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Discussions

How rainfall event characteristics affect the applicability of I_{30} as an index of intense or erosive rainfall: a brief review with proposed new rainfall index.

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Abstract. In many fields, the intensity of rainfall events is expressed using indexes such as I_{30}, the wettest 30-minute interval within a rainfall event. Various limitations attend this usage: I_{30} cannot be estimated for rainfall events shorter than 30 minutes, including many intense convective storms, and it represents a diminishing proportion of increasingly long rainfall events (representing 10% of the duration of a 5-hour event but declining to < 2% of the duration in a 30-hour event). These and other issues connected with I_{30} and related indices based on fixed clock periods (I_{15}, I_{60}, etc.) can be eliminated if instead, a nominated fraction of the event duration is used as an index, such as the wettest 5% of the event duration. This index (termed ED_{f5}) can be derived for both short and long rainfall events. Illustrative results are presented for two Australian locations having high-resolution rainfall data and contrasting rainfall climatologies, one arid and one wet tropical. The value of I_{30} is similar at both sites (7.7 mm h^{-1} and 7.9 mm h^{-1}) and fails to differentiate between them. In contrast, the average intensity of the wettest 5% of event durations (ED_{f5}) at the arid site is 7.4 mm h^{-1}, whilst at the wet tropical site, the corresponding value is 3.8 mm h^{-1}. Thus, the ED_{f5} index indicates a greater concentration of rain at the arid site (i.e., intensity sustained for 5% of event duration at the wet tropical site is lower). Results exemplify the capacity of the ED_{f5} index to be applied to short, intense events. The use of a fixed 30-minute clock period to describe intensity at the contrasting field locations has less discriminatory power and may be of less use in the investigation of rainfall characteristics that drive landsurface processes.

1. Introduction

Many studies of landsurface hydrologic and geomorphic processes have highlighted the effects of short-lived, but intense, periods of rain (Dunkerley 2018). These intense periods are particularly important in soil erosion, and commonly occur within longer rainfall events in which the intensity is generally lower. Some examples of affected landsurface processes are considered below. A notable early example is the work of Wischmeier (1959) on rates of soil erosion from croplands in the eastern USA. There, analysis of more than 10,000 plot-years of soil loss data using multivariate methods drew attention to the correlation between I_{30}, the equivalent intensity of the wettest 30-minute period within a storm, and the soil loss from cropped or fallow plots. This led to the development of the widely-used EI_{30} index, which combines I_{30} with a measure of the erosional energy (E) delivered by rain to the soil surface, forming the 'R' (rainfall-runoff) term in the original Universal Soil

Loss Equation (USLE). I_{30} is not an actual intensity, in the sense that no rain at that actual rate need have fallen; rather, it is a measure of the largest rainfall depth accumulated in 30 minutes, some of which may have fallen at intensities exceeding I_{30} and some at intensities less than I_{30}. The term applied here to describe I_{30} is 'equivalent intensity': the unvarying intensity that would deliver the observed depth in a period of 30 minutes. Having been defined on the basis of empirical data collected in the USA, the EI_{30} index has been widely used globally, including locations where the rainfall characteristics differ from those of the original field study sites (e.g. Panagos et al. 2015, Borrelli et al. 2018, Tan et al. 2018).

The I_{30} index itself has found application in research areas well beyond soil erosion from agricultural lands, and has often been adopted as 'stand-alone' descriptor of erosive rainfall. The applications include post-fire erosion, triggering of mass movements, runoff from catchments, and others. A few examples only are mentioned here, selected from a range of environments. Zheng (2006) used I_{30} to explain the role of rainfall intensity in soil erosion on the Loess Plateau. Marques et al. (2008) adopted I_{30} in exploring the controls on sheet erosion in central Spain. From records of natural rainfall on bounded plots in Iran, Mohamadi & Kavian (2015) showed that soil loss could be correlated with intensity indices from I_{10} to I_{90}, though in complex ways in which the relationship was linear for some indices such as I_{10} and I_{20} but logarithmic for I_{45}-I_{55}. Indices calculated over short time periods are to be found in many other works, including I_5 and I_{15} (Godsey et al. 2004), I_5 (de Lima et al. 2013), I_{10} and I_{30} (Fernandez et al. 2019), and I_6, I_{20}, and I_{30} (Elsenbeer et al.1994). Hubbert et al. (2012) reported I_{10} I_{30} and I_{60} for field sites in southern California in the aftermath of chaparral fire, and stressed their significance. For the tropical Lutzito rainforest catchment (3.3. ha) in Panama, Zimmermann et al. (2014) investigated the overland flow connectivity between hillslopes and the main channel. They showed that short-term intensity measures such as I_5 – I_{60} were important in this overland flow-dominated environment.

