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Wavelet analysis of dengue transmission pattern in Sri Lanka

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Abstract
Dengue fever is a deadly infectious mosquito borne disease that has placed an enormous economic burden upon the health system in Sri Lanka. The geographic distribution of dengue, both classical dengue fever and its more severe form dengue hemorrhagic fever has been expanded dramatically in recent decades. However, we have a limited understanding of the disease transmission pattern in Sri Lanka. The objective of this study is to identify the epidemic outbreak patterns of dengue cases in 25 districts in Sri Lanka. Wavelet analyses were performed on weekly notified dengue cases from January 2009 to September 2014 to explore periodicity in dengue counts. Dengue dynamics showed multiple periodic patterns (1-8 weeks, 26 weeks and 52 weeks) across twenty five districts which can be divided into two groups based on wavelet cluster analysis. These findings will provide a scientific basis for dengue control and prevention in Sri Lanka.

Keywords: Dengue, Wavelet Analysis, Sri Lanka, Cluster Analysis, Wavelet Power Spectrum, Time Series

1. Introduction
Dengue has become a major global health concern due to increasing incidence and geographic spread [1, 2, 3]. According to current estimates, approximately 3.5 billion people, which is about 55% of the world's population live in countries at risk for dengue infection [3]. Estimates of the World Health Organization indicate that up to 50 million people get infected with dengue every year and another 3.6 billion are at risk of getting infection [4].
Sri Lanka has a favorable climate for development and transmission of dengue. The number of hospitalizations and reported deaths due to dengue fever (DF) and its life threatening form dengue hemorrhagic fever (DHF) proliferated over the last decade despite enormous efforts and money being put into its control. First dengue case in Sri Lanka was reported in the middle of the 19th century. The presence of virus was serologically confirmed in 1962[5]. Currently, both *Aedes aegypti* and *Aedes albopictus* are found in Sri Lanka [6]. The Western Province of Sri Lanka reported highest number of dengue cases in each year [7]. At present, there are two important trends related to dengue transmission in Sri Lanka; there has been a dramatic rise in the number of cases and dengue has started to appear in the districts outside the Western province. However, the epidemiological patterns of dengue in 25 districts in Sri Lanka are not yet well understood. The published studies are mainly limited to examine the clinical and epidemiological characteristics of dengue [8].
Time series of number of dengue cases are distinguished by nonlinear dynamics with strong seasonal epidemics, multiyear oscillations and nonstationarity [1, 3, 9]. Therefore, mathematical and statistical methods such as Fourier analysis, General Linear Models and Box Jenkins time series are inadequate to capture these features. To overcome the problems of analysing complex, nonstationary time series, it has recently been introduced to apply wavelet analysis, which decomposes time series into the time-frequency domain [4]. Wavelet analysis is free from the assumption of stationarity that makes most techniques unsuitable for analyzing many environmental and epidemiological time series [10]. Through this approach it is possible to detect scales related to the periodic components and shifts in the recurrent periodic components of a given time series. It is argued wavelet analysis can be used as an initial step for exploring the complexity of ecological time series before the modeling stage [11]. In this study we applied wavelet analysis on time series of dengue cases in each district to explore the periodicity in the dengue incidence and how periodicity changes with time. We have analysed the time series from the 25 districts individually. Furthermore, to identify districts with similar dengue dynamic pattern, wavelet cluster analysis was performed.

Dengue prevention and control including cleanup and awareness campaigns in many disease endemic areas start on the prompt notification once patient is being admitted for treatment. Economic and financial burden of dengue due to hospitalization, mortality and morbidity costs along with opportunity costs of time and productivity losses due to illness far exceed the cost of vector control. To date, there is no specific dengue therapeutics available to prevent dengue fever. In absence of a vaccine for the prevention and control of dengue fever, eradicating breeding places of *Aedes* mosquitoes is still the only effective strategy [12, 13]. Hence to strengthen dengue prevention and control activities, public health officials need to know much more about the patterns of dengue incidence time series. Thus understanding the spatial dynamics and timing of dengue epidemics would benefit for optimizing current dengue surveillance and control programmes.

