TEMPORAL SENSITIVITY ANALYSIS OF EROSIVITY ESTIMATIONS IN A HIGH RAINFALL TROPICAL ISLAND ENVIRONMENT

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ABSTRACT. The Erosivity Index (EI) and the Modified Fournier Index (MFI) are two commonly used methods in calculating the $R$ factor of the universal soil loss equation/ revised universal soil loss equation formula. Using Mauritius as a case study, the value of high-resolution data versus long-term totals in erosivity calculations is investigated. A limited number of four Mauritius Meteorological Services stations located on the west coast and the Central Plateau provided the study with detailed rainfall data for 6 years at 6-min intervals. Rainfall erosivity for erosive events was calculated using different set interval data. In this study, within the EI, the use of 6-min rainfall intervals during erosive rainfall gave estimates of around 10% more erosivity than the 30-min time intervals and 33% more rainfall erosivity than the 60-min rainfall measurements. When the MFI was used to determine erosivity through annual and monthly rainfall totals, substantially higher erosivity than the EI method was calculated using different set interval data. In this study, within the EI, the use of 6-min rainfall intervals during erosive rainfall gave estimates of around 10% more erosivity than the 30-min time intervals and 33% more rainfall erosivity than the 60-min rainfall measurements. When the MFI was used to determine erosivity through annual and monthly rainfall totals, substantially higher erosivity than the EI method was calculated in both regions. This stems from the large amount of non-erosive rainfall that is generated on Mauritius. Even when the MFI was used to calculate erosivity through monthly and annual rainfall totals derived purely from erosive rainfall, erosivity calculations were not comparable to those from high-resolution data within the EI. We suggest that for the computation of erosivity, rainfall data with the highest possible resolution should be utilised if available and that the application of annual and monthly rainfall totals to assess absolute soil erosion risk within a high rainfall tropical environment must be used with caution.

Key words: Mauritius, rainfall erosivity, Modified Fournier Index, RUSLE

Introduction

Within tropical island environments, erosive rainfall is related to rainfall depth, topography and altitude (Joshua 1977; Nigel and Rughooputh 2010a). Intense rainfall on tropical islands has high erosive potential (Nel et al. 2012) and can detach and transport large amounts of sediment (Calhoun and Fletcher 1999). Erosion risk and soil loss on tropical islands is not necessarily only dependent on rainfall amount, but also on the physical characteristics of rainfall. To quantify the potential of rainfall to cause soil loss on slopes, one of the key factors in the universal soil loss equation (USLE) (Wischmeier and Smith 1978) and the revised universal soil loss equation (RUSLE) (Renard et al. 1997) is rainfall erosivity $R$. In computing rainfall erosivity for the USLE/RUSLE the average of the annual sum of storm $EI_{30}$ values is normally calculated, where $E$ is the rainfall energy and $I_{30}$ is the maximum 30-min rainfall intensity during the storm (Wischmeier and Smith 1978).

Yin et al. (2007) assessed the accuracy of $EI_{30}$ estimations based on incremental time-resolution rainfall data compared with $EI_{30}$ estimations from breakpoint rainfall information. For erosivity calculations, Yin et al. (2007) note that the more detailed the rainfall data used, the more accurate the computed $EI_{30}$. Automatically recorded rainfall data in fixed time intervals, such as 60-min, 15-min, and possibly shorter time-resolution interval data, may then provide the preferred method for $EI_{30}$ estimation. In the absence of detailed intensity data, different alternatives have been developed to compute rainfall erosivity based on commonly available rainfall data, namely, rainfall depth measurements. Most rainfall erosivity indexing on tropical islands is thus through annual and monthly rainfall depth (e.g. Lo et al. 1985; Aguilar and Waite 1991; Renard and Freimund 1994; Nigel and
Rughupooth 2010a, 2010b). In particular the Modified Fournier Index (MFI) (Arnoldus 1980) has been extensively used on Mauritius as a substitute in the $R$ factor to parameterize soil erosion risk (Atawoo and Heerasing 1997; Le Roux et al. 2005; Kamminga 2008).

