Novel ellipsoid spatial analysis for determining malaria risk at the village level

Usa Lek-Uthai, Jare Sangsayan, Boonlue Kachenchart, Kasem Kulpradit, Dusit Sujirarat, Kiyoshi Honda

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ABSTRACT

The distribution patterns of malaria incidence at a village level in Thailand were demonstrated with the use of a geographical information system (GIS), and provided the study of the malaria situation at a household level. Mosaic imageries from aerial photographs were used to create maps that contained X and Y coordinates. These digitized base maps were kept as computerized files. Standard Distance Ellipse (SDE) was used to measure the prevalence of dispersion around the mean center of malaria cases and points. Households in the SDE were at greater risk of malaria infection than those located outside the SDE. The spatial pattern of malaria incidence was investigated using spatial autocorrelation using Geary's ratio and Moran's index. Five of seven villages had a clustered spatial distribution of malaria incidence, the vector point of which had a 2–3 km range from the patient’s houses. Only one village had a significant clustered spatial distribution of malaria incidence (p < 0.05). Control efforts should be focused on high-risk areas, especially those households with the heaviest caseloads. This approach would probably be more cost effective than the conventional malaria control methods. This SDE analytical technique would be a novel and useful epidemiological control method for use by public health administrators. The ellipsoidal areas required malaria control intervention.

1. Introduction

There are between 300 and 500 million reported clinical malaria cases globally and malaria causes 1.5–2.7 million deaths annually (Srivastava et al., 1999). Each year malaria causes the death of about 1 million children, especially in Africa (Looareesuwan et al., 1990). Malaria outbreaks are characteristically found in the annual May–July rainy season in Northern and Central Thailand and in both the Northeast and South of Thailand. There are malaria epidemics during the annual November to December rainy season. Even though the number of malaria patients is reduced every year, malaria has not been eradicated from Thailand. Migrants from Myanmar and Cambodia, who work in Thailand, have malaria parasites in their blood and cause a significant number of malaria deaths among Thai people. The 5 provinces with the highest number of malaria infections in 2007 were Ranong, Yala, Mae Hong Son, Tak, and Songkla. These provinces also have a high prevalence of both falciparum and vivax infections. Malaria elimination and eradication strategies are difficult to implement (Lek-Uthai, 1999). It has been demonstrated that the GIS is a popular worldwide disease control measurement (Srivastava et al., 1999). GIS and spatial analysis provide the necessary methods for the study of malaria situations at both the household and village levels. The goals of these surveillance methods are numerous and facilitate the collation of the following types of information about the study area populations: to define the geographical area affected by the mosquitoes which have originated from identified habitats, to
identify the geographical area that needs to be treated in order to control larval mosquitoes, to determine the geographical distribution and incidence of malaria infection, to map the population at risk of malaria infection, and to stratify the risk factors. The forecasting, monitoring, and intervening into malaria epidemics with adulticidal and larvicidal strategies was undertaken with great concern. However, this study used Standard Distance Ellipse (SDE) to measure the dispersion of the incidence around the mean center of malaria cases and points (Diggle, 1983; Weinstock, 1981). We studied the malaria distribution patterns using the distance between malaria incidents and the water bodies that were vector breeding sites to determine the relationship between the environmental factors of the water bodies that were vector breeding sites and the density rate of their mosquito’s larva. Spatial analysis is one function that can explain or link a relationship between factors such as the physical, biological, and socioeconomic phenomena (Chou, 1997), and emphasizes the measurement of the spatial localization phenomenon. That is, the mean center analysis was considered to incorporate the endemic area (Câmara et al., 2005). Point pattern analysis (Saraf et al., n.d.), was used to identify whether or not the occurrences or events of endemic areas were related to the epidemiological factors and also to determine whether the endemic areas were randomly clustered or formed regular patterns. This study focused on the assessment and estimation of the distribution patterns of disease occurrence and explains the relationship between malaria distribution and the epidemiological and environmental factors at the village level of endemic regions.

2. Materials and methods

The Disease Prevention and Control Office undertook a survey among a target population of malaria positive cases in the 2004 fiscal year. Their report titled, ‘Investigation and Radical Treatment of Malaria cases’ (EP.3), surveillance risk groups, risk factors, and environmental factors at a household level using purposeful sampling within seven villages of two perennial transmission areas. These were (A1) non-endemic areas, and (B2) an area including: Ban Pha Pok Kao, Suan-Puang sub-district, Suan-Puang district, Ratchaburi province (RA), Ban Tra Kor Neuar, Bu Fai sub-district, Pra Chan Ta Karm district, Prachin Buri province (PF), Ban Na Bon/Tung Krang, Tub sai sub-district, Pong Nam Rorn district, Chanthaburi province (CT), Ban Rai Phum, Par Deng Neuar sub-district, Kang Kra Charn district, Phetchaburi province (PE), Ban Kao Ta Lard Mai, Tha Ta Keab sub-district, Tha Ta Keab district, Chachoengsao province (CS), Ban Mern Darn, Bor Ploy sub-district, Bor Rai district, Trat province (TR), Ban Kao Cha Ang Bon, Ploung Thong sub-district, Bor Thong district, and Chonburi province (CH) (Fig. 1). This was the reduced area subject to this study.

