INTRA-EVENT CHARACTERISTICS OF EXTREME EROSIVE RAINFALL ON MAURITIUS

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Abstract: Mauritius is a typical tropical volcanic island with a raised interior where extreme rainfall events generate the bulk of the erosivity. Intra-event characteristics of the 120 highest erosive events at six selected locations between 2004 and 2008 were analysed to provide the first detailed intra-storm data for a tropical island environment. On Mauritius, spatial variation is evident in the characteristics of the extreme erosive rainfall recorded at the stations, with a noticeable increase in rainfall depth, duration, kinetic energy and erosivity of extreme events with altitude. Extreme events in the raised interior (central plateau) show a high variability in peak intensity over time as well as a higher percentage of events with the greatest intensities in the latter part of the event. Intra-event distribution of rainfall in the interior of the island shows that rainfall has a higher potential to exceed infiltration rates as well as the ability to generate high peak runoff rates and substantial soil loss. The study suggests that even though the within-event rainfall characteristics is complex it has implications for soil erosion risk, and that in tropical island environments the within-storm distribution of rainfall must be incorporated in soil loss modelling.

Keywords: erosivity, rainfall intensity, rainfall kinetic energy, Mauritius

INTRODUCTION

In the tropics, rainfall events are typically of high intensity and are deemed erosive (Hudson, 1971). Erosive rainfall on tropical islands can detach and transport significant amounts of sediment (Calhoun and Fletcher, 1999) and the distribution of rainfall erosivity can be associated with the topography (Nel et al., 2012). Volcanic islands tend to have a raised interior due to the nature of their formation and the elevation has a significant influence on erosive rainfall (Barcelo et al., 1997; Yen and Chen, 2000; Nel et al., 2012). Mauritius, like most tropical islands, has a high soil erosion risk because of its climate, topography and land use practices (Nigel and Rughooputh, 2010a) and rainfall is a major driving force of erosional processes. Soil erosion risk can occur from storm scale to synoptic scale events and extreme rainfall events generate the bulk of the erosivity (Nel et al., 2012).

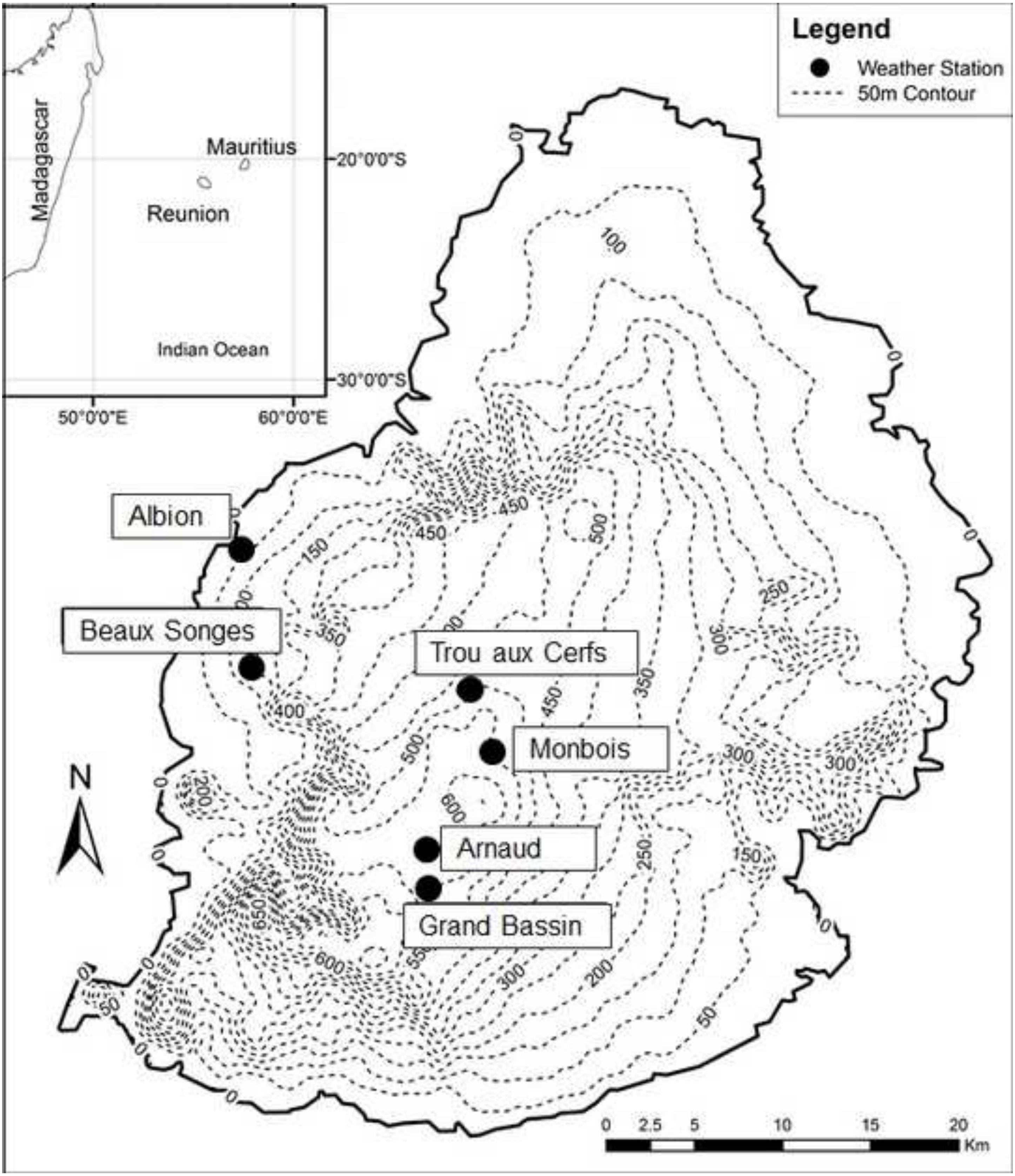
The amount of erosion caused by rainfall is a function of the event's physical characteristics, including total rainfall and intensity (Obi and Salako, 1995). However, rainfall is long known to be highly variable (Schiff, 1943; Huff, 1967) and storm patterns can be complex with the peak rainfall intensity early, in the middle or at the end of the event (Flanagan et al., 1987; Nyssen et al., 2005; Dunkerley, 2008). Furthermore, rainfall events can also demonstrate repeated fluctuations in peak intensity and peak rainfall rates in an event can exceed the mean event rate by an order of magnitude (Dunkerley, 2008). This intra-storm variation in peak intensity has been shown to affect runoff rates, infiltration and soil loss (Flanagan et al., 1987). Significant differences in eroded material are also apparent across different soil types for specific storm patterns (Parsons and Stone, 2006), however, distinct rainfall intensity fluctuations are neglected by the majority of studies on soil hydraulic properties and soil erosion processes (Dunkerley, 2012). Although storm kinetic energy and erosivity on Mauritius have been investigated (Nel et al., 2012; 2013) no studies have considered intra-storm distribution of rainfall parameters in such a tropical island setting. The aim of this study is to investigate the within-storm distribution of rainfall depth, extreme rainfall intensity and cumulative kinetic energies. Event-scale rainfall at two distinct altitudes on Mauritius are contrasted; the dry west coast and the wetter elevated central plateau area. We report on the effect altitude has on intra-event rainfall characteristics and discuss possible implications on soil erosion risk.