Recent research on the nature of erosive rainfall on Mauritius (Nel et al. 2012) has shown that in the calculation of rainfall erosivity the timescale at which rainfall records are used needs to be at an event scale (storm and synoptic scale) to be effective. Since many tropical volcanic islands have an environment where there is a noticeable altitudinal and temporal difference in rainfall due to the nature of the topography and its orographic effects, a few extreme rainfall events with high rainfall intensity can generate the bulk of the cumulative erosivity (Nel et al. 2012). Since calculating erosion risk from short intense tropical rainfall events necessitates high-resolution data, the nature of rainfall on tropical islands could influence the effectiveness of methods estimating erosivity through low-resolution (monthly and yearly) data. Using the tropical maritime island environment of Mauritius as a case study, this paper aims to contrast erosivity values from individual erosive events using different resolution rainfall data. Given the extensive use of the MFI in erosive studies, this paper also compares the erosivity values derived from the MFI (using both general and erosive rainfall totals) with those derived from the Erosivity Index (EI) as generated from high-resolution data.

Study area

Mauritius is located at 20° 10’ S and 57° 30’ E in the Indian Ocean and, together with Reunion and Rodrigues, form the Mascarene Islands. Mauritius is approximately 63 km long and 43 km wide on its North–South axis and the East–West axis respectively. A distinctive feature of the island is the central plateau area that rises steadily towards the southwest of the island bordered by remnants of the primary shield volcano as chain mountains (Johnson et al. 2010) (Fig. 1). The climate is essentially tropical maritime with two seasons, a rainy
summer from November to April dominated by cyclone passage and a dryer winter from May to October dominated by the SE trade wind and frontal systems (Nigel and Rughooputh 2010b). Long-term (1971–2000) mean annual rainfall is approximately 1400 mm on the eastern coast, 4000 mm in the central elevated interior and 600 mm on the drier western coast (WRU 2007).

The Central Plateau lies above 500 m a.s.l. and is closer to the west coast than the east (Fig. 1). Long-term records indicate a large spatial contrast in rainfall depth caused by the rain shadow effect of the interior and orographic forcing of the SE trade winds. Marked differences with regards to erosivity are thus also experienced between the western plains and the central interior (Nel et al. 2012).

Methodology

Rainfall data between 2003 and 2008 (6 years) from automated weather stations at four locations on Mauritius were analyzed. The data were provided by the Mauritius Meteorological Services (MMS) from weather stations where Precis Mécanique R01-3030 rainfall gauges logged total rainfall every 6 min on a tipping resolution of 0.2 mm rainfall. The R01-3030 gauge has a collection diameter of 230 mm with an area of 1000 cm2 (Alexandropoulos and Lacombe 2006, http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-94-ECO2006/P3%2810%29_Alexandropoulos_France.pdf, 3-Oct-11). Two weather station sites are located on the west coast of the island, one on the coast at Albion (12 m a.s.l.) and one approximately 4 km from the coastline at Beaux Songes (225 m a.s.l.). Data were also obtained from two weather stations in the Central Plateau area at Grand Bassin (605 m) and Trou aux Cerfs (614 m) (Fig. 1). The two west coast stations examine the rainfall intensity in the driest part of the island, while the higher altitude stations provide data from the highest rainfall area.

Establishing an erosive event

Stocking and Elwell (1976) classify a distinct erosive rainfall event as a storm when total rainfall exceeds 12.5 mm, maximum 5-min intensity exceeds 25 mm h⁻¹ and the event is isolated by at least a 2 h period of no rain. As the rainfall on Mauritius is logged every 6 min the definition by Stocking and Elwell (1976) was adjusted for a 6-min interval exceeding 12.5 mm (see also Nel et al. 2012). An event was also classified erosive if 6.3 mm of rain occurred within 15 min (Wischmeier and Smith 1978; Diodato 2005; Angulo-Martínez and Beguería 2009). When both the above definitions for an erosive event are satisfied, a total of 280 erosive events were recorded for the four stations over the 6-year study period.

