An environmental suitability index based on the ecological constraints of *Aedes aegypti*, vector of dengue

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ABSTRACT. *Aedes aegypti* is the main vector of dengue and Zika virus. Along with vaccine research, vector control is a major lever for fighting these diseases. Studying dynamical and non-linear relationships between the environment and vectors provides guidance for monitoring and control strategies. MODE’s objective is to identify environmental dynamics that contribute to the spatiotemporal distribution of *Aedes aegypti* in urban areas. This paper presents (1) the resource-based habitat concept and its application to *Aedes aegypti*, (2) the generic methods for estimating the environmental factor of this habitat and (3) the factors dynamics. These concepts and methods are illustrated in (4) with an application on Bangkok, Thailand and (5) with the mapping of an environmental suitability index.

RÉSUMÉ. *Aedes aegypti* est le principal vecteur des virus Zika et de la dengue. Avec la recherche vaccinale, le contrôle vectoriel est un levier important de lutte contre ces maladies. Étudier les relations dynamiques, multifactorielles et non linéaires entre l’environnement et le vecteur doit permettre d’améliorer les stratégies de surveillance et de contrôle de ce dernier. Les objectifs de MODE sont de décrire ces relations afin d’identifier les contextes environnementaux qui en résultent et qui contribuent potentiellement à la distribution spatiotemporelle d’*Aedes aegypti* en milieu urbain. Cet article présente (1) le concept d’un « habitat basé sur les ressources » et son adaptation à *Aedes aegypti*, (2) les méthodes génériques d’estimation des facteurs environnementaux de cet habitat et (3) les dynamiques de ces facteurs. Ces concepts et méthodes sont illustrés en (4) par une application sur Bangkok (Thaïlande) et (5) par la réalisation de cartes de l’aléa environnemental.

KEYWORDS: vector-borne disease, resource-based habitat concept, biogeography, spatial simulation, GIS, remote sensing.

MOTS-CLÉS : maladies à transmission vectorielle, resource-based habitat concept, biogéographie, simulation spatiale, SIG, télédétection.

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1. Introduction

*Aedes aegypti* is a mosquito found in the tropical and inter-tropical areas of Africa, America and Asia. It is the main vector for dengue, Zika virus and, to a lesser extent, Chikungunya and yellow fever. Its synanthropic nature (Rodhain et Rosen, 1997) makes cities the main transmission areas. According to a devastating observation by the WHO (2016), the spread of these viruses, notably Zika, is a result of the failure of mosquito control policies in several countries since the 1970s. While vaccination is the goal to be achieved in the not so distant future, in the meanwhile, vector control remains the main strategy for ensuring a decline in these diseases. This involves acting directly on the environment with the aim of (a) preventing mosquitoes from developing (sanitation, drainage and destruction of potential breeding sites), (b) reduce vector population (chemical treatment of breeding sites, fumigation, introduction of predators or sterile males) and (c) restrict the interactions between hosts and vectors through measures for protecting buildings (mosquito nets for windows, mosquito repellent paints). Improvement in the way vector distribution areas (potential and confirmed) are monitored in urban and peri-urban settings should help health authorities to optimize their actions in time and space (Gubler, 2002). In this perspective, environmental hazard mapping in cities (at resolution finer than 100 m according to Smith et al. (2014)) should help to evaluate the risk that *Aedes aegypti’s* presence constitutes (Eisen and Lozano-Fuentes, 2009; Machault et al., 2014). Numerous studies have provided health authorities with tools which can be used to map this environmental hazard in specific cities (e.g. Machault et al. (2014), Attaway et al. (2014), Rogers et al. (2014)). As Lima et al. (2016), we did not find generic solutions that can be used to build fine-scale dynamic maps in any urban context.

Environmental factors influencing *Ae. aegypti* are unevenly distributed in the urban areas and their presence evolves over time. The range of possible combinations of these factors makes it increasingly difficult to highlight simple causalities that could allow one to explain and estimate vector densities. Rain, for example, is relatively homogeneous in the urban areas. Consequently, this factor does not explain the presence of mosquito hotspots, which reflect the heterogeneous nature of their spatial distribution. Besides, with natural selection, the mosquitoes can evolve from the biological or behavioral point of view with more or less long term changes to their environment. Mosquito nets treated with insecticides, which were distributed in Africa to fight mainly against malaria vectors, *Anopheles gambiae* and *An. funestus*, seem to have contributed to a change in the predation time of these previously nocturnal mosquitoes (Smith et al., 2009; Sougoufara et al., 2014).

MODE ((Model of Dynamical Environment)) is a generic model; it is possible to transpose the data processing system and the methods developed from one urban area to another. MODE estimates the environmental variables that form the mosquito’s living

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spaces. This model can be used to produce detailed maps of potential ecological niches of *Ae. aegypti* at different times of the year and thus orient vector control operations.

