Climatic and Social Risk Factors for *Aedes* Infestation in Rural Thailand

Yoshiro Nagao¹, Usavadee Thavara², Pensri Chitnumsup³, Apiwat Tawatsin², Chitti Chansang² and Diarmid Campbell-Lendrum¹

1 London School of Hygiene and Tropical Medicine, London, UK.
2 National Institute of Health, Department of Medical Sciences, Ministry of Public Health.
3 Division of Epidemiology, Ministry of Public Health.

Published in *Tropical Medicine and International Health* Vol. 8, NO. 7: 650-659, 2003.

**Abstract**

An intense epidemic of dengue haemorrhagic fever in 1998 prompted the Thai government to investigate the feasibility of focalized vector (*Aedes aegypti*) control programmes. We tested for correlations of three indices of *Aedes* larval abundance (housing index, container index and Breteau index) against 38 socio-economic and four climatic variables. Availability of public water wells, existence of transport services and proportion of tin houses were positively associated with larval indices. Private water wells, health education, health insurance coverage, thatched houses and use of firewood for cooking were negatively associated. These probably represent both direct effects on breeding sites (private vs. public wells decrease necessity to store water, and health education may encourage breeding site removal), and more general effects of health-related attitude, housing quality and remoteness from urban areas. Indices were positively associated with daily minimum temperature, an increase in precipitation from the previous month (reflecting the onset of the rainy season) and daily maximum temperatures of approximately 33-34 °C. The associations were used to derive statistical models to predict the rank order of larval indices within the study area (Spearman’s correlation coefficients = 0.525-0.554). The study provides a rational basis for identifying possible social interventions, and for prioritizing previously unsurveyed villages for further monitoring and focalized vector control.

**Keywords**

Dengue, climate, socio-economic, risk factors, risk map, *Aedes*
Introduction

*Aedes* mosquitoes transmit dengue virus, causing both classical dengue fever and potentially fatal dengue haemorrhagic fever (DHF). The first reported epidemic of DHF occurred in southeast Asia in 1953 (Gubler 1997). The disease has subsequently expanded in distribution to become a major public health problem throughout the tropics, with about 3,700,000 cases worldwide between 1956 and 1995. Approximately one-third of these cases were reported from Thailand (Halstead 1997). This represents a large disease burden for patients, and high financial costs of medical treatment and vector control for the Thai Government (Okanurak et al. 1997). In 1998, Thailand experienced an exceptionally intense epidemic of DHF: 112,488 cases (23.3% increase from 1997) and 415 deaths (64.0% increase).

In the continued absence of an effective vaccine, efforts to control dengue are generally through control of the principal vector *Aedes aegypti*, and the secondary vector *Ae. albopictus*. Control measures targeting larvae in and around houses (i.e. source reduction and larvicide application) are usually considered more effective than adulticidal aerosols, which show poor penetration to *Aedes* resting sites (Reiter & Gubler 1997). Thailand operates integrated vector control. A community-level health education campaign has been conducted from late 1980s (Swaddiwudhipong et al. 1992a,b). Since 1992, the Ministry of Public Health (MOPH) and the Ministry of Education have integrated information about dengue into the primary school curriculum, and since 1998, vector control and health education specialists have worked throughout the country, applying larvicide and fogging during the epidemic season.

However, limited financial and human resources restrict further expansion of this costly government programme. There is a need to focus vector control interventions on those areas that are most at risk, and to recommend social and environmental changes that will have the greatest effect on vector abundance, and therefore (presumably) disease incidence.

Both climatic and socio-economic risk factors are known to affect the abundance of *Aedes* mosquitoes. Temperature has been shown to affect population biology in the laboratory (Rueda et al. 1990; Tun-Lin et al. 2000), while models based on precipitation, temperature and atmospheric moisture explain much of the intra-annual variation in *Aedes* abundance (Moore 1985;
Focks et al. 1993a,b) and dengue incidence (Focks et al. 1995; Jetten & Focks 1997). In addition to these climatological factors, cultural and socio-economic factors, particularly housing, may effect vector abundance and disease transmission (Kuno 1995; Tun-Lin et al. 1995). As vector control programmes are heavily focussed on community involvement in environmental modification, it would clearly be an advantage to identify, and subsequently modify, community level behavioural and housing risk factors for *Ae. aegypti*.

