Investigating the impact of climate on dengue disease transmission in urban Colombo: A Fuzzy logic model

WPTM Wickramaarachchi, SSN Perera
Research and Development Center for Mathematical Modeling, Department of Mathematics
Faculty of Science, University of Colombo
Colombo 03, Sri Lanka
Wptharindu86uoc@gmail.com

S Jayasinghe
Department of Clinical Medicine
Faculty of Medicine, University of Colombo
Colombo 03, Sri Lanka

Abstract — Dengue has been a major public health concern in the tropical world for decades now. The dynamics of dengue disease transmission depends on various external factors such as climate, human behavior, geography and demography. Modeling dengue dynamics is difficult with classical approaches due to this complexity. Fuzzy logic and fuzzy set theory is a useful tool in mathematics to model systems under uncertainty. We were particularly concerned with modeling unfavorable environmental conditions produced by climate for dengue transmission. We used fuzzy set theory to define membership functions for rainfall and temperature. Then we used a fuzzy operator and generated a fuzzy valued time series of the overall effect from rainfall and temperature. This simulated time series is then compared with the dengue cases time series reported in Colombo.

Keywords-fuzzy set, membership function, dengue, unfavorable environment, combined effect

I. INTRODUCTION

Dengue is one of the burning public health problems in the world mainly in the tropical regions. It has been an epidemic in Sri Lanka now since it was identified five decades ago. Dynamics of the dengue transmission mainly in the urban context has been changed due to various reasons. Dengue is an epidemic disease which is highly sensitive to climate and human behavior [10]. Some level of rainfall supports mosquito breeding and increased temperature levels reduce the incubation period of mosquitoes and increase the vector capacity to transmit the dengue virus [9]. Various researchers such as Puntani P. [5] and Pinho T.R [6] have discussed the applicability of classical SIR models in terms of population dynamics to understand the dynamics of dengue disease transmission. The classical SIR models explain the interaction among of susceptible (S), infected (I) and recovered (R) human populations together with the susceptible and infected vector populations. But they have used fixed parameter values in their models so that the influence of external factors to change in the parameters has not been addressed in detail. The estimation of these parameters should be done under uncertainty and the fully stochastic models are not appropriate since we do not know the underlying probability distributions. Some researchers have attempted statistical models such as time series and poison regression models but they only predicted dengue cases as changing the external parameters such as rainfall, temperature, humidity and wind speed one at each time [13, 14]. Their models do not reflect an overall risk measure of dengue disease as all the external parameters taken together with different levels.

Fuzzy logic and fuzzy set theory are emerging areas in mathematical research which help researchers modeling systems under uncertainty [1]. Fuzzy models in biology, epidemiology and medicine are having tremendous capabilities of explaining complex system behaviors under uncertainties.

The aim of this paper is to model the influence of rainfall and temperature to create unfavorable environmental conditions for the spread of dengue disease in urban Colombo using fuzzy set theory. We used fuzzy set theory to investigate the influence from eight weeks leading rainfall (RF) and the weekly averaged maximum temperature (TEMP) for dengue transmission in urban Colombo [7]. We defined our membership functions for weekly average rainfall with eight week lead time and weekly average maximum temperature with the degree of membership value in [0, 1] as the response variable which is the effect from each variable respectively to establish unfavorable environmental conditions for dengue transmission. Then we used a suitable fuzzy operator to measure the combined effect from above factors.

II. METHODOLOGY

A. Preliminaries

A fuzzy subset F of U is described by the function $F: U \rightarrow [0, 1]$ called the membership function of fuzzy set F where U is a classical non-empty set.

The value $F(x) \in [0, 1]$ indicates the membership degree of the element x of U in fuzzy set F, with $F(x) = 1$ and $F(x) = 0$ representing, respectively, the belongingness and not-belongingness of x in F [1, 2].