A questionnaire concerning disease protection behaviors including the use of mosquito repellent, mosquito coils, impregnated mosquito nets, and the use of electric fans was undertaken. The environmental factors survey, such as the studies of suitable water bodies being vector breeding sites, were composed of eight factors: air temperature (A-temp), wind velocity (V-wind), absolute humidity (Humid), sunlight around vector breeding sites (LUX), water temperature (W-temp), pH, dissolved oxygen (DO), and the density rate of the mosquito’s larva were recorded. These environmental factors were recorded with the use of a Mini thermo-hygrometer, a Mini anemometer, a Mini thermo-hygrometer, a Light meter, a DO meter kit, and a pH meter kit. The first data recorded was that of the low malaria transmission period data which was collected in March 2004. The second and third data collections, according to the history report of high peak of malaria transmission, were collected in July and December 2004, respectively. Co-ordination of the data of the houses of malaria positive case locations in the study areas were recorded using a GPS. The mosquitoes preferred breeding in natural water bodies such as a body of slowly flowing water, a shallow stream or in human made water bodies in a shady area, rather than in clean water. Aerial photographs at a scale of 1:25,000 from the Ministry of Agriculture and Cooperatives, digital topographic maps at a scale of 1:50,000, and sheets numbered 4840III, 4934IV, 5237III, 5335I, 5335III, 5435II, and 5534III from the Royal Thai Survey Department were performed. Hand made maps of villages from the Vector-Borne Disease Control Unit showed the house positions without scale imaging. Malaria Risk behaviors, the vector breeding sites characteristics, such as the water body position and malaria patient houses were organized with the use of the Microsoft Excel program and then a DBASE IV program was used to study the malaria study cases and related study data. Household points of malaria patients and water body’s environments were collected and transferred to develop a Map Source version 5.4 program and this data was converted from DXF files to shape files by means analysis using the ArcView GIS version 3.2a and the ArcGIS version 8.3 programs. Aerial photography facilitated the reporting of the malaria positive cases and the household points position were geometrically collected by referring to the reference points from the topographic maps to imagery using the Image Geometric Correction function of the ERDAS IMAGINE 8.5 program. Then, re-sampled aerial photographs were used to fix points in every village and these were compared to the maps of each village. The data preparation for the spatial analysis included scrutiny of the data in order to omit anomalies from a total study population, so only those who stayed in the village household were included in the study population. Similarly, malaria patients at risk of malaria infection and those who were protected from malaria transmission from other sources, such as work in the forest, and who traveled to other malaria risk areas were excluded (Koram et al., 1995).

In addition, a relationship study of the distance between the patient’s houses and the vector breeding sites was considered. The package program, Statistical Package for the Social Science/Personal Computer plus (SPSS/PC+) was used to analyze the general characteristics. Percentages of malaria personal protection behavior were also analyzed. The mean distance between each patient’s house and all variables of the water bodies environments were reported. The dispersion of water bodies data were recorded using standard deviation. The distribution of environmental factors was analyzed using the Pearson correlation coefficient and the personal protection behavior criteria were analyzed using the Chi-Square test. The central tendency of point distributions of malaria incidents was analyzed by mean center in order to explain an area value trend to the mean center of malaria patient’s houses. A mean center or spatial mean was calculated to determine the central tendency of malaria incidence. These two values could explain the average location of a malaria incidence point. Standard Distance (SD) and Standard Deviation Ellipse (SDE) were used to explain the dispersion around the mean center of malaria incidence. To measure the spatial distribution pattern of malaria incidence by spatial autocorrelation, two indexes, Geary’s ratio and Moran’s index were used. If Geary’s ratio approached a value of 1, greater than 1, or less than 1, the point distribution patterns under the specific conditions among the distance between the patient’s houses and vector breeding sites were considered as random, regular and clustered, respectively. If Moran’s Index approached a value of E(I), less than E(I), or greater than E(I), the point distribution patterns were classified as random, regular, and clustered, respectively. Where \( E(I) = \frac{1}{n} - \frac{1}{n(n-1)} \) spatial autocorrelation could analyze both the locations of points and the attributed data (Lee and Wong, 2001). Therefore, field survey fieldwork was undertaken to collate and co-ordinate the average distance between the patient’s houses and the vector breeding sites and the results were recorded and cal-
Fig. 1. The map of Thailand shows the studied villages positions in the studied area. The endemic areas of western and eastern villages in Ratchaburi (RA), Prachinburi (PJ), Chonburi (CH), Trat (TR), Chanthaburi (CT), Chachoengsao (CS) and Phetchaburi (PE) provinces.

culated. Then, the distribution patterns of malaria were obtained. Maps, aerial photographs and a satellite coordination surveillance system were used to survey the village. This information was used to prevent other at risk households in areas where environmental factors were suitable for the study of a malaria outbreak. The patients of this study had not been infected from other areas. Furthermore, this study used the household location or point as a patient household.