Risk factor investigations have generally been restricted to detailed studies of characteristics of breeding sites recorded in specifically entomological surveys, and concentrated on urban areas. In order to be of practical value in Thailand, it is needed to carry out risk factor analysis and prioritization based on the more generally available socio-economic indicators (i.e. not requiring expensive additional surveys). Rural areas, which have become the important sites of dengue transmission in Thailand since the late 1960s (Jatanasen & Thongcharoen 1993), should be included in such analyses, not least because of their economic importance as tourist centres. The present study tests for statistical associations between climatic and socio-economic variables and three indices of mosquito abundance, in order to identify risk factors which could be used to identify high-risk villages, and could potentially be modified to decrease risk. It then generates models to predict abundance in unsampled villages, and tests their accuracy against independent observations.

**Materials and methods**

**Study area**

Thailand is composed of 76 provinces, which in turn consist of approximately 900 districts, 7,000 subdistricts and 60,000 villages. The present analysis included 18 provinces in the northern region of the country (Figure 1). A computerized map of Thailand, TDS Pro plus® (scale 1:250,000, representing borders for 875 districts registered in November 1998), was used as the basis for geographical analysis using the geographical information system software, Mapinfo® version 4.
Vector abundance data

Bi-monthly household surveys of *Aedes* larvae were conducted by trained community volunteers from 1992 to 1996 in 91 districts in northern Thailand, under the supervision of the Communicable Disease Center (CDC) of Thailand (Suwonkerd & Prachakwong 1996) (Figure 1). The survey teams recorded House Index (HI): percentage of houses with containers positive for *Aedes* (subgenus *Stegomyia*) larvae or pupae, Container Index (CI): percentage of positive water-holding containers, Breteau Index (BI): number of positive containers per 100 houses. The volunteers did not have to differentiate *Ae. aegypti* and *Ae. albopictus*. However, in Thailand larvae and adults captured outdoors are usually *Ae. albopictus*, while those found indoors are almost exclusively *Ae. aegypti* (Thavara et al. 2001), as in other countries (Rodhain & Rosen 1997). These indices are therefore considered to mainly reflect the abundance of *Ae. aegypti*. 

Figure 1. Coverage of the entomological survey and weather stations used in the analysis. Shading indicates 91 districts where entomological surveys were conducted. Squares denote the locations of weather stations in Thailand and Vietnam used in the analysis.
Entomological data are reported to the vector control authority at the village level. Observations were registered to the subdistrict name because villages in Thailand sometimes change their names. In total, 1092 entomological records were available (367 in 1994; 489 in 1995; 236 in 1996).

**Climatological data**

Daily Surface Observation Data From 1994 to 1998 was purchased from the US Department of Commerce, National Oceanic and Atmospheric Admisiatration. Monthly averages of minimum and maximum temperatures, and total precipitation were calculated for 144 weather stations on the Indo-China peninsula, for the period January 1994 to December 1998. Weather stations were excluded if any variable was missing for more than 10 days in any month. Data from 48 stations (44 in Thailand; four in Vietnam) remained eligible for analysis (Figure 1). The climate in each district was estimated by interpolating the data from all enrolled weather stations to the geographical centre for each district, using the Inverse Distance Weighting (IDW) method (reviewed by Roberts et al. 1993). To validate the reliability of IDW, monthly means of daily maximum and minimum temperatures, and precipitation, were interpolated to the location of each of the 48 weather stations by using the other (47) weather stations. The correlation coefficients (r) between interpolated and actual values were: 0.791 for mean maximum temperature; 0.885 for mean minimum temperature; 0.644 for mean precipitation (n = 2880). IDW gave a better fit than an alternative technique of interpolation, weighing by inverse of the exponential of distance.

The following climatic variables from the month prior to each entomological survey, used as explanatory variables:

- Mean maximum temperature (°C), and its quadratic term.
- Mean minimum temperature (°C), and its quadratic term.
- Mean precipitation (mm/day).
- Increase of mean precipitation before 2 months (mm/day).

Quadratic terms were introduced to allow the fitting of non-linear relationships between larval indices and temperature, as excessively low or high temperatures are known to decrease mosquito fitness (Rueda et al. 1990; Clements 1992; Tun-Lin et al. 2000).
In addition, one sine and one cosine term with annual periodicity were included as explanatory variables to account for any stable seasonal variation other than that already explained by climatic factors (Montgomery et al. 1990).