4th Annual International Conference on Computational Mathematics, Computational Geometry & Statistics (CMCGS 2015)

ISSN 2251-1911
doi: 10.5176/2251-1911_CMCGS15.10

B. Mathematical Model

We assumed that at least 5mm averaged weekly rainfall is required to make breeding sites available for mosquitoes and the breeding sites are washed out due to the heavy rainfall which is over 55mm [11, 12]. Further we assumed that a weekly averag temperature less than 16^0 C is unfavorable for mosquitoes to transmit the virus and a temperature between 30 ^{0} C and 34^0 C is ideal for mosquitoes to rapidly transmit of the virus due to the increased vector capacity and reduced incubation period. According to literature extreme heating conditions do not support dengue virus transmission so that we assumed our threshold temperature to be 37^0 C [8, 11, 12]. Based on our assumptions, we defined the trapezoidal-shaped membership functions to represent the effect from eight weeks leading RF and immediate TEMP to create an unfavorable environment for dengue spread as follows

$$U_{RF}(x) = \begin{cases} 1 & \text{if } x \le 5 \\ -\dfrac{x+10}{5} & \text{if } 5 \le x \le 10 \\ 0 & \text{if } 10 \le x \le 30 \\ \dfrac{x\text{-}30}{25} & \text{if } 30 \le x \le 55 \\ 1 & \text{if } x \ge 55 \end{cases} \qquad (1)$$

$$U_{TEMP}(x) = \begin{cases} 1 & \text{if } x \le 16 \\ -\dfrac{x+30}{14} & \text{if } 16 \le x \le 30 \\ 0 & \text{if } 30 \le x \le 34 \\ \dfrac{x\text{-}34}{3} & \text{if } 34 \le x \le 37 \\ 1 & \text{if } x \ge 37 \end{cases} \qquad (2)$$

C. Choice of the fuzzy operator

The choice of the fuzzy operator is not done arbitrary. It may depend on the real world phenomena being considered. We are concerned with simulating the overall effect of rainfall (RF) and temperature (TEMP) in order to produce unfavorable environmental conditions to transmit dengue disease. Thus the operator should have the following properties [4].

a. If RF is unfavorable and TEMP is unfavorable then it may be highly unfavorable for dengue transmission.
b. If RF is unfavorable and TEMP is favorable or RF is favorable and TEMP is unfavorable then it may be favorable for dengue transmission.
c. If RF is favorable and TEMP is favorable then it may be highly favorable for dengue transmission.

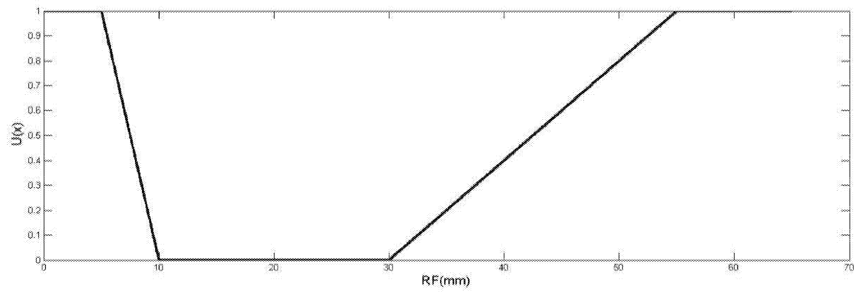
Therefore we used the Hamacher operator to simulate the overall effect which is defined as [3, 4].The Hamacher operator is flexible since we can vary the parameter p accordingly.

$$U_H^p(x) = \frac{U_A(x)U_B(x)}{p + (1-p)[U_A(x) + U_B(x) - U_A(x)U_B(x)]}$$
for $0 \le p \le 1$. (3)

The above trapezoidal-shaped membership functions (1) and (2) are illustrated in Fig 1.

.

(a)



(b)

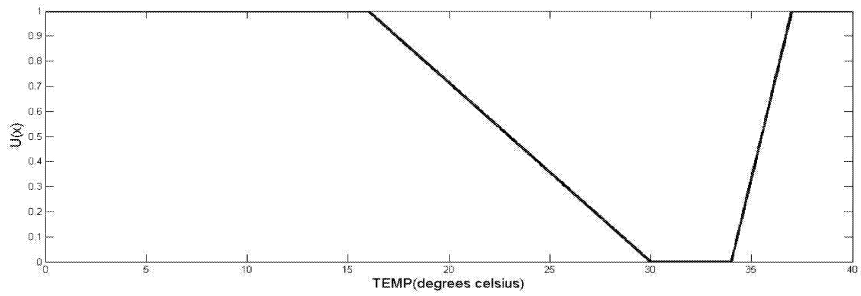


Figure 1: Membership functions defined for rainfall (a) and temperature (b).

