How Is the Intensity of Rainfall Events Best Characterised? A Brief Critical Review and Proposed New Rainfall Intensity Index for Application in the Study of Landsurface Processes

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Abstract: In many studies of landsurface processes, the intensity of rainfall events is expressed with clock-period indexes such as $I_{30}$, the wettest 30-minute interval within a rainfall event. Problematically, the value of $I_{30}$ cannot be estimated for rainfall events shorter than 30 min, excluding many intense convective storms. Further, it represents a diminishing proportion of increasingly long rainfall events, declining to <2% of the duration of a 30-hour event but representing 25% of the duration of a two-hour event. Here, a new index termed $ED_{5\%}$ is proposed: It is the rainfall depth in the wettest 5% of the event duration. This can be derived for events of any duration. Exploratory determinations of $ED_{5\%}$ are presented for two Australian locations with contrasting rainfall climatologies—one arid and one wet tropical. The $I_{30}$ index was similar at both sites (7.7 and 7.9 mm h$^{-1}$) and was unable to differentiate between them. In contrast, $ED_{5\%}$ at the arid site was 7.4 mm h$^{-1}$, whilst at the wet tropical site, it was 3.8 mm h$^{-1}$. Thus, the $ED_{5\%}$ index indicated a greater concentration of rain at the arid site where convective storms occurred (i.e., the intensity sustained for 5% of event duration at that site is higher). The $ED_{5\%}$ index can be applied to short, intense events that can readily be included in the analysis of event-based rainfall intensity. $I_{30}$ therefore appears to offer less discriminatory power and consequently may be of less value in the investigation of rainfall characteristics that drive many important landsurface processes.

Keywords: soil erosion; $I_{30}$ intensity; rainfall event; rainfall duration; rainfall intensity; $ED_{5\%}$ index

1. Introduction

Many studies of landsurface hydrologic and geomorphic processes have highlighted the effects of short-lived but intense periods of rain [1]. These intense periods commonly occur within longer rainfall events in which the intensity is generally lower. Some examples of landsurface processes upon which short-term rainfall intensity exerts an important influence are considered below. A widely-used index of rainfall intensity during rainfall events is $I_{30}$, which denotes the wettest 30-minute interval during the event. Dunkerley [2] presented high-resolution rainfall intensity records and showed that the $I_{30}$ period may have a range of characteristics: It need not consist of continuous rain, it may not include brief periods of rain of even higher intensity that occur outside the $I_{30}$ interval, and it typically contains periods of rain at intensities lower than the $I_{30}$ value. The single defining characteristic of the $I_{30}$ period is that it receives the highest aggregate rainfall depth and not that it includes the highest rainfall intensity. A final aspect of $I_{30}$ that is worth recalling is that it may be calculated from times locked to hour boundaries (09:00 to 09:30, 09:30 to 10:00, etc.) or from floating 30-minute windows that may define $I_{30}$ as extending from 09:07 to 09:37, for example. The use of 30-minute periods locked to hour boundaries generally results in slightly lower intensity values, since peaks of intensity are not
synchronised with clock time [3]. Frequently, studies employing $I_{30}$ have failed to report which of these protocols was used.

Some examples of the areas of application of the $I_{30}$ index of rainfall intensity and the series of related indexes that include clock periods from $I_5$ to $I_{60}$ (e.g., [4]) are presented next. These are intended to highlight the range of studies of landsurface processes where an intensity index has been found useful and to highlight some of the limitations of $I_{30}$, the most widely-used rainfall event intensity indexes. Subsequently, a new index is proposed that avoids some of the limitations arising with the use of $I_{30}$.

1.1. Studies Using Intensity Indexes Based on Fixed Clock Periods

Li et al. [5] investigated the behaviour of pollutant loading in stormwater runoff in China. They found that the maximum five-minute intensity (which they referred to as $I_{\text{max}5}$) offered explanatory power. The intense rainfall was shown to affect both runoff volume and ‘first flush’ contaminant concentrations. Likewise, Schiff et al. [6] investigated rainfall intensity and duration effects on the ‘first flush’ effect from parking lots in California. They found that washoff pollutant concentrations were highest in the first 10–12 min of multiple 40-min rainfall simulations; concentrations in the ‘first flush’ period were up to 10x higher than levels later in the event. These studies and others like them have highlighted the need for an intensity index that is appropriate for capturing short-term intensity maxima with durations as short as 5–10 min. Brodie and Egodawatta [7] argued that in urban runoff studies, the assessment of rainfall intensity using fixed time periods such as 30 min may offer less explanatory power than indexes that reflect the duration of rainfall exceeding a nominated threshold intensity.