Multiple indices of short-duration intra-event rainfall rates (IERRs) are thus also in use, including I_{10}, I_{15}, I_{45}, and I_{60} (Dunkerley 2010, Wagenbrenner & Robichaud 2014, Kampf et al. 2016). In the remainder of this paper, reference is made to I_{30}, but much of what is said is applicable to the other indices also.

It is apparent that I_{30} has been widely-adopted, and continues to be a key term in the revised USLE (RUSLE) model. Example applications of this approach include Brooks et al. (2014; estimating erosion in northern Australia), Litschert et al. (2014; analysing post-wildfire erosion with the 'R' factor estimated indirectly from annual precipitation) Kampf et al. (2016; with application to post-wildfire erosion), Panagos et al. (2015; estimating soil loss rates across Europe) and by Lee et al. (2017; mapping soil erosion rates in Korea). However, despite this wide application, the use of I_{30} is attended by several difficulties that appear generally to be given little or no attention. These include the following:

1. The I_{30} index cannot be derived for rainfall events shorter than 30 minutes. Moreover, for events whose duration is little more than 30 minutes, I_{30} is close to the mean intensity, since almost the whole event duration contributes to the index. It thus

ceases to be a measure of peak intensity comparable to its role in longer rainfall events. This difficulty appears rarely to have been considered.

2. Given that short events have to be excluded from analyses of I_{30}, the resulting value is potentially skewed by the exclusion of brief but intense events, such as many convective thunderstorms. This means that rainfall events for which I_{30} can be determined may have a lower average intensity, and a longer average duration, than the set of all erosive rainfall events. A reliance on I_{30} may thus lead to the mis-characterisation of the peak value of rainfall intensity.

3. Long-duration rainfall events pose another challenge to the use of I_{30}, because this index reflects a diminishing fraction of the event duration for longer events. Thus, whilst I_{30} reflects virtually the mean intensity in a 35-minute event, and reflects the amount of rain during the wettest 10% of a 5-hour event, it only reflects the wettest ~ 2% of a 30-hour event. This limits the ability of this index to serve as a consistent measure of 'sustained intensity' as originally proposed by Wischmeier (1959). Rather, the ability of I_{30} to adequately reflect the nature of periods of high intensity within an event diminishes as event duration increases.

4. A reliance on fixed clock-periods may result in important periods of intense rain being diluted by enclosing periods of less intense rain. For example, if the wettest 30-minute period during a rainfall event included 17 minutes at 20 mm h^{-1} flanked by a total of 13 minutes at 5 mm h^{-1}, the resulting I_{30} value would be 13.5 mm h^{-1}, which is more than 30% less than the true peak intensity that was sustained for 17 minutes. Thus, the use of arbitrary, fixed clock periods affects the intensity statistics that result, and may result in a misleading representation of intensity. It is likely that at many field sites, 17 minutes of rainfall at 20 mm h^{-1}, set within a longer event that caused soil antecedent soil wetting, would be geomorphically a highly significant trigger of sediment movement.

5. The position of the I_{30} interval in relation to the intensity profile of the rainfall event has not been explored. It is likely that I_{30} has a different significance when this interval occurs early in a rainfall event (with rain falling on relatively dry soils) or late in an event (when soils are wet and infiltrability has declined). The importance of such rainfall characteristics has been explored by Dunkerley (2012) and others.

The above brief review suggests the need for further evaluation of how well I_{30} serves as a rainfall index in areas where the rainfall character is different to that used in the original development of the I_{30} index (namely, the USA east of the Rocky Mountains). Indeed, I_{30} appears to have been adopted as a kind of universal index of rainfall intensity that can be usefully applied in diverse geographical regions, from arid to wet tropical. A factor that may have contributed to the lack of scrutiny of I_{30} is that in many areas, rainfall data having sufficient temporal resolution for the direct estimation of I_{30} are unavailable; frequently, hourly data are the most resolved available. This limitation affects many potential analyses of rainfall data at sub-daily or event timescales. In some studies, owing to the lack of rainfall data at suitable resolution, the (R)USLE 'R' factor is estimated indirectly from annual or monthly rainfalls. Risal et al. (2018) have proposed the alternative of deriving the required data from rain radar.