2. Materials and methods

2.1 Study Area

Sri Lanka is primarily a tropical island located in southern tip of India (71^0N, 81^0E) with high humidity and warm temperature throughout the year. Total area of the country is 65610 km^2 with 64740 km^2 of land and 870 km^2 of water. The topography of the country is divided into three areas namely; plains, the coastal belt and central highlands. Climate consists of both wet and dry seasons. The rainfall pattern in Sri Lanka is influences by monsoon winds. The Western and Southern regions of the country receive abundant rainfall from May to September while the area experiences its dry season during December through March. The monsoon affects northern and eastern parts of Sri Lanka from October to January, with the dry season usually lasting from May to September. This region receives approximately 1000 mm of precipitation annually which is significantly less than the other half of the country. The inter-monsoon period prevails from October to November during which rain and thunderstorms occur frequently across the island. The Central Highlands of Sri Lanka are cooler than other parts of the country, with a yearly average temperature around 16 ^{0}C – 20 ^{0}C and coastal areas are warmer with an average temperature around 27 ^{0}C – 30 ^{0}C year-round. Humidity is typically high in Sri Lanka, averaging out at around 80% year-round. The climate conditions in Sri Lanka play an important role in transmission and multiplication of dengue virus.

2.2 Data Description

Weekly notified dengue cases in 25 districts of Sri Lanka were obtained from weekly epidemiological reports published by the Epidemiological Unit, Ministry of Health, Sri Lanka. Data were obtained for the period extending from 1st week of January 2009 to 36th week of September 2014. These dengue data included dengue records from health posts and centres and hospitals compiled at district levels.

2.3 Statistical Method

The wavelet methodology has been used in many fields such as signal processing, image analysis, geophysics, atmospheric sciences and climatology [14]. Wavelet analysis extracts the time and frequency information of a time series simultaneously. In addition, wavelet analysis is capable of detecting changes in periodicity in time series. According to Cazelles *et al*. [1] wavelet analysis approach is the most efficient method among the various methods developed to study nonstationary data. The Morlet wavelet was used and all analyses were performed using the R software (version 3.1.2). Much of the code was adopted from MATLAB code by Torrence and Compo [14] and Grinsted [15]. To deeply understand the similarities and dissimilarities between dengue dynamic behaviour in different districts wavelet cluster analysis was performed. All dengue time series were square root transformed and normalized before applying the wavelet transformation, because the number of cases may vary among populations, but the epidemiological pattern may be similar [1]. Then, we transformed the data for dengue cases with continuous wavelet analysis and then hierarchical cluster analysis was performed. Ward's distance measure was used to calculate pairwise distance matrix.

2.4 Continuous Wavelet Transformation

Wavelet transformation is a measure of similarity between the basis function (wavelet) and dengue time series and calculated continuous wavelet transformation coefficients refer to the closeness of the dengue time series profile to the wavelet at the current scale. Hence wavelet approach can be considered as a cross-correlation between a time signal with a set of wavelets of various 'widths' or scales at different time positions [11].
In analysis of epidemiological time series Morlet wavelet is often applied [1]. The Morlet Wavelet is defined as,

$$\psi_0(t) = \pi^{-1/4} e^{i\omega_0 t} e^{\frac{-t^2}{2}} \qquad (1)$$

Where t is a scaled time unit and ω_0 is the relative frequency of the sine wave ($\omega_0 = 6$ here to satisfy admission criteria.) The continuous wavelet transform of a discrete time series $\{x_n\}_0^{N-1}$ of time step δt is defined as,

$$W_n(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=0}^{N-1} x_{n'} \psi_0^* \left[\frac{(n' - n)\delta t}{s} \right] \qquad (2)$$

Where ψ^* is the complex conjugate. $|W_n(s)|^2$ is called the wavelet power spectrum of $\{x_n\}_0^{N-1}$. By varying the wavelet scale s and translating along the localized time index n, one can construct a picture showing both the amplitude of any features versus the scale and how this amplitude varies with time.
Fourier transformation is also a widely used method for signal processing. In contrast to Fourier analysis wavelet analysis uses scalable window which has a compressed window for analyzing high frequency details and a diluted window for uncovering low frequency trends within the signal. This time-frequency analysis of the signal provides information on the different periodic patterns as time progresses.