**Socio-economic data**

Information on a wide variety of socio-economic characteristics has been collected biannually, for every region in Thailand, excluding Bangkok. These data are based on questionnaire surveys, applied to each ‘village office’ by provincial representatives from governmental ministries, under the initiative of the National Rural Development Committee (NRDC). Each district has a central subdistrict (‘municipality’), which was excluded from this survey. The collected information is then compiled into NRDC ‘rural database’ at the Information Processing Institute for Education and Development. In our analyses, the rural database of 1994 was used to represent conditions in 1994/1995, and the 1996 survey was used to represent 1996 conditions. In total, 121,267 village-level records were available (60,133 villages in 1994; 61,134 in 1996).

Of 249 items in the questionnaire, 38 variables (Table 1) were selected based on the following criteria: scale or dichotomous items; items for which more than 95% of all the records have meaningful values; items which are defined only with objective terminology (e.g. such words as ‘sufficient’ or ‘hygienic’ were rejected as subjective); items which do not contain monetary value (because of the difficulty in adjusting for inflation between different census years); items for which duplicated independent translations of the questionnaire were consistent; items which cannot be calculated automatically by combining other items (e.g. the number of concrete houses from the total number); items for which all the records are within a meaningful range (e.g. between 0% and 100% for proportional data). Only the total size of population was used to represent demography. Summary values of these 38 variables were calculated for each subdistrict and district.

**Statistical analysis**

Stata 5.0 was used to analyse the relationships between climatological and socio-economic predictors, and *Aedes* abundance at the subdistrict level (dictated by the resolution of the entomological data). The entomological indices
were transformed to approximately normal distributions, by using aresine (square root) transformation for HI, and CI, and taking the natural logarithm of BI (Campbell 1989). A total of 1092 records (covering 12 provinces, 91 districts and 115 subdistricts) were linked to socio-economic and climatic variables.

To allow robust and easily interpretable multivariate analysis, we first used univariate analysis to pre-select amongst the 38 socio-economic indices above. As each subdistrict was surveyed several times, random effect regression was applied, with subdistrict identity being assigned as the random effect parameter, to account for similarities within each subdistrict in both these analyses, and subsequent multivariate analyses. Socio-economic indices which showed a significant association (P < 0.05) with all the entomological indices were retained for the multivariate analysis. All the climatic variables (or variable pairs), and the sine/cosine terms, showed a significant association with all three entomological indices.

The pre-selected socio-economic, climatic and sine/cosine variables were used as predictor variables in random effect multivariate linear regression. The least significant explanatory variables were omitted in a stepwise fashion until all remaining variables explained a significant proportion of the variance (backward Wald’s test). Odd-numbered entomological records (n=546) were used to build predictive models for each entomological index. These models were then applied to the remaining even-numbered records (‘validation data set’). To assess the fit of the model, predicted and observed values were compared using Sperman’s rank correlation coefficient (r). Rank correlation is used rather than the correlation of absolute values, both because it is not affected by the transformation used in the present study, and because the main aim of our models is to rank different regions in order of priority for vector surveillance and control programmes. Finally, the statistical significance of the variables selected by Wald’s test and the fit of multivariate models were examined by reversing the data set for model building and that for validation.

**Risk map**

The resulting models were applied to socio-economic indices since 1994 and climatic values of July 1995 (i.e. during the epidemic season), to generate a risk map of *Aedes* abundance for 183 districts in 18 provinces in northern
Thailand (including 91 districts included in the original survey). Districts that were present in TDS but absent in the 1994 rural database, were left blank. As the predictions are based on a socio-economic database that excludes one central (usually the most urban) municipality in each district, the map represents the risks in rural areas.

**Table 1. Socio-economic indices tested for association with larval indices.**

<table>
<thead>
<tr>
<th>Number, per total population</th>
<th>Number, per total families</th>
<th>Proportion of all villages</th>
<th>Number, per total houses</th>
<th>Number, per total area</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Population with senior high school education</td>
<td>17. Participation in weekly traditional rites</td>
<td>22. With kindergarten</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Population with higher education</td>
<td></td>
<td>23. With primary school</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Illiterate population 14-50 years of age</td>
<td></td>
<td>24. With high school</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Population with health insurance</td>
<td></td>
<td>25. With community centre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Participations in occupational training in last 2 years</td>
<td></td>
<td>26. With library</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Participations in ethics education in past 2 years</td>
<td></td>
<td>27. With rubber factory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Participations in military exercise in past 2 years</td>
<td></td>
<td>28. With occupational school</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Participations in health education in past 2 years</td>
<td></td>
<td>29. With post office</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30. With road to district centre</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31. With transport to district centre</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>32. Using firewood for cooking</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>33. Located in the national forest</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Observed infestation of *Aedes*, represented as House Index (HI), in the surveyed region. HI observed between May and September in 1994-1996 was averaged for each district.

