquitoes on human bait (Djènontin, 2010) and larval surveys using the Bruce-Chwatt method in 1985 (Bruce-Chwatt, 1985; Bio-Bangana, 2008).

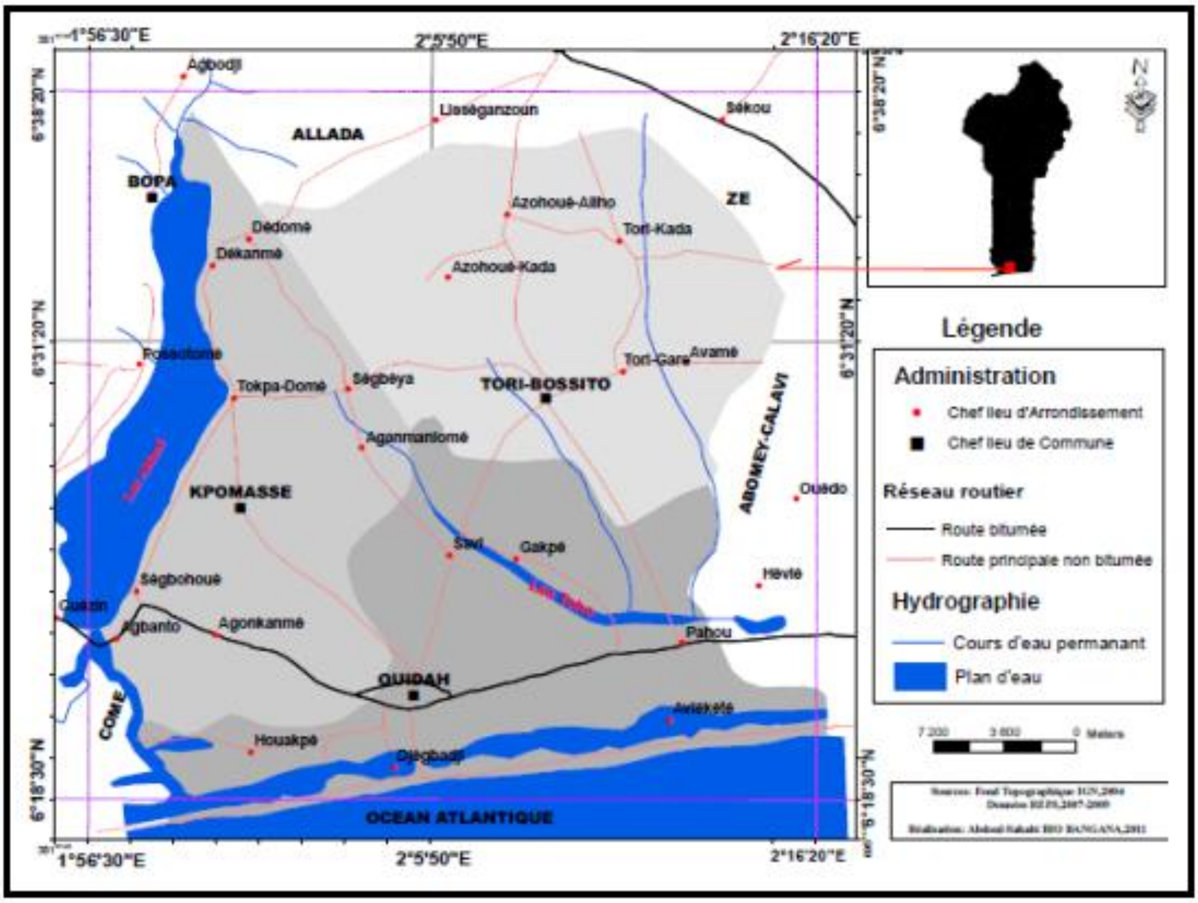

Fig. 1. Ouidah-Kpomassè-Tori Bossito health district Administrative map.