3. Results & Discussion

Figure 1 shows the time series of aggregated dengue incidence in 25 districts in Sri Lanka. Dengue cases occur year round but there is a seasonal trend, where two peaks of dengue occur following monsoon rains in June - July and October – December. The country experienced an unexpected dengue outbreak in 2009 and 2014. Drastic downward trend at the end of 2011 and mid of 2012 were partially due to the effectiveness of strengthened vector control programmes implemented by the government. Wavelet power spectrum of aggregated dengue incidence is shown in figure 2. The plot of wavelet power spectrum shows that dengue outbreaks varied at different periods and the periodicity of the signal varies through time. Wavelet analysis reveals a significant 26 week periodicity during 2009 – 2011, 2012 and in 2014. Several very high frequency periodicities with peaks at 2-8 week periods are also seen in figure 2. These periodicities appear in an intermittent pattern.

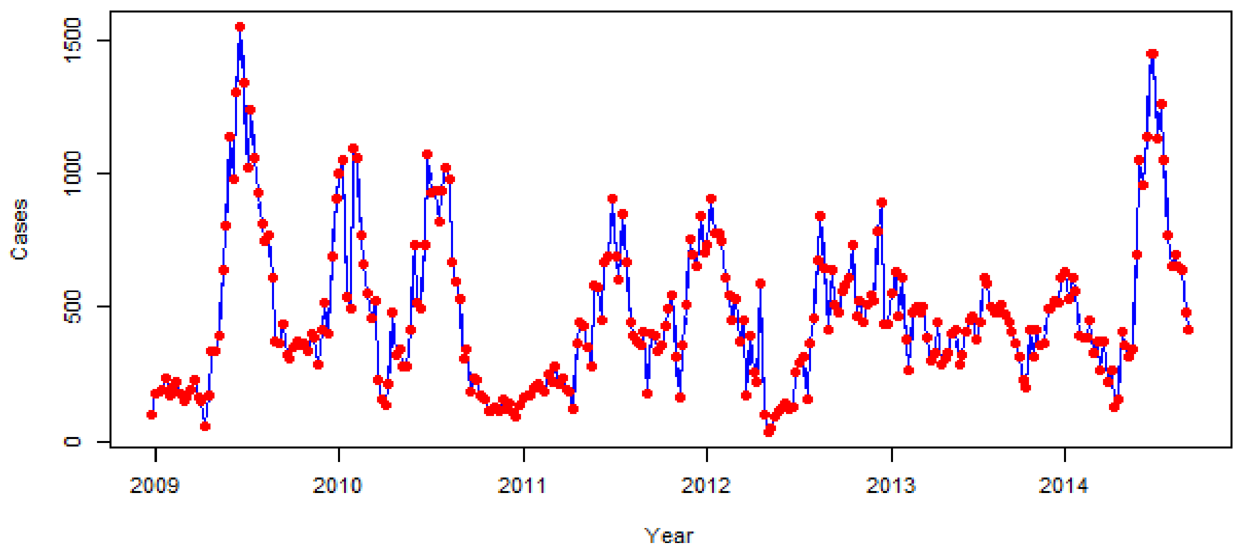

Fig 1: Time series plot of aggregated dengue cases in Sri Lanka from January, 2009 to September, 2014.