3. Results

There were a significant difference between the Eastern (Thai-Cambodian), and the Western (Thai-Myanmese) studied villages among the *Anopheles* species rate and the water body environments, household settlements, and their distances from the forest ($p > 0.05$). The results showed the areas of high and low risk for malaria and presents the different bionomics of the *Anopheles* species breeding patterns. The monthly A1 and B2 malaria blood positive rates from the Eastern and Western provinces were no different ($p = 0.513$). The high and low risk areas of the Thai-Myanmar border and the Thai-Cambodian border provinces were compared. The retrospective study showed a higher prevalence of *Plasmodium vivax* than *P. falciparum* in the October 2002–August 2004 period and the endemic Kanchanaburi province recorded the highest number of cases of *P. falciparum* since 2002–2003. The year 2004 had the highest prevalence of *P. vivax*, particularly in the April–July period. Rachaburi, Petchaburi, and Prachuap–kirkun provinces consistently had higher numbers of cases of *P. vivax* than *P. falciparum* in the October–January period. Sa-Kaew, Prachinburi, Chonburi, and Chachuangsao provinces had their highest peaks of *P. vivax* in the April–May and December periods and the data fluctuated over the whole year. There was a wide range of differences between the water sources where other water arthropods were found ($p < 0.001$). The associations among other water arthropods and *Anopheles* larvae in the water breeding sites and the proportion of water arthropods found and the larvae of *An. dirus*, *An. minimus* and *An. maculatus* were significantly different ($p < 0.001$), but the *An. aconitus*, and *An. barbirostes* were not different. The proportions of *Culex* larvae densities were significantly different among the water sources which had water arthropods and those which did not ($p < 0.001$). The proportion of *Aedes* larvae densities prevalent in water bodies without water arthropods showed significant differences from the *Aedes* larvae densities from water bodies without water arthropods ($p = 0.012$). The prevalence of infection of A1 was in the range of 1–6.7% and the prevalence of B2 infection was about 57–81%. The *P. falciparum* proportions of the Eastern and Western provinces were compared, but there were not any significant differences in their mean blood positive rates: mean = 17.04 ($\pm 27.03$),
and 12.09 (±23.60), respectively. There were significant differences in the Eastern and Western provinces as regards the prevalence of the Anopheles species rate as well as their water body environments, household settlements, and distances from the forest (p < 0.05).

### 3.1. The correlation of environmental factors of vector breeding sites

To analyze the relationship of environmental factors of the vector breeding sites, this survey was undertaken in March, July and December, 2004. The average values of the environmental characteristics of the vector breeding sites of all seven villages were as follows: The A-temp was 32–34.04 °C, the W-temp was 26.77–30.35 °C, the pH was 7.04–8.36, the DO was 38.50 ± 0.14 unit/200 dips. The PE’s environmental factors and those of the CH were significantly related to the quantity of mosquito larva (p < 0.05) as the presented details show (Table 3). The RA: A-temperature correlated with the D-Larva more than the other factors (r = 0.684). When comparing the V-wind and the pH levels, statistically significant differences were found (p < 0.05). For the PE, the values of the V-wind and the D-Larva showed a significantly high negative correlation with the coefficient value −0.712 at p < 0.05, but the other factors had a low correlation with the D-Larva. It could be observed that the A-temp correlated with the W-temp (p < 0.01) and the pH level (p < 0.05). For the TR, the W-temp correlated with the D-Larva more than the other factors (r = 0.317). It was observed that the W-temp correlated with the A-temp (p < 0.01) and the LUX (p < 0.01), while the LUX correlated with the A-temp (p < 0.01), and humidity level (p < 0.05). For the CH, the DO correlated with the D-Larva (p < 0.05). It was observed that the A-temp correlated with the W-temp (p < 0.01), while the A-temp correlated with pH level (p < 0.05) and V-wind (p < 0.05). For the CS, the V-wind correlated with the D-Larva more than the other factors (r = 0.300). It was also observed that the W-temp correlated with the A-temp (p < 0.01), and humidity level (p < 0.01), while the humidity level correlated with the V-wind (p < 0.05). Also, the LUX correlated with the A-temp level (p < 0.05).

Of all the recorded environmental factors in the villages, the CS village had the highest mean average. There were higher than mean values recorded for factors such as A-temp, LUX, W-temp, and pH but the mean values for these four factors were 34.04, 18,523, 30.35, and 8.36, respectively. While the TR had the highest humidity level of 64.24, it’s A-temp and W-temp were the lowest at 29.07 and 26.77 °C, respectively. The CH had the highest level of sunlight at 14894 LUX, but it’s W-temp level was lower than of the PE which had a lower level of 0.14. Nevertheless, the PE village, where the V-wind level was 0.63 had the highest D-Larva detection level at about 38.50 larva/200 dips. The second highest level of 9.81 larva/200 dips was found at the CH village. The study site at CH village had the softest of all the sites, 8477 LUX, while the CT village had a humidity level equal to 48.64. This area had the lowest density of mosquito larva, 1.81 larva/200 dips. The proportion of the Anopheles rate associated to the malaria positive rate (p < 0.001), had an anemometer velocity and direction flow at (p = 0.034) at the water body’s temperature (p = 0.001) at the impregnated mosquito net (p = 0.032). The air temperature associated to the humidity (humidity meter) (p = 0.001), pH (p = 0.036) at the water body’s temperature (p < 0.001). The velocity associated to the light level (LUX) (p = 0.004), humidity (p < 0.001), and pH (p < 0.001). The light concentration associated to the humidity (p = 0.037), and pH (p = 0.006), and dissolved oxygen (DO meter) (p = 0.001). The humidity associated to the DO (p < 0.001), pH (p < 0.001) and pH associated to the DO (p = 0.001). The table of correlation analysis of environmental factors for each site was not shown. There were no relationship among the larval density of malaria incidence and the environmental factors in different endemic areas. The multiple regression analysis table was not shown.

