Determination of rainfall erosivity in Penang

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ABSTRACT

Rainfall erosivity considers the rainfall amount and its intensity. This is an important parameter for soil erosion risk assessment under future land use and climate change. Comparisons of all climatic parameters show that rainfall is directly involved in the loss of soil quality during torrential rain. The effect of rainfall erosivity in Penang was considered for two stations, Air Itam and Simpang Amapat. Monthly as well as annual rainfall was obtained from the Department of Drainage and Irrigation, Malaysia for thirty years (1983-2012). Trends analysis of the rainfall data were obtained for each decade that shows trends for mean monthly rainfall. This was conducted using Mann-Kendall trend analysis and Sen's slope tests. Trend analysis shows that there is no significant difference in mean monthly rainfall for the studied period except for Simpang Amapat. The Fournier indexes were used to determine the effect of extreme rainfall events towards soil erosivity. Air Itam recorded 10% cases of very severe impact using Fournier index and 3.33% cases of very high impact using modified Fournier index. The result shows that there is a positive correlation between rainfall trends and soil erosivity.

Keywords: climate change, soil erosivity, trend analysis, Fournier index, modified Fournier index

1. INTRODUCTION

The global greenhouse effect is expected not only to increase mean global temperatures, but also to influence characteristics of rainfall. Water is related to river flows, and with soil moisture availability for spontaneous vegetation and cultivated species.

Increased variability of precipitation and a higher amount of erosive rainfall in Malaysia may also increase soil erosion. Rainfall erosivity, the potential ability of rain to cause erosion, is a function of the physical characteristics of rainfall (Mikhailova et al. 1997). In the tropics, the rains are comparatively intense and sometimes of long duration. Soil erosion has been of much concern especially to countries like Malaysia whose most economies depend on agriculture. Generalized maps of the geographical distribution of rainfall and wind erosion, puts Malaysia in the area designated as particularly susceptible to rainfall erosion. Population growth, with its attendant increase in development demand for land and agricultural products, is likely to worsen the problem.

Many scientists predict rising atmospheric temperatures and subsequently more intensive hydrologic cycles may also lead to a change of rainfall characteristics and particularly to a higher variability of rainfall. Possible consequences are a decreasing frequency of light and medium rainfalls as well as shorter return periods for intensive rainstorms.

A growing frequency of intensive rainstorms may be accompanied by a clustering of dry periods which represent a dangerous combination with regard to water and wind erosion. Dry soils are much more susceptible to water erosion than moist soils because infiltration water compresses the air in soil aggregates, destabilizing them and causing their break-down (Potratz, 1993). Subsequently, the soil particles can easily be carried away by surface runoff.

The universal soil loss equation (USLE) is presently the model most widely applied to estimate soil loss. The simple equation is a multiplicative model in which four non dimensional factors representing the influence of topography, cultural and management practices are used to modify a basic soil loss named potential erosion (Ferro et al. 1991). Potential erosion is the product of two parameters representing the influence of rainfall and soil characteristics. The rainfall index R is a useful tool for establishing areas of soil erosion risk in which soil conservation structures are necessary. Fournier (1960) proposed the index in which the maximum monthly rainfalls (mm) were used. Since Fournier's index does not consider the monthly rainfall distribution during the year, it does not always increase when the number of erosive rainfalls in the year increases. In order to avoid this drawback, Arnoldus (1980) proposed the modified Fournier index.
The first part of this research will analyze the trend of rainfall and estimate the steepness of the slope for two areas in Penang. Gocic and Trajkovic (2013) used the Mann-Kendall tau-b for testing trend and Sen’s slope estimator to determine the annual and seasonal trends for several variables in Serbia for the period of 1980-2010. Similar studies using Mann-Kendall trend test were done by Gemmer et al. (2004) and Xu et al. (2004). The Fournier and Fournier’s modified index was used to derive future rainfall erosivity values by the use of average monthly rainfall amounts for elaborating an index in accordance with the universal soil loss equation.