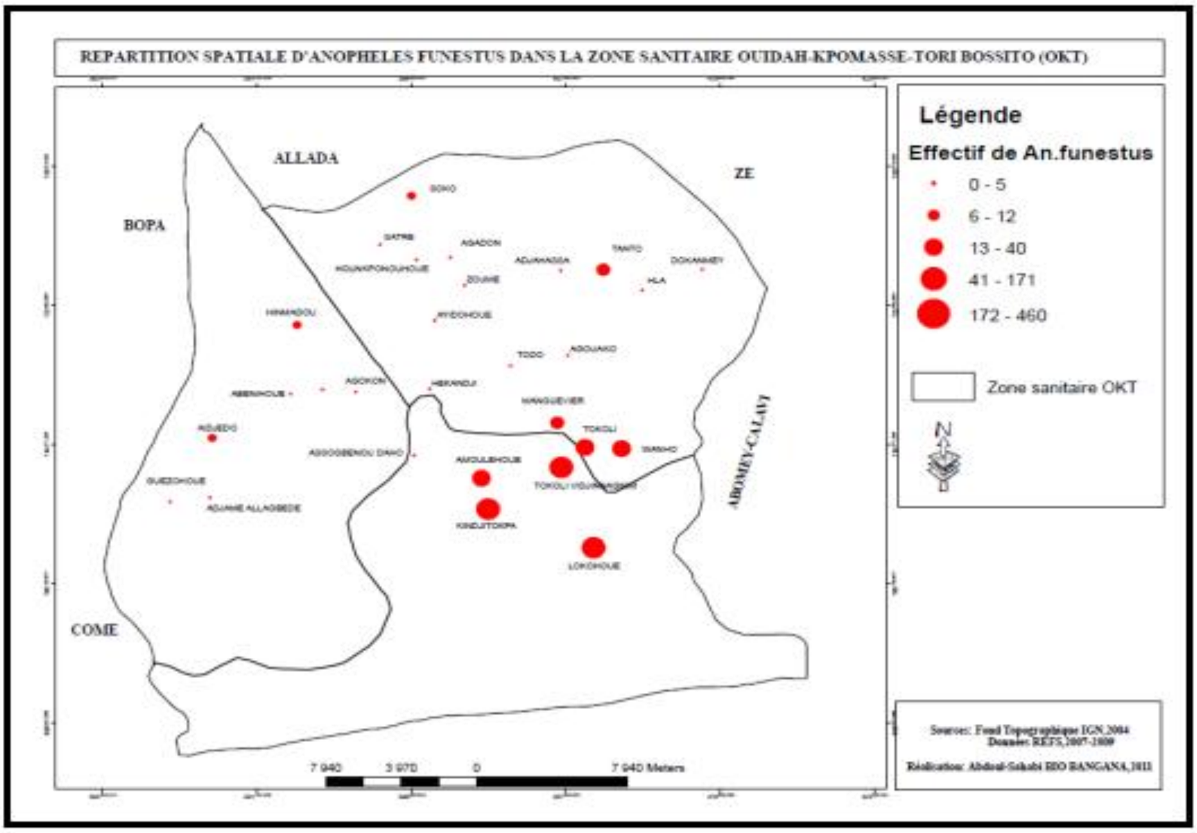

Fig. 2. Spatial distribution of *Anopheles funestus.*

The collection of these data covers the period from October 2007 to December 2009. Every six weeks, a mosquito capture mission was organized. A total of 17 entomological missions were carried out. Environmental data are varied and cover several areas: climate data, geographical data and biotic data. Climatological variables include temperature, precipitation, and number of rainy days, relative humidity, wind, visibility and vapour pressure.