**Results**

**Entomological data**

Figure 2 shows the spatial variation in the abundance of *Aedes* averaged from the records taken during the epidemic season (May-September) between 1994 and 1996. HI, CI, and BI had highly skewed distributions: HI (mean 38.3, range 0-99.9); CI (mean 11.9, range 0-80.7); BI (mean 95.2, range 0-7.50). The transformations described above approximately normalized the distributions: HI (mean 0.650, range 0-1.54); CI (mean 0.315, range 0-1.12); BI (mean 3.96, range -0.511-6.62).

**Temporal variation**

Temporal variations of climate and entomological indices are shown in Figure 3a, b. The climatic variables are the means of 11 weather stations located in the surveyed area (Figure 1). As all indices are highly correlated with each other (r > 0.83), only HI is shown.
**Socio-economic indices in univariate analysis**

Public water wells (item one in Table 1), transport services (31), and tin houses (35) were all significantly positively correlated with each of HI, CI and BI. Private water wells (2), health insurance (8), ethics education (10), health education (12), religious rites (16), rice bank (19), kindergarten (22), primary school (23), community center (25), library (26), use of firewood (32), thatched houses (36) and house density (38) were all significantly negatively correlated.

**Multivariate analysis**

Table 2 shows those variables that remained in the minimum adequate model for each *Aedes* index and the fit of each model, expressed as Spearman’s rank correlation coefficient (r) between the actual and predicted values for validation data set. Potential positive risk factors were tin houses (for HI, CI and BI), public water wells and transport services (for HI and CI). Factors associated with negative risk were: private water wells, health insurance, health education, use of firewood, thatched houses.

Indices were positively associated with minimum temperature, and the increase in precipitation from 2 months to 1 month before. The relationship with maximum temperature was non-linear for each index. Differentiation of the expression combining the linear and quadratic temperature terms (Kuhn et al. 2002) indicated the various indices reached maxima at very similar temperature values: 33.2 °C for HI; 33.2 °C for CI; 34.2 °C for BI.

When the data set for model building and that for model validation were reversed, thatched houses did not remain as a statistically significant variable for HI and CI, suggesting that this variable is not as robust as other variables in Table 2. However, the fits of the predictive models were similar even without this variable (r = 0.619-0.637), and all other risk factors remain significant.

Table 3 shows mean and standard deviations for the significant socio-economic variables (measured at district level in the 1996 rural database), both for the original 91 entomological survey districts, and for all 183 districts in 18 provinces in northern Thailand. Socio-economic characteristics in the survey districts were broadly similar to those elsewhere, suggesting that they provide a reasonable basis for generating predictive models for elsewhere in the northern region.
Figure 3. Temporal variation of climate and House Index (HI). (a) mean maximum temperature, mean minimum temperature and mean precipitation, averaged from the monthly summary records of 11 weather stations within the surveyed area. (b) HI averaged from all entomological surveys.

Risk map

The spatial variation of *Aedes* mosquitoes predicted by the final model is shown for 18 northern provinces in Figure 4. In general, southern provinces within the region have higher values of HI.
**Discussion**

**Socio-economic risk factors**

Considering the strict conditions applied in identifying socio-economic risk factors, the associations are statistically robust. However, biological judgement and caution are necessary in interpreting whether each represents a direct causal relationship. Among the positively correlated variables, the proportion of tin houses may be only an indirect indicator, as such houses are often found in poorer regions and slums, including housing for transient workers. They, therefore, tend to have generally unhygienic conditions (e.g. irregular garbage collection, promoting *Aedes* breeding sites) and poor house design (e.g. absence of window screens and water supply), both of which may promote *Aedes* proliferation. The association with transport services probably reflects the fact that *Ae. aegypti* have a limited flight range, and their dispersal is largely assisted by human movement (e.g. transportation of larvae in used tries) (Hawley et al. 1987). Public water wells, however, are very likely to have a direct causal link, as they necessitate water storage in individual containers inside houses. Concern that neighbours might consume the water in the public well may also encourage water storage in greater quantities, for longer period.