D. Data and Analysis

We used daily rainfall and maximum temperature data in urban Colombo from year 2006 to 2011 obtained from the department of meteorology and transformed into average weekly data for the above two parameters. MatLab was used for the simulations. The outcomes of the simulations are given in section III.

III. RESULTS

Using the trapezoidal-shaped membership function, we found the membership values for RF and TEMP from year 2006 to 2011. The membership values for each parameter, RF and TEMP were simulated and the resulted two time series are presented in Fig 2(a) and Fig 2(b) respectively.

Then we used the Hamacher operator with $p = 0.5$ defined in section II to simulate the overall effect from RF and TEMP to produce unfavorable environmental conditions for dengue transmission in urban Colombo. The value of $p = 0.5$ was chosen as an average value since we observed that the overall effect was not changing dramatically with varying p in [0, 1]. The simulated fuzzy time series together with the weekly dengue cases time series is given in the Fig 3.

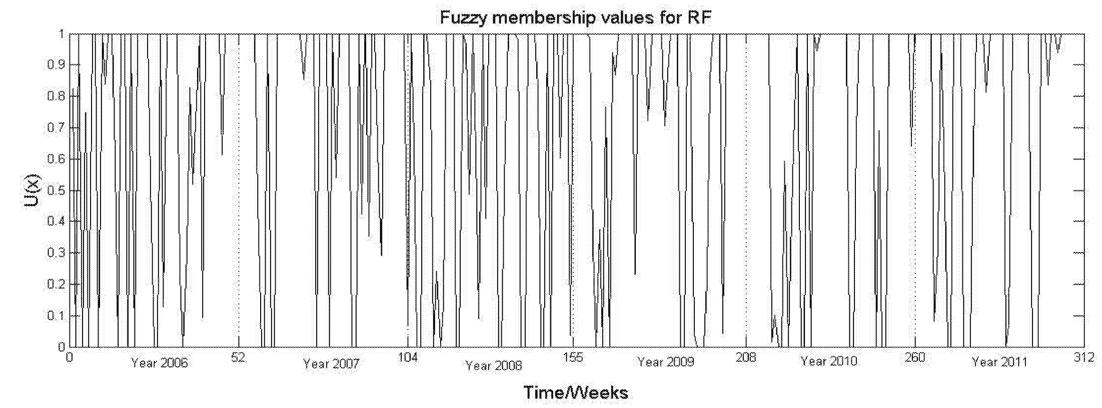
IV. DISCUSSIONS

It is seen in Fig 3(a) that the membership values obtained during the end of the year are higher. Further, the Hamacher operator shows higher values at the beginning of the year 2011. These may be corresponding to more unfavorable conditions for dengue since less RF and lower TEMP. The small dengue outbreak in January 2011 can be due to this unfavorable condition produced by lack of rainfall and low temperature shown by Fig 3(b).

Further, it can be seen in Fig 3(a) that the combined effect is zero in the middle of the year 2009 which implies favorable conditions to dengue spread. If we carefully investigate Fig 3(b) then we can see a relatively large outbreak during April-June in year 2009.This may be due to considerable amount of rainfall with the increased temperature during that period which is supportive for dengue transmission.

The observations in Fig 3 (a) indicate that the membership values simulated by the Hamacher operator vary between 0 and 0.2 throughout the time period from year 2006 to 2011 considered for this study. This implies that the unfavorable measure is very small and the rainfall and temperature support dengue transmission throughout the time period taken into the study.

(a)



(b)