The foregoing studies have suggested that $I_{30}$ might be of limited utility in studies of urban contaminant washoff, as the 30-minute duration is too long to capture the rapid hydrologic response of impervious surfaces and is not able to reflect the varying duration of rainfall events. More generally, a significant problem with $I_{30}$ is that it cannot be calculated for rainfall events that are of short duration, including many that are important to urban flash flood hazards. For example, Ogura and Takahashi [8] determined that the mature raining phase of a thunderstorm typically only lasts for 15–30 min, after which dissipation begins. Furthermore, from a large database of thunderstorms in the USA (>130,000 events), Liu and Li [9] reported a mean lifetime of just 23.1 min; 65.8% of the storms had durations between 5 and 20 min. Evidently, $I_{30}$ may not be the most appropriate rainfall index with which to attempt to characterise such short-lived rainfall events.

Despite the above limitations, $I_{30}$ is perhaps the most widely employed index of short-term rainfall intensity, especially in studies of landsurface hydrology, and erosion processes. A few examples, listed in Table 1, are presented here to illustrate the uses to which $I_{30}$ has been put.

Table 1. Rainfall intensity indexes and their areas of application.

| Area of Application of $I_{30}$ and Related Indexes | Reference |
|---------------------------------------------------|-----------|
| predict unit-area peak stream discharge, USA ($I_{30}$) | Moody and Martin [10] |
| influence of rainfall intensity on soil erosion, Loess Plateau ($I_{30}$) | Zheng [11] |
| intensity in relation to sheet erosion, Spain ($I_{30}$) | Marques et al. [12] |
| rainfall-runoff relationships in cropping lands, Queensland, Australia ($I_{30}$) | Freebairn et al. [13] |
| urban rainwater storage, Paris ($I_{30}$) | Petrucci et al. [14] |
| urban flash flooding, Calabria, Italy ($I_{30}$) | Terranova and Gariano [15] |
| post-fire debris flows ($I_5$) | Kean et al. [16] |
| soil loss from erosion plots, Iran ($I_{10}$ to $I_{60}$) | Mohamadi and Kavian [17] |
| erosion after chaparral fire, California ($I_{30}$, $I_{50}$, $I_{60}$) | Hubbert et al. [18] |
| Overland flow in rainforest, Panama | Zimmermann et al. [19] |
| rainfall interception, Brazil $I_5$ to $I_{60}$, including $I_5$ | Brasil et al. [4] |
Indices calculated over short time periods are to be found in many other works, including I_5 and I_15 [20]; I_10 and I_30 [21]; and I_6, I_20, and I_30 [22]. Many different indices of short-duration intra-event rainfall rates (IERRs) are thus in use, including I_5, I_10, I_15, I_30, I_45, and I_60 (Dunkerley [24], Wagenbrenner and Robichaud [25], and Kampf et al. [26]).

In the remainder of this paper, reference is primarily made to I_30, since this is the most commonly-used intensity index, but much of what is said is also applicable to the other indices.

Though not directly related to the analysis of rainfall intensity, it is worth noting that the I_30 intensity index is a key parameter in the revised Universal Soil Loss Equation (RUSLE) model. Examples of applications to soil erosion include Brooks et al. [27] estimating erosion in northern Australia, Litschert et al. [28] and Kampf et al. [26] analysing post-wildfire erosion, Panagos et al. [29] exploring soil loss rates across Europe, and by Lee et al. [30] mapping soil erosion rates in Korea. In work on soil erosion, I_30 is commonly combined with estimates of rainfall kinetic energy to create the hybrid variable EI_30, which is designed to parameterise rainfall erosivity. Consequently, this is a slightly different application of I_30 and is not further considered here.