The goal of the current work is to draw attention to and quantify some of the issues relating to I_{30} using high-resolution rainfall data. This is followed by the proposal of a new index that could be used to describe intra-event wet intervals. It is hypothesised that moving away from fixed clock-periods such as 30 minutes might yield indices with greater local appropriateness and relevance to studies of landsurface processes, and more explanatory power. The proposed index identifies the wettest fraction of a rainfall event, not limited by a fixed clock period. Various fractions are explored below, but 5% of event duration appears to be an appropriate value in light of the field data presented below. Such a measure can be applied equally well to short and long events. Though simple, as will be shown below, the proposed index offers greater capacity to distinguish between the rainfall climatology of different locations than does I_{30}. It constitutes an index of the wettest interval within a rainfall event that can be applied without the associated limitations listed above that attend the use of I_{30}.

2. Field data and methods

This study uses completely unaggregated tipping-bucket raingauge data, in which the Gregorian calendar date and time of each bucket tip was logged using Hobo Event data loggers (www.onsetcomp.com) with 1 s resolution. Two Australian field sites were used, an arid location (Fowlers Gap Arid Zone Research Station, in New South Wales; hereafter FG) and a wet tropical location (near the township of Millaa Millaa on the Atherton Tableland in far northern Queensland; hereafter MM). The arid FG site has a mean annual rainfall of ~ 220 mm, but with wide year-to-year variability, and MM in the wet tropics has a mean annual rainfall of > 2.5 m (i.e., at least an order-of-magnitude larger than at FG). The data consist of unbroken records (i.e., having no missing data) of more than 10 years at FG and ~ 3.5 years at MM. Total rainfall recorded at each site amounted to 2676.5 mm (on 307 rain days at FG) and 9147.8 mm (on 783 rain days at MM).

For data processing, all tip event data were converted to Modified Julian Days, using FORTRAN code from the International Astronomical Union's 'SOFA' (Standards of Fundamental Astronomy') subroutine library (http://www.iausofa.org). Rainfall events were defined using the minimum inter-event time (MIT) approach (Dunkerley 2008) with MIT = 6 h. Events consisting of isolated single tip events were excluded from analysis.

The alternative to I_{30} proposed here is a measure of the wettest nominated fraction of the duration of a rainfall event. In the analyses reported next, the wettest 5% of an event is proposed as an index with fewer attendant problems than I_{30}. In order to illustrate the effect of changing this proportion, the wettest 1% - 10% of event durations was determined for both field locations. For the new index, the symbol ED_{f5} is proposed; this is derived from 'Event Duration fraction, 5%'. ED_{fx} in used as a general descriptor allowing for varying event fractions (x%) to be used.

I_{30} was calculated by using a moving window of width 30 minutes, stepped through the file of bucket tip events from the start of the event in increments of 1 min. The maximum rainfall in 5% (and other fractions) of the event duration was found by the same method, stepping a window of the calculated width through the file of tip events in increments of 1 min. In the latter procedure, the width of the moving window was different for each rainfall event, depending on the duration of rainfall.

3. Results

3.1 Statistics of rainfall events at FG and MM

More than 1,000 rainfall events were delineated using MIT = 6 h (MM 652 events; FG 356 events). For all events at MM the mean duration was 18.6 h (max 206.6 h), the mean depth 21.3 mm, and the mean intensity 2.22 mm h^{-1}. For FG the mean event duration was shorter (5.1 h), the mean depth of 10.2 mm about half that at MM, but the mean intensity (4.3 mm h^{-1}) was almost twice that at MM. The two field locations also differed in the waiting time between rainfall events, which at MM averaged 32.1 h, but was more than 7 times longer, averaging 230.8 h (almost 10 days), at FG. These field sites thus provide two very different rainfall climatologies as contexts within which to explore the meaning of I_{30}.

The inability to apply I_{30} to short rainfall events was noted earlier. For FG, of 262 multi-tip events, 15.3% were shorter than 30 minutes; 8.8% were shorter than 20 minutes, and 6.5% were shorter than 15 minutes. At MM, the figures were comparable: 9.5% of 430 multi-tip events were shorter than 30 minutes; 8.6% were shorter than 20 minutes, and 6.5% were shorter than 15 minutes. Therefore, at the two field sites, 10-15% of all rainfall events were excluded from the analysis of I_{30}. This must be an issue at many research locations, but the exclusion of short events appears not to be discussed in the literature. In many locations this would probably not be a problem owing to the small rainfall depth delivered by short events.