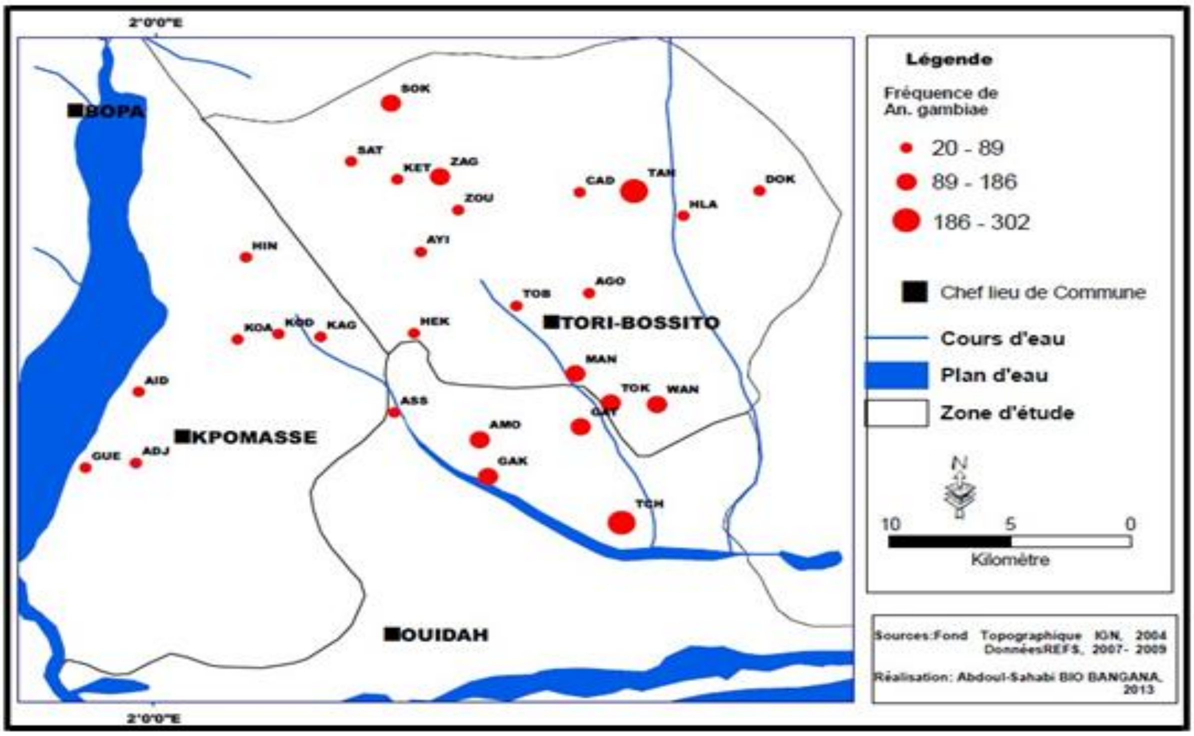

Fig. 3. Spatial distribution of *Anopheles gambiae*.

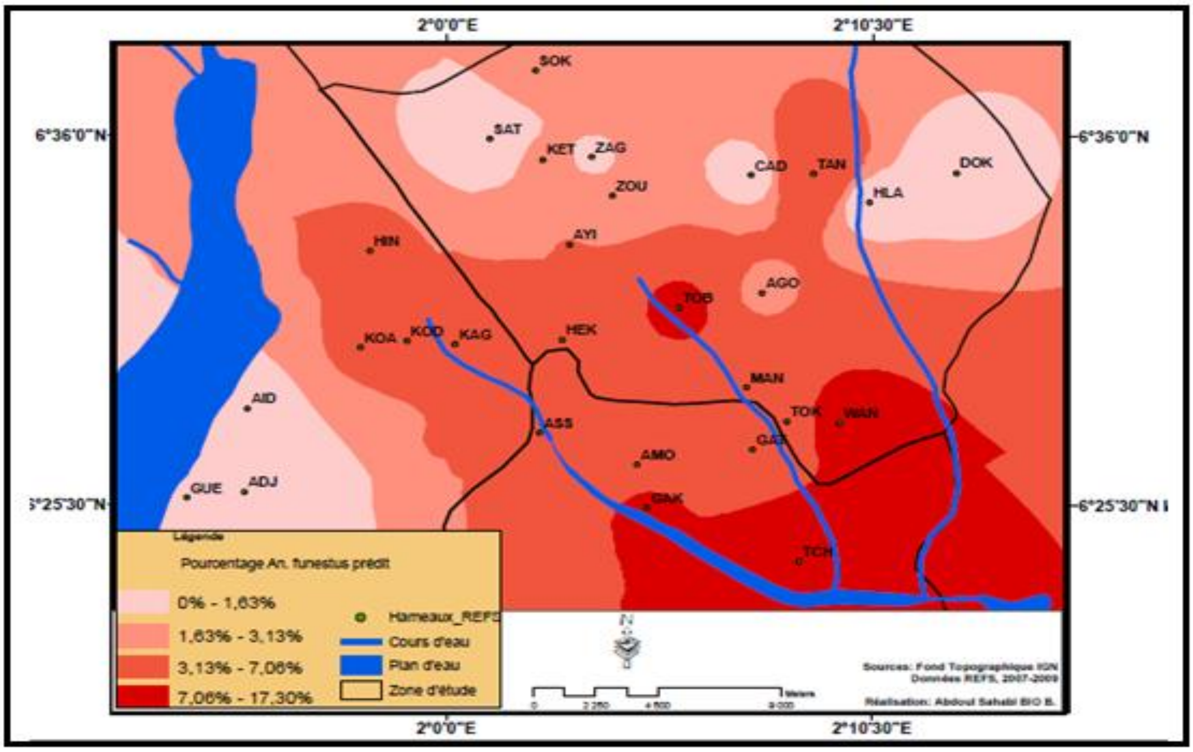

Fig. 4. Prediction of the spatial distribution of *Anophelesfunestus*percentages.

The geographical variables include hydrography, relief, localities from the General Directorate of Water's hydrography database, the CRU Digital Terrain Model, the INSAE Database in 2002 and hamlet census data from the REFS Project in 2007.

The biotic variables are composed of human presence and vegetation (NDVI), which were obtained respectively from the 2007 population census by the REFS/ CREC project and the SPOT Vegetation image covering the period from 1 July to 31 October 2005.