As a first step, we present the concept of resource-based habitat, which defines all possible actions and interactions between *Ae. aegypti* and the environment. As a second step, we will present the 5 stages of MODE model’s construction allowing us to generate different environmental contexts and their evolutions. The third section is devoted to the application of MODE to Bangkok (Thailand). The fourth section presents the Environmental Suitability Index for *Aedes aegypti* (ESIAA). This index allows us to gather the environmental elements with a significant impact on *Aedes aegypti*’s life cycle as well as create a dynamic mapping of the environmental hazards of vector risk.

2. Resource-based habitat concept applied to *Aedes aegypti*

The Resource-Based Habitat Concept (RBHC) (Dennis *et al*., 2003), used in conservation biology, involves relying on the primary needs of an organism to deduce its functional habitat or its potential ecological niche. It was used to predict the risk of occurrence of vector-borne diseases by Hartemink *et al.* (Hartemink *et al*., 2014). According to these authors, the RBHC approach would allow one to overcome the limitations of inductive models based on statistical relationships measured between the environmental variables observed and the presence of a vector or a pathogenic agent (Peterson, 2014). The RBHC approach would also allow one to overcome the limitations of deductive models based on equations that do not take into account the spatial aspect of the modeled phenomenon (Reiner *et al*., 2013). In the field of vector-borne diseases, the RBHC thus offers the possibility of reconstructing potential areas of viral transmission by assembling the functional spaces of both the vectors and the hosts. With MODE, we focus on constructing a dynamic environmental model of the dengue vector mosquito. This involves linking this mosquito’s perceptual aspects and the resources or conditions influencing its biological development and its behavior. On the basis of the classification proposed by Hartemink *et al.* (Hartemink *et al*., 2014), the environmental elements that can be perceived by *Ae. aegypti* may in fact be divided into two categories: on one hand, the resources representing all the environmental elements that may be consumed by the mosquito (for example, nectar, blood) and on the other hand, the conditions representing all the environmental states that have an influence on the mosquito’s behavior (presence of breeding sites) or its biological function (temperature).

These resources and conditions vary during the life of *Ae. aegypti*. Its life cycle is divided into 4 stages, from the aquatic phase (egg, larva and pupa) to the aerial phase (adult). During its aquatic phase, the water conditions (chemical quality and temperature) have an important role to play in the mosquito’s survival and the duration of its development. Once it is an adult, it is capable of moving about, reproducing, feeding on nectar and, for the females, taking blood feeds. The proteins present in the blood allow the latter to hold its eggs till they mature. During its gonotrophic cycle (the cycle of blood feed – egg maturation – oviposition), it spends a
great deal of its time resting in cool and shady areas (Vezzani et al., 2005). Oviposition occurs in an environmental element containing (or likely to contain) water (container). This container can either be an object created by man (a flowerpot) or an object whose existence is related to vegetation (hollow of a tree). In an urban setting, there may be numerous containers related to human activities. They constitute a primordial factor for the proliferation of *Ae. aegypti* populations in cities (Arunachalam et al., 2010).

While the importance of these various resources and conditions varies during the course of *Aedes*’ life cycle, the cycle is partly determined by what the mosquito is capable of perceiving at each stage of its development. An adult *Ae. aegypti*’s perceptual capacities limit its interaction field to around thirty meters (Gillies and Wilkes, 1972). It has olfactory, visual, tactile, chemotaxic, thermo-sensorial and photo-censorial capacities. These capacities allow it to identify and react, depending on its state, to the presence of certain environmental elements: human beings, water, plant nectar, light, humidity and temperature. The relationship between the mosquito’s perceptual capacities at the pre-adult and adult stages and the objects (conditions and resources) perceived make it possible to define the types of data required in order to describe these relationships. For example, at the adult stage, the mosquito can perceive breeding sites that are or are likely to contain water when it needs to oviposit. Five local environmental factors were thus defined as being part of *Aedes aegypti*’s RBHC: water (related to rainfall or human activities), temperature, vegetation, human presence and breeding sites. In the following section, we describe the methods for evaluating these factors and the models describing their dynamics, which, together, define the protocol MODE.

3. MODE: Model of dynamic environment

MODE is a dynamic model consisting in a grid made of environmental cells (EC) that represent the basic environmental entity. This entity is described by characteristics representing RBHC resources and conditions for *Ae. aegypti*. This basic unit also has methods that simulate the dynamics of filling and emptying breeding sites as well as the variation in temperatures.