STUDY SITES AND METHODS

Mauritius is a volcanic island located in the Indian Ocean at 20º 10' S and 57º 30' E and together with Reunion and Rodrigues forms the Mascarene Islands. A distinctive feature is the central plateau area that rises steadily towards the southwest of the island and is bordered by remnants of the primary shield volcano as chain mountains (Johnson et al., 2010) (Fig. 1). The plateau at above 500 m.a.s.l. is only approximately 20 km away from the west coast but the long-term records indicate that this elevation causes a large contrast in rainfall depth due to upward forcing of the SE trade winds (Fowdur et al., 2006) and a rain-shadow effect on the leeward side of the island. Rainfall can exceed 4000 mm in the central region declining to below 600 mm per year on the dryer west coast (Padya, 1989).

Long duration high intensity rainstorms occur frequently on Mauritius (Yahya et al., 2010). During extreme erosive events, the relative small basins generate high discharge rates and the small size of the island makes sediment delivery ratios at the outlets especially high (WRU and GIBB, 2002). The island has a typical tropical maritime climate with a rainy summer season (November–April) and a dry winter (May–October) dominated by the South-East Trade Wind and frontal systems (Nigel and Rughooputh, 2010b). Notwithstanding this, large percentages of winter rainfall on Mauritius are deemed equally as erosive and non-tropical cyclone rainfall can pose a substantial erosion risk (Nel et al., 2012).

Figure 1: Map of Mauritius and the rainfall study sites



Rainfall data between 2004 and 2008 (5-years) from automated weather stations at six sites were provided by the Mauritius Meteorological Services (MMS). The gauges logged total rainfall every 6 minutes on a tipping resolution of 0.2 mm rainfall (see Nel et al., 2012). Two sites are 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.). Four station sites are located on the central plateau area at Arnaud (576 m.a.s.l.), Monbois (590 m.a.s.l.), Grand Bassin (605 m.a.s.l.) and Trou aux Cerfs (614 m.a.s.l.) (Fig. 1). The two west coast rainfall stations are in the driest part of the island, while the high altitude stations provide detailed rainfall event data from the upper reaches of the catchments in the highest rainfall area. This allows for contrasting erosive events on two diverse climates on the island.