The nature of the excluded short events is however worth examining. Events excluded from the analysis of I_{30} owing to their short duration were analysed separately in order to characterise their intensity and duration. For FG, the mean intensity of events < 30 min duration was 14.9 mm h^{-1}; for MM, the corresponding figure was 10.7 mm h^{-1}. The excluded events had a mean duration of 16.1 min (FG) and 11.6 min (MM). Though many are indeed small, the FG events excluded included several having depths of 10-15 mm. These are sufficient depths to trigger overland flow in this field area. At MM, the depths of excluded events were smaller, but several events had depths in the range 3-6 mm.

These results may be compared with the corresponding values for all events longer than 30 minutes, for which I_{30} could be calculated, again analysed separately. For FG, their mean intensity was 2.4 mm h^{-1} and mean duration 6.0 h. At MM, their mean intensity was 1.3 mm h^{-1} and mean duration 20.55 h. Notice that in both cases the duration is longer than the mean for the set of all rainfall events, including those of < 30 minutes.

These results demonstrate that the exclusion of events shorter than 30 minutes, many of which are considerably more intense than longer events, leads to a mis-representation of the intensity (and duration) of rainfall at both field sites. It therefore seems likely that in other areas having climates ranging from arid to wet tropical, the exclusion of short events has the potential to lead to errors in soil erosion rates predicted using (R)USLE-type models that rely on I_{30}. Moreover, the use of I_{30} as a stand-alone index of erosive rainfall also has the attendant risk that it excludes potentially important events of short duration but higher intensity. The actual outcome in the field is likely to depend on several factors, including the sequence of rainfall events. For instance, a short intense shower falling soon after a previous event, when soils were already wet, could have a greater effect on soil loss than if the same short event had been preceded and followed by rainless conditions. The exclusion of all events shorter than 30 minutes, rather than those delivering less than a nominated threshold depth, seems potentially unhelpful in building an understanding of local rainfall characteristics.

3.2 I_{30} at FG and MM

From 430 multi-tip rainfall events at MM, I_{30} indices could be calculated for 372 events. The minimum event duration included among these events was 32.4 min (for which I_{30} represented 92.6% of the event duration) and the longest 206.6 h (8.6 days). For this long event, the I_{30} interval represented only 0.2% of the event duration. The average event duration (21.0 h) was slightly less than a day. The mean I_{30} was 7.9 mm h^{-1} (std dev 11.7 mm h^{-1}) and the maximum I_{30} was 80.4 mm h^{-1}. The 90th, 95th and 99th percentiles were 21.1, 28.8, and 62.5 mm h^{-1}. The mean and maximum I_{30} intensities are notably larger than the mean and maximum intensity of the 372 enclosing rainfall events, which were 1.3 mm h^{-1} and 26.9 mm h^{-1} (note that these are lower values than listed above for all rainfall events, owing to the exclusion of those events shorter than 30 minutes). Considering all 372 events, the average I_{30} intensity is 7.1 times higher than the mean intensity of the enclosing rainfall event (maximum 39.9 times higher).

For FG, I_{30} could be calculated for 222 of the 356 rainfall events. The mean I_{30} at FG was 7.66 mm h^{-1} (std dev = 8.6 mm h^{-1}). The maximum I_{30} was 69 mm h^{-1}, while the 90th, 95th and 99th percentiles were 19.0, 26.1, and 33 mm h^{-1}. The enclosing events had a mean intensity of 2.4 mm h^{-1} (maximum 22.7 mm h^{-1}) and a mean duration of 6.0 h. Again, owing to the exclusion of events shorter than 30 min, this is less than the average intensity of all events at FG, which was 4.3 mm h^{-1}. At MM the enclosing events were in the 'light' intensity class of Tokay & Short (1996) and at FG, they were in the 'moderate' intensity class. As reported above, at both sites the I_{30} intensity in contrast was 'heavy'. Nevertheless, about 75% of I_{30} values at both sites were < 10 mm h^{-1}, and the mean I_{30} at both sites was < 8 mm h^{-1}.

3.3 The proposed 'ED_{fx}' index: moving away from fixed clock-periods

The proposed index, introduced above, is ED_{f5} (Event Duration fraction 5%), identifying the rainfall depth delivered in the wettest 5% of the event duration. Other fractional event durations could be used as alternatives to 5%, and as an illustration, ED_{f1} is also evaluated below (the rainfall depth delivered in the wettest 1% of event duration).