2 STUDY AREA

Pulau Pinang was selected to be the study area. Two stations were selected that is Simpang Ampat, located at the mainland of Pulau Pinang and Air Itam, located at the island of Pulau Pinang. Simpang Ampat is located at latitude 5.1457830 and longitude 100.4905196 while Air Itam is located at latitude 5.406111 and longitude 100.296389. Figure 1 shows the location of the study area.

![Fig. 1. Map of study area](image)

3 DATA AND METHODS

This section describes the data used and the methods used in this research.

3.1 Data

The data was obtained from Department of Drainage and Irrigation, Malaysia (Department of Irrigation and Drainage, 2013) from 1983 until 2012. The data consist of information on daily rainfall, minimum, maximum and total rainfall per month as well as annual rainfall. The unit of measurement is millimeters. For each month, the total maximum rainfall was divided by the numbers of days in that month to determine the mean monthly rainfall. The analysis was done using the mean monthly rainfall.

3.2 Mann-Kendall test for trend

The Mann-Kendall tau-b nonparametric test (Gocic and Trajkovic, 2013; Helsel and Hirsch, 1992) was used to test for trend. This test is calculated as

\[ S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \]  

where \( n \) is the number of rainfall event, \( x_i \) and \( x_j \) are the observed rainfall events, and \( sgn \) is the sign function.

The variance is given by

\[ Var(S) = \frac{n(n-1)(2n+5)}{18} \left( \sum_{i=1}^{m} t_i(t_i-1)(2t_i+1) \right) \]  

where \( n \) is the number of rainfall events, \( m \) is the number of tied events, \( t_i \) is the number of events that are tied. For sample size greater than 10, the test can be approximated using the test statistic based on the normal distribution given below:

\[ Z_S = \begin{cases} \frac{S+1}{\sqrt{Var(S)}} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S-1}{\sqrt{Var(S)}} & \text{for } S < 0 \end{cases} \]  

For increasing rainfall trends, the values of \( Z_S \) is positive and for decreasing rainfall trends the values of \( Z_S \) is negative.

3.3 Sen’s estimator for slope

Sen’s slope test (Gocic and Trajkovic, 2013; Brauner, 2010) is a nonparametric test for the steepness of the trend. For \( N \) pair’s of data,

\[ Q_i = \frac{x_j-x_k}{j-k} \text{ for } i = 1, \ldots, n \]  

where \( x_j \) and \( x_k \) are the rainfall values at times \( j \) and \( k \) (\( j > k \)) respectively. The \( N \) values of \( Q_i \) are ranked from smallest to largest and the median of the slope or Sen’s slope estimator is given by

\[ Q_{med} = \begin{cases} Q_{\lceil(N+1)/2\rceil} & \text{for } N \text{ odd} \\ \frac{Q_{\lceil N/2 \rceil} + Q_{\lceil N/2 \rceil + 1}}{2} & \text{for } N \text{ even} \end{cases} \]  

The confidence interval for \( Q_{med} \) was obtained to determine the significance of the slope.

3.4 Fournier and Fournier modified index

The Fournier index (Fournier, 1960) and the Fournier modified index (Arnoldus, 1980) was calculated according to equations (6) and (7) below:

\[ P = \frac{P_{max}}{\overline{P}} \]  

with \( P_{max} \) = monthly average amount of rainfall of the most rainy month (mm) and \( P \) = average annual quantity of rainfall.

\[ F_M = \frac{1}{\overline{P}}[P_1^2 + P_2^2 + \ldots + P_{12}^2] \]  

where \( P_i \) is the monthly average amount of rainfall for month \( i \) (mm), and \( \overline{P} \) is the average annual quantity of rainfall (mm).
Table 1 describes the classifications of erosivity using the Fournier and Fournier modified index.