Determining an Erosive Event

Wischmeier and Smith (1958) indicate that for significant amounts of soil erosion to occur rainfall intensities larger than 25 mm/h are needed. Stocking and Elwell (1976) classify a distinct erosive rainfall event as a storm when total rainfall exceeds 12.5 mm, maximum 5-minute intensity exceeds 25 mm/h and the event is isolated by at least a two-hour period of no rain. This definition has been used in previous studies (Nel, 2007; Nel and Sumner, 2007; Nel et al., 2012) to determine an erosive event. 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 30 mm/h and applied to the data series.

Determining Kinetic Energy

Rainfall intensity can be measured directly, but measurements of kinetic energy and raindrop sizes are, in most cases, unavailable; hence the relationships between rain intensity and kinetic energy (Nyssen et al., 2005). Van Dijk et al., (2002) based on the average parameter values that were derived from the best international data-sets created the following general global equation to predict storm kinetic energy content from rainfall intensity data:

$$E_K = 28.3\ [1-0.52\ \exp(-0.042R)] \qquad (1)$$

where the intensity (R) is in mm/h. As such, for the purpose of an intra-station comparison on Mauritius and to compare it with previous studies (Nel et al., 2012; 2013) this equation (eq. 1) was used here to assess the 6-minutes incremental kinetic energy content derived from rainfall intensity. In analysis of kinetic energy a uniform drop size distribution is assumed. Total event kinetic energy (E_k) generated during each individual erosive rainfall event (J m^{-2}) is calculated through the 6-minutes kinetic energy content, multiplied by the quantity of rain (mm) falling in that specific 6 minutes to give the 6-minutes kinetic energy. Each of the 6-minutes kinetic energy values generated during the event is then summed to give the total kinetic energy for the individual event.

Determining Erosivity

On Mauritius, soil erosion risk has been mapped using the MauSERM model (Mauritius Soil Erosion Risk Mapping) (Nigel and Rughooputh, 2010a) which uses the Modified Fournier Index as an indicator of rainfall erosivity (Nigel and Rughooputh, 2010b). Erosivity can also be determined by the product (EI_{30}) of the total kinetic energy (E) of the storm times its maximum 30-minute intensity (I_{30}) developed by Wischmeier and Smith (1978). This equation has been used globally as part of the (Revised) Universal Soil Loss Equation (R)USLE and in Mauritius to assess the spatial distribution of erosivity (Le Roux, 2005; Nel et al., 2012; 2013) and reflects the combined potential of raindrop impact and turbulence created in overland flow. For the computation of erosivity in a tropical island environment, rainfall data with the highest possible resolution should be utilised (Nel et al., 2013). Therefore to be consistent with erosivity studies in Mauritius the spatial distribution of erosivity in this study was determined by the product (EI_{30}) of each individual storm (J mm m^{-2} h^{-1}).

RESULTS

From the adapted definition of Stocking and Elwell (1976), the data series from the six automatic rainfall gauges over the five year period contained 444 erosive rainfall events. To investigate the intra-storm distribution of the most extreme rainfall, the highest twenty kinetic energy events were identified at each station (n=120) and analysed further following the approach used by Nel (2007).

The 120 events had an average duration of 1451 minutes (24 hours and 18 minutes). Rainfall data indicate that 88% of the events have a total storm duration of less than 3000 minutes while 95% of the events receive less than 300mm of rainfall. In general, with regards to mean and maximum values for rainfall event characteristics a clear differentiation is apparent between the coast (Albion and Beaux Songes) and the raised central area (Table 1.) In all respects the top rainfall events measured at the stations on the central plateau are of longer duration, generate more rainfall at a higher intensity and generate more kinetic energy and erosivity than those at low altitude (Table 1).

When the cumulative kinetic energies generated are plotted over rainfall duration (Fig. 2) then all the rainfall stations show an exponential distribution. The kinetic energy distribution over time at the two coastal stations (Albion and Beaux Songes) are similar with rainfall at both stations generating nearly all of the total kinetic energy in the first 1500 minutes from the onset of the erosive event. The stations in the centre show different distributions to the coastal stations with between 70 and 80% of the total kinetic energy received within the first 1500 minutes (Arnaud, Monbois and Grand Bassin). The station at Trou aux Cerfs received 90% of the total kinetic energy within this time period.

Table 1. Characteristics of extreme erosive events measured at the individual stations (n=120)

Station	Attribute:	Storm depth (mm)	Storm duration (min)	Intensity (I_6) (mm/h)	Kinetic Energy ($J.m^{-2}$)	Erosivity (EI_{30}) ($J\ mm.\ m^{-2}.\ h^{-1}$)
Albion	**Maximum**	177.6	2682	116	3015	97852
(12 m.a.s.l.)	**Mean**	70.3	743	59	1268	45291
Beaux Songes	**Maximum**	138.0	2286	116	2673	151849
(225 m.a.s.l.)	**Mean**	64.9	700	60	1160	40515
Arnaud	**Maximum**	435.8	4560	102	7293	235963
(576 m.a.s.l.)	**Mean**	150.3	1901	67	2585	91361
Monbois	**Maximum**	310.2	4932	198	4984	195617
(590 m.a.s.l.)	**Mean**	115.2	1790	70	2002	71977
Grand Bassin	**Maximum**	384.8	3924	122	6334	197612
(605 m.a.s.l.)	**Mean**	161.1	2390	62	2700	86993
Trou aux Cerfs	**Maximum**	615.0	3972	198	14738	2240158
(614 m.a.s.l.)	**Mean**	140.4	1181	98	2802	226654