The evaluation of ED_{f5} in rainfall events proceeds in the same fashion as for I_{30}, except that rather than using a moving window of 30 minutes, the moving window is scaled in width to be 5% (or another fraction) of the event duration.

The durations associated with ED_{f5} were recorded for all rainfall events. For FG, the average length of the wettest 5% was 17.0 min (less than half the length of the I_{30} interval), and the maximum value 117.5 min. The median duration was 11.4 min and the 90th, 95th and 99th percentiles were 39.3 min, 56.3 min, and 81.4 min. A duration of 30 minutes corresponded approximately to the 85th percentile of ED_{f5}. At MM, the average duration of the wettest 5% was 63.9 min (more than twice the length of the I_{30} interval) and the maximum value 619.8 min. The median duration was 28.7 min, and the 90th, 95th and 99th percentiles were 173.0 min, 266.1 min, and 460.7 min. A duration of 30 minutes corresponded approximately to the 51st percentile of ED_{f5}.

For FG and MM, the equivalent intensity data for 1%, 2%, 4%, 5% and 10% of the event duration are summarised in Table 1. At FG, the mean intensity in the wettest 1% of event duration was 19.7 mm h^{-1}, and declined to 5.6 mm h^{-1} for the mean of the wettest 10% of the event duration. At MM, the corresponding figures were 8.7 mm h^{-1} at 1% of event duration and 2.7 mm h^{-1} at 10% of duration.

Field location:	FG		MM	
ED_{fx} parameter	Mean intensity mm h^{-1}	Mean duration (minutes)	Mean intensity mm h^{-1}	Mean duration (minutes)
ED_{f1}	19.7	3.4	8.7	12.8
ED_{f2}	12.1	6.8	6.0	25.6
ED_{f4}	8.1	13.6	4.2	51.1

ED_{f5}	7.4	17.0	3.9	63.9
EDf$_{10}$	5.6	34.0	2.7	127.9

Table 1. ED_{fx} values for the two field sites, FG and MM. The mean equivalent intensity derived from varying fractions of the rainfall event duration are shown, as well as the corresponding duration of each specified fraction.

It is helpful to visualise the different measures of short-interval intensity within rainfall events at the two field sites. Figs. 1 - 3 present a small sample of rainfall events from FG and MM with the time interval corresponding to I_{30}, ED_{f1} and ED_{f5} marked. In the three FG examples shown, ED_{f5} is longer than the I_{30} interval and ED_{f1} is shorter in duration. Moreover, in events 58 and 130, the ED_{f1} interval is located in a different part of the rainfall event than I_{30} and ED_{f5}. In the case of the MM events 1, 171, and 219, I_{30} is the shortest of the three measures. In short event MM 366, I_{30} is the longest measure, whilst in event 576, the ED_{f1} interval is located some hours away from the intervals occupied by I_{30} and ED_{f5}. The lengths of the intervals are summarised in Table 1.