The spatial resolution of a basic unit is 30m by 30m, which corresponds to the resolution of Landsat 8 images (OLI). This resolution is consistent with the perception field of the mosquito and the average area of its “living space” observed from “mark–release–recapture” type of studies (Getis et al., 2003). It also corresponds to the maximum average dispersal distance of mosquito cohorts simulated in an urban context (Maneerat and Daudé, 2016; Maneerat and Daudé, 2017). This resolution is used in other simulation models (Karl et al., 2014).

3.1. Method to estimate resources and conditions

Methods to estimate the environmental characteristics integrated in MODE were developed for application to various urban areas. Satellite images, major inputs of the model, are provided by satellites covering almost the entire terrestrial space (Terra and
Aqua (MODIS) and Landsat 8). These data are freely available. Even though the use of high-resolution images is not necessary for MODE to function well, these provide an interesting perspective (however this data remains very expensive). Moreover, there is abundant and mostly freely accessible data pertaining to the population census, rainfall and temperature. A schematic view of the data and processes used in MODE is given in Figure 1.

3.1.1. Water: an essential element of Aedes aegypti’s emergence

The presence of water is a prerequisite for the presence of mosquitoes. In areas with a monsoon climate and colonized by Aedes aegypti, the rainy season generally corresponds to a period of maximum mosquito proliferation. Rainfall data used in MODE are taken from the meteorological station readings, freely accessible in most cases. This data corresponds to the amount (in mm) of rainfall recorded per day for a station preferably located in the city center. In our model, rainfalls data varies only in time. Water storage systems constitute a second opportunity for the mosquito’s development. These systems can be related to the absence of a water distribution system or cultural practices such as watering flowers. In the case of storage, water is considered as being kept inside homes and is subject to a special process in MODE (cf. Section 2.1.6).

3.1.2. Air temperature: Aedes aegypti’s comfort zones

Air temperature influences not only the biological dynamics of the mosquito and the virus (Lambrechts et al., 2011; Cianci et al., 2015), but also the host behavior (use of air conditioners and life indoors or outdoors). Several studies thus emphasize the relationship between temperatures and dengue epidemics (Descloux et al., 2012; Hopp and Foley, 2003). Local temperatures evolve during the day depending on several factors with the main factor being the land use type (Misslin et al., 2016). In MODE, air temperature data (Ta) is estimated using MODIS images of Land Surface Temperature (LST). The latter represents the heat emitted by the land surface and differs by a few degrees from Ta.

It is thus calculated using the temperature-vegetation index (TVX) method (Vancutsem et al., 2010; Zhu et al., 2013), which relies on the existence of strong correlations between LST and Ta as well as between plant cover and Ta. Applying this method to estimate Ta requires the use of local meteorological readings. Temperature data resulting from Ta estimation is assigned to environment cells. This temperature evolves with a time resolution of 12 hours in accordance with the MODIS LST (MOD11A1 or MYD11A1) readings. When these are available, the environment cell takes on the corresponding value. When overcast conditions prevent the acquisition of LST images, Ta from the closest weather station is assigned to the environment cell in question.
Figure 1. Schematic view of MODE and the ESIAA
3.1.3. Vegetation: resting places and nectar producers

*Anopheles gambiae* may get attracted to areas with plant cover in order to take rest, lay eggs or, when it is looking for nectar, feed. The vegetal areas close to built-up areas produce a high number of mosquitoes (Vezzani et al., 2005). In order to evaluate the presence of these areas at a fine resolution, we use NDVI (Normalized Difference Vegetation Index) (Tucker, 1979). This vegetation index is commonly used in remote sensing. It is calculated using the red and infrared bands of a satellite image (Landsat 8). The results are between -1 and 1. The negative values generally indicate a lack of vegetation. The value of 1 indicates a high presence of vegetation. Vegetation is considered as static, given that vegetal dynamics, which, in any case, are not documented in the tropical zone, have little impact on the dynamics of the vector population.

3.1.4. Human densities: blood feeding opportunities

Human densities represent stocks of blood for the mosquito. It is an essential element for its gonotrophic cycle. MODE estimates these densities at the place of residence but the role of host mobility in the spread of epidemics is not addressed here (Cebeillac et al., 2017). The first difficulty pertains to the population census data aggregation level: in MODE, the environment cells are defined at a resolution of 30 m by 30 m while the census data is often aggregated over administrative units of several km². Dasymetric mapping makes it possible to resolve this first problem (Yuan et al., 1997). It is mainly used to refine demographic data by redistributing from a larger scale to a finer scale, with the latter defined according to the satellite data (raw images, land use, surface temperature, spectral indices, etc.). Dasymetric mapping is described in several publications (Li and Weng, 2010; Mennis, 2015). Schematically, this method involves ventilating population data (number of inhabitants and number of households in MODE) at the place of residence provided at an administrative scale in built-up areas present in this administrative scale. In the case of MODE, this satellite data is extracted from Landsat 8 satellite images. Land use classification is obtained by applying an unsupervised ISODATA classification.