Figure 2: Cumulative kinetic energies generated as a function of rainfall duration

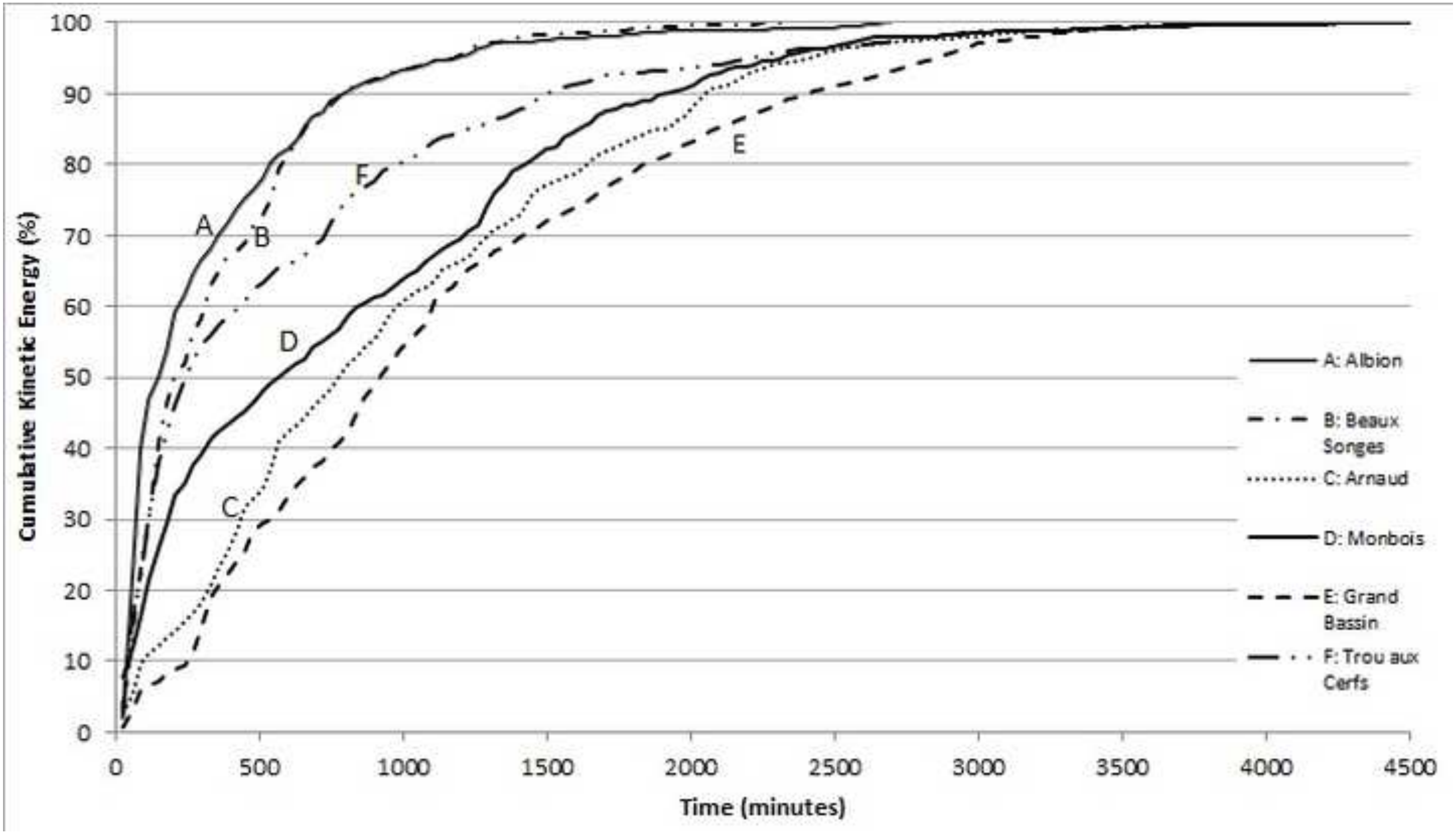
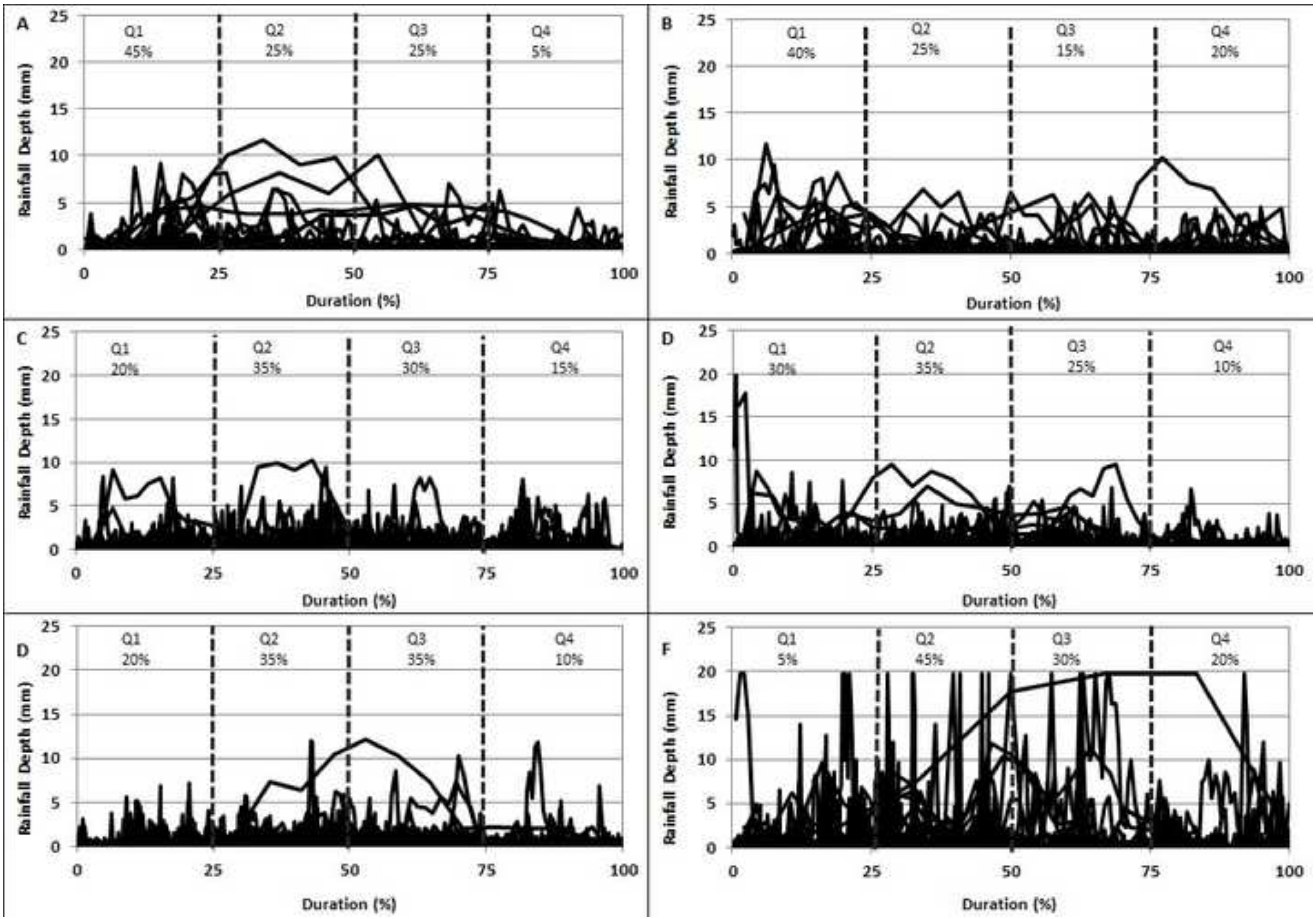