The literature cited above suggests that, especially for studies of first-flush pollutant washoff, canopy interception, and urban hydrology, the use of I_30 is not straightforward; rather, it is attended by various difficulties or limitations. Depending upon the particular area of application, these may include the following:

1. The I_30 index cannot be derived for rainfall events with a duration of less than 30 min. Moreover, for events whose duration is only slightly longer than 30 min, 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 to have rarely been considered in the literature where I_30 has been applied.

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 rainfall events. A reliance on I_30 may thus lead to the mischaracterisation of the peak value of rainfall intensity.

3. Long-duration rainfall events pose a difficulty for the use of I_30, because this index reflects a diminishing fraction of the event duration for longer events. Thus, whilst I_30 virtually reflects the mean intensity in a 35-minute rainfall event and reflects the amount of rain during the wettest 10% of a five-hour event, it only reflects the wettest ~2% of a 30-hour event. Thus, 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 15 min at 20 mm h^{-1} flanked by a total of 15 min at 5 mm h^{-1}, the resulting I_30 value would be 12.5 mm h^{-1}, which is almost 40% less than the true peak intensity that was sustained for 15 min. 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, 15 min of rainfall at 20 mm h^{-1}, set within a longer event that caused soil antecedent soil wetting, would exert a strong influence on a number of hydrologic and geomorphic land surfaces processes.

5. The position of the I_30 interval in relation to the intensity profile of the rainfall event has not been sufficiently explored. It is likely that I_30 has a different significance when this interval occurs early in a rainfall event (with rain consequently falling on relatively dry soils) or late in an event (when soils have already become wet and infiltrability has declined). The importance of such rainfall characteristics has been explored by Dunkerley [31] and others, but it remains in need of wider and more systematic investigation in a range of climatic environments and for a wider range of land surfaces processes.
The above brief review suggests the need for the further evaluation of how well $I_{30}$ serves as a rainfall intensity index. In light of its wide adoption, $I_{30}$ appears to be regarded as an 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 with a sufficient temporal resolution for the critical evaluation of $I_{30}$ as an intensity index are unavailable; for the same reason, indexes not involving fixed clock-periods have been largely neglected.

1.2. A Proposed New Index of Intensity in Rainfall Events

It is hypothesised that moving away from fixed clock-periods such as 30 min might yield rainfall intensity indices with greater local appropriateness and relevance to studies of landsurface processes, as well as more explanatory power.

The alternative to $I_{30}$ (and other fixed clock-period indexes) 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 were determined for both field locations. For the new index, the symbol $ED_{5}$ is proposed. This is derived from ‘event duration fraction, 5%.’ Such an index can be applied equally well to short and long events. Though simple, as will be shown below, the proposed index offers a greater capacity to distinguish between the rainfall climatology of different locations than $I_{30}$. $ED_{5}$ 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 $I_{30}$ and other relatively long-interval indices (such as $I_{45}$ and $I_{60}$).

The goal of the current paper is therefore 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 can be used to describe the intensity of intra-event wet intervals. In the following section, the proposed index is briefly introduced. This is followed by an account of the two field observing stations from which rainfall data with a high temporal resolution were obtained, as well as the methods used in data analysis. Results from the analyses of $ED_{15}$ and $I_{30}$ are then presented, following which Discussion and Conclusions sections draw out the main implications of this study.

2. Materials and Methods

This study used unaggregated tipping-bucket rainfall data in which the Gregorian calendar date and time of each bucket tip was logged with Hobo Event data loggers (www.onsetcomp.com) with a 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, where the bucket size was 0.5 mm, and ~3.5 years at MM, where the bucket size was 0.2 mm. The total rainfall recorded was 2676.5 mm (on 307 rain days) at FG and 9147.8 mm (on 783 rain days) at MM.