3.1.5. Potential breeding sites: oviposition opportunities

The presence of containers in the field is a difficult to estimate: it is practically impossible to take readings directly using satellite images (Moloney et al., 1998) and it is expensive to collect this data on the ground. In fact, several studies have shown that *Aedes aegypti* oviposits preferably in small breeding sites found in homes or peri-homes containing cool and stagnant water. The distribution of these sites in the urban space is very largely related to the presence of human beings and their activities (Ooi et al., 2006). Thus jars, flower pots, buckets, tires or basins are much sought-after breeding sites for the mosquitoes for the purpose of laying their eggs. The water areas such as ponds, rivers or open sewers are not potential breeding sites for *Aedes aegypti*. Karl et al. (Karl et al., 2014) proposes to use the number of households and vegetation to
estimate the presence of breeding sites in the environment by creating a breeding site abundance index. Our approach is inspired from this index. The number of potential breeding sites in an environment cell is a stock value that is estimated by assuming that households are the main producers:

\[ Gpotint_i = D_i \cdot \alpha_i \cdot \Delta \]  

(1)

\[ Gpo\text{text}_i = \mu_i + (D_i \cdot \alpha_i)(1 - \Delta) + D_{j(i)} \cdot \beta_{j(i)} \]  

(2)

\[ Gpot\text{tot}_i = Gpot\text{int}_i + Gpo\text{text}_i \]  

(3)

In all the equations mentioned above, \( i \) refers to an environment cell, \( j(i) \) refers to the first order neighboring cells to the cell \( i \), \( Gpo\text{text}_i \) corresponds to the number of containers located outside a building in \( i \), \( Gpot\text{int}_i \) is the number of containers located inside a building in \( i \), \( Gpot\text{tot}_i \) refers to the total number of containers in \( i \) and \( D_i \) corresponds to the number of households in \( i \). Four parameters are used in these equations: \( \mu_i \), corresponds to the number of containers in \( i \) produced irrespective of the number of households living in \( i \) (random integer), this parameter makes it possible to estimate breeding sites in vegetated type of cells, for example; \( \alpha_i \) represents the number of containers created in \( i \) by a household living in \( i \), \( \Delta \) represents the percentage of breeding sites less than the containers created by households living in \( i \) \((0<\Delta<1)\) and \( \beta_{j(i)} \) corresponds to the number of containers created in \( i \) by the households living in \( j \).

The values \( \mu_i, \alpha_i \) and \( \beta_{j(i)} \) are defined for the environmental cell \( i \) through a random draw. Parameters \( \mu, \alpha \) and \( \beta \) are integers fixed for the entire study area by the modeler according to the local context; they are used for each cell as a mathematical expectation of a Poisson distribution. These parameters subsequently make it possible to calculate the number of breeding sites in each cell, according to the number of containers found per unit area in nonbuilt-up areas \( (\mu) \), per household unit in built-up areas \( (\alpha) \) and per household units living in adjacent cells \( (\beta) \) (see Figure 1). A spatial variability of these parameters according to the economic status of the households or prevention campaigns held, for example, could be introduced. This estimation method has not been validated yet. For such a purpose, estimated data could be compared to field data collected through a study aiming to count all potential breeding sites available in one place.

3.1.6. Evolution of water stocks

MODE simulates the dynamics of both indoor and outdoor containers stocks of each cell based on two processes: (a) filling of these stocks naturally through rainfall or artificially through the watering of plants, the use of air conditioners or water storage and (b) depletion of these stocks through evaporation or human action.

However, the filling occurs differently depending on the breeding site’s situation, inside or outside a building. As rainfalls and evaporation are modeled globally, every
outdoor containers in the study area show the same dynamics. The indoor sites are filled by human beings. They have a maximum and a minimum capacity (in mm) fixed by the modeler. The initial water level in the indoor breeding sites is given by a uniformly distributed random number in the interval [0,1]. When the water level reaches its minimum capacity, it is filled till it reaches its maximum capacity in order to simulate water storage or plant watering. The stock of outdoor breeding sites is filled through rainfall. When a stock of breeding sites reaches its maximum capacity and receives more water through rainwater, it overflows. This mechanism should be considered as the overflowing is going to reduce the stocks of eggs, larvae and pupae, a phenomenon usually observed during the heavy monsoon rains (Jetten and Focks, 1997).

The water level in the breeding sites decreases due to evaporation for outdoor sites. This is calculated at the scale of the city using the Linacre equation (Linacre, 1977), which requires notably sunrise and sunset times, air temperature and latitude as inputs. Indoor breeding sites are considered as being always filled with water. The quantity of water present in an outdoor container is calculated using the following formula:

\[
LW_d = LW_{d-1} + R_d - E_d
\]

(4)

where \(LW\) is the level of water in mm, \(d\) is the current day, \(R\) is the level of rainfalls and \(E\) is the evaporation level.