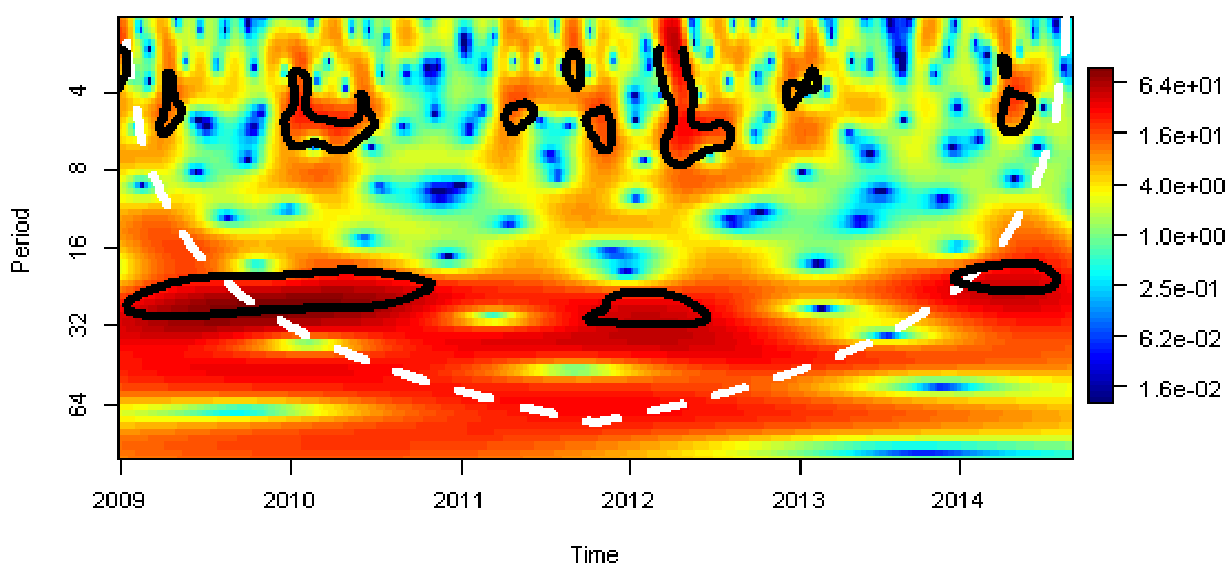

Fig 2: Wavelet power spectrum of the aggregated weekly dengue cases time series for Sri Lanka, from January, 2009 to September, 2014.

Wavelet analysis of time series data from 25 districts of Sri Lanka are displayed in figure 3. Almost all the districts in Sri Lanka have reported dengue cases while Colombo, Gampaha, Kalutara and Kandy districts have recorded the highest number of cases. In general, the spectra show periodicity for all districts with substantial heterogeneity in the relative strength.

More specifically periodicities were detected in the 2-8 week and 20-60 week bands. There is no consistent significant band in any of these 25 districts. Overall, high power bands are mostly distributed in 26 and 52 week period indicating both annual and sub annual periodicity. Nevertheless, these modes of oscillation vary in strength. The dominant mode was 26 week periodicity. Moreover, in Colombo district, 26 week periodicity is significant in 2010, 2011-2012 and in 2014. Gampaha district shows a significant 26 week periodicity in 2009 – 2010 and in 2012. In both districts annual periodicity was not statistically significant. In contrast to Colombo and Gampaha, the only other district in the Western province, Kalutara district, shows significant multiple frequency bands from 2011 to 2013.