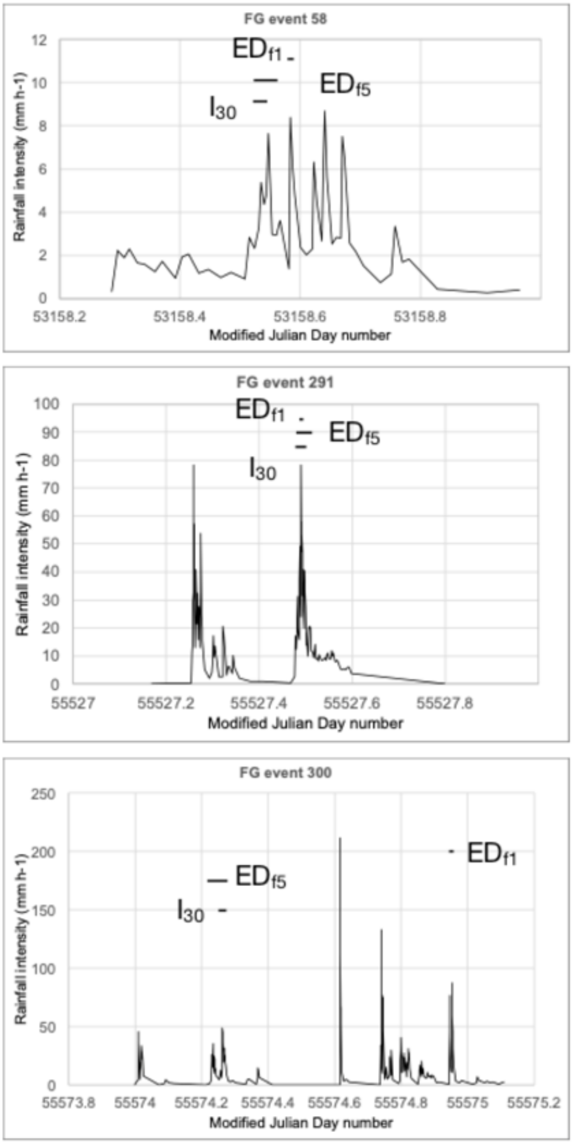

Fig. 1 Three rainfall events from FG. Each plot shows the duration of I_{30}, ED_{f5} and ED_{f1}. Refer to text for details.

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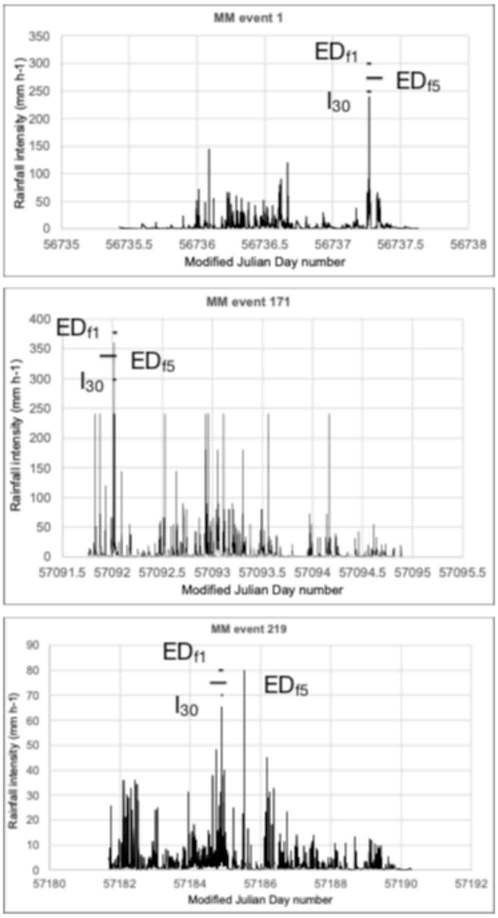

Figure 2. Three rainfall events from MM. Each plot shows the duration of I_{30}, ED_{f5} and ED_{f1}. Refer to text for details.

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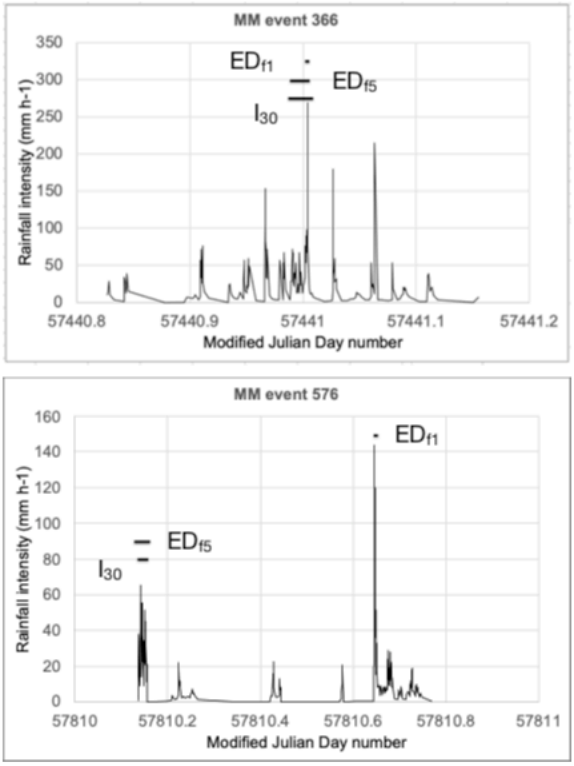

Figure 3. Two rainfall events from MM. Each plot shows the duration of I_{30}, ED_{f5} and ED_{f1}. Refer to text for details.

