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

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ABSTRACT: The Erosivity Index and the Modified Fournier Index are two commonly used methods in calculating the *R*-factor of the USLE/RUSLE formula. Using Mauritius as 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 six years at six minute intervals. Rainfall erosivity for erosive events was calculated using different set interval data. In this study, within the Erosivity Index, the use of 6 min rainfall intervals during erosive rainfall give 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 Modified Fournier Index is used to determine erosivity through annual and monthly rainfall totals, substantially higher erosivity than the Erosivity Index method in both regions was calculated. This stems from the large amount of non-erosive rainfall that is generated on Mauritius. Even when the Modified Fournier Index was used to calculate erosivity through monthly and annual rainfall totals derived purely from erosive rainfall, erosivity calculations were not comparable to that from high resolution data within the Erosivity Index. We suggest that for the computation of erosivity, rainfall data with the highest possible resolution should be utilised where 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-minute rainfall intensity during the storm (Wischmeier and Smith 1978).

Yin e*t al*. (2007) assessed the accuracy of EI_{30} estimations based on incremental time resolution rainfall data as compared to EI_{30} estimations from breakpoint rainfall information. For erosivity calculations, Yin e*t al*. (2007) note that the more detailed the rainfall data used, the more accurate will be 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 one of the most 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. Aguilar and Waite 1991; Renard and Freimund 1994; Lo *et al*. 1998; 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 time scale 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 necessitate 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) to those derived from the *EI* as generated from high resolution data.

Study Area

Mauritius is located at 20º 10' S and 57º 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–April dominated by cyclone passage and a dryer winter from May–October dominated by the South-East 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 analysed. The data were provided by the Mauritius Meteorological Services (MMS) from weather stations where Precis Mecanique 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 cm^2 (Alexandropoulos and Lacombe 2006). 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 two-hour period of no rain. As the rainfall on Mauritius is logged every 6-minutes the definition by Stocking and Elwell (1976) was adjusted for a six minute 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-Martinez and Begueria 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 six 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.* 2004). Van Dijk *et al.* (2002) critically appraised literature on the rainfall intensity–kinetic energy ($R - E_K$) relationship and, based on the average parameter values that were derived from the best data-sets, suggest the following general equation to predict storm kinetic energy content from rainfall intensity data:

$$E_K = 28.3[1 - 0.52^{(-0.042R)}] \tag{1}$$

where R is the rainfall intensity. In this study, for each storm event, Eqn (1) was used to calculate the 6 minute incremental kinetic energy content derived from rainfall intensity. For each 6 minute interval, the kinetic energy is totaled and then multiplied by the amount of rain falling in that 6 minute 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):

$$R = \frac{1}{N}\sum_{j=1}^{n}[\sum_{k=1}^{m}(E)(I_{30})_k]_j \tag{2}$$

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 storm 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; Santosa $et\ al.$ 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 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 was used to calculate the maximum intensity of the erosive event in three ways. First, the maximum 30 minute intensity for an event was calculated using five consecutive 6-min intervals which had the greatest intensity values (called $EI_{30\ (C)}$). Second, we used set 30-min periods that started and ended at set intervals (called $EI_{30\ (S)}$). In this case, the period starts at either the head of the hour or the half way mark between it. (For e.g. Start: 07h00 End: 07h30 Start: 07h30 End: 08h00). Last, 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 one hour, for example: Start: 07h00 End: 08h00 Start: 08h00 End: 09h00).

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):

$$RI = \sum_{i=1}^{12}(MR)^2/AR \tag{3}$$

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

$$EI_{30}= 0.0302 \times (RI)^{1.9} \tag{4}$$

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. Firstly 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 through just using the monthly and annual rainfall totals generated through erosive events (as defined under *Establishing and 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, under estimation 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 six minute 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

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data is used ($EI_{30\ (S)}$), and between 2.9 and 3.1 time greater with the 60-min interval (EI_{60}). For the stations on the drier region of the island, the underestimated erosivity is substantial when considering the low erosivity values that already exist there.

Using the Modified Fournier Index (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 Erosivity Index Method (EI_{30}) and the Modified Fournier Index is the calculated absolute value of annual erosivity. The values calculated by the Modified Fournier Index were found to be around 20 times greater than the calculated erosivity for the same stations using the EI_{30}. 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 EI_{30} (individual erosive events) (Table 1).