These dynamics of filling and emptying indoor and outdoor potential breeding sites allow us to consider processes resulting in water accumulation for several consecutive days, which, in turn, leads to the immersion of the eggs in water and the development of the mosquito. They also make it possible to consider the overflowing of outdoor breeding sites, which leads to the potential loss of a part of the larva population from active breeding sites. Finally, they allow us to consider the presence of breeding sites outside the rainy season because of human usage.

While spatialization of these 5 environmental resources and conditions (water, air temperature, human densities and potential breeding sites) at a fine scale provides an overview of the high level of intra-urban heterogeneity of the conditions suitable for the emergence, maintenance and development of vector populations, it is the interaction between these different resources in time and space that should make it possible to identify the mosquito’s micro comfort zones.

4. Application of MODE to Bangkok (Thailand)

The test area chosen is the city of Bangkok (Thailand) located in the intertropical zone (13° 45' 22" N, 100° 30' 06" E). Its climate is tropical with a dry season (5 to 44mm rainfall) from November to March and a wet season (160 to 342mm rainfall) from April to October. The temperatures are between 26 and 30°C (an average of 28°C). The city of Bangkok has a population of 8.2 million individuals (NSO 2010 census) for an

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administrative territory covering 1,568km². There is a great diversity in terms of population density and land-use. *Aedes aegypti* is detected throughout the year, with a minimum presence during the dry season and the maximum figures attained during the monsoon.

The software R (3.1.3) was used to build data sets. MODE is developed under GAMA (1.7). Remote-sensing images are generated by the satellite Landsat 8 OLI (dated 01/17/2014) and the satellites MODIS Aqua and Terra (MYD11A1 and MOD11A1, two images per day between 2009-2011). The latter are downloaded and pre-processed using MRTtools R package. The demographic data is taken from the 2010 census (NSO 2010). Finally, the meteorological data is freely accessible on the Thai Meteorological Department website[^3]. This data was collected for the period 2009-2012. The 30 m resolution chosen for the basic spatial units thus generates approximately 1.75 × 10⁶ environment cells.

### 4.1. Rainfall: meteorological data

Rainfall data is taken from a meteorological station situated in central Bangkok. It is collected for the period 2009-2012. This data is the basis for the dynamics of filling potential breeding sites located outside buildings (Figure 2b). With readings taken from only one station, the same daily value is applied to all the cells.

### 4.2. Air temperature: estimation using the TVX method

The satellite AQUA flies over Bangkok around 2.00am and 2.00pm (local time). The satellite TERRA does so around 10.30am and 10.30pm. The images from the first satellite are thus more pertinent as we want to estimate the minimum and maximum day temperatures in Bangkok. These are estimated for the period 2009-2011 and for an area larger than the Bangkok Municipal Administration (BMA). This allows us to increase the number of reference stations in order to apply the TVX method. On this wider area, 19.8% of the night-time MYD11A1 images and 17.6% of the day-time MYD11A1 images contain at least half the valid pixels. These images are converted into surface temperature and then the air temperature is estimated. In all, air temperature is estimated for 217 day-time thermal images. Figure 3a gives an example of spatial distribution of air temperature (night-time minimum temperatures for 01/20/2009).

Given that air temperature data was provided at a higher resolution than the size of the environment cells, the latter take the Ta value of the 1 × 1 km pixel on which it is found. Ta data is not available when there is too much cloud cover, especially during the monsoon. When the pixel’s Ta is not given, MODE attributes the Ta measured by the station which is the closest geographically for each cell.

4.3. Vegetation: estimation using NDVI

NDVI is calculated using red and infrared bands of the Landsat 8 image. The NDVI values (Figure 3a) vary from -0.32 to 0.82. The values less than 0 were raised to 0. They correspond to the total absence of vegetation. On the whole, Bangkok appears to be a territory with a significant vegetal cover, notably in the rural periphery. In central Bangkok, green areas are more fragmented. These correspond essentially to parks and gardens. Transport routes appear distinctly by virtue of the densely built-up areas adjoining them. The data provided by NDVI shall be used as a resource for the Aedes mosquito (the basic entity of the MOMA model).
4.4. Population density and households: estimation using dasymetric mapping

Land use data is taken from the Landsat 8 image. Two main categories of built-up areas were identified: densely built-up area (corresponding to Bangkok city center) and sparsely built-up area (corresponding to the city’s peripheral areas), without distinction of usage or function. The population is distributed into these categories of potentially inhabitable land use categories using the dasymetric mapping method (Figure 3c). This method allows us to estimate the population distribution at the finer scale of Kwaeng (administrative reference unit for NSO census with a surface area is between 0.15 and 73.92km²). The strongest densities estimated are located mainly in the city center, to the east of the Chao Phraya River, which runs through it. The urban fabric is very dense albeit a few uninhabited green areas. In the peripheral areas to the east and the west, the

*Figure 3. Estimation of resources and conditions for Ae. aegypti in Bangkok*
strongest densities are distributed along important highways. A large part of the western periphery has a loosely knit urban fabric with low population densities.