For data processing, the tip event data were converted from the Gregorian calendar used by the data loggers (consisting of year, month, day, minute, and second) to Modified Julian Days. These are represented as a single decimal number. A Modified Julian Day begins at midnight, which is preferable to the Julian Day numbering system, which begins at mid-day. The conversion from Gregorian to Modified Julian systems was completed by using FORTRAN code from the International Astronomical Union’s ‘SOFA’ (Standards of Fundamental Astronomy) subroutine library (http://www.iausofa.org). The long rainfall records were broken into separate rainfall events, and $I_{30}$ and $ED_{5}$ were separately determined for each rainfall event. Each rainfall event was delineated by using the minimum inter-event time (MIT) approach [32] with MIT = 6 h. This means that a period of rainfall that was bounded by dry periods of at least 6 h preceding and following was regarded as a separate event. This was the method
adopted by Dunkerley [33] and many other studies. Events consisting of isolated single tip events were excluded from analysis.

Each bucket tip event indicates that 0.2 mm (MM) or 0.5 mm (FG) of rain had fallen. The number of these small increments of rainfall was tallied through two durations by processing every rainfall event contained in the entire rainfall record of each site.

$I_{30}$ was calculated by using a moving window of width 30 min, stepped through the file of bucket tip events from the start of the event in increments of 1 min. In each position of the window, the number of tip events was counted, and in this way, the rainfall associated with each window position was recorded. The largest value reached in each event was recorded as the $I_{30}$ rainfall amount. The analysis was not synchronised with clock hour boundaries in order to avoid the potential timing errors noted above. The same procedure was followed with the proposed new intensity index. Thus, 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 the rainfall. Thus, for an event lasting 3 h, the moving window would have a width of 9 min (this is 5% of 3 h, or 180 min); in that case, $ED_{5}$ would characterize the wettest 9 min within the rainfall event. Likewise, if an event had a duration of 5.5 h, the moving window width would have 16.5 min (this is 5% of 5.5 h). These procedures are the accepted method for identifying indices such as $I_{30}$.

3. Results

3.1. Statistics of Rainfall Events at FG and MM

More than 1000 rainfall events were delineated using MIT = 6 h (at MM, 652 events; at FG, 356 events). For all events at MM the mean duration was 18.6 h (max 206.6 h), the mean depth was 21.3 mm, and the mean intensity was 2.22 mm h$^{-1}$. For FG, the mean event duration was shorter (5.1 h), the mean depth of 10.2 mm was about half that at MM, and the mean intensity (4.3 mm h$^{-1}$) was almost twice that at MM. The rainfall event data thus suggest that rain is more intense at the arid FG field site. The two field locations also differed in the waiting time between rainfall events, which at MM averaged 32.1 h, but was more than seven times longer, averaging 230.8 h (almost 10 days), at FG. These field sites thus provided two very different rainfall climatologies as contexts within which to explore the meaning of $I_{30}$.

An important test can now be applied: Can $I_{30}$ appropriately identify rainfall as more intense at FG than at MM?

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 min, 8.8% were shorter than 20 min, and 6.5% were shorter than 15 min. At MM, the figures were comparable: 9.5% of 430 multi-tip events were shorter than 30 min, 8.6% were shorter than 20 min, and 6.5% were shorter than 15 min. 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 have been widely discussed in the literature. In many locations, this would probably not be a problem due to the small rainfall depth delivered by short events; however, short convective events of high rainfall intensity may deliver a larger total rainfall (and be more important to local landsurface processes) than short, non-convective rainfall events. Thus, the effect of excluding short events on the resulting value of $I_{30}$ may itself vary with the rainfall climatology of the analysed sites. This is a potentially important issue, since it means that the value of $I_{30}$ as an index may to some extent vary depending on the rainfall climatology of the site to which it is applied. Differences between sites in terms of rainfall intensity may thus not be strictly comparable, since they may include rain of contrasting character.

The nature of the excluded short events is, however, worth examining. 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 were indeed small, the FG events included several with depths of 10–15 mm. These were 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 of 3–6 mm.