### 3.2. The relationship of malaria protection behaviors

The relationship of malaria protection behaviors indicated that there were other factors affecting malaria and not just the distance and environmental factors. The main four malaria protection behaviors were the use of mosquito repellent, the use of mosquito coils to protect from mosquito bites, impregnated mosquito nets, and the use of electric fans. The numbers of people at risk at the RA, PJ, PE, TR, CH, and CS villages were 48, 27, 77, 18, 31, 38, and 35 people respectively. The protection behaviors among those seven studied areas were compared (Suppl 3). Three of the malaria prevention behavior factors which were not related to the cause of malaria infection at PJ were the use of mosquito repellent, mosquito coils and electric fan usage. At the CT village, the use of impregnated mosquito nets and the use of electric fans was related to malaria infection and statistically significant differences were found at p < 0.05 (χ² = 0.016, 14.418, df = 1).
Presented the mean center of the patient’s houses and the distance between the mean center of the patient’s houses and the vector breeding sites. Numbers and location of all households, patient’s houses, vector breeding sites, and area of villages (m²) which Standard Distance (SD) around the mean center of malaria transmission. Thereupon, ArcInfo software can be utilized to integrate collated data from several environmental and entomological factors played a major role in the determination of malaria transmission. Nevertheless, the risk of malaria infection would vary according to the environmental and the entomological factors played. The epidemiological study also exemplified the value of a computerized GIS in providing quick and reliable information used for planning purposes, particularly in the buffer zones around geographical landmarks such as water bodies and house construction types. Therefore, control efforts should be focused on high-risk areas, especially those households with the heaviest caseloads. This method would probably be more cost effective than conventional malaria control methods especially in densely populated regions.

### 4. Discussion

The GIS could be applied in many public health and environmental research studies (Lee and Wong, 2001; Saraf et al., n.d.). Nevertheless, the risk of malaria infection would vary according to the season and the distance between the breeding sites and the patient’s houses within these studied areas. Most cases were clustered in the studied villages where multiple cases were recorded and often located near the water bodies. These results suggest that the environmental and the entomological factors played a major role in the determination of malaria transmission. Therefore, ArcInfo software can be utilized to integrate collated data obtained with the use of GIS as can topographical and satellite-generated maps, aerial photographs and survey data records. The geographic landmarks such as water bodies and house construction types.

### Table 1

<table>
<thead>
<tr>
<th>Villages</th>
<th>Houses</th>
<th>Patient houses</th>
<th>Breeding sites</th>
<th>SD from mean center (meters)</th>
<th>Number of houses in SD (houses)</th>
<th>Angle of rotation (°)</th>
<th>Number of houses in SDE (houses)</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>417</td>
<td>31</td>
<td>6</td>
<td>1,076.93</td>
<td>185</td>
<td>68.5</td>
<td>137</td>
<td>18,110,952</td>
</tr>
<tr>
<td>TR</td>
<td>122</td>
<td>11</td>
<td>5</td>
<td>1,296.48</td>
<td>98</td>
<td>73.3</td>
<td>31</td>
<td>9,953,600</td>
</tr>
<tr>
<td>RA</td>
<td>80</td>
<td>24</td>
<td>3</td>
<td>337.13</td>
<td>46</td>
<td>45.4</td>
<td>28</td>
<td>639,128</td>
</tr>
<tr>
<td>PE</td>
<td>92</td>
<td>9</td>
<td>3</td>
<td>1,032.68</td>
<td>69</td>
<td>33.0</td>
<td>45</td>
<td>8,761,185</td>
</tr>
<tr>
<td>CH</td>
<td>106</td>
<td>2</td>
<td>7</td>
<td>313.94</td>
<td>8</td>
<td>–</td>
<td>–</td>
<td>17,715,019</td>
</tr>
<tr>
<td>PJ</td>
<td>96</td>
<td>7</td>
<td>5</td>
<td>326.01</td>
<td>33</td>
<td>25.6</td>
<td>16</td>
<td>2,361,968</td>
</tr>
<tr>
<td>CS</td>
<td>217</td>
<td>1</td>
<td>12</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15,856,598</td>
</tr>
</tbody>
</table>

### Table 2

Geary’s ratio and Moran’s index of spatial autocorrelation in each studied area; CS has not shown the central tendency. The index could not be calculated.