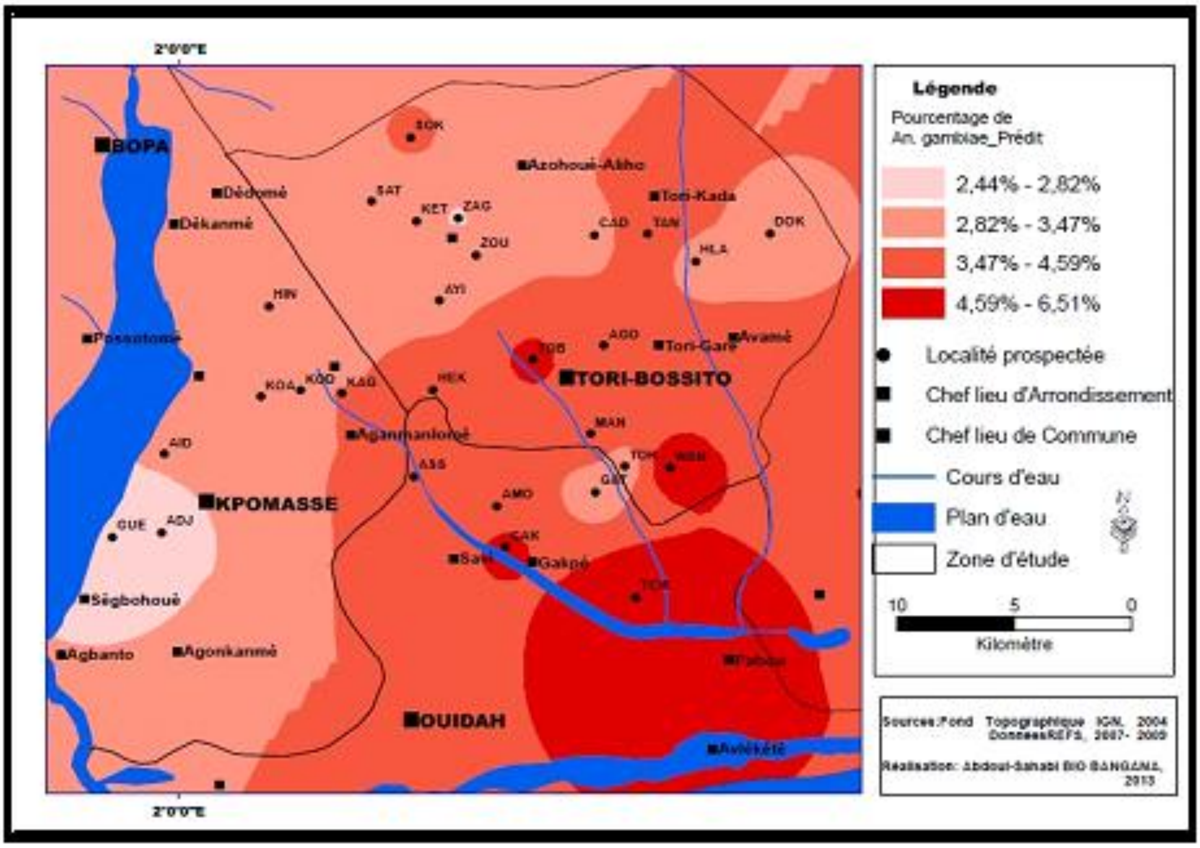

Fig. 5. Prediction of the spatial distribution of *Anopheles gambiae* percentages.

Data processing

Descriptive spatial analysis using ArcGis 10.3 software was used and consisted in the analysis of the spatial structure through the use of indices (Moran, Getis-Ord General G, Anselin Local Moran and Getis-Ord Gi*).Five interpolation methods were used: Global Polynomial Interpolation (GPI), Local Polynomial Interpolation (LPI), Inverse Distance Weigthing (IDW), Radial Basis Function (RBF) and Kriging were applied to obtain values at any point on the site. The main component analysis was used to analyze the statistical data structure through correlations between variables and the identification of factorial axes. The SPSS 18 software was used for this main component analysis. The regression function generated two distribution models that were then mapped from the spatial application Analyst Tool of Arc Gis 10.3. These two models were evaluated from the residue normality test and the BREUSH-PAGAN variance homogeneity test.

Results

Distribution of malaria vectors

The spatial distribution of *Anopheles funestus* (Fig. 2) is characterized by a population density concentrated in the southeastern part of the Ouidah-Kpomassè-Tori Bossito health zone.

The Moran spatial autocorrelation index used gives the following results: Moran Index = 0.515182; Expected Index = 0.037037; Variance = 0.017741; Z score = 4.145941. The value of this index is not close to 0, so the realization of the regionalized random variable is not independent.

Table 1. Correlation coefficients between the three axes and environmental parameters.