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

These results demonstrate that the exclusion of events shorter than 30 min, many of which were considerably more intense than longer events, led to a misrepresentation of the intensity (and duration) of rainfall at both field sites. It therefore seems likely that in other areas with climates ranging from arid to wet tropical, the exclusion of short events may be problematic and 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 the 372 events that were sufficiently long. 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 was 206.6 h (8.6 days) for which 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 of the distribution of $I_{30}$ values were 21.1, 28.8, and 62.5 mm h$^{-1}$, respectively. The mean and maximum $I_{30}$ intensities were notably larger than the mean and maximum intensity of the 372 enclosing rainfall events at 1.3 and 26.9 mm h$^{-1}$, respectively (note that these are lower values than listed above for all rainfall events, owing to the exclusion of those events shorter than 30 min). Considering all 372 events, the average $I_{30}$ intensity was 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 that were of sufficient duration. 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 of the distribution of $I_{30}$ values were 19.0, 26.1, and 33 mm h$^{-1}$, respectively. 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 was 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 and Short [33], and at FG, they were in the ‘moderate’ intensity class. As reported above, at both sites the $I_{30}$ intensity fell in the category of ‘heavy’ rainfall. 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 ‘% of Rainfall Event Duration’ Index, ED$_{5}$: Moving away from Fixed Clock-Periods

The proposed intensity index, introduced above, is ED$_{5}$ (event duration fraction 5%), and it identifies the rainfall depth delivered in the wettest 5% of the duration of a rainfall event. Other fractional event durations could be used as alternatives to 5%, and several other values are set out in Table 2.

The evaluation of ED$_{5}$ in rainfall events proceeds in the same fashion as for $I_{30}$, except that rather than using a moving window of 30 min, the moving window is scaled in width to be 5% (or another fraction) of the event duration.
Table 2. Rainfall intensity and rain duration for ED$_{f1}$ to ED$_{f5}$ (event duration fraction, 1%–5%), for the Fowlers Gap Arid Zone Research Station in New South Wales (FG) and Millaa Millaa on the Atherton Tableland in far northern Queensland (MM) field sites.

| Field Location: | FG | MM |
|-----------------|----|----|
| ED$_{fx}$ Parameter | Mean Intensity (mm h$^{-1}$) | Mean Duration (min) | Mean Intensity (mm h$^{-1}$) | Mean Duration (min) |
| 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 |
| ED$_{f10}$ | 5.6 | 34.0 | 2.7 | 127.9 |

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 was 117.5 min. The median duration was 11.4 min, and the 90th, 95th, and 99th percentiles of the distribution of ED$_{f5}$ values were 39.3, 56.3, and 81.4 min, respectively. A duration of 30 min corresponded approximately to the 85th percentile of ED$_{f5}$. At MM, the average duration of the wettest 5% of all rainfall events was 63.9 min (more than twice the length of the I$_{30}$ interval), and the maximum value was 619.8 min. The median duration was 28.7 min, and the 90th, 95th, and 99th percentiles of the distribution of ED$_{f5}$ values were 173.0, 266.1, and 460.7 min, respectively. A duration of 30 min 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 2. 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.

It is helpful to visualise the different measures of short-interval intensity within rainfall events at the two field sites. Figures 1–4 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$_{f5}$ was longer than the I$_{30}$ interval, and ED$_{f1}$ was shorter in duration. Moreover, in events 58 and 130, the ED$_{f1}$ interval was located in a different part of the rainfall event than I$_{30}$ and ED$_{f5}$. In the case of MM events 1, 171, and 219, I$_{30}$ was the shortest of the three measures. In short event MM 366, I$_{30}$ was the longest measure, whilst in event 576, the ED$_{f1}$ interval was located some hours away from the intervals occupied by I$_{30}$ and ED$_{f5}$. The lengths of the intervals are summarised in Table 2.

It is evident that at MM, the ED$_{f1}$ and I$_{30}$ intervals were generally coincident though of slightly different durations. For FG event 300, the ED$_{f5}$ interval captured the double rainfall intensity burst better than I$_{30}$, which only captured one peak. The same benefit of the ED$_{f5}$ criterion could be seen in MM event 1, where it captured two intensity peaks. Likewise, in FG events 58 and 291, ED$_{f5}$ captured a more representative fraction of the intensity peaks where I$_{30}$ and ED$_{f1}$ were located. The same could be seen in MM event 219, where the ED$_{f5}$ index captures a more typical period of intense rain (though including intensity fluctuations).
Figure 1. Position of the time intervals of $I_{30}$ (wettest 30-minute interval within a rainfall event), $ED_{f1}$, and $ED_{f5}$ in FG rainfall events 58, 291, and 300. Refer to text for details.
Figure 2. Position of the time intervals of $I_{30}$, $ED_{f1}$, and $ED_{f5}$ in MM rainfall events MM 1, 171, and 291. Refer to text for details.
It is evident that at MM, the ED_{f1} and I_{30} intervals were generally coincident though of slightly different durations. For FG event 300, the ED_{f5} interval captured the double rainfall intensity burst better than I_{30}, which only captured one peak. The same benefit of the ED_{f5} criterion could be seen in MM event 1, where it captured two intensity peaks. Likewise, in FG events 58 and 291, ED_{f5} captured a more representative fraction of the intensity peaks where I_{30} and ED_{f5} were located. The same could 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 a fraction of event duration ED_{fx} (%) where the fraction fx ranges from 1% to 10% were:

