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Identifying individual rain events from pluviograph records: a review with analysis of data from an Australian dryland site

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Abstract:

Rainfall is routinely reported as falling in 'events' or 'storms' whose beginning and end are defined by rainless intervals of a nominated duration (minimum inter-event time, MIT). Rain events commonly exhibit fluctuations in rain rate as well as periods when rain ceases altogether. Event characteristics such as depth, mean rain rate, and the surface runoff volume generated, are defined in relation to the length of the rain event. These derived properties are dependent upon the value of MIT adopted to define the event, and the literature reveals a wide range of MIT criteria. Surprisingly little attention has been paid to this dependency, which limits the inter-comparison of results in published work. The diversity in criteria also diminishes the usefulness of historical data on event durations, rain rates, etc., in attempts to document changes in the rainfall climate. This paper reviews the range of approaches used in the recognition of rain events, and a 5 year pluviograph record from an arid location is analysed. Changing MIT from 15 min to 24 h (lying within the range of published criteria) alters the number of rain events from 550 to 118. The mean rain rate declines from 2·04 mm h^{-1} to 0·94 mm h^{-1}, and the geometric mean event duration rises from 0·66 h to 3·98 h. This wide variation in the properties of rain events indicates that more attention needs to be paid to the selection and reporting of event criteria in studies that adopt event-based data analysis. The selection of a MIT criterion is shown to involve a compromise between the independence of widely-spaced events and their increasingly variable intra-event characteristics. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS rain event; storm event; intensity; inter-event time; Fowlers Gap

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INTRODUCTION

Rainfall is an environmental parameter of great importance and complexity. Widespread diurnal variation in rainfall amount results primarily from altered frequency of rainfall, and to a lesser extent from variation in rain rates (Dai *et al.* 2007). In the context of global and regional environmental change, there is a need for systematic analyses of the occurrence of rain on sub-daily timescales, including measures of timing, intensity and duration, that can be used effectively in the detection and understanding of environmental change (Haylock and Nicholls, 2000). In researching trends in rainfall, the statistical properties of long records of daily rain depths have been examined for any trend toward increasing frequency of extreme rain events (Suppiah and Hennessy, 1998; Haylock and Nicholls 2000). Interest in this is driven by forecasts that changes in atmospheric composition will result in an intensification of some hydrologic processes, including rainfalls (Palmer and Räisänen, 2002; Milly *et al.* 2002; Chauvan and Denvil 2007; Déqué 2007), as well as greater occurrence of drought and a shift to generally more arid climate in some regions (see Seager *et al.* 2007 on the instance of the south-west USA). A study of storm precipitation in the USA based on a 30 year database (1972–2002), and involving more than 1500 pluviograph records, showed regional differences among temporal trends, but a widespread tendency for 15 min rain rates to increase toward the present day (Palecki *et al.* 2005). In contrast, rain rates assessed from daily totals appear to be declining in the south-east of Australia, and perhaps in other parts of the continent also (Murphy and Timball 2007). Shifts in rainfall totals and rain rates through time and space thus appear to exhibit considerable complexity. Various ecological consequences of altered temporal distribution of rainfall, which may include altered rain rates but also longer dry intervals between showers, have been suggested. For instance, changes in rainfall arrival would affect soil moisture regimes and ecosystem function (Fay *et al.* 2002). The ongoing hydrologic changes also suggest a need for adaptive management of urban drainage systems and flood management (Trefry *et al.* 2005; Guo 2006). Potential consequences for surface runoff and for soil erosion have also been highlighted (Angel *et al.* 2005). Nearing *et al.* (2004) estimated that soil loss rates would increase by 1·7% for each 1% increase in annual rainfall total. Increases in extremes of rain intensity may provide a significant component of any future increase in soil loss related to rainfall environment. Following from these various concerns is a need for a detailed understanding of

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rain event intensities and durations, and of the changes envisaged for coming decades. This may in turn guide and support work exploring the wider implications of changes in rain events for infiltration, the production of overland flow, erosion, and wider ecosystem functioning.