<table>
<thead>
<tr>
<th>Villages</th>
<th>Geary’s ratio</th>
<th>Moran’s index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index value</td>
<td>Expected value</td>
</tr>
<tr>
<td>CT</td>
<td>0.313</td>
<td>1</td>
</tr>
<tr>
<td>TR</td>
<td>0.294</td>
<td>1</td>
</tr>
<tr>
<td>RA</td>
<td>0.002357</td>
<td>1</td>
</tr>
<tr>
<td>PE</td>
<td>0.297</td>
<td>1</td>
</tr>
<tr>
<td>CH</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PJ</td>
<td>0.710</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3 shows that the five of the seven villages located at comparably similar distances far from the breeding sites, namely: CT, TR, RA, PE, and PJ, had clustered spatial patterns of malaria incidence. It was noted that only the TR village had a significant clustered spatial pattern (p < 0.05). This method of investigating the spatial pattern of malaria incidence was similar to that of a study by Saraf et al. (n.d.), in that a spatial statistic technique was used to study the relationship of earthquake epicenters to affected geographical structures. Saraf’s study found that the affected areas were clustered in relation to the earthquake’s epicenter. Wall et al., 1985 used point pattern analysis when planning a residential project in Toronto. They discovered that a number of hotels were being built to replace motels, which meant that there was a significant increase in the number of buildings being built in the same sized area. Most of these buildings were located in the business and airport districts.
The analysis of the spatial data for the incidence of malaria was done by determining the co-ordinates of all households, patient’s houses, and the water bodies that were the breeding sites of mosquito vectors in the seven villages that were surveyed under the main headings of (i) the distance between patient’s houses and the vector breeding sites. The mosquito’s life cycle necessitates their breeding in water bodies. When the adult mosquito emerges, they will live and feed near their breeding sites. Only adult female mosquitoes feed on blood and do so in order to develop their eggs. For this reason, female mosquitoes are capable of flying 2–3 km from water body breeding sites. The study found that the average distance between patient’s houses and the vector breeding sites was 3 km. (ii) Measuring the center of the distribution point of malaria incidence using a mean center in order to explain an
area value trend to the mean center of the malaria patient. People living in households located nearby the mean center of a malaria-affected area are at higher risk of infection than those located far away from the mean center. The study also found that the mean centers of malaria incidence of the CT and CH villages were more than 200 m. The mean centers of malaria incidence of the TR, RA, PE and PJ villages were no further than 200 m from their respective village centers. This implies the dispersion of malaria over these four villages. The maximum average distance from mean center of six villages to vector breeding sites did not exceed 2000 m or 2 km except for the CS village for which a mean center could not be obtained because this village only had one patient. (iii) Studying the dispersion of malaria incidence points by the SD and the SDE because Standard Deviation Circle (SDC) is an efficient tool used to calculate average distance points as well as to display the spatial patterns of location points. The study proved that an area’s size could not determine its level of malaria dispersion. The study exemplified the patient’s households as being representative locations of those patients. This location was then considered as a geographic phenomenon. This geographic phenomenon creates a directional bias. Thus, the SDE is an efficient method of measuring the dispersion of a malaria incident’s location because the SDE can capture the directional bias of an incidence of malaria because the malaria is in the direction of the household’s location. The number of households located in the SDC was greater than those in the SDE. Households in the SDE were at greater risk of malaria infection than those located outside the SDE. (iv) The spatial pattern of malaria incidence was investigated using spatial autocorrelation using Geary’s ratio and Moran’s index. This methodology can also be used to measure the locations of points and attributes.

4.2. The coordination of all households, patient’s houses, vector breeding sites and the distance between patient’s houses and the vector breeding sites

Fig. 2 and Suppl. 2 show the differences in spatial patterns of the household’s locations and the patient’s households. The vector breeding sites also had different spatial patterns due to their different geographical locations and water storage demands. The mosquito’s life cycle needs a water body as a breeding site, so the researcher focused the survey and data collection on water bodies. The distance between patient’s households and the vector breeding sites was a cause of malaria infection. The patients suspected of infection from other factors, such as a history of illness or travel was excluded from this study. In addition, the study found that water bodies 2–3 km from the patient’s houses were one of the factors increasing the risk of malaria infection. From this knowledge, malaria infection prevention could be managed through the improvement of household characteristics such as plugging holes in houses, and placing mosquito nets at doors and windows. This result was in line with a study by Taneeuwit (1997) on the factors related with malaria incidence in the Tong Pa Phum district, Kanchanaburi province, in which similar statements were made about the necessity of residential improvements: e.g. cottages (OR = 3.06, 95% CI = 1.20–8), bamboo houses (OR = 3.21, 95% CI = 1.16–9.06), houses with bamboo walls (OR = 4.26, 95% CI = 1.63–11.35), houses with less than 4 walls (OR = 2.69, 95% CI = 1.09–6.79) and houses nearby water bodies (OR = 3.06, 95% CI = 1.20–8). Moving houses from nearby water bodies to safer areas also could reduce the incidence of malaria. Abeyesekera et al. (1996) used a GIS to determine what measures should be implemented to prevent malaria incidence in the residents of better houses made of brick walls and tiled roofs and poorer houses made of mud walls and cadjan roofs. The study indicated that there was a significant relationship between the distance of poor houses from vector breeding sites and malaria incidence. Moving the poor houses to an area far beyond the 200 m buffer zone could reduce malaria incidence by 30%.

4.3. The mean center of patient’s houses and the distance between the mean center of patient’s houses to vector breeding sites

Suppl. 2 and Table 1 show that the mean center of malaria incidence was located at a part of the middle of the villages. It was known that the residents of households located nearer the mean center were at greater risk of malaria infection than residents living far from the mean center. The results, which included the distance between the mean center and the water bodies, showed that all the surveyed villages were at an average distance of no more than 2 km between the village mean center and the water bodies.

Based on the results in seven villages, the maximum average distance from the patient’s houses to breeding sites was 3 km. This result is consistent with the study of Lek-Uthai (1999), which stated that a malaria mosquito vector is within 2–3 km from its breeding site. Buttraporn et al. (1986) studied the relationship between social factors, behaviors, and household characteristics with malaria incidence in Eastern Thailand. The results indicated that most of the patients worked 2 km from the forest. Menach et al. (2005) studied the unexpected behavior of carrier mosquito’s laying of eggs. The results showed a poor management of water bodies, which could be points of origin of malaria transmission. Adult mosquitoes may disperse highly between villages and can fly up to 5 km but mostly fly within 1 km from a village. Walker (1997) studied the behaviors of the Anopheles gambiae and found that the mosquitoes lived and died nearby their breeding water bodies as did other mosquito species. Male mosquitoes fly around their breeding water bodies and near the flowers they considered their feeding sites and may not ever fly beyond a kilometer from these areas.