From these examples, it is evident that at MM, the ED_{f1} and I_{30} intervals are generally coincident, though of slightly different durations. For FG event 300, the ED_{f5} interval captures the double rainfall intensity burst better than does I_{30}, which only captures one peak. The same benefit of the ED_{f5} criterion can be seen in MM event 1, where it captures two intensity peaks. Likewise, in FG events 58 and 291, ED_{f5} captures a more representative fraction of the intensity peaks where I_{30} and ED_{f5} are located. The same can be seen in MM event 219, where the ED_{f5} index captures a more typical period of intense rain (though including intensity fluctuations).

For both field sites, significant regression ($p<0.001$) models were fitted to the intensity and % duration data (Figure 4). The relationships describing the variation of mean equivalent intensity I_{equiv} (mm h^{-1}) with fraction of event duration ED_{fx} (%) where the fraction fx ranges from 1% - 10% were

FG: $I_{equiv} = 18.5\ ED_f^{\ -0.55}$ ($r^2 = 0.98$)

MM: $I_{equiv} = 8.6\ ED_f^{\ -0.51}$ ($r^2 = 0.99$)

Exchanging the dependent and independent variables yields the following equations that can be used to predict the mean event duration fraction ED_f as a function of the mean equivalent intensity I_{equiv}:

FG $ED_f = 187.4\ I_{equiv}\ -1.79$ ($r^2 = 0.98$)

MM: $ED_f = 69.8\ I_{equiv}\ -1.97$ ($r^2 = 0.99$)

These relations suggest the following duration fractions corresponding to I_{30} at FG and MM:
For FG (average $I_{30} = 7.66$ mm h^{-1}) the closest corresponding ED_{fx} is x = 4.89%. For MM (average $I_{30} = 7.9$ mm h^{-1}) the closest corresponding ED_f is x = 1.19% of event duration.

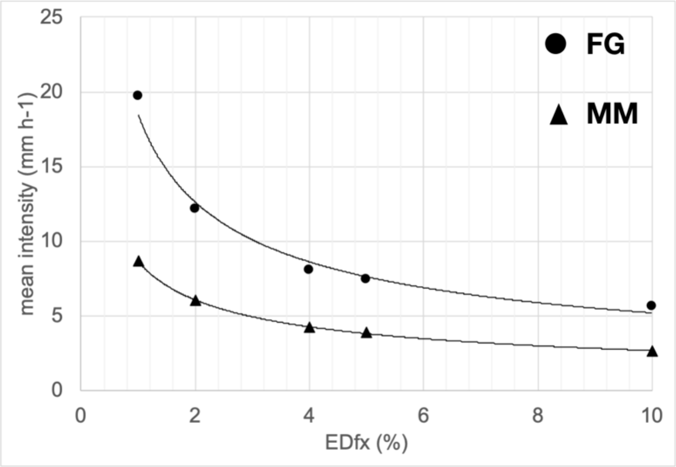

Figure 4. The relationship between mean intensity averaged across all rainfall events and the EDfx fraction, for both FG and MM field sites.

Thus, the I_{30} intensity at FG corresponds approximately to the wettest ~ 5% of the event duration there (ED_{f5}), whilst at MM, I_{30} corresponds to the wettest ~ 1% of the event duration (ED_{f1}). Evidently, therefore, these are different measures of event rainfall intensity that are not strictly comparable. Given that it represents about 5% of average event duration at FG, I_{30} probably has better predictive power in relation to landsurface processes there than at MM where it samples only 1% of the event duration.

However, the proposed index is suggested for describing and comparing rainfall at different field locations (where intensity and duration of events may differ) using a single nominated value of ED_{fx}. Taking 5% as a duration fraction that is likely to be able to reflect adequately the wettest part of a rainfall event (and which yields an intensity of 7.4 mm h^{-1}, close to I_{30} of 7.7 mm h^{-1} at FG), the corresponding ED_{f5} for MM is 3.9 mm h^{-1}. This is slightly less than half of the I_{30} value there, which is 7.9 mm h^{-1}. This means that an intensity comparable to the I_{30} intensity persists for 5% of the average event duration at FG, but does not do so at MM. Rather, the intensity through 5% of the duration there is much lower, showing that in events at MM, intensities comparable to I_{30} do not occur over sufficient durations to reach 5% of the event duration. This appears to provide a more informative description of the rainfall than I_{30}, which as noted above, is very similar at the two field sites.