Estimating erosivity from erosive events

Key processes in water erosion, especially the amount of soil that is detached, are related to rainfall intensity (Van Dijk et al. 2002). The extent of erosion caused by a rainfall event depends on the physical characteristics of the rainfall, which includes intensity, amount, drop-size distribution, terminal fall velocity, wind speed and inclination (Obi and Salako 1995). Rainfall intensity can be measured directly, but measurements of kinetic energy and raindrop sizes are, in most cases, unavailable, hence the empirical relationships between rain intensity and kinetic energy (Nyssen et al. 2005). Van Dijk et al. (2002) critically appraised the literature on the rainfall intensity–kinetic energy (R–EK) relationship and, based on the average parameter values that were derived from the best datasets, suggest the following general equation to predict storm kinetic energy content from rainfall intensity data:

\[ E_K = 28.3 \left[ 1 - 0.52^{0.042R} \right] \]  

where \( R \) is the rainfall intensity. In this study, for each storm event, Eqn (1) was used to calculate the 6-min incremental kinetic energy content derived from rainfall intensity. For each 6-min interval, the kinetic energy is totaled and then multiplied by the amount of rain falling in that 6-min period to give the kinetic energy generated. These values are subsequently summed to give the total kinetic energy of the storm.

Within the USLE/RUSLE, the \( R \) factor is calculated as follows (Renard et al. 1997):

\[ R = \frac{1}{\bar{N}} \sum_{j=1}^{n} \left[ \sum_{k=1}^{m} \frac{E(I_{30})_k}{j} \right] \]  

where \( E \) is the total storm kinetic energy (MJ h⁻¹), \( I_{30} \) is the maximum 30-min rainfall intensity (mm h⁻¹), \( j \) is an index of the number of years used to produce the average, \( k \) is an index of the number of storms in a year, \( N \) is the number of years used
to obtain the average $R$, and $m$ is the number of storms in each year. In rainfall erosivity calculations, studies have successfully used rainfall data recorded at varying resolutions (Salako et al. 1995; Yin et al. 2007; Capolongo et al. 2008; Shamshad et al. 2008; Santos et al. 2010; Meusburger et al. 2012). It is commonly accepted that the 30-min interval is used when calculating the erosivity (Yin et al. 2007), but the peak of the storm (the maximum intensity) can occur or extend through the end of one set interval and into the start of the next, thus the peak intensity of a storm is ‘broken’ in the measurements and can be missed when longer time intervals are used.

To investigate the effect different resolution data have on erosivity calculations (EI), the 6-min data were used to calculate the maximum intensity of the erosive event in three ways. First, the maximum 30-min intensity for an event was calculated using five consecutive 6-min intervals which had the greatest intensity values (called $EI_{30(C)}$). Second, set 30-min periods were used that started and ended at set intervals (called $EI_{30(S)}$). In this case, the period started at either the head of the hour or the halfway mark (e.g. start: 07:00, end: 07:30; start: 07:30, end: 08:00). Finally, the 60-min interval was used from hourly rainfall totals to calculate rainfall intensity ($EI_{60}$). As with the former, we used set time intervals of 1 h, for example, start: 07:00, end: 08:00; start: 08:00, end: 09:00).