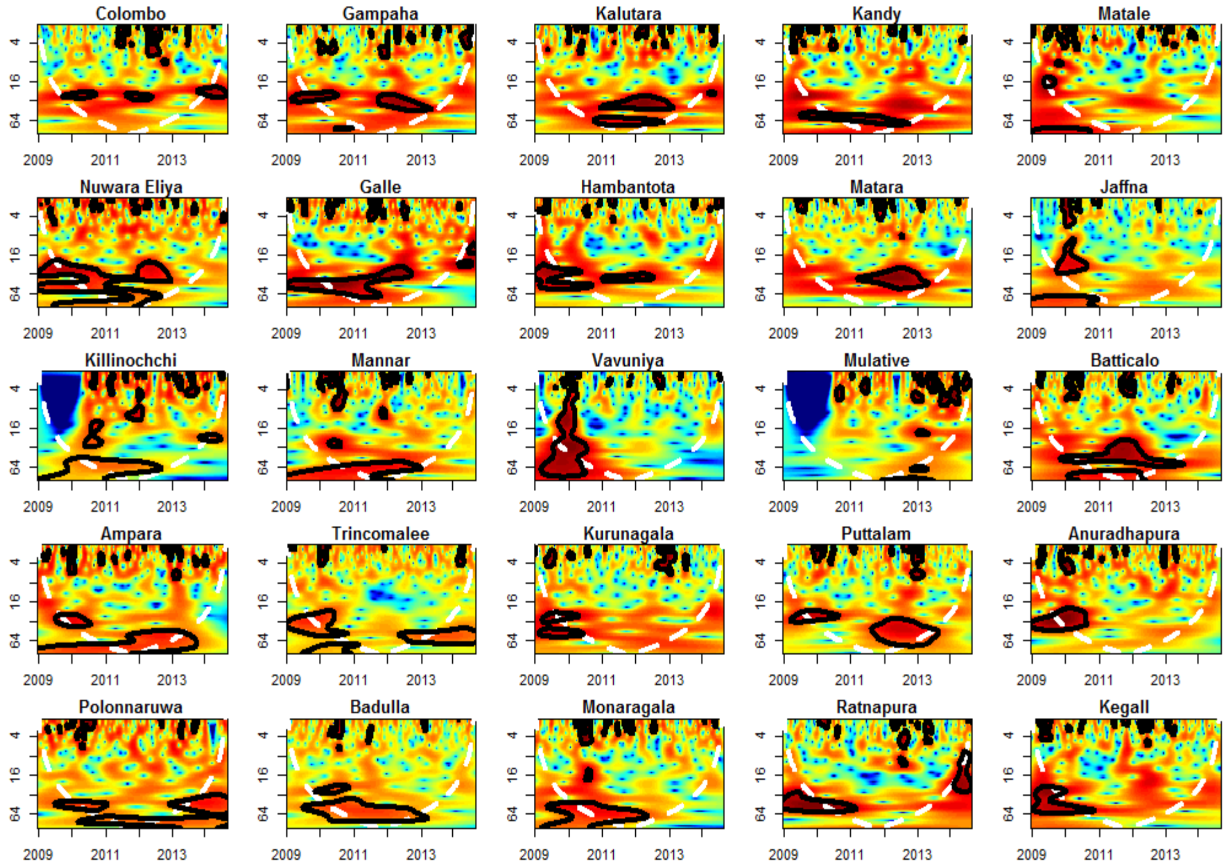

Fig 3: Wavelet power spectra of dengue incidence in 25 districts in Sri Lanka (time on x-axis, period on y axis)