4. Discussion and Conclusions

The above results showed that I_{30} represented about 5% of event duration at FG, but only ~ 1% of event duration at MM. Thus, I_{30} necessarily reflects a somewhat different aspect of the rainfall at each site, and I_{30} is therefore not strictly comparable between locations. In other words, I_{30} is not capable of revealing whether the wettest parts of rainfall events at the two sites are similar or different, because it reflects differing durations at the two sites. This is a consequence of the use of a fixed 30-minute clock period when deriving I_{30}, with no adjustment to take account of the influence of the duration of the enclosing rainfall event.

The close similarity (and hence, poor discriminatory value) of the I_{30} values at FG and MM (7.7 mm h^{-1} and 7.9 mm h^{-1} respectively) arises despite events at the two field sites having different durations, intensities, and depths, as noted earlier. The ED_{f5} result, in contrast, yields quite distinct values for the two field sites: 7.4 mm h^{-1} at FG but just 3.9 mm h^{-1} at MM. Other values of ED_f that might be used, such as 10% of event duration, yield results that show the same relationship. These ED_{f5} results are in the same relationship as the mean event intensities, which are greater at FG (4.3 mm h^{-1}) than at MM (2.2 mm h^{-1}). This suggests that applying the ED_{f5} criterion to the longer rainfall events at MM (where 5% represents about 56 minutes, given the mean event duration of 18.6 hours) reduces the resulting equivalent intensity toward the mean event intensity, in comparison with the shorter 30-minute clock period underlying I_{30}. At FG, the ED_{f5} criterion would represent about 15 minutes within the average 5.1-hour rainfall event (the actual mean value if the ED_{f5} interval for all analysed events was 17 minutes, as noted earlier).

In summary, the 30-minute clock period used to calculate I_{30} represents a changing proportion of each rainfall event analysed, depending upon its duration. This may not be a significant issue within a single study area, where durations might differ less than between the FG and MM sites explored here. However, when comparing I_{30} indices between sites like FG and MM, or indeed between the eastern USA and southern Spain, that have very different rainfall climatologies, including very different rainfall event durations, I_{30} fails to capture these differences. What is needed is an index that does reflect the nature of the rainfall at each field site or study region. The ED_{f5} criterion appears to fulfil this need. It always reflects the same significant fraction of the event duration, in contrast to I_{30}, which as noted earlier, reflects diminishing (and less representative) fraction as events become longer. An example from MM is the longest rainfall event, which had a duration of 206.6 h. For this rainfall event, I_{30} reflects just 0.2% of the event duration – which seems insufficient to characterise the intensity. In contrast, the ED_{f5} duration criterion would reflect the intensity during 10.3 h of this long event, which seems more likely to represent adequately the wettest part of such a prolonged rainfall event.

The difficulties attendant on the use of I_{30} are problematic for comparing rainfall character between locations, and for characterising rainfall at event a single observing station (e.g. by excluding short events). However, they may also affect attempts to use such indices to identify changes in rainfall climatology associated with global and regional climate change. Roque-Malo & Kumar (2017) have shown that there is a tendency in many rainfall records from the USA for the duration of groups of successive wet days to increase. Shi et al. (2018) have shown the reverse for China – a decline in the length of consecutive wet days by 0.1 days per decade in the interval 1961-2015. These trends, if they apply also to the regional shortening or extension of rainfall events as defined here, will mean that the interpretation of change using short-interval indices like I_{30} will be complex. Actual changes in rainfall intensity will be compounded with the effect of changing event duration on the fraction of the event that is reflected in the value of I_{30}.

Long rainfall events are not uncommon. Nojumuddin et al. (2015) reported rainfall event durations for Johor, Malaysia, exceeding 43 hours (for events defined using MIT = 8 h). Duan et al. (2017) reported events of about 44 hours duration from southern China. For events of such lengths, I_{30} represents just over 1% of the duration. On the other hand, short events are also predominant in some regions. For the Czech Republic, Hanel & Máca (2013) show that rainfall events rarely exceed 6 hours in duration. For the Dead Sea region (Israel) Belachsen et al. (2017) recorded a mean rainfall event duration of 5.4 h (but ranging from < 0.1 h to > 50 h). There, the convective rain cells lasted for an average of 18.1 minutes. For a 6 h event I_{30} reflects intensity during >8% of the event duration. There is thus considerable regional variability in the period of rainfall reflected in I_{30}. The ED_{f5} index proposed here, the depth of rain accumulated in the wettest 5% of the event duration, is very straightforward but appears to remove many of the limitations attached to the use of I_{30} or other indexes that rely on fixed clock-periods.

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