4.5. Potential breeding sites: estimation of their spatial distribution

The number of households per environment cell calculated by the dasymetric method is an essential parameter for calculating the number of potential breeding sites (containers) per cell (Equation 2). Water areas (canals, rice fields, ponds) are the only ones where it is not possible to find containers.

The factors $\mu = 4$, $\alpha = 6$, $\beta = 3$ used for Bangkok are fixed based on literature (Tsuda et al., 2006) and our field experience. The values chosen allow us to get an average of 17.8 breeding sites per EC and a standard deviation of 28.5 for the entire city (min. = 0, Q1 = 4, med. = 8, Q3 = 17, max. = 452). Let us recall here that these parameters are chosen, in the absence of field studies, in an arbitrary manner and with a single hypothesis: a quantitative differential such that $\beta < \mu < \alpha$. Analyzing sensibility shows that the average number of overall containers hardly varies from one estimation to another because of the very large number of environment cells ($1.75 \times 10^8$). For example, for 100 estimations made with the parameter values given above, the standard deviation of the average number of containers is less than 0.01.

The areas where the model estimates the most number of potential breeding sites are mainly situated in the city center and in low-rise residential areas located in the immediate periphery. The minimum values, less than 10 breeding sites in all per cell, are found in the cells with green cover and far from the inhabited areas, such as the Eastern and the Western peripheries, or in the urban sparsely built-up areas, such as the Kweng of Phra Borom Maha Ratchawang (Western part in the insert in Figure 3d) where the royal place, temples and the ministries are located.

4.6. Evolution of the water stocks available in the breeding sites

Potential outdoor breeding sites are filled with water because of rainfall. Given the great variety of volumes and surface areas of the potential breeding sites in the environment, we chose to retain the rainfall measurement unit (given in mm) to characterize the maximum capacity of a potential breeding site. In Thailand, the most productive containers are known to be water jars and discarded containers. In MODE, every container is considered to be the same size, that is, an amount of 200 mm, which is the size of a small water jar or a discarded flower pot. This size is, for example, Figure 2a, represents the water dynamics of a stock of outdoor breeding sites. The quantity of water present in a breeding site is calculated using Equation (4) and cannot exceed the maximum capacity of the container.

The phenomenon of water accumulation can then be compared to the occasional rainfall recorded. The possibility of simulating accumulation and evaporation is fundamental for interaction with the mosquito model (Maneerat and Daudé, 2016). In
the absence of entomological data, this temporal dynamics of the availability of water-filled breeding sites can be compared to the temporal distribution of the monthly incidence of dengue in Bangkok in 2012. Between 2010 and 2012, the monthly incidence and the mean level of water per month for a 200 mm high breeding site show a Pearson correlation coefficient of 0.55 ($p<0.005$). With a one month lag, this coefficient rises up to 0.72 ($p<0.005$). This can be explained by the time the eggs take to reach the adult stage and by the infection cycle. This is an encouraging result from the macroscopic point of view.

5. The environmental suitability index for *Aedes Aegypti* (ESIAA)

Despite the growing interest of Geographic Information Systems (GIS) in the vector-control research field, few studies have implemented spatial models which enable researchers to generate environmental suitability maps, at city-scale, without using ancillary datasets (entomological or epidemiological data). Rocklöv *et al.* (2016) implemented a climate driven mathematical model which aims to estimate basic reproduction numbers ($R_0$) at a continental scale in Europe. Leandro-Reguillo *et al.* (2017) developed a fuzzy mapping method suited for the Mediterranean urban context. They applied their model in the city of Barcelona and were able to provide vector surveillance recommendations. The ESIAA, introduced in this section, was implemented with a similar perspective.

ESIAA involves multiplying five indices that were constituted based on MODE environmental data. Each of these indices aims to characterize one essential aspect of the environment of *Aedes aegypti* in terms of availability. The five environmental aspects matches the five resources and conditions identified in Section 1 using the RBHC and described in Section 2. Among these indices, three are articulated in space: distribution of human beings, that of the vegetation and that of shady areas. The two others are articulated in space and in time: containers distribution and availability, spatio-temporal evolution of air temperature.