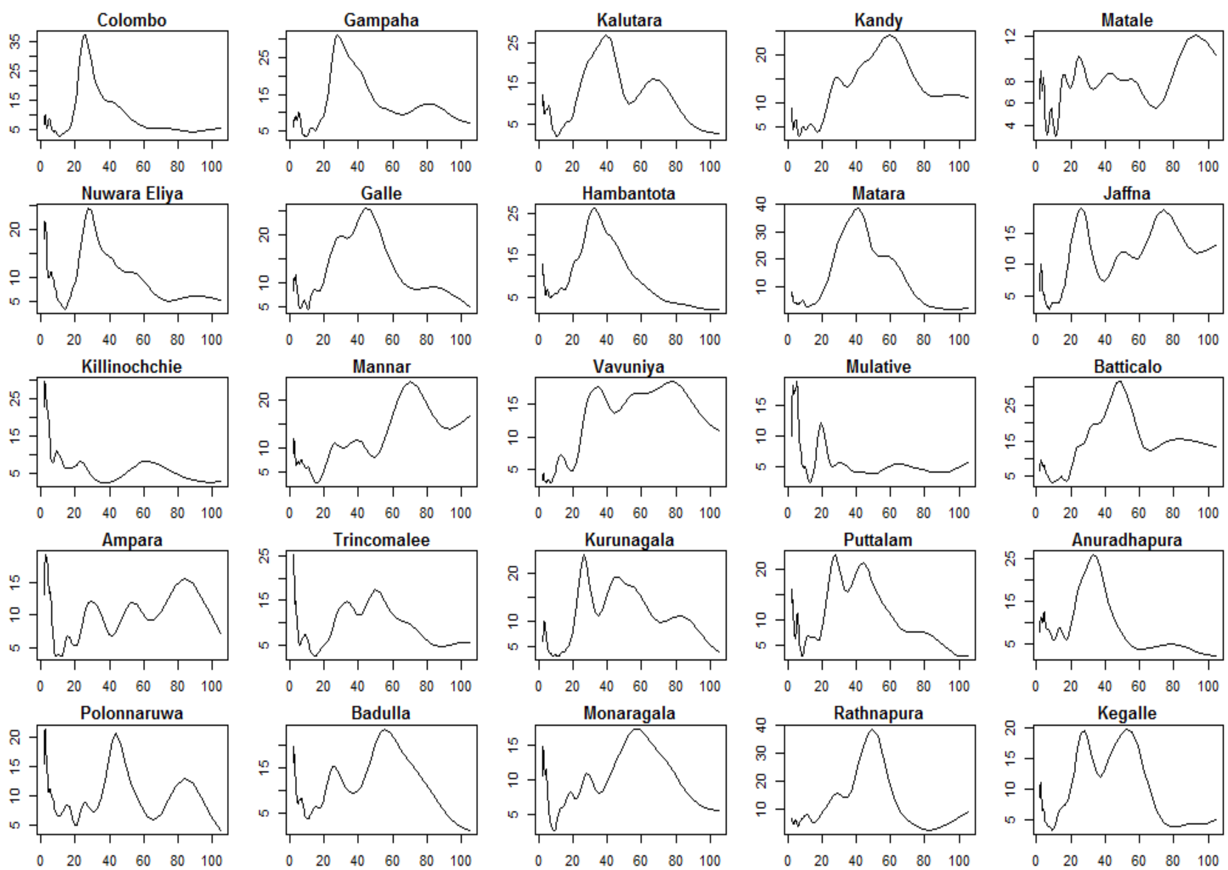

Fig 4: Average wavelet power spectrums (periodicity on x axis, average power on the y-axis)

For Galle district in Southern Province, a significant annual periodicity was detected from 2009 to 2012, and then a decreasing period from approximately 52 week to 26 week was clearly seen from 2nd half of 2011 to 2013. In addition, several high significant frequency periodicities were seen in 2-6 week band. In Kilinochchi and Mulative, the dark blue portion of the figure corresponds to the dengue epidemics in year 2009. Both districts recorded zero number of dengue cases throughout the whole year. The large significant red portion in Vavuniya district corresponds to sudden increase in the number of dengue incidence in the year of 2010. Nuwara Eliya district, which is located 1868 meters above the sea level, showed significant multiple periodicities from 2009 to 2013.

The average wavelet power spectra (figure 4) showed peak in power at periods of ~26 weeks and/ or 52 weeks. This suggestes annual and/ or semi annual periodicities are dominated in the dengue transmission pattern in Sri Lanka. The annual periodicity is reflected in the DF incidence time series by increase of incidence in December and semi-annual periodicity is due to faster increase of incidence in weeks 26 – 27.

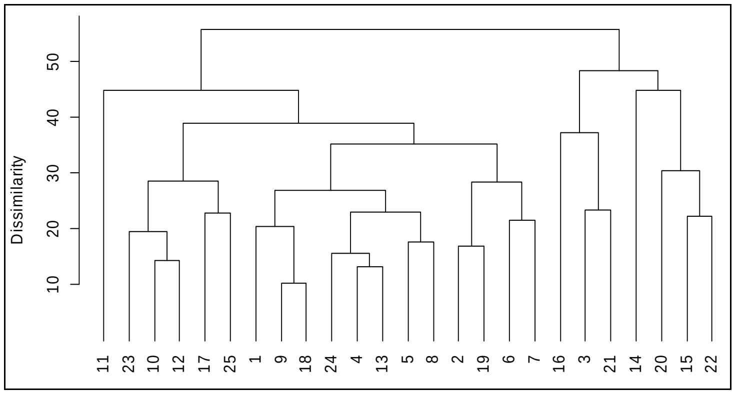

Fig 5: Dendrogram of wavelet cluster analysis

[11-Killinochchi, 23 – Monaragala, 10-Jaffna, 12-Mannar, 17-Trincomalee, 25-Kegalle, 1-Colombo, 9-Matara, 18-Kurunegala, 24-Ratnapura, 4-kandy, 13-Vavuniya, 5-Matale, 8-Hambantota, 2-Gampaha, 19-Puttalam, 6-Nuwara Eliya, 7-Galle, 16-Ampara, 3-Kalutara, 21-Polonnaruwa, 14-Mullative, 20-Anuradhapura, 15-Batticaloa, 22-Badulla]

Based on wavelet cluster analysis periodicities that appeared in dengue dynamics pattern in twenty five districts can be divided into two groups. The map of distribution of districts among clusters is shown in figure 6. The first cluster consists of 18 districts while the 2nd cluster second cluster consists 7 districts. The wavelet cluster tree is shown in figure 5. The timing of statistically significant periodicities differs among districts even within a cluster.