One major limitation to a wide use of the USLE in the tropics is the lack of data to estimate the rainfall erosivity factor $R$. An alternative procedure to estimate $R$ is the MFI of Arnoldus (1980). The formula to calculate rainfall intensity ($RI$), as used for research on Mauritius, is as follows (Arnoldus 1980):

$$RI = \sum_{i=1}^{12} \frac{(MR)^2}{AR}$$

where $MR$ is the monthly rainfall and $AR$ is the annual rainfall. Then $RI$ is substituted in the following equation to estimate $EI_{30}$:

$$EI_{30} = 0.0302 \times (RI)^{1.9}$$

As with the other $EI_{30}$ methods, the annual totals from the MFI are also averaged to estimate the $R$-factor value within the USLE/RUSLE. The MFI was calculated in two ways. First, the MFI was calculated as intended (Arnoldus 1980), through the use of annual and monthly rainfall totals of all rainfall events. However, we also calculated the MFI by using the monthly and annual rainfall totals generated through erosive events (as defined under Establishing an erosive event). The MFI calculated using erosive rainfall totals has been designated as MFI$_{ER}$.

**Results**

Erosivity calculations ($R$ factor) from the different resolution data indicate uniform rainfall erosivities within the individual rainfall zones, but large differences in erosivity generated from rainfall in the wet Central Plateau area versus the dry West coast region (Table 1). $R$-factor values generated from rainfall data in the dry west coast area are between 67% and 70% lower than values generated in the wet interior.

If we apply the highest resolution of rainfall intensity measurements ($EI_{30(C)}$) as our benchmark, then an underestimation of rainfall erosivity in the dry West Coast of between 10% and 11% can be noted when $EI_{30(S)}$ is calculated and as much as 39% of rainfall erosivity is underestimated from the 60-min interval ($EI_{60}$) data. In the high rainfall zone of the interior, underestimation is higher, with 9.5% at Trou aux Cerfs and 14% at Grand Bassin when $EI_{30(S)}$ is used. The use of hourly interval ($EI_{60}$) data shows that 33–42% of rainfall erosivity values are underestimated against 6-min interval data. Underestimated values in the central interior are between 2.2 and 4.8 times higher than the underestimated values in the west coast when 30-min interval data are used ($EI_{30(S)}$), and between 2.9 and 3.1 times greater with the 60-min interval ($EI_{60}$) data. For the stations on the drier region of

### Table 1. Erosivity calculated ($J \text{ mm ha}^{-1} \text{ h}^{-1}$) using different resolution data and the different methods for all stations (2003–2008).

<table>
<thead>
<tr>
<th>Station</th>
<th>$EI_{30(C)}$</th>
<th>$EI_{30(S)}$</th>
<th>$EI_{60}$</th>
<th>MFI$_{ER}$</th>
<th>MFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albion</td>
<td>42 878</td>
<td>39 707</td>
<td>28 421</td>
<td>134 000</td>
<td>530 000</td>
</tr>
<tr>
<td>Beaux Songes</td>
<td>43 698</td>
<td>39 006</td>
<td>28 760</td>
<td>127 000</td>
<td>496 000</td>
</tr>
<tr>
<td>Trou aux Cerfs</td>
<td>139 806</td>
<td>129 417</td>
<td>96 910</td>
<td>268 000</td>
<td>2 277 000</td>
</tr>
<tr>
<td>Grand Bassin</td>
<td>136 626</td>
<td>121 237</td>
<td>91 622</td>
<td>284 000</td>
<td>2 641 000</td>
</tr>
</tbody>
</table>
the island, the underestimated erosivity is substantial when considering the low erosivity values that already exist there.

Using the MFI (based on monthly and annual rainfall totals to measure erosivity) to calculate R-factor values, the low erosivity generated by rainfall in the dry western coastal areas and the relative high erosivity received in the wet central interior is shown (Table 1). However, the major difference between the EI method (EI30) and the MFI is the calculated absolute value of annual erosivity. The values calculated by the MFI were found to be around 20 times greater than the calculated erosivity for the same stations using the EI30. For example, total rainfall erosivity of 530 000 J mm ha–1 h–1 was calculated for Albion when using MFI (monthly and annual totals) and 39 707 J mm ha–1 h–1 when using EI30 (individual erosive events) (Table 1).