Because rain is intermittent, with most time being rainless, many hydrologic and geomorphic studies employ the concept of rainfall 'events'. For example, Acreman (1990) reported that for the UK, average storm event durations were only about 20% as long as the preceding rainless period. However, defining any period of consecutive days with rain as an event, as adopted in some of the studies cited earlier, provides insufficient temporal resolution for a wide range of investigations of environmental processes, and there is often a need for data with much finer temporal resolution, notably for application in hydrological models (Hastings *et al.* 2005; van Dijk *et al.* 2005). Certainly, some studies have shown that for very restricted purposes, daily rain totals are adequate. For example, having defined rain events as being separated by a 3 h rainless period, Tsubo *et al.* (2005) showed that in fact, in their South African sites, 94–96% of rain days had only a single event, so that daily totals were in effect event totals. Despite this, neither true rain durations, rain rates, nor rain intermittency (one of the fundamental properties of rain) can be resolved from data aggregated to daily level. Where pluviograph records with higher temporal resolution are available, the properties of rain events have been quite widely analysed in studies of environmental processes. Prebble and Stirk (1980) demonstrated greater interception losses in intermittent than in continuous rain, intermittency being defined by a rainless period of more than 30 min. In a study of rainforest interception in Indonesia, Vernimmen *et al.* (2007) reported that rain events during the day on average lasted less than 40 min, and at night, 70 min. Rainfall rates were highest in afternoon rain events, and there were thus clearly diurnal patterns of rain arrival and diurnal shifts in rain event properties. For a site in New Mexico where rain was delivered by short but intense convective storms, Hastings *et al.* (2005) concluded that even 15 minute temporal resolution in rainfall would be inadequate to understand the erosional effects of storms. Rather, they suggest, intense intra-event bursts of high rain rate, lasting perhaps 1–2 min, may drive both runoff and erosion. The challenge is that when high temporal resolution in rainfall is available, more approaches to aggregation of the record into discrete events become possible, since rainless intervals can be resolved in the data. Rain events are commonly delimited by nominating the required length of rainless intervals that precede and follow a rain event, such as the 3 h inter-event gap of Tsubo *et al.* (2005) referred to previously. Though a reasoned basis for identifying events through the use of a particular fixed inter-event gap is sometimes provided (Elsenbeer *et al.* 1994), in many studies that employ rain events, the criterion for 'lumping' or 'splitting' events on the basis of the length of an intervening rainless time is not clearly stated, and this raises the primary concern of the present study. The consequences of varying the operational definition of 'rain event' appear not to have been thoroughly explored, and as will be shown later, a wide diversity of criteria for separating events has evolved. In view of the widely-reported burst-like behaviour of rainfall, with fractal scaling properties (Peters and Christensen, 2002), the question of where to separate one event from the next is not straightforward to answer, and events closely-spaced in time might be regarded as a single event according to one study, but as two distinct events in another. Nevertheless, Palynchuk and Guo (2008) have argued in favour of storm event analysis in preference to more traditional intensity–duration–frequency curve methods in the description of the storm environment, and note some bases for selecting a value for the length of the rainless interval used to identify distinct events in a pluviograph record.

Using both a review of published literature and exploratory analyses of a 5 year pluviograph record from an arid Australian site, this paper addresses a series of questions relating to the definition of rain events using rainfall data with high temporal resolution:

1. What range of inter-event gap criteria has been employed for delimiting rain events?
2. How does the particular criterion used for separating rain events affect resulting rain event statistics, such as the number of rain events identified in a pluviograph record, and the distributions of event rain depth, event rain rate, and the duration of events?
3. How sensitive are the outcomes in (2) to the size of the events being analysed? In other words, are the effects of a particular criterion for separating rain events different if used only to identify rain events above or below a depth threshold? This is clearly relevant to the identification of extreme events, both small and large.
4. What is the distribution of inter-event dry periods, and how are the statistics of these dry periods affected by the choice of criterion for event definition? The length of time between events, during which the soil surface or damp foliage may dry out, is of great significance to many hydrologic and ecological processes. Published examples of this will be cited later.

This paper deals only with the description and analysis of point rainfall. Brief mention is made of areal rainfall, but the description and analysis of network rain events across sets of pluviographs is a distinct issue on its own and is not treated here. Network analysis adds several complications, including the likelihood of differences in the timing of rain event onset and termination at different gauges across the network, as well as spatially varying rain duration, depth, rain rate and event intermittency. Most studies in hydrology and geomorphology rely on only a single pluviograph, perhaps with one or more check gauges, and adopt point rainfalls as estimates of areal rainfall over plots, hillslopes, or small catchments.