4.4. The relationship between environmental factors and vector breeding sites

The GIS analysis results indicated that the spatial patterns of malaria were related with the distance from patient’s houses and vector breeding sites. This result is consistent with a finding of Menach et al. (2005), who stated that water bodies, which were not suitable for mosquito breeding, could also be origin points of malaria transmission.

At the PE site, wind velocity had a negative relation to larva density, which meant that the higher the wind velocity, the lower the larva density. This was because wind disturbs mosquito’s breeding. At the CH site, the quantity of DO had a positive relationship to larva density. The reasoning supporting this result was the vector breeding sites dependency on a high level of DO. Therefore, the clean vector breeding sites were suitable as mosquito breeding sites.

At the PJ site where there was a pH increase, an increase in the density rate of mosquito’s larva was found (Table 3). These results are consistent with the findings of Reid (2000) on the relationship between climate change and malaria incidence. The study stated that temperature, rainfall, humidity, and wind velocity are associated with malaria infection. Temperatures of 25–27 °C are suitable for mosquito vector life. A temperature of 40 °C harmed mosquito life and malaria infection. Rainfall is also associated with malaria infection because rainfall also affected humidity and temperature resulting in a breeding place of a mosquito vector. Although humidity had no effect on malaria infection, it did relate to mosquito life. It was believed that a humidity level lower than 60% shortens a mosquito’s life cycle, whereas wind velocity had both negative and positive impacts on malaria incidence. Although a strong wind velocity reduced, mosquito’s biting and mosquito’s breeding, it also supported mosquito’s flying longer distances. This will change the mosquito’s spatial pattern. The study by Walker (1997) on the
behavior of the *Anopheles gambiae* stated that a clean water body with enough light was a suitable breeding site for this species of mosquito, but a temperature of 38.1°C around the water body harmed this mosquito’s life. Since a suitable breeding site was a clean water body with enough sunlight, malaria control measures could be formulated using this result. The recommended malaria prevention and control measures were putting killer fish in such water bodies to control the mosquito’s larva, and changing the physical characteristics of water bodies in order to eliminate these water bodies as preferred mosquito breeding sites.

To study the correlation of the environmental factors of vector breeding sites, field surveys were conducted in March, July and December of 2004 in order to investigate the eight environmental factors, which make water body’s suitable mosquito breeding places. Thus, malaria control measures can then be designed to make water body’s unsuitable mosquito breeding sites. The results indicated that the environmental factors of vector breeding sites at PE, and CH were significantly associated with the density rate of mosquito’s larva ($p < 0.05$).

### 4.5 Measuring the dispersion of the malaria incidence’s location

A patient’s house was representative of a patient’s particular geographic phenomena. As a result, directional bias occurred. Therefore, the SDE was more efficient than the SDC in measuring the dispersion of malaria incidence. The CF area was the biggest whereas the RA area was the smallest (Table 1 and Fig. 2). Thus, the size of the area was not the factor that determined the dispersion of malaria incidence. Having compared the SD and the SDE from each village (Table 1 and suppl. 1), it was found that the center of the malaria was located in the same position. It was noted that number of households in the SDC was higher than the number of households in the SDE. Thus, the SDE showed that the dispersion of malaria incidence was in the same direction as the household’s location. This was consistent with the study by Saraf et al. (n.d.) on the relationship of earthquake epicenters and geographical characteristics using spatial statistics. This study also referred to Lee and Wong’s (2001) methodology, calculating the data set from the SD and the SDE of earthquake epicenters. Consequently, an SDE can be used as an efficient tool to monitor malaria incidence. Residents of households located in the ellipse area are at greater risk of malaria infection than residents of households located outside the ellipse area. In conclusion, the risk area was clearly determined. This technique also reduced field survey costs.

### 4.6 The correlation of malaria prevention behaviors

Malaria prevention behaviors in this study were the applying of mosquito repellent, and the use of mosquito coils, impregnated mosquito nets and electric fans. These preventative measures were easy for people to apply and prevented malaria infection. If people were aware of these measures, they could prevent themselves from infection even if they lived in high-risk areas. Conversely, if people ignored these preventative measures, the number of malaria infections may increase. The report of a WTO Study Group: Malaria Vector Control and Personal Protection (2006), mentioned that the protection measure that most directly controls adult mosquitoes, was the use of impregnated mosquito nets, Suppl. 3 indicated that all four malaria prevention behaviors in each village had different associations with malaria infection. At TR, the use of mosquito coils with malaria patients had a significant association with malaria infection ($p < 0.05$), and so did especially, the applying of mosquito repellent ($p = 0.008$). This result was consistent with a report of a WTO Study Group: Malaria Vector Control and Personal Protection (2006), in which was stated that mosquito repellent was widely used by tourists in developed and developing countries as a means of protection from mosquito bites. At CT, the use of impregnated mosquito nets had significant associations with malaria infection ($p < 0.05$), and so did especially, the use of electric fans ($p < 0.001$). This is consistent with the article from the National Institute of Health, U.S. Department of Health and Human Services (2007), on the relationship of understanding malaria and the free outbreak disease. They stated that mosquito nets impregnated with pyrethroid were able to prevent people from mosquito bites. The use of such nets affected a decrease of malaria infection and was certainly consistent with the findings of Funglada et al. (1987) on the relationship of socioeconomic factors, environmental factors, and the behavior of malaria infection in malaria patients who were treated at Pahanponpayahasena hospital, Kanchanaburi province. There was a relationship between the use of mosquito nets and malaria infection ($OR = 2.45$, $95\% CI = 1.02–5.92$).