Figure 3: Rainfall depth as a percentage of rainfall duration for A) Albion B) Beaux Songes C) Arnaud D) Monbois E) Grand Bassin and F) Trou aux Cerfs



To test the rainfall generation as a function of rainfall duration, the six-minute rainfall depth of each individual event measured at each station was plotted as a percentage of rainfall duration and then each erosive event was divided into quartiles (Fig. 3). At the low altitude coastal stations (Albion and Beaux Songes) a high proportion of the events (65%) generate peak rainfall within the first half of the event while only 55% of the events in the interior at two sites (Arnaud and Grand Bassin) generated peak rainfall during the first half of the event. The intra-rainfall distribution at Trou aux Cerfs show that 75% of all the events generate peak rainfall within the second and third quartiles. Only 5% of the peak rainfall is generated during the first quartile at this station, which is distinctly different from all the other stations.

In order to test at what stage during the event the rainfall becomes erosive (as adapted from Stocking and Elwell, 1976), the intra-storms variations of six-minute intensity exceeding 30mm/h were considered and plotted over rainfall duration. Three quarters of all the erosive events (75%) measured at all six stations have intensities above 30mm/h during the first 500 minutes, while 81% of all extreme erosive events receive their peak rainfall intensities within the first 1500 minutes of the event (Fig 4.). At the coast (Albion and Beaux Songes) approximately 80% of the high rainfall intensities are received within the first 500 minutes of the onset of the event, with all of the events generating peak intensities within the 1500 minutes of the onset of the storm. However, on the Central Plateau at Arnaud and Trou aux Cerfs approximately 70% of the high rainfall intensities are received within the first 1000 minutes and rainfall events measured here can generate intensities above this threshold as late as 3400 minutes since the onset of the rain event.