Environmental parameters	Axis1	Axis2	Axis3
WIND	0,97	-0,05	-0,16
VISIBILITY	-0,68	0,01	-0,35
RAIN	0,94	0,09	0,27
RELATIVE HUMIDITY	0,97	-0,07	-0,19
PRESSURE	-0,97	0,06	-0,03
TEMPERATURE	0,65	-0,22	-0,31
NUMBER OF RAINY DAYS	0,63	0,24	0,65
NDVI	-0,01	0,12	0,83
TOPOGRAPHY	-0,7	0,2	0,51
POPULATION	-0,03	0,9	-0,22
NUMBER OF HABITATS	0,04	0,95	-0,18
DCED	-0,83	0,02	-0,02
DCES	0,58	0,29	0,62
NUMBER OF ALCOHOL PRODUCERS	0,42	0,06	-0,31
FREQUENCY OF ALCOHOL PRODUCTION	0,56	-0,2	-0,09
GDCP	0,32	0,31	-0,12
GDAE	-0,05	-0,09	0,06
GDR	0,45	0,06	-0,25
TH_TB	-0,1	0,9	-0,1
TH_MB	0,37	0,38	-0,29
TH_A	0,14	-0,09	0,2

Legend: DCED=Distance from localities to the Freshwater River; DCES=Distance from localities to brackish watercourses;GDCP=Domestic deposits, epigees linked to the behaviour of populations; GDAE=Domestic deposits, epigees linked to economic activities; GDR=Domestic deposits, epigees linked to the relief; TH_TB = number of dwellings with clay walls; TH_MB= Number of dwellings with brick (cement) walls; TH_A=Number of dwellings with brick (cement) and clay walls.

There is therefore spatial autocorrelation in the observed distribution. This means that the frequencies of funerary Anopheles collected in a hamlet are influenced by the frequencies observed in neighboring hamlets. It is therefore possible to predict the frequencies of *Anophelesfunestus* in any hamlet, knowing the frequencies observed in another hamlet based on the distance between them. However, the statistical test to validate this spatial dependence for the entire regionalized random variable gives a Z score of 4.145941 which relativizes the interpretation of the Moran autocorrelation index. The calculation of the Getis-Ord General G high and low concentration index gives the following values: Observed General G = 0, 000147; Expected General G = 0, 000040; General G Variance = 0, 000000; ZScore = 3, 742241.

There may be a spatial autocorrelation, but it is local. As far as *Anopheles gambiae* is concerned, its spatial distribution (Fig. 3) is characterized by a density population in the northeast and southeast part of the site. Such a distribution suggests a spatial dependence in the distribution of *Anopheles gambiae* frequencies, hence the need to test spatial autocorrelation. Moran's spatial autocorrelation index = 0.290596; Expected index = -0.037037; Variance = 0.020007; Z score = 2.316324.

This index is close to 0, which means that the frequencies of *Anopheles gambiae* in a collection hamlet are not influenced by the frequencies observed in neighboring hamlets. The statistical test of independence of the regionalized variable gives a Z score equal to 2.316324 at the 95% confidence level. It is outside the confidence interval [-1.96; 1.96].

It is difficult to deduce from this the total absence of spatial autocorrelation over the entire variable. There are probably spatial aggregates expressing the local existence of spatial autocorrelation. The calculation of the concentrations of high and low Getis-Ord General G values shows the following results: General G Observed = 0.000047; General G expected = 0.000040; Variance of General G = 0.000000; Z score = 1.040106. The Z score is different from 0 and low.

According to these statistics, there is spatial independence on the observations made. However, there are spatial aggregates of low values within which spatial autocorrelation can be expressed. Autocorrelation tests show local spatial dependence and the fact that the (absolute) space is insufficient to explain the observed distribution. The environmental factors and mosquito frequencies of *Anopheles funestus* and *Anopheles gambiae*, the main vectors of malaria in Benin, should be linked.

Table 2. Correlation coefficients between mosquito disease vector species and major components.

Axis	Correlation coefficient and Probability	*An.funestus*	*An.gambiae*
Axis1	R	0,41	0,49
	Prob.	0,031	0,008
Axis2	R	0,03	0,25
	Prob.	0,874	0,195
Axis3	R	0,01	0,04
	Prob.	0,967	0,843

Environmental factors in the spatial distribution of Anophelesfunestus and Anopheles gambiae

If the space in its geometric dimension is insufficient to explain the distribution of observed frequencies, some of its characteristics may be more relevant. It is therefore necessary to verify the relationship between the attributes of space as a living environment, the environment of disease-carrying mosquitoes and the frequencies observed. The environment is positioned in this perspective as a factor that may explain the observed distribution. It therefore plays the role of an explanatory variable. The main component analysis carried out on the data related to the environmental parameters obtained in the various hamlets shows that all the first three axes explain 62.25% of the initial information, which is sufficient to guarantee accurate interpretation. Table1 shows the correlation coefficients between each of the three axes and the environmental parameters. The quality of the representation of the different variables in relation to the factor axis is expressed through the Pearson correlation coefficient values recorded in the Table2.