Mugisha and Arinaitwe (2003) studied of sleeping management and mosquito net use by Ugandan children under the age of five, found that children had used mosquito nets because they had slept with their parents. In conclusion, these behaviors were associated with malaria infection. It was consistent with the findings of Wongchantarapong (1990), who stated that even though malaria patients from the Krang district of Rayong province, when working in the forest, used mosquito coils, electric fans, and slept in mosquito nets, when they left their houses during the night, they were infected with malaria and required hospitalization. Taneewut (1997) studied factors related with malaria sickness in the Tong Pha Phum district of Kanchanaburi province. The investigation on self behavior prevention yielded that; sleep without mosquito nets resulted in (OR = 4.03, $95\% CI = 1.42–11.97$), not using an electric fan resulted in (OR = 4.00, $95\% CI = 1.01–18.75$), and not using mosquito repellent when working in the forest resulted in (OR = 2.67, $95\% CI = 1.30–5.49$).

Malaria control efforts should be focused on high-risk areas especially on those households with the heaviest caseloads. This is also probably more cost effective than employing malaria control methods in a conventional manner. Hung and Yasuoka (1994) found that the use of remote sensing data, as well as physiological and socioeconomic factors were of assistance in the study of a cross-sectional view of imbalanced rural and urban developments in the Chiang Mai and Lumphang provinces in Thailand. Abeyesekera et al. (1996) mentioned that malaria might not be distributed in a homogenous pattern even in those regions that were located in a region affected by the same climatic event. They found that the high prevalence risk areas were more in dry areas than humid areas. They also found that malaria infection was related to environmental factors, mosquito life span, breeding sites, population movement and a low immunity to malaria. The proportions of the *Anopheles* rate ($p < 0.001$), velocity and direction flow (anemometer) ($p = 0.034$), water body temperature ($p = 0.001$), and impregnated mosquito nets ($p = 0.032$) was associated with the malaria positive rate. The risk of malaria also varied according to season, and the distance between the breeding sites and the patient’s houses within the studied areas. This study showed a higher rate of *P. vivax* than *P. falciparum* since the October 2001 to August 2004 period. The endemic Kanchanaburi province recorded the highest number of cases of *P. falciparum* since the 2002/2003 period, while the year 2004 presented the highest rate of *P. vivax* in the April/July period. The study of correlations among other water arthropods and *Anopheles* larvae in the water of breeding sites ($p < 0.001$), and the proportions of water arthropods and the larvae of *An. dirus*, *An. minimus* and *An. maculatus* were significantly different ($p < 0.001$), while those in *An. aconitus* and *An. barbirostris* were not. The proportion of *Culex* larvae densities was significantly different among the water sources ($p < 0.001$). The proportion of *Aedes* larvae densities which preferred water bodies without water arthropods were significantly different from the *Aedes* lar-
The P. falciparum proportions of the Eastern and Western provinces did not have different mean blood positive rates (mean = 17.04 (±27.03), and 12.09 (±23.60). Most of the malaria cases were clustered in the studied villages where multiple cases were recorded, and using standard ellipse analysis, were often found to be located near water bodies. Guthmann et al. (2002) studied the association between environmental factors and malaria infection. They found that the prevalence and incidence of malaria infection at the low endemic areas showed the incidence of 40 per 1000 of the population. Indaratana et al. (1998) analyzed the association between the malaria and Dengue infection situations and the economic items in Thailand using GIS analysis. Their results showed that the provincial Gross Domestic Product (GDP), health sector, and distance and location were related to the geographical distribution of these infections. They suggested proper participation measures for the collection and recording of the socioeconomic and epidemiological related factors including their respective vectors. They also suggested that Leishmaniasis, Trypanosomiasis and Schistosomiasis were important data requiring analysis for both national and international control measures. Such analysis may also affect a reduction in national economic loss. Craig et al. (1999) who reported that rain fall and temperature related to malaria transmission, agreed with Booman et al. (2000) who had studied the association of malaria transmission with the population movement, insecticide resistance, malaria drug resistance, that these factors were dynamic. Sharp et al. (1988, 2001) studied the vector control measure by insecticide fogging for the mosquito’s life span and reduction in mating ability. Nobre et al. (1997) studied the malaria surveillance system and control measures in Brazil. They suggested the importance of strongly connecting the potential skill of health workers on the collection of epidemiological data in order to eliminate and control the disease. Sithiprasasna et al. (2003) reported the malaria vector distribution at a household level of three villages in Mae Sod in the Tak Province of Thailand. Using GIS management, the study site was located in a 20 km surrounding area. 86% of An. minimus was related to malaria infection. Buttraporn et al. (1986) said that malaria infection was related to people who worked near the forest or who entered the forest 2 km from the forest. They also found that the locations of the houses near the breeding site and the types of houses, such as those constructed from wood, were also pertinent factors. They also stated that malaria infection was related to socioeconomic factors such as education, income, and occupation. Taneeuwit (1997) reported the relationship of malaria infection at Thongpapum district, Kanchanaburi province, to the socioeconomic factors relating to malaria infection, and found that low-income earners were at greater risk of infection than higher income earners. Chou (1997) said that spatial analysis could explain or link phenomenon including physical, biological, and socioeconomic factors. At present, the GIS is a popular instrument used in disease control strategy in the public health field. Srivastava et al. (1999) wrote that it was easier to assess, correct and change a situation at a community district level than at a large province level. Schellenberg et al. (1998) studied the malaria endemic area at a community level to emphasize the feasibility of the use of a GIS and data management in endemic regions and the relationship of malaria distribution and environmental factors at community levels. The SD and the SDE were used to analyze the direction of dispersion from point distributions. The residents of the houses located in the ellipsoidal area were at high risk of malaria infection but the residents of the houses located outside the ellipsoidal area were at low risk of malaria infection. The dispersion of clustered malaria cases was affected by the factor of distance between the patients and the breeding sites. The dispersion from distribution points, the direction of the case points, as well as the locating of adult mosquito catching points, was determined using standard distances and the SDE for the SD from the mean center. This provided information that could be used to facilitate malaria control program intervention measures. This spatial data is most useful because it provides standardized and exact geographical coordinates through its use of the global positioning system (GPS) which is also used for overlaying in order to establish an operational GIS for epidemiological surveillance. The geo-references of the studied villages corresponded to the digitized base maps. Using a GIS to link health risk factors and mapping systems, provides a comprehensive picture of any situation requiring cross-sector analysis. Using recent advances in GIS technology and mapping technology systems, GIS can play a vital role in detection management and can also be used in responding to health problems. Public Health administrators can make any decision reliant upon on consistent surveillance and health information data obtained with the use of a GIS system. So, information on epidemiology, entomology, ecology, control intervention, and health care resources can be collated to facilitate the development of a dynamic atlas of public health information. This includes the analyzing of spatial and longitudinal trends, assessing resource allocation, stratifying risk factors, forecasting epidemics due to the climate changes, mapping populations at risk at household levels and determining the geographical distribution, variance, prevalence, and incidence of malaria infection. Further, it can also be used to monitor malaria control programs.