When considering the distribution of the high intensity rainfall as a function of rainfall duration, then 57% of the extreme events generate peak intensities within the first and second quartile of rainfall duration. At both Albion and Beaux Songes approximately 45% of the erosive events

Figure 4: Timing of extreme rainfall intensity (above 30 mm/h) generated byerosive events at A) Albion B) Beaux Songes C) Arnaud D) Monbois E) Grand Bassin and F) Trou aux Cerfs (each individual storm is presented by a different symbol).

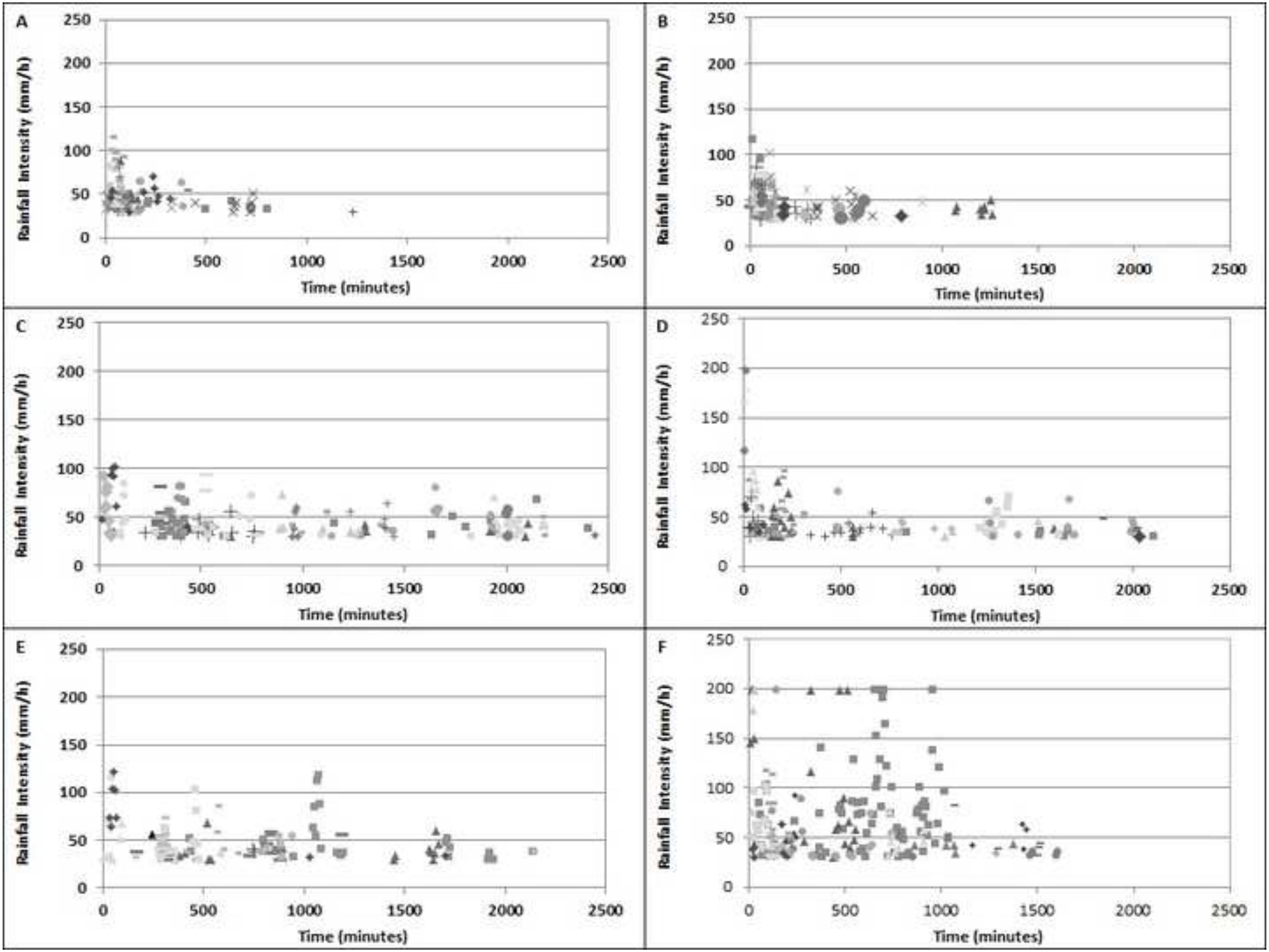
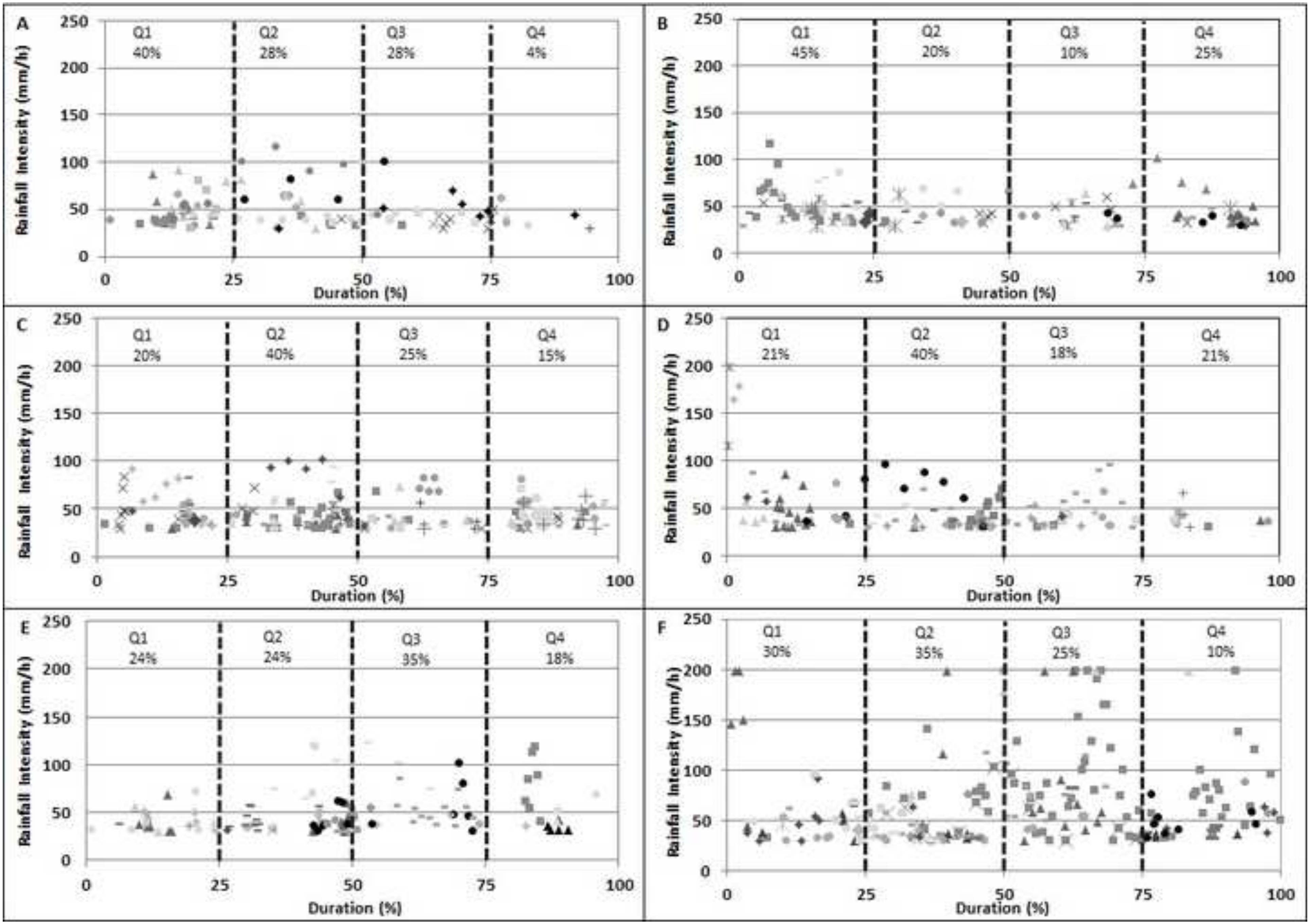