The analysis of this table indicates a highly significant correlation at the 5% threshold between axis 1 and the *Anopheles gambiae* frequency. Taking into account the environmental parameters by this axis, it is deduced that when there is a high wind, rain, relative humidity, temperature, and a high frequency of alcohol production, the frequencies of *Anopheles funestus* and *Anopheles gambiae* increase as opposed to low visibility, low pressure, low topographic relief and a short distance from localities in the freshwater stream that lower their frequencies. Axis 2 and 3 do not have a significant correlation with the frequencies of malaria-bearing mosquitoes.

From this main component analysis, we first deduce that there are relationships between environmental factors and the distribution of disease-carrying mosquitoes; then that there is an opposition between the ecological preferences of disease-carrying mosquitoes and finally that the ecological factors number of alcohol producers, domestic deposits (GDCP, GDAE and GDR) and habitat types (TH_MB and TH_A) are not relevant in determining the distribution; their contributions are negligible in the spatial distribution of the malaria mosquitoes considered. The analysis of the relationships between the environment and frequency distribution of these two vectors suggests that their distribution may be mathematically formalized on the basis of environmental factors. The regression performed is of a linear type. Of the 28 hamlets in the sample, 28 (or 100%) were used for modelling.

Table 3. Parameters of the distribution model of *Anopheles funestus* according to environmental parameters.

Parameters	Value	Standard deviation	Student's test	Probability
CONSTANT	-744,5	862,8	-0,86	0,398
WIND	-3,833	4,308	-0,383	0,383
DCES	-1,4182	0,2991	-4,74	1E-04
RAIN	0,6859	0,2062	3,33	0,003
TEMPERATURE	-23,82	21,38	-1,11	0,277
VISIBILITY	67,9	33,49	2,03	0,055

The results of this regression for *Anopheles funestus* give an R^2-adjusted value of 73.1%; the probability associated with the Fisher F test is 0.0001 or less than 0.01% chance of being wrong when considering that the amounts of information provided by wind, distance of localities to brackish streams, rain, temperature, and visibility as a whole are significant for the model. Since the variables are relevant to the model because of the significance of the amount of information provided, the model parameters can be presented (Table3). The equation of the model for *Anopheles funestus* can therefore be written:

Rac(FR_AF) = - 745 - 3, 83 WIND - 1, 42 DCES + 0, 686 RAIN - 23,8 TEMPERATURE + 67,9 VISIBILITY

For the *Anopheles gambiae* model, the adjusted coefficient of determination is 0.487. This means that 48.7% of the variance is explained by the linear combination of the two variables: the RAIN and the distance from localities to brackish rivers (DCES). Since the variables are relevant to the model because of the significance of the amount of information provided, the model parameters can be presented (Table 4). The equation is written: Rac(FR_AG) = - 185 + 0.163 RAIN - 0.429 DCES.

Cartographic expression of equations

The mathematical formalization of the distribution models of *Anopheles funestus* and *Anopheles gambiae* provides the possibility of producing theoretical maps of the distribution of these two species in the study area. Fig.4 shows the prediction of the spatial distribution of *Anopheles funestus* percentages. We observe on this map very homogeneous areas of percentage of this species.

Apart from a few very small islets, especially in the northern part of the area, the predicted percentages are arranged in bands, with an almost regular increase from southeast to northwest. Fig. 5 shows the prediction of the spatial distribution of *Anopheles gambiae* percentages.

Analysis of this map shows that the predicted percentages are arranged in bands, with an almost regular increase from east to west. We can therefore say that the quality of the environment for this species decreases as we move from east to west.

The west is therefore not favourable to the proliferation of the *Anopheles gambiae* species and also corresponds to areas where the water table is very deep. Even temporary watercourses are rare. They present the least favourable conditions for the ecology of the *Anopheles gambiae* species, since the model predicts low relative abundances. Basically, these are the driest areas. It also shows that ecological factors invoking moisture/aridity remain the most important determinants in the distribution of the species *Anopheles gambiae*.

Table 4. Parameters of the distribution equation of *Anopheles gambiae* as a function of environmental parameters.

Parameters	Value	Standard deviation	Student's test	Probability
CONSTANT	-184,66	37,5	-4,92	0,000
RAIN	0,1625	0,03161	5,14	0,000
DCES	-0,429	0,1221	-3,51	0.002

Legend: DCES=Distance from localities to brackish watercourses.