For FG:
$$I_{equiv} = 18.5 ED_{fx}^{-0.55} \quad (r^2 = 0.98) \quad (1)$$

For MM:
$$I_{equiv} = 8.6 ED_{fx}^{-0.51} \quad (r^2 = 0.99) \quad (2)$$

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

For FG:
$$ED_{fx} = 187.4 I_{equiv}^{-0.55} - 1.79 \quad (r^2 = 0.98) \quad (3)$$

For MM:
$$ED_{fx} = 69.8 I_{equiv}^{-0.51} - 1.97 \quad (r^2 = 0.99) \quad (4)$$
These relations suggest the following duration fractions corresponding to $I_{30}$ at FG and MM: For FG (average $I_{30} = 7.66 \text{ mm h}^{-1}$), the closest corresponding $ED_{f1}$ was $x = 4.89\%$. For MM (average $I_{30} = 7.9 \text{ mm h}^{-1}$), the closest corresponding $ED_{f1}$ was $x = 1.19\%$ of event duration.

![Figure 4](image_url)

**Figure 4.** Variation of mean rainfall intensity expressed by the $ED_{fx}$ index for values from 1% of event duration to 10% of event duration. The lines drawn through the data points are the regression models as described in the text (Equations (1) and (2)).

Thus, the $I_{30}$ intensity at FG corresponded approximately to the wettest ~5% of the event duration there ($ED_{f5}$), whilst at MM, $I_{30}$ corresponded to the wettest ~1% of the event duration ($ED_{f1}$). This is readily explained by the observation that rainfall events at MM were recorded as considerably longer than those at FG. Evidently, therefore, the $I_{30}$ and $ED_{f5}$ indexes represent different measures of event rainfall intensity that are not strictly comparable. Given that it represented about 5% of average event duration at FG, $I_{30}$ probably had better predictive power in relation to landsurface processes there than it does at MM, where it sampled only 1% of the event duration. This again suggests that the application of $I_{30}$ to sites with quite different rainfall climatologies may not offer the most explanatory power in relation to studies of landsurface processes.

The proposed $ED_{f5}$ index may be more appropriate for describing and comparing rainfall at different field locations, where the intensity and duration of rainfall events may differ. Taking 5% as a duration fraction that is likely to be able to reflect adequately the wettest part of a rainfall event (and which yielded 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 was 3.9 mm h$^{-1}$. This was slightly less than half of the $I_{30}$ value there, which was 7.9 mm h$^{-1}$. This means that an intensity comparable to the $I_{30}$ intensity persisted for 5% of the average event duration at FG, but it did not do so at MM. Rather, the intensity through 5% of the duration there was much lower, showing that in events at MM, intensities comparable to $I_{30}$ did not occur for a sufficiently long time to reach 5% of the event duration. Thus, $ED_{f5}$ appeared to provide a more informative description of the rainfall than $I_{30}$, which as noted above, was very similar at the two field sites despite the rainfall events as a whole being more intense at FG. However, if event-based data were not available, a reliance on $I_{30}$ may have led to the erroneous conclusion that maximum intensities were comparable at the two study locations.
4. Discussion

The above results showed that $I_{30}$ represented about 5% of event duration at FG but only ~1% of the longer event durations at MM. Thus, $I_{30}$ necessarily reflected a somewhat different aspect of the rainfall at each site, and $I_{90}$ reflected different aspects of the rainfall at the two locations. In other words, the $I_{30}$ index was not capable of revealing whether the wettest parts of rainfall events at the two sites were similar or different in terms of their intensity because it reflected differing durations at the two sites.