Amongst the factors which are apparently protective, coverage of health insurance and health education are likely to reflect general commitment to healthly behaviours within both the local community (e.g. co-operation in vector control programmes), and on behalf of local health authorities (e.g. regular garbage collection); many of those not covered by health insurance are engaged in informal occupations (Mongkolsmai 1997), and hence may pay less attention to community hygiene. Similarly, the use of firewood for cooking may indicate remoteness from urban centres and therefore reduced passive transport of vectors, while the proportion of thatched houses may possibly reflect greater traditional knowledge about hygiene. The availability of private water wells is probably directly protective, as they would reduce the necessity to store water in containers.

**Climate**

The associations with the different temperature variables confirm that *Aedes* populations are generally favoured by higher temperatures (shown by the positive relationship with minimum temperature), provided they do not
exceed harmful upper limits (defined by the optimum maximum temperatures of 33.2-34.2 °C for the various entomological indices). This suggests that global warming may decrease vector populations in warmer regions that are currently close to these limits. It is therefore likely to lead to changes in the endemic ranges of mosquito-borne diseases, rather than necessarily leading to expansion in all areas (Rogers & Randolph 2000).

The observation that the indices did not correlate with the mean precipitation, but with the increase in precipitation from 2 months to 1 month before, suggests that the greatest rate of increase of *Aedes* population coincides with the onset, rather than the peak, of the rainy season (Figure 3a, b). This is probably because eggs of *Aedes*, laid on the inner surface of water containers, hatch when dampened by rising water levels [reviewed by Rodhain & Rosen (1997)]. This is consistent with the observations that the number of DHF cases in Thailand generally starts to rise about 1 month after the onset of the rains (Wellmer 1983), and that *Aedes* proliferate during the first half of the rainy season but not during the latter half (Mogi et al. 1988).

**Table 2. Regression coefficients for significant predictors of entomological indices.**

<table>
<thead>
<tr>
<th>n = 1092</th>
<th>( \text{asin(HI/100)}^{1/2} )</th>
<th>( \text{asin(CI/100)}^{1/2} )</th>
<th>In(BI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public water wells</td>
<td>+19.2</td>
<td>+8.81</td>
<td></td>
</tr>
<tr>
<td>Private water wells</td>
<td>-1.74</td>
<td>-0.763</td>
<td>-6.02</td>
</tr>
<tr>
<td>Health insurance</td>
<td>-0.136</td>
<td>-0.0650</td>
<td>-0.487</td>
</tr>
<tr>
<td>Health education</td>
<td>-0.779</td>
<td>-0.316</td>
<td>-2.44</td>
</tr>
<tr>
<td>Transportation</td>
<td>+0.125</td>
<td>+0.0766</td>
<td></td>
</tr>
<tr>
<td>Use of firewood</td>
<td>-0.0949</td>
<td>-0.0483</td>
<td>-0.538</td>
</tr>
<tr>
<td>Tin houses</td>
<td>+0.315</td>
<td>+0.199</td>
<td>+1.37</td>
</tr>
<tr>
<td>Thatched houses</td>
<td>-0.355</td>
<td>-0.183</td>
<td>-1.07</td>
</tr>
<tr>
<td>Mean maximum temperature</td>
<td>+0.407</td>
<td>+0.262</td>
<td>+2.23</td>
</tr>
<tr>
<td>Quadratic term of mean Maximum temperature</td>
<td>-0.00613</td>
<td>-0.00394</td>
<td>-0.0326</td>
</tr>
<tr>
<td>Mean minimum temperature</td>
<td>+0.0187</td>
<td>+0.00978</td>
<td></td>
</tr>
<tr>
<td>Increase in precipitation</td>
<td>+0.0116</td>
<td>+0.00657</td>
<td>+0.0422</td>
</tr>
<tr>
<td>Constant</td>
<td>-6.58</td>
<td>-4.30</td>
<td>-33.9</td>
</tr>
<tr>
<td>Spearman’s rank Correlation coefficient</td>
<td>0.554(P&lt;0.0001)</td>
<td>0.551(P&lt;0.0001)</td>
<td>0.525(P&lt;0.0001)</td>
</tr>
</tbody>
</table>

Spearman’s rank correlation coefficient shows the correlation between the predicted and actual values in the validation data set. Definition and measurement units for socio-economic indices are given in Table 1.
Table 3. Values of significant socio-economic predictors of entomological indices, both within the study area and throughout northern Thailand, based on the 1996 rural database.