Figure 5: Timing of extreme rainfall intensity (above 30 mm/h) as a function of storm duration at A) Albion B) Beaux Songes C) Arnaud D) Monbois E) Grand Bassin and F) Trou aux Cerfs (each individual storm is presented by a different symbol).



receive their highest rainfall intensities during the first quartile and 65% of the peak intensity during the first half of the event (Fig. 5). At the high altitude stations of Arnaud and Monbois 40% of the events have their peak intensities during the second half of the event. Trou aux Cerfs displays a similar pattern to these with 35% of peak intensities being generated during the second half of the event and the highest individual intensities (198mm/h) are received during the third and fourth quartiles. The stations in the interior also exhibit more frequent high intensities as well as a more variable distribution of peak intensities for individual events.

DISCUSSION

The elevated interior of Mauritius is an environment that normally receives rainstorms by means of topographic forms drawing out atmospheric moisture through orographic precipitation mechanisms (Smith and Barstad, 2004). Therefore on Mauritius, like many tropical volcanic islands, there is a noticeable spatial difference in rainfall across the island due to the orographic effects of the central uplands on the SE trade winds (Fowdur et al., 2006). Annual rainfall of less than 600 mm is measured on the west coast and over 4000 mm has been reported for the central plateau area (Rughooputh, 1997; WRU, 2007, Dhurmea et al., 2009). This spatial differentiation is also evident in the characteristics of the extreme erosive rainfall recorded at the stations. Noticeable increases in all variables are measured at the coastal versus the interior stations, including an increase in rainfall depth, event duration and kinetic energy. Potential erosivity generated by individual events in the central area can also be up to an order of magnitude greater than that measured at the coast.