A disparity in total erosivity is notably evident in the high rainfall areas of the Central Plateau. Comparing the $EI_{30\ (C)}$ to the MFI in the dry region, rainfall erosivity is predicted to be 12 times greater, but in the central interior erosivity 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 notably. The erosivity derived from the MFI$_{ER}$ for the coastal stations of Albion and Beaux Songes is then approximately triple the erosivity calculated using the Erosivity Index from 6-minute resolution data ($EI_{30\ (c)}$), 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 (EI_{30} and EI_{60}) 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 increase and as the rainfall data resolution decrease. Although coarser time intervals may produce less

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accurate results, the Erosivity Index 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 over-calculation 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 SLEMSA, used the MFI in the erosivity calculations. Atawoo and Hearasing (1998) 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 (eq. 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 possibly be over-estimated 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 over-estimation 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 time scale 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 over-calculation is somewhat mitigated when the MFI is calculated from individual erosive events, but still remains double or triple the erosivity

calculated with the Erosivity Index. The data presented here suggest that the MFI does not compare well to the EI_{30} 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 gives substantial differences in erosivity calculations. Of particular concern is the over-calculation of erosivity values when using monthly and annual rainfall totals for the Modified Fournier Index. 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 Erosivity Index in assessing absolute erosivity values even if it is calculated from individual erosive events through sufficiently high resolution data. Erosivity values should always where possible 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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Figure captions:

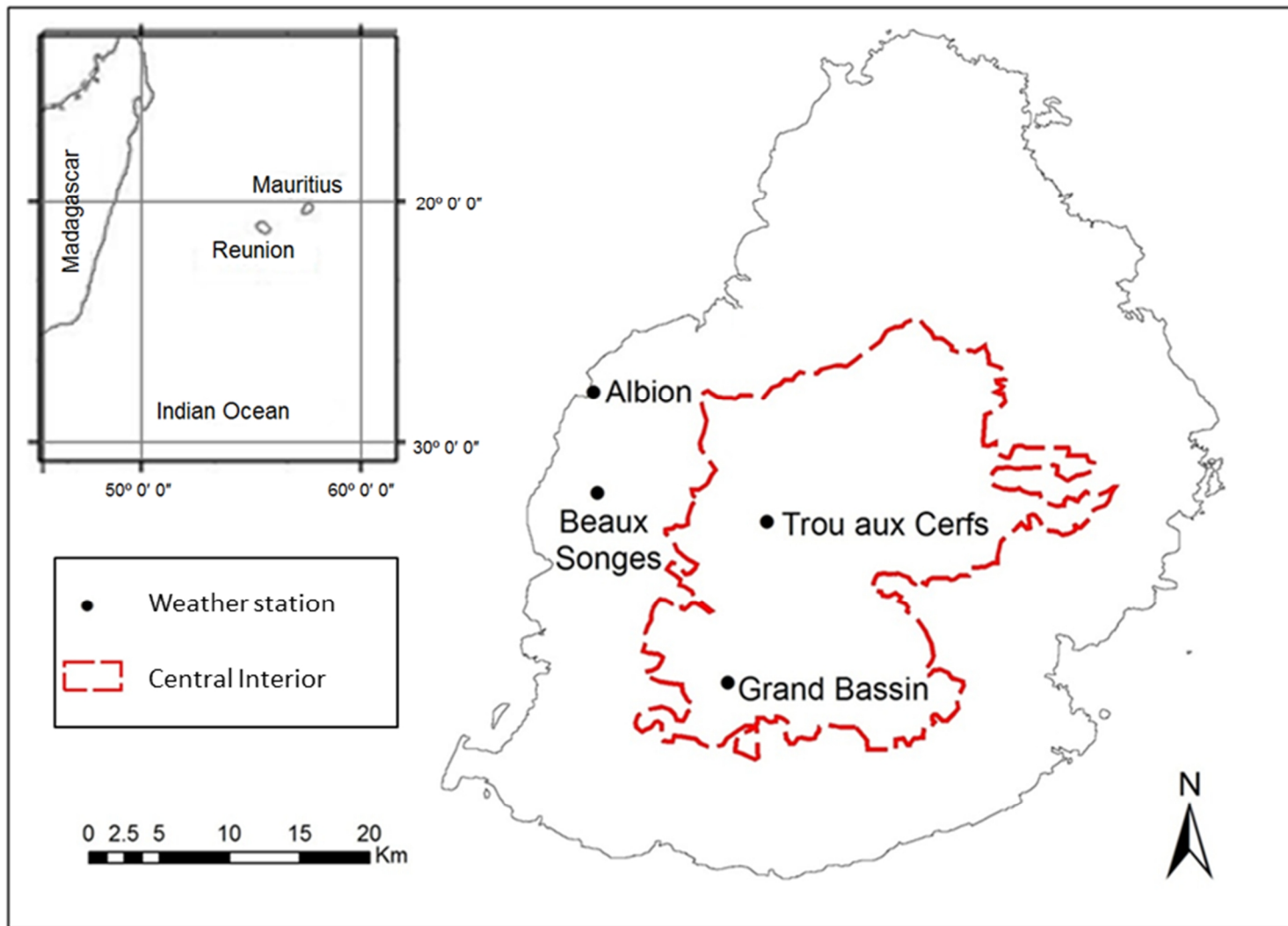Figure 1:   Mauritius, showing the location of rainfall stations

Figure 1

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

Station	$EI_{30(C)}$	$EI_{30(S)}$	EI_{60}	MFI_{ER}	MFI
Albion	42 878	39 707	28 421	134 000	530 000
Beaux Songes	43 698	39 006	28 760	127 000	496 000
Trou aux Cerfs	139 806	129 417	96 910	268 000	2 277 000
Grand Bassin	136 626	121 237	91 622	284 000	2 641 000