Each index is continuously distributed over $[1; 10]$. We chose to fix the minimum for each sub-index at 1 in order to avoid giving too much importance to very low values or to the complete absence of a factor in an environment cell (EC). This allows us to consider the fact that the resolution of the initial data (30m) does not allow us to be certain that an environmental characteristic is completely absent. Dealing with values strictly superior to 1 also ensures that the result of the multiplication of the 5 variables is always greater or equal to the highest variable. This makes sense from an ecological perspective: the absence of one resource does not affect the availability of another. However, the overall suitability is estimated through a multiplication process because it can be affected by the absence of only one resource. ESIAA can take a minimum value of 1 and a maximum value of 100 000. For further clarity, this final value is divided by 1000. The final value of ESIAA is between 0.001 and 100. An EC with a value of 0.01 is extremely detrimental to the presence of *Aedes aegypti* and an EC with a value of 100 provides ideal conditions for its survival and development. In practice, because of
multiplication, few EC go beyond 15 in the monsoon period:

\[ ESIAA_i = \frac{I_{v_i} \cdot I_{t_i} \cdot I_{p_i} \cdot I_{c_i}}{1000} \]  

(5)

where \( I_v \) is the vegetation index, \( I_t \) is the temperature index, \( I_p \) is the population index and \( I_c \) is the container index.

The neighborhood effect is taken directly into account in the indices based on two parameters: order of adjacency according to Moore neighborhood and weight of the cell index values in this neighborhood according to a decreasing function with distance from the cell center. These two parameters have to be fixed in advance. As for the choice of multiplication, it is based on the hypothesis according to which, the five resources considered are essential for the mosquito’s survival. If in an area (EC) including its neighborhood, four of the five fundamental environmental conditions are given but one of them is absent, the area in question will be least favorable for the mosquito’s development.

5.1. Vegetation index (Iv)

The vegetation level is given by NDVI whose negative values are increased to 0. Following this, the neighborhood effect is considered through a leveling process carried out using a mobile 3 × 3 window. This window allows us to consider the first order cells. The weight of the central cell with respect to its neighboring cells is fixed by the modeler. The method of considering neighborhood is the same as for the other indices. Concerning \( I_v \), the leveled values are taken into account without any additional modification to determine the value of \( I_v \).

5.2. Temperature index (It)

The ability of an area to correspond to the needs of a mosquito in terms of temperature is complex to determine. In fact, this ability depends on the stage in the mosquito’s life. Because of this fact, we chose to rely on the thermal window ([\( T_{p_{\text{min}}} \), \( T_{p_{\text{max}}} \)]) which is conducive for a majority of the behaviors (20°C–30°C) as well as on the minimum (\( T_{\text{min}} \)) and the maximum (\( T_{\text{max}} \)) temperatures at which the mosquito can survive (10°C–45°C). These four values are modifiable parameters. The value of \( I_t \) is considered as the maximum in the most favorable thermal window for the mosquito ([\( T_{p_{\text{min}}} \), \( T_{p_{\text{max}}} \)]). When the temperature of a cell is higher or lower than this window, \( I_t \) decreases linearly till the closest extreme temperature.

The temperatures constitute one of the dynamic data of this ESIAA. They change every day, taking the Ta data value when it is available and taking the temperature value of the meteorological station Bangkok Metropolis, situated in central Bangkok, when Ta cannot be estimated using MODIS images.
5.3. Population index ($Ip$)

The capacity of a space to respond to the mosquito’s needs in terms of blood availability can be understood as the facility with which it can find a human prey. It is this faculty, which is noted when calculating the population index ($Ip$). Our hypothesis is that there is a threshold (number of humans per EC) at which finding a prey is not a problem for the mosquito. The value of this threshold is a parameter that can be modified ($Poplim$). The $Ip$ value for an uninhabited EC is 1. Therefore we consider that there is always the possibility of getting a blood feed in an urban area, even if this opportunity is rare; for an EC inhabited by $Poplim$ inhabitants or more, this value is 10.

5.4. Container index ($Ic$)

The index of the breeding sites available ($Ic$) depends on two different elements: the water level in the city’s breeding sites and the spatial distribution of these breeding sites. This index is divided into two parts: the index of indoor breeding sites ($Gint$) and the index of outdoor breeding sites ($Gext$). The respective weights of $Gint$ and $Gext$ in calculating $Ic$ can be modified such that the user can choose to give more weight to one or the other, according to the characteristics of its study area. The values $Gint_{max}$ and $Gext_{max}$ are maximum values that $Gint$ and $Gext$ can take. These values are fixed between 1 and 9 per user; the value of one depends on the value of the other. In both the cases, the calculating principle is similar to the one used for $Ip$: the objective is to estimate the facility with which a mosquito is likely to find a potential breeding site. This calculation depends on a threshold which can be set and whose value may be different or equal for the outdoor containers ($Gext_{lim}$) and for the indoor containers ($Gint_{lim}$).