A disparity in total erosivity is notably evident in the high rainfall areas of the Central Plateau. Comparing the EI30(c) with the MFI in the dry region, rainfall erosivity is predicted to be 12 times greater, but in the central interior erosivity it is 18 times greater than that calculated from actual individual rainfall events. When the MFI is calculated using rainfall totals derived from only erosive events, this disparity in erosivity values decreases significantly. The erosivity derived from the MFI30 for the coastal stations of Albion and Beaux Songes is then approximately triple the erosivity calculated using the EI from 6-min resolution data (EI60(c)), and double at the interior stations of Albion and Trou aux Cerfs (Table 1).

Discussion

It is clear that the use of different resolution rainfall data within established methods (EI30 and EI60) affects the outcome of the calculated erosivity calculations (R factor) for USLE/RUSLE soil-loss modeling. The discrepancy in erosivity values increases as measured rainfall increases and the rainfall data resolution decreases. Although coarser time intervals may produce less accurate results, the EI as well as the MFI still remain useful in determining the relative spatial relationships of erosivity, even if high-resolution data are unavailable. Notwithstanding this, the significant overcalculation of erosivity derived from the MFI is a concern when deriving absolute erosion risk assessment on tropical islands like Mauritius. Le Roux et al. (2005), who investigated erosion at a catchment scale in southern Mauritius using the RUSLE and Soil Loss Estimation Model for Southern Africa (SLEMSA), used the MFI in the erosivity calculations. Atawoo and Hearasing (1997) also performed a comparative study using the MFI and a model developed by Lo et al. (1985). In these studies, the same method of calculating erosivity derived from monthly and annual rainfall data through the MFI was used (Eqn 3). Within the RUSLE, if all other parameters of the formula are held constant, soil loss is directly proportional to the calculated rainfall erosivity (Wang et al. 2002). Therefore, absolute erosivity calculations may be overestimated as inaccurate erosivity results from low-resolution data will carry through in erosion calculations, greatly increasing the predicted soil loss of an area.

Tropical islands are found to have excessively high rainfall, but large proportions of rainfall are deemed non-erosive and often erosion risk is only from a small proportion of rainfall, mostly due to short, sharp intense tropical rainfall events and cyclones (Nel et al. 2012). An overestimation of rainfall erosivity by the MFI thus stems from rainfall that is effectively non-erosive. Non-erosive rainfall is embedded within the MFI calculations causing potentially inaccurate predicted soil erosion risk assessments. It has been suggested that when modeling rainfall erosivity in a tropical maritime environment, the timescale at which rainfall records are used needs to be at an event scale (storm and synoptic scale) to be effective (Nel et al. 2012). When considering the over-calculation of erosivity shown within the MFI (which only uses totals) against high-resolution data (which capture the individual erosive events), the predicted erosion on tropical islands can be prejudiced. An overcalculation is somewhat mitigated when the MFI is calculated from individual erosive events, but still remains double or triple the erosivity calculated with the EI. The data presented here suggest that the MFI does not compare well to the EI30 method, even when the erosivity from individual erosive events is assessed.

Conclusion

Mauritius, like many tropical islands, is a high rainfall environment where soil erosion impacts the landscape. Calculation of rainfall erosivity within soil erosion models is key to understanding soil erosion risk but the data here show that different resolution rainfall data result in substantial differences in erosivity calculations. Of particular
concern is the over-calculation of erosivity values when using monthly and annual rainfall totals for the MFI. When considering the over-calculation of erosivity shown from the MFI against the actual erosive events measured with high-resolution data, the predicted erosion on tropical islands can be severely biased. Erosivity values generated through the MFI are also not comparable to those generated through the EI in assessing absolute erosivity values, even if it is calculated from individual erosive events through sufficiently high-resolution data. Erosivity values should always be calculated with the highest resolution data. However, in the absence of high-resolution data, the MFI is still a valid predictive tool if it is used to assess the relative spatial extent and differentiation of erosivity, such as in erosion risk mapping.

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