Confrontation of the malaria incidence at Plasmodium falciparum with the truth of the field

For both vector species, the correlation coefficient between the observed distribution and the malaria incidence at *Plasmodium falciparum* is 0.825 (Fig. 6). The correlation coefficient is positive, high and close to 1, the maximum level of similarity, the perfect level of identity. This means that malaria vector abundance is evolving in the same direction as the malaria incidence. This situation clearly shows that targeted control of malaria vectors will inevitably have a significant impact on malaria incidence.

Discussion

The Culicidian fauna of Lower Dahomey had already been studied in June and July by Huttel, 1947. This author had mainly worked on mosquitoes collected in homes and had identified 13 species in the vicinity of Porto Novo and Cotonou. Hamon followed in 1953. The localities targeted by the work of Hamon and his collaborators during two visits to Lower Dahomey, in March, November and December 1953, covered a coastal area from the Benin-Nigeria border to 20 kilometers west of Cotonou and extending about 20 kilometers inland. Zoographically, according to Chapin, this whole area is part of the Western sub-region, and more precisely of the Upper Guinea Savanna District.

In fact, the study area of Hamon takes into account the current communes of Porto Novo, Sème, Aguégués, Abomey Calavi, Sô-Ava, the district of Pahou in the commune of Ouidah and Cotonou (Bio-Bangana, 2012). A main component analysis (ACP) carried out on environmental factors has generated three uncorrelated factor axes. These three axes were correlated with the frequencies of mosquitoes carrying diseases identified. Our results are in line with those of Somé, 2010. The correlation between the frequencies of *Anopheles gambiae*, and *Anopheles funestus* is significant with axis 1. Taking into account the environmental parameters by this axis, it is deduced that when there is a high wind, rainfall, relative humidity, temperature, and high frequency of alcohol production, the frequencies of *Anopheles funestus* and *Anpheles gambiae* increase as opposed to low visibility, low pressure, low topographic relief and a short distance from localities to the freshwater riverthat lower their frequencies (Bio-Bangana, 2013). Indeed, not all environmental factors contribute in the same way to the determination of the observed spatial structure. Some environmental factors can more easily become a major constraint, a factor limiting the development and spread of species (Bio-Bangana, 2013). Based on the results of the analysis, we reduced the number of explanatory variables by excluding the variables: number of alcohol producers (NPA), domestic lodges and habitat types; identified the best model by comparing the AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) criteria of the models (fish model, negative binomial model, linear regression model with transformation of the Box-Cox family of the dependent variable; performed separate modelling of the two malaria vector mosquito species and finally performed multiple linear regression.

The distribution model of *Anopheles funestus* clearly shows that the five main determinants of its distribution are wind, distance from localities to brackish rivers, rainfall, temperature and visibility. It should also be remembered that the closer you get to brackish rivers, the more the frequency of the *Anopheles funestus* species decreases.