<table>
<thead>
<tr>
<th></th>
<th>183 districts in northern Thailand</th>
<th>91 districts surveyed for <em>Aedes</em> mosquitoes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Public water wells</td>
<td>0.00360</td>
<td>0.00227</td>
</tr>
<tr>
<td>Private water wells</td>
<td>0.0207</td>
<td>0.0276</td>
</tr>
<tr>
<td>Health insurance</td>
<td>0.418</td>
<td>0.179</td>
</tr>
<tr>
<td>Health education</td>
<td>0.0477</td>
<td>0.0241</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.747</td>
<td>0.165</td>
</tr>
<tr>
<td>Firewood</td>
<td>0.604</td>
<td>0.298</td>
</tr>
<tr>
<td>Tin houses</td>
<td>0.529</td>
<td>0.340</td>
</tr>
<tr>
<td>Thatched houses</td>
<td>0.0774</td>
<td>0.0949</td>
</tr>
</tbody>
</table>

Figure 4. Predicted House Index (HI) of *Aedes* mosquitoes in northern Thailand in July 1995. HI was extrapolated for 183 districts (18 provinces) in northern Thailand using climate data from July 1995. Districts without suitable socio-economic data are left blank.
**Risk map**

Within the survey area, the derived risk map correlated reasonably well with the spatial pattern observed in actual surveillance data (Figure 2 vs. Figure 4), reproducing the tendency of higher HI in lower latitudes. The predictive map also gave a reasonable description of the rank order of observed vs. predicted indices (Spearman’s correlation coefficients for all indices >0.5). It should be noted that the predictive map specifically described a risk only in rural areas, as the database used in our analysis lacked information about the central (usually the most crowded and developed) subdistrict. However, as conditions in central subdistricts are likely to correlate with the rural areas surrounding them, the risk map should also have some predictive values for the central subdistricts, and for districts as a whole.

Because the northern half of the study area has higher altitude and cooler climate, rainfall surplus (i.e. rainfall which exceeds evaporation) is higher than in the southern half. In contrast, the southern half of the study area is relatively arid and inspection of the rural database indicates that private water wells are rare there, probably because they are difficult to construct under such conditions. Instead, large earthenware containers are commonly used for water storage (Wellmer 1983). In this case a socio-economic factor (i.e. more frequent storage of water) in turn influenced by a climatic factor (i.e. smaller rainfall surplus) is likely to explain the larger abundance of *Aedes* mosquitoes in the southern part of the study area.

**Control implications**

The statistical models and risk map presented here have several applications to control programmes aiming to reduce the economic and human costs of this virus in Thailand. Firstly, they indicate specific risk factors that might be targeted in rural development programmes. The finding that public water wells increase risk suggests that their replacement with private wells or water pipelines could effectively supplement direct targeting of breeding sites of *Ae. aegypti*. This could be further investigated with a randomized controlled trial. They also indicate how more general societal changes might affect prevalence of infestation. For example, increasing health education should reduce *Aedes* prevalence, while improved transport services, although clearly desirable for other reasons, may increase risk.
Second, they allow predictions for villages that have not been covered in entomological surveys which are otherwise time-consuming and expensive. Although it would benefit from further refinement, the predictive map derived above provides a rational basis for prioritizing unsampled villages either for interventions, or for further monitoring.

The ultimate aim of risk factor identification and risk mapping for *Aedes* is to control dengue and DHF. Indices such as the number of pupae per person (Focks et al. 2000) may be better indicators of thresholds for sustainable transmission of human disease than the larval indices used here and in many other countries. In addition, these larval indices are imperfect indicators of the number of *Aedes* within a community because they do not take into account variation in larval production between different types of containers. However, the most productive breeding containers are usually large earthen drinking water containers (Kittayapong & Strickman 1993; Thavara et al. 2001), and these containers are commonly used throughout the country. Therefore these larval indices should show a reasonable correlation with the total number of larvae. While this assumption should be tested further, HI is currently used by the Thai CDC as a criterion to prioritize villages for vector control. Our analysis informs decisions about which villages should be prioritized for further surveillance and vector control programme. An unpublished study carried out by the authors indicates that HI was positively correlated with the district-level monthly incidence of DHF in the pre-epidemic season, suggesting that it could usefully contribute to the focalization of control programmes. The relationship between *Aedes* indices and human disease will be explored in detail in a subsequent paper.

**Acknowledgements**

We are grateful to Dr. Sombat Thanprasertsuk from Division of Epidemiology, Ministry of Public Health and Professor Pongsvas Svasti from Thammasat University for their assistance in the preparation of data and their review of this manuscript, and to Paul Coleman, Neal Alexander and Clive Davies of the London School of Hygiene and Tropical medicine for advice on data analysis and early drafts of the manuscript. This study was in part funded by the government of Thailand.
References