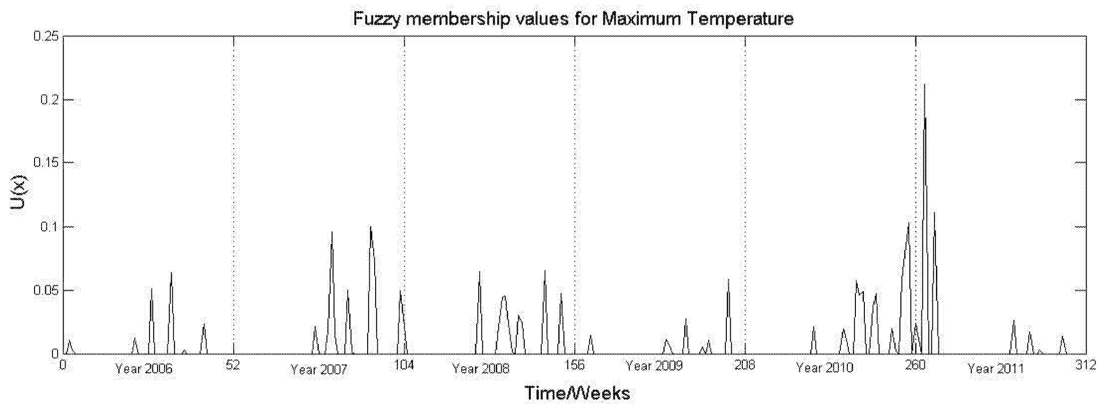
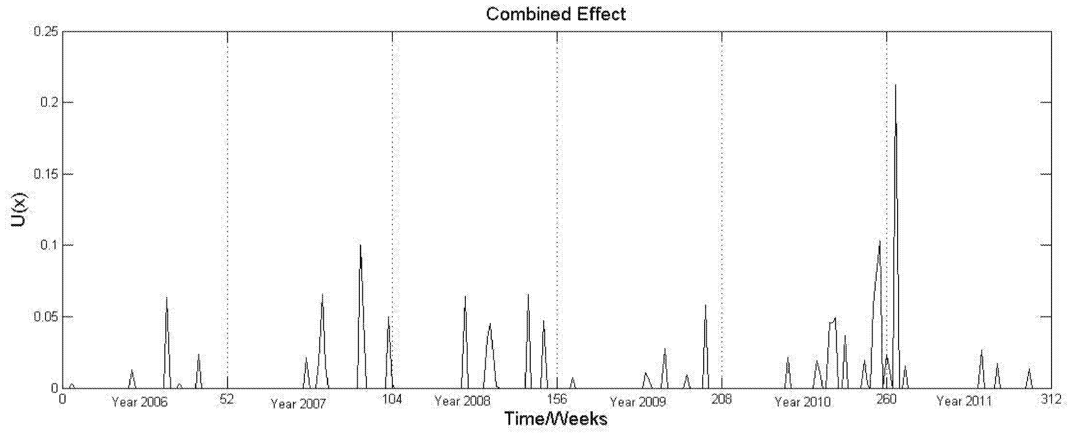


Figure 2: The simulated membership values for Rainfall (a) and Temperature (b).

(a)



(b)

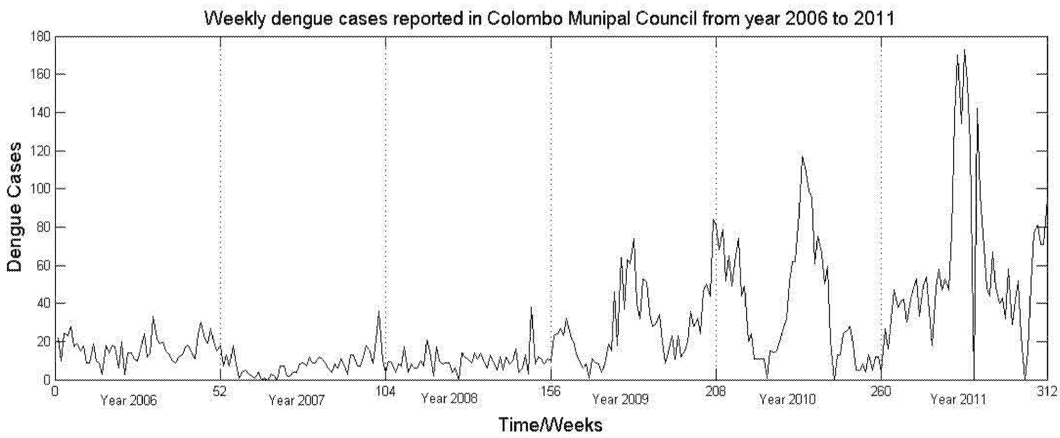


Figure 3: The simulated fuzzy values time series for the combined effect using Hamacher operator with $p = 0.5$ from year 2006 tom 2011(a) and weekly dengue cases time series in Colombo Municipal Council area from year 2006 to 2011(b).