The close similarity (and hence, poor discriminatory value) of the $I_{30}$ index at FG and MM (7.7 and 7.9 mm h$^{-1}$, respectively) arose despite events at the two field sites with different durations, intensities, and depths, as noted earlier. The $ED_{5}$ result, in contrast, yielded 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 $ED_{t}$ that might be used, such as 10% of event duration, yielded results that show the same relationship. The $ED_{5}$ results were also in the same relationship as the mean event intensities, which were greater at FG (4.3 mm h$^{-1}$) than at MM (2.2 mm h$^{-1}$). This suggests that applying the $ED_{5}$ criterion to the longer rainfall events at MM (where 5% represented about 56 min, given the mean event duration of 18.6 h) reduced the resulting equivalent intensity toward the mean event intensity in comparison with the shorter 30-minute clock period underlying $I_{30}$. At FG, the $ED_{5}$ criterion represented about 15 min within the average 5.1-hour rainfall event (the actual mean duration of the $ED_{5}$ interval for all analysed events at FG was 17 min).

In summary, the 30-minute clock period used to calculate $I_{30}$ represented 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 they do between the arid FG and wet tropical MM sites explored here. However, when comparing $I_{30}$ indices between sites like FG and MM, or indeed between any observing sites with different rainfall climatologies including very different rainfall event durations, $I_{30}$ may fail to reflect key differences in rainfall intensity. The $ED_{5}$ criterion appears to be better able to distinguish between such sites. It always reflects the same fraction of the event duration, in contrast to $I_{30}$, which as noted earlier, reflects a diminishing (and less representative) fraction as events become longer. An example from MM was the longest rainfall event, which had a duration of 206.6 h. For this rainfall event, $I_{30}$ reflected just 0.2% of the event duration. This small fraction seems insufficient to characterise the intensity of such a long rainfall event. In contrast, the $ED_{5}$ 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 the rainfall.

The difficulties connected with the use of $I_{30}$ arise both for comparing rainfall character between locations and for characterising rainfall at a single observing station (e.g., by excluding short events that may be quite intense). They may also affect attempts to use such indices to identify changes in rainfall climatology associated with global and regional climate change. Roque-Malo and Kumar [34] showed 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. [35] showed the reverse for China—a decline in the length of consecutive wet days by 0.1 days per decade in the interval of 1961–2015. These trends, if they also apply 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 $I_{30}$. As a result, secular change in $I_{30}$ might not reflect an actual change in rainfall intensity, instead reflecting, in whole or in part, changing rainfall event durations.

Short rainfall events may preclude the calculation of $I_{30}$. They are predominant in some regions, such that $I_{30}$ (and related clock-period indexes) represents a large fraction of the rain duration. For the Czech Republic, Hanel and Máca [36] showed that rainfall events rarely exceed six hours in duration. For the Dead Sea region (Israel), Belachsen et al. [37] recorded a mean rainfall event duration of 5.4 h (but ranging from <0.1 to >50 h). There, the convective rain cells lasted for an average of 18.1 min. Long rainfall events occur in many regions where intensity is important to landsurface processes. Nojumuddin et al. [38] reported rainfall event durations for Johor, Malaysia, exceeding 43 h (for events
defined using \( MIT = 8 \) h). Duan et al. [39] reported events of about 44 h duration from southern China. For events of such lengths, \( I_{30} \) represents just over 1% of the duration. In contrast, for a 5 h event, \( I_{30} \) reflects intensity during 10% of the event duration. There is thus considerable regional variability in the period of rainfall reflected in \( I_{30} \), from <1% to ~10% for a common range of rainfall event durations.

5. Conclusions

The ED\(_5\) index proposed here, which expresses the depth of rain accumulated in the wettest 5% of the event duration, allows for straightforward calculation and appears to remove many of the limitations attached to the use of \( I_{30} \) or other indexes that rely on fixed clock-periods. The application of the ED\(_5\) index may thus offer more explanatory power and less confounding of site-to-site differences in rainfall character in the study of landsurface processes. The testing of this hypothesis will require evaluation in fields such as urban hydrology, ecohydrology, and geomorphology.

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