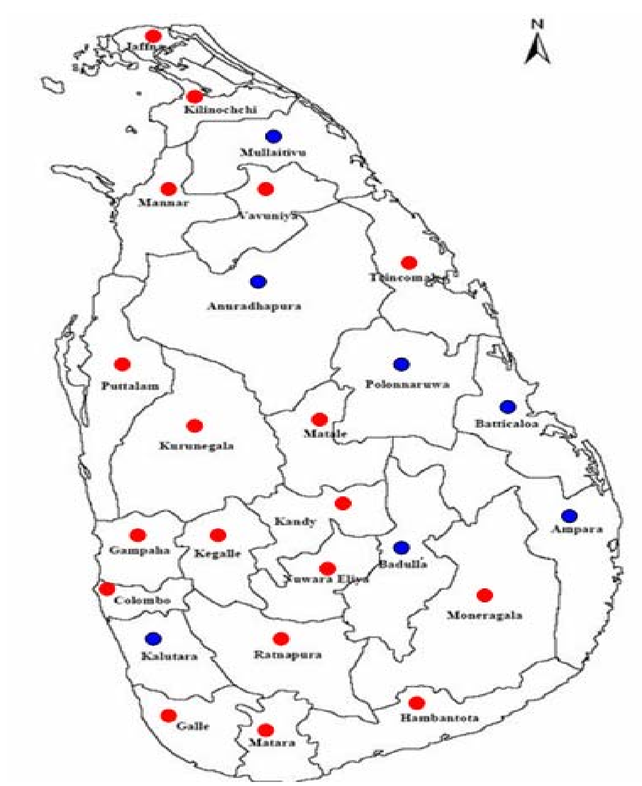

Fig 6: Results of wavelet cluster analysis (red – cluster 01, blue – cluster 02)

Except Trincomalee district all districts in cluster 01 were located in the left side of the country while in cluster 02, except Kalutara district all the other districts were located in the right side of the country. These two clusters might have been influenced from southwest monsoon and northeast monsoon. The unusual pattern of dengue incidence in Kalutara district could be due to rubber cultivation. Massive number of coconut shells used for collection of rubber milk in rubber plantations and discarded coconut shells caused breeding of mosquitoes. Moreover, rubber tree rain gutter system forms an ideal condition for the proliferation of mosquitoes. Furthermore, massive pineapple cultivation in rubber estates are also fueling for dengue vector profusion in the district. Palaniyandi [16] found coconut shells used in rubber plantations and pineapple cultivation fueling dengue incidence in Kerala state, India.

The periodicities of dengue incidence in cluster 01 are in accordance with dengue dynamics in Thailand [17, 18] and South Vietnam [4]. Annual periodic patterns are a common characteristic in dengue incidence time series and have been reported in many countries in tropical and subtropical regions [3]. Sudden variations in periodicities could be due to changes in climate conditions, human and mosquito populations, and new methods for diagnosis, classification and reporting dengue cases.

4. Conclusions

This paper presents an alternative way to extract features of dengue transmission pattern in 25 districts of Sri Lanka with wavelet analysis. It provides information on different rhythmic components and intermittent periodicities of spatial-temporal dengue incidence in Sri Lanka. The wavelet power spectra of dengue dynamics indicate periodicities around 2-8 weeks, 26-32 weeks and 52-64 weeks. 2-8 weeks periodicity appeared in an intermittent pattern. Though we found high power at annual and semi-annual scales in wavelet power spectra of all 25 districts, the significance of those bands are discontinuous. However, dengue dynamics showed different periodicities across 25 districts which could be divided into two clusters based on wavelet cluster analysis.

Moreover, *Aedes* mosquito, the principal vector for dengue transmission heavily depends on temperature, rainfall, humidity and few other climatic factors to complete their life cycle. Therefore, climate conditions play an indefinite role on the occurrence of dengue incidence and further studies are needed to examine the role played by climate on the pattern of dengue transmission.

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