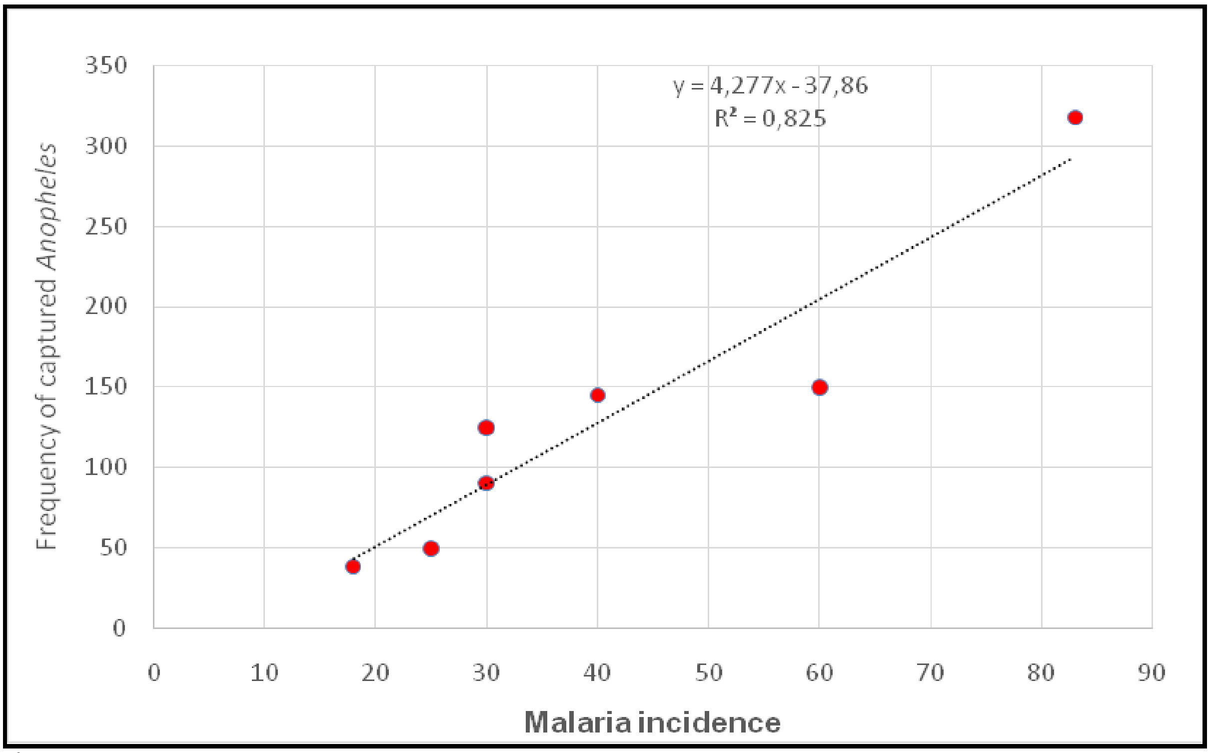

Fig. 6. Correlation between the frequencies of captured *Anopheles* and malaria incidence from October 2007 to December 2009 in seven localities in the Ouidah-Kpomassè-ToriBossito health zone.

This species prefers larger, more permanent natural habitats (ponds, lakes, river arms, rice fields) with shade and clear water. These results are in line with those of Hamon who, working under the same conditions in 1959, had recorded the same results. This distribution model shows that the *Anopheles funestus* does not proliferate in brackish and salt water. These results are confirmed by other researchers (Diagne, 1994). The *Anopheles gambiae* model involves two main determinants: rainfall and distance from localities to brackish rivers. Rainfall is the main factor in the submergence of breeding sites. A study by Cozon the contribution to the study of the *Anopheles gambiae* complex in West Africa showed that *Anopheles gambiae* is not very demanding on water quality but prefers shallow, unshaded salty water collections close to homes and of small size, ditches, puddles (Coz ,1973) as laying sites. In the Ouidah- Kpomassè-Tori Bossito health area, larvae of the *Anopheles gambiae* species were exceptionally found in jars (Bio-Bangana, 2012) Based on these trends, the distribution of these vector species was formally described by two functions. During this formalization, we proceeded to express the transformed frequencies of the two species according to the most determining factors. These results are in line with those of Somé who is working on the modelling of the spatial distribution of the M and S molecular forms of *Anopheles gambiae* sensu stricto in Burkina Faso with GIS and spatial analysis;has successfully generated two different distribution models of these two species (Somé, 2010). These spatial distribution functions have made it possible to produce distribution maps of each of the two species. The interest in characterizing malaria risk areas due to the *Anopheles gambiae* and *Anopheles funestus* species is to contribute to the implementation of targeted control strategies against these vectors to better control malaria, by conducting investigations on one of the links in the transmission chain of these species (Bio-Bangana, 2012).

Conclusion

This research work made it possible to describe the spatial organization of the *Anopheles gambiae sl* and *Anopheles funestus* species in the Ouidah-Kpomassè-Tori Bossito health area and to identify the determining factors. It has also made it possible to produce models of the spatial distribution of the species encountered. This study showed spatial heterogeneity in the ecological preferences of the *Anopheles gambiae* and *Anopheles funestus* species. *Anopheles funestus* species prefers southeastern regions where marshes and water meadows predominate while *Anopheles gambiae* has a wider distribution. Two groups of environmental factors characterize the concentration areas and significantly influence the spatial distribution of the two vector species. The first group of factors is natural and consists of wind, visibility, relative humidity, temperature and precipitation. The second group refers more to the anthropization of the environment and consists of the distance from localities to brackish rivers. Based on these factors of the spatial organization of the two species, two spatial distribution models were developed. These models made it possible to produce a spatial distribution map of the frequencies of these species in the Ouidah-Kpomassè-Tori Bossito area.In view of these results, we can affirm that the distribution of the species *Anopheles gambiae sl* and *Anopheles funestus* is non-random. Environmental factors explain well the spatial distribution of vectors. However, they contribute to it in a differential way. A prediction of the frequencies of mosquito vectors that know certain parameters of a medium is therefore possible. Mapping and statistical descriptions of the spatial distribution of the two vector species are available. Validated spatial distribution models have been developed. By combining in a geographical approach, spatial analysis, statistical data analysis, remote sensing, geographic information systems, sociology and entomology, this work provides a point of application for geographical methods in the analysis of health problems, particularly in their environmental aspects. A good vector control strategy must first take into account the environment that provides these vectors with the ecological conditions favourable to their survival and reproduction.

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