Table 1. The erosivity classes by Fournier index ($F$) and Fournier modified index ($F_M$) (Source: Fournier; 1960, Arnoldus; 1980)

| Erosivity class | $F$  | $F_M$  |
|-----------------|------|--------|
| Very low        | 0-20 | 0-60   |
| Low             | 20-40| 60-90  |
| Moderate        | 40-60| 90-120 |
| Severe          | 60-80| 120-160|
| Very severe     | 80-100| >160  |
| Extremely severe| >100 | -      |

4 RESULTS AND DISCUSSIONS

4.1 Descriptive Analysis

The mean and standard deviation for the two stations are given in Table 2. For the different time periods, the mean rainfall for Air Itam is higher than the mean rainfall for Simpang Ampat. However, coefficient of variation is less than 0.3 for all time periods and for both stations showing that the mean rainfall have a very small variability.

Table 2. Descriptive statistics

| Year   | Air Itam(1,2) | Simpang Ampat(1,2) |
|--------|---------------|--------------------|
| 1983-1992 | 6.497mm, 1.068mm | 3.162mm, 0.533mm |
| 1993-2002 | 7.258mm, 1.542mm | 5.697mm, 0.983mm |
| 2003-2012 | 6.775mm, 0.737mm | 6.007mm, 1.030mm |
| 1983-2012 | 6.843mm, 1.1658mm | 5.622mm, 0.918mm |

*(1,2) denotes (mean, std dev)

From Figure 2, the regression line has a very small slope indicating that there is a very slight trend in mean rainfall at Air Itam. The slope of the regression line shows a moderate positive slope indicating that there is an upward trend in mean rainfall for Simpang Ampat for the studied period.

4.2 Trend and slope analyses

The Mann-Kendall tau-b statistics for trend and Sen's slope estimator is given in Table 3 for Air Itam and in Table 4 for Simpang Ampat. The trend analysis using Mann-Kendall tau-b statistics show that the trend is not significant ($p$-value > 0.05). However for the period 1983-1992 and 1993-2002, there is a downward trend in mean rainfall for Air Itam and an upward trend for 2003-2012 and 1983-2012. The Sen's slope estimator show negative slope for 1983-1992 and 1993-2002 and positive slope for 2003-2012 and 1983-2012. However, the slope is not significant for all periods.

Table 3. Trend and slope results for Air Itam

| Year     | Z   | p-value | Sen    | CI for Sen       |
|----------|-----|---------|--------|------------------|
| 1983-1992 | -1.073 | 0.1412 | -0.106 | (-0.396,0.296) |
| 1993-2002 | -0.358 | 0.360 | -0.093 | (-0.597,0.399) |
| 2003-2012 | 0.358  | 0.640 | 0.053  | (-0.216,0.257) |
| 1983-2012 | 0.143  | 0.557 | 0.003  | (-0.047,0.061) |

Table 4. Trend and slope results for Simpang Ampat

| Year     | Z   | p-value | Sen    | CI for Sen       |
|----------|-----|---------|--------|------------------|
| 1983-1992 | -0.200 | 0.237 | -0.063 | (-0.172,0.100) |
| 1993-2002 | 0.000  | 0.500 | -0.004 | (-0.407,0.303) |
| 2003-2012 | -0.179 | 0.429 | -0.023 | (-0.336,0.377) |
| 1983-2012 | 1.678  | 0.047 | 0.032  | (-0.009,0.073) |

For Simpang Ampat, there are no significant trends for periods 1983-1992, 1993-2002 and 2003-2012. There is a downward trend in mean rainfall for 1983-1992 and 2003-2012. For the period of 1983-2012, there is an upward and significant trend ($p$-value = 0.047). The Sen's slope estimators do not show any significance for all time periods.
2 Erosivity analysis

Figure 4 shows the Fournier index for Simpang Ampat and Air Itam from 1983-2012.

Two years show very low impact (7.67%), low impact is 63.33%, while 20% and 10% of years have moderate and very severe impact respectively for Air Itam. For Simpang Ampat, there are no recorded severe and very severe impact years. 46.67% of years have low impact, 43.33% has very low impact and only 10% of years have moderate impact. Thus it can be concluded that for Simpang Ampat, the occurrence of soil erosion is very small while for Air Itam there are certain years that soil erosion and ultimately landslide can occur.