The indoor breeding sites are considered as being always filled with water. As for $Ip$, the value of $Gint$ for a cell without any indoor breeding sites is 1, which does not increase or nullify the overall index value. Beyond a certain number of indoor breeding sites, which corresponds to the $Gint_{lim}$ value fixed by the user, $Gint$ takes on its maximum value ($Gint_{max}$) and does not increase anymore, regardless of the number of additional breeding sites.

The outdoor breeding sites are made available depending on rainfall and evaporation. $Gext$ represents the level of suitability associated with the outdoor breeding sites. Estimation of this suitability level is based on the following principle: longer the time during which a breeding site is filled with water, more it is conducive to the emergence of adult Aedes aegypti, and hence higher is the suitability level. This suitability level is thus at its maximum when the number of successive days during which the breeding site contained water is more than the number of days required for a mosquito to move to the egg or the adult stage. For Aedes aegypti, this time span is a minimum of 8 days. The latter may vary depending on the temperature. However, the minimum duration for development is, for the time being, taken into account by means of a modifiable parameter ($Dev_{min}$). The maximum water level that a containers may
6. Calculating ESIAA for Bangkok

We developed a web application prototype Rshiny\(^4\), which makes it possible to calculate ESIAA for Bangkok. This prototype provides all the data and satellite images described in the previous sections and makes it possible to consider spatialized air temperatures that are available for the years 2009, 2010 and 2011. However, the temperatures in Bangkok, even if they vary over the course of an year, have little impact on the dynamics of hazard index because of the narrow range of this variation which does not move beyond the mosquito’s comfort temperatures. From a range of parameter values left free for the user, calculating the index makes it possible to identify the areas in Bangkok (Thailand) that are the most conducive for the development of mosquito populations.

Generally for the whole year, the values of ESIAA are (a) higher in the city center than in the periphery and (b) the local evolution of environmental risk in Bangkok is largely related to rainfall (from July to October) and is higher in the densely populated areas (see Figure 3). In practice, the only sub-indices whose values evolve between these two periods are the temperature index \((T)\) and the ratio of the breeding site index \((B)\).

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\(^4\) https://www.rstudio.com/products/shiny/
(Ic) which represents the presence of outdoor breeding sites filled with water (Gext). Among the five sub-indices, three are directly related to the presence of human population. This is the case of population index (Ip) and Ic (whose value depends on the number of households). Hence, despite the fact that neighboring is taken into account, the most populated EC are also the ones with the highest ESIAA value (highly populated EC tend to have highly populated neighbors). This relationship is logical as *Aedes aegypti* is a synanthropic mosquito. The most populated areas are all the more important as they contribute largely to the formation of urban heat islands.

7. Conclusion

The methodological implementation of the Resource-Based Habitat Concept based on the resources allowed us to quantify for each one of the elementary spatial entities, 4 factors which are necessary for the implantation and development of the mosquito *Aedes aegypti*: vegetation, human population, the number of indoor and outdoor breeding sites and air temperature. A fifth element, the rainfall, is provided as an overall input parameter in the model. Among these attributes, two are dynamic, temperature and rainfall, and act directly on the filling rate of the breeding sites and water temperature. This methodological context, MODE, makes it possible to construct dynamic computerized simulation environments.

MODE is to be coupled with MOMA, an agent based model of the mosquito *Aedes aegypti* (Maneerat and Daudé, 2016). The mosquito agent’s capacities of perceiving and acting allows it to interact with its environment. It can thus lay its eggs in the breeding sites or be influenced by local temperatures. Coupling these two models should thus enable us to explore important issues concerning the vector population dynamics under climatic constraints and in accordance with geographic configurations as well as the control scenarios aimed at the breeding sites and their effects on the evolution of these populations.

Subsequently, spatialization and quantification of these various factors led us to propose a method for mapping and discretizing the areas according to their potential to attract, maintain and develop the *Aedes aegypti* mosquitoes. Hence, we calculated that bringing these various factors together locally could have a multiplying effect with respect to the risks to the development of mosquito populations. The local results of the ESIAA are therefore highly sensible. This sensibility is actually being tested using the CRIANN’s (Normandy Computer Resource Center) supercomputer. However as the indices are based on real environmental data, the variable space is reduced by the fact that possible combinations are limited to those that can be observed in real environmental conditions. A perspective of ESIAA calculation tool development would be to establish the link between temperature and the duration of the development using simple linear equations.

This method of evaluating environmental risk by taking evolving data as input data has the advantage of producing, as an output, risk maps that are themselves evolving. Thus the environmental risk in Bangkok, while it is closely linked to rainfall, does not
appear to be homogeneous in the urban area. Creating the hazard index makes it possible to identify the areas presenting a high risk with a high degree of accuracy and thus to geographically orient the available means in order to monitor vector populations.

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