V. CONCLUSIONS

Fuzzy set theory can be highly useful when modeling and analyzing uncertain, complex systems such as disease spread. Theory of fuzzy operators can be used to investigate the overall potential of dengue transmission from several sensitive parameters such as rainfall and temperature. We considered the overall effect from rainfall and temperature to produce unfavorable environmental conditions for dengue transmission. The output measure explains the level of risk to transmit dengue with respect to climate. We only considered the influence of rainfall and temperature in the model discussed in this paper. Human mobility, demography and geography are other vital factors which are sensitive for the dynamics of dengue disease transmission. The methodology in this paper can be used to model and study the influence of those factors as a future work.

ACKNOWLEDGMENT

The HETC Window 3 grant under Ministry of Higher Education, Sri Lanka is highly acknowledged for funding the corresponding author to carry out this research project. We acknowledge Colombo Municipal Council (CMC) for providing dengue cases data.

REFERENCES

[1] Eduardo Massad, Neli Regina Siqueria Ortega, Laecio Carvalho de Barros, Claudio Jose Struchiner (2008)"Fuzzy Logic in Action: Applications in Epidemiology and Beyond", Springer, Volume 232.

[2] Guanrong Chen, Trung Tat Pham,"Introduction to Fuzzy sets, Fuzzy logic and Fuzzy control systems", CRC Press, Chapters 1 and 2.

[3] H.J Zimmermann (2010),"Fuzzy set theory", Advanced Review-John Wiley and Sons Inc, Volume 2, pp 317-321.

[4] Jean Lemaire,"Fuzzy Insurance", Wharton School, University of Pennsylvania, USA, Austin Bulletin. Volume 20 No1, pp 34-45.

[5] Puntani P. (2006), "Transmission model for dengue disease with and without the effect of extrinsic Incubation period". KMITL Sci. Tech. J. Volume 6 No. 2 Jul. pp 74-82.

[6] Pinho S. T. R., Ferreira C. P. (2010),"Modeling the dynamics of dengue real epidemics", The Royal Society, Mathematical, Physical and Engineering Sciences, 368, pp 5679-5693.

[7] Wickramaarchchi WPTM, Perera SSN, Jayasinghe S, Karunanayake P, Kariyawasam P (2013), "The influence of climate variability on dengue transmission in urban Colombo: a cross wavelet approach", Annual Research Symposium 2013,University of Colombo, pp 152.

[8] Yien Ling Hii, Huaiping Zhu, Nawi Ng, Lee Ching Ng, Joacim Rocklo (2012), "Forecast of Dengue Incidence Using Temperature and Rainfall", PLOS Neglected Tropical Diseases, Volume 6,Issue 11,pp 1-9.

[9] Louis Lambrechtsa, Krijn P. Paaijmans, Thanyalak Fansiria, Lauren B. Carrington, Laura D. Kramere, Matthew B. Thomas, (2011) "Impact of daily temperature fluctuations on dengue virus transmission by Aedes Aegypti", PNAS Early Edition, pp 1-6.

[10] R A Erickson, K Hayhoe, S M Presley, L J S Allen, K R Long and S B Cox (2012) , "Potential impacts of climate change on the ecology of dengue and its mosquito vector the Asian tiger mosquito (Aedes albopictus)",IOP Science, Environ. Res. Lett. 7 (2012) 034003, pp1-6.

[11] Xiaodong Huang, Archie CA Clements, Gail William, Gabriel Milinovich and Wenbiao Hu (2013), "A threshold analysis of dengue transmission in terms of weather variables and imported dengue cases in Australia", Emerging Microbes and Infections(2013), pp 1-7.

[12] Suchithra Naish, Pat Dale, John S Mackenzie, John McBride, Kerrie Mengersen and Shilu Tong (2014), "Climate change and dengue: a critical and systematic review of quantitative modeling approaches", BMC Infectious Diseases 2014, pp 1-14.

[13] Yien Ling Hii, Huaiping Zhu, Nawi Ng, Lee Ching Ng, Joacim Rocklo v (2012),"Forecast of Dengue Incidence Using Temperature and Rainfall", PLOS Neglected Tropical Diseases, Volume 6, Issue 11, pp 1-9.

[14] Michael A. Johansson1, Francesca Dominici, Gregory E. Glass (2009), "Local and Global Effects of Climate on Dengue Transmission in Puerto Rico", PLOS Neglected Tropical Diseases, Volume 3, Issue 2, pp 1-5.