Fournier modified index (Figure 5) showed that for Air Itam the highest impact is moderate and high which makes up 40% from all years. Only one year has very high impact (3.33%), and low impact is 16.67% which is five years. For Simpang Ampat, there is no very high recorded impact. The highest percentage of impact is low (50%) which is 15 years, 40% moderate and 6.67% of the years has very low impact.

Figure 6 illustrates the trend for Fournier and Fournier modified index. For Simpang Ampat, the Fournier and Fournier modified index shows the trend is increasing from each decade under study period. However, for Air Itam, it shows a decreasing trend for both indices.

5 CONCLUSIONS

Rainfall erosivity is the ability of rainfall to cause erosion due to the function of physical characteristic of rainfall (Mikhailova et al. 1997). This study is to determine the rainfall erosivity in Penang (Air Itam, Simpang Ampat) based on the rainfall data from 1983 until 2012.

Descriptive statistics show that the mean and variance for mean monthly rainfall for Air Itam were higher in most periods compared to Simpang Ampat. The time series and regression lines illustrated a very slight upward trend in mean rainfall at Air Itam and a moderate positive slope in mean rainfall for Simpang Ampat.

For Air Itam the Mann-Kendall tau-b statistics for trend and Sen's slope estimator show the trend and slope are not significant for all periods. This finding is in agreement with Xu et al. (2003). Meanwhile for Simpang Ampat, Mann-Kendall tau-b statistics for trend for the period of 1983-2012 shows there is an upward and significant trend but for Sen's slope estimator, it did not show any significance for all time periods. This finding is similar to Gemmer et al. (2004) who has reported that several stations show significant trends.

Both Fournier index and Fournier modified index show higher impact for Air Itam compared to Simpang Ampat. For Air Itam, the Fournier modified index show that there are 14 years where the impact is high and very high while for Simpang Ampat shows only one year with high impact.

The result shows that Air Itam is prone to soil erosion incidences that can lead to the possibility of landslide. It also shows that there is a positive correlation between rainfall trends and soil erosivity.
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REFERENCES

1) Arnoldus, H. M. J. (1980): *An Approximation of the Rainfall Factor in the Universal Soil Loss Equation in: Assessment Of Erosion* (ed. M. De Boedt & D. Gabriels), Wiley, Chichester, West Sussex, UK.
2) Brauner, J.S. (2010): Nonparametric Estimation of Slope: Sen's Method in *Environmental Pollution*, viewed 2 January 2015, <http://www.webapps.cee.vt.edu/ewr/environmental/teach/smprimer/sen/sen.html>.
3) Department of Irrigation and Drainage, (2013): Annual Flooding Report of Penang State 2012/2013.
4) Ferro, V., Giordano, G., & Iovino, M. (1991): Isoerosivity and Erosion Risk Map for Sicily. *Journal of Hydrological Sciences*, 36(6), 549-564.
5) Fournier, F. (1960): *Climat at Erosion*. Press Universitaires de France, Paris, France.
6) Gemner, M., Becket, S. and Jiang, T. (2004): Observed Monthly Precipitation Trends in China 1951-2002, *Theoretical and Applied Climatology*, 77, 39-45.
7) Goicic, M. and Trajkovic, S. (2013): Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia, *Global and Planetary Change*, 100, 172-182.
8) Helsel, D.R. and Hirsch, R.M. (1992): Statistical Methods in Water Resources, *Techniques of Water Resources Investigations*, Book 4, Chapter A3, US Geological Survey, 522 pages.
9) Mikhailova, E.A., Bryant, R.B., Schwager, S.J., Smith, S.D., (1997): Predicting rainfall erosivity in Honduras. *Journal of Soil Science Society of America*, 61(1), 273–279.
10) Potratz, K. (1993): Bedeutung von Feuchte und Struktur der Bodenoberfläche für die Bodenerosion. *Bonner Bodenkundl. Abh.*, 11, 70 pp.
11) Xu, Z.X., Takeuchi, K. and Ishidaira, H. (2003): Monotonic Trend and Step Changes in Japanese Precipitation, *Journal of Hydrology*, 279, 144–150.