The study found that the studied villages had a clustered incidence of malaria infected patients whose homes were located 2–3 km from the vector breeding sites. Therefore, the prevention of malaria infection could be managed through the improvement of household characteristics such as plugging the holes of a house and putting mosquito nets at doors and windows. Moving houses from nearby water bodies to safe areas would also reduce the incidence of malaria. In practice however, these preventative measures are difficult to implement and are also costly. High-level policy makers should base their decisions only after considering and comparing other preventative options. The vector breeding sites are the mosquito’s points of origin. Thus, the surveying of density populations of mosquito’s larva in water bodies should be a continuous process. Moreover, releasing mosquito larva eating fish in the vector breeding sites or adding environmentally friendly substances into the vector breeding sites that destroy eggs or mosquito’s larva should also be considered. Activities or a work plan for people living in a high-risk area, which promotes their awareness of possible malaria infection, should be formulated. At the village level, all households need to be co-ordinated and recorded to ensure the accuracy of data collection of maps created for long term use before being utilized in a study of buffer risk zoning. The surveying of both permanent and temporary water bodies of a village should be investigated. Further, a study should be developed to locate water sources, such as dams, that will be useful in formulating a proper strategic plan to stop mosquito’s breeding. The survey results regarding self-prevention behavior from the villages should be considered. The collection of data of the malaria related environmental factors presented the various pertinent environmental characteristics. During the season changes, the characteristics of mosquito breeding places also change. The cross-sectional survey method has shown the relationship between malaria cases and the distance between the mosquito breeding places and the patient’s household. The time series of cross-sectional surveys, geographical information, and the co-ordinates of houses should be scrutinized. The GPS receiver should be used for of a point-by-point survey of these houses. The information obtained about malaria infection with the use of a GIS and mapping techniques are useful for public health administrators, including policy makers, national program managers, epidemiologists, as well as regional and district officers in establishing GIS operations for epidemiological, environmental, and entomological surveillance tasks. Neverthe-
less, this method is both timely and expensive. However, the researcher’s aerial photographs, the points of which locate those co-ordinated houses to an unscaled map of the villages, which mark the Vector-Borne Disease Control Unit, should be compared. Based on these results, a lack of preventative measures was associated with malaria infection. Households in the SDE should implement preventative measures such as using impregnated mosquito nets and mosquito repellent to avoid being bitten by mosquitoes. Alternatively, public health officials should provide information on how to prevent malaria infection in their villages.

Contributors

All authors helped in the design of this study and in the undertaking of its methodology. UL, BK, and JS co-ordinated the field studies and surveyed point-by-point-using GPS, sample collections, and provided intellectual guidance throughout this study. UL conceived the study, designed and participated in the experiments, and drafted the manuscript. UL cross-checked the manuscript’s findings for entomological identification and was responsible for the aerial photographs and production of figures. JS did the initial drafting of the manuscript and also obtained ethical approval from the Ministry of Public Health. HK provided invaluable intellectual input throughout the study and contributed significantly to the production of the final manuscript. UL and HK jointly directed the study as a whole by providing major intellectual guidance including the preparation of the manuscript. All authors read and approved the final manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.actatropica.2010.05.009.

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