Rainfall intensity is regarded as a fundamental control of interrill runoff and erosion because rainfall intensity can have an effect on the size distribution as well as the total amount of the detached sediment (Parsons and Stone, 2006). Since runoff is inversely related to infiltration the effect of rainfall intensity on runoff can be understood through its effects on infiltration

(Parsons and Stone, 2006). In some cases the rainfall event profile and not the mean rain rate most noticeably control the relative magnitudes of infiltration and runoff in a real event (Dunkerley, 2012) and storms that peak in intensity towards the end of the storm duration has the highest peak runoff rates, soil loss and largest particle size of eroded soil (Flanegan et al, 1987). Therefore, the timing of the peak rainfall depth and peak extreme intensity is paramount to the infiltration as well as the potential runoff and erosion experienced at each station on Mauritius. Although, the extreme erosive events display variability in both rainfall depth and rainfall intensity some similarities are evident. In general, the peak rainfall depth corresponds almost directly to the peak rainfall intensities experienced. The peak rainfall depth and peak rainfall intensities are received during the first half of the event at both low altitude stations (Albion and Beaux Songes) as well as Monbois on the windward side of the central plateau. At Grand Bassin and Arnaud the peak rainfall is more variable with more rainfall events showing peak intensity in the second half of the event. At Trou aux Cerfs the peak rainfall and intensities are generated during the second half of the storm when a substantial amount of rainfall has preceded the peak intensity and where the soil could be supersaturated. The timing of the peak rainfall depth and peak intensities as well as the specific storm pattern have important implications for the amount of soil loss and the size of the particle being eroded.

IMPLICATIONS FOR SOIL EROSION RISK

On Mauritius, areas with flat terrain and lowly erodible soils, similar to the soils found at Albion, have low erosion susceptibility while sites with undulating terrain, similar to the terrain and position of Beaux Songes, experience moderate erosion susceptibility (Nigel, 2011). However, the mountainous areas and valley sides, comparable to the terrain at Arnaud, Monbois, Grand Bassin and Trou aux Cerfs have very high levels of erosion susceptibility. The central plateau, the mountain environment and the southern and eastern regions also have the highest erosion risk (Nigel and Rughooputh, 2010a). Storm rainfall measured at the coastal stations in the west tend to peak in the beginning of the rain event, which could possibly decrease peak runoff rates, soil loss and overall erosivity from the storms. However, the intra-event distribution of extreme rainfall at the stations in the Central Plateau area show a higher frequency and duration of intense rainfall and also a higher percentage of peak intensity at the latter part of the storm. All rainfall events also show a high variability in intensity over time. This implies that rainfall in this area has a higher potential to exceed infiltration rates as well as the ability to generate high peak runoff rates and large particle size of eroded soil.

All soil erosion risk models and assessments on Mauritius mainly use daily, monthly or annual rainfall totals as an indication of rainfall erosivity (Kremer, 2000; Le Roux et al., 2005; Nigel and Rughooputh, 2010a; 2010b). Inherent in these and many other assessments is the assumption that erosive rainfall falls at a constant intensity, yet constant intensity rainfall events are non-existent on Mauritius and probably in any tropical island environment. This study thus shows that the within-event rainfall characteristics has additional implications for soil erosion risk, especially in the raised interior and that a certain complexity is evident with regards to the characteristics of extreme rain events measured at a specific station.

SUMMARY

On Mauritius, spatial variation is evident in the characteristics of the extreme erosive rainfall recorded at the stations, with a noticeable increase in rainfall depth, duration, kinetic energy and erosivity of extreme events with altitude. The intensity of rainfall received from extreme rainfall on Mauritius also exhibits intra-storm temporal variability. Events in the raised interior show a high variability in peak intensity over time as well as a higher percentage with extreme intensities in the latter part of the event. The central Plateau is the most exposed to soil erosion risk due to the amount of rainfall received (Nigel, 2011). However, the intra-event distribution of rainfall in this area exacerbates the situation since the rainfall generated has the ability to generate high peak runoff rates in the latter parts of the storm. All soil erosion risk models and assessments on Mauritius use daily, monthly or annual rainfall totals as an indication of rainfall erosivity (see Nel et al., 2013) but the findings here suggest that even though the within-event rainfall characteristics are complex and have implications for soil erosion risk, especially in the raised interior. In tropical Island environments the within-storm distribution of rainfall must be incorporated in the modelling of potential soil loss but it will be necessary to first ascertain the actual effect within-storm distribution of rainfall specifically has on soil erosion processes.

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