Owing to its dominance in the published literature, the focus here is the procedure in which rain events are identified by specifying a minimum rainless period that must separate one event from another. Brief mention is made of less widely-used approaches to the identification of rain events. It is appropriate to note here that among the very large body of literature that adopts rain events as a basis for data reduction and interpretation, a large proportion do not report how the events were identified. Examples include Hartanto *et al.* (2003), Pardini *et al.* (2003), Hoyos *et al.* (2005), Valmis *et al.* (2005), Abesser *et al.* (2006), Hammad *et al.* (2006), Léonard *et al.* (2006), Ramos and Martínez-Casanovas (2006), Vischel and Lebel (2007), Wei *et al.* (2007), and Onda *et al.* (2008). Given the importance of rain event properties, it is important that in all cases the identification protocols employed in data reduction should be reported.

THE SIGNIFICANCE OF RAIN EVENTS: A BRIEF REVIEW

Historically, the recognition of rain events has been crucial in the study of phenomena such as soil erosion, where it is clear that short intense falls can have quite different consequences from longer light showers. The USLE soil erosion prediction model is fundamentally event based, owing to the formulation of the 'R' factor describing rainfall and runoff (van Dijk *et al.* 2005). This factor is based on an annual mean of the well-known EI30 term (kinetic energy delivered multiplied by maximum 30 min rain rate), which is evaluated on an event basis and summed over all events. In this context, an event is only significant if it has properties that can result in erosion, and events were only tallied by Wischmeier and Smith (1978) if either (a) the rain depth was $\geq 12{\cdot}5$ mm, or (b) the rain rate reached 6·5 mm in 15 min (Kinnell, 2003). As will be shown below, many other criteria for identifying rain events have been adopted in the literature.

The delimiting of rain events enables the corresponding output of water, soil, or nutrients from plots or catchments to be related to the properties of the event, such as the event duration or rain rate (intensity), as well as to catchment conditions such as antecedent soil moisture deficit (Wheater *et al.* 1982). In research dealing with water balance, such as the study of canopy interception losses within vegetation, the study of events with differing characteristics provides a means to reveal how key processes operate. For example, interception losses increase in events with higher event mean rain rates (Murakami 2006). Other examples of studies relying on the identification of rain events include Nunes *et al.* (2005), Godt *et al.* (2006), Cannon *et al.* (2007) and Robichaud *et al.* (2007). There is also a growing literature on rain events in relation to the design of systems appropriate for the capture and storage of roof runoff to supplement the reticulated supply in urban environments (Guo and Baetz 2007). The literature on flood generation has also demonstrated the significance of rainfall structure at the event scale, including intra-storm fluctuations in rain rate (Kusumastuti *et al.*, 2007).

Analytical treatments of rain events commonly regard these as independent events having a Poisson distribution of arrival times. Yet there are clearly deterministic features of the local rainfall climatology that systematically affect the properties of rain events. For example, Ulanski and Garstang (1978) showed that higher rain depths were delivered in Florida by once-daily convective events than from multi-shower days having the same total rain duration. They recognised multiple events occurring on the same day if they were separated by 15 min without rain. For a 1 h duration, a single event day could deliver a network total depth of 1000 mm, while a day with multiple showers might only deliver 200 mm. They speculated that larger convective events are more efficient at gathering moisture supply and in converting this to precipitation.

Acreman (1990) has outlined other circumstances related to the synoptic situation in which a different dry inter-event interval might be required for event identification in frontal rain, anticyclonic rain, etc. He also found correlations between event rain depth and inter-event duration, which suggest that atmospheric processes that are not random in time are involved in the mechanisms underlying the occurrence of rain events. Nevertheless, the correlations were small and an assumed independence of event depths and inter-event intervals was adopted by Acreman (1990) as a working approximation. There is evidently still much to be learned about the spatio-temporal behaviour of rain events in global environments (Dai *et al.*, 2007).

IDENTIFYING RAIN EVENTS USING A FIXED MIT CRITERION

In the majority of papers that present rain event data and that report how the events were identified, a fixed rainless period—the minimum inter-event time (MIT)—is required to be reached or exceeded before and after each event. The value of the MIT ranges from 3 min to 24 h (Table I). Values of 6–8 h are widely adopted. It is evident that owing to the use of different values for the MIT, different researchers would report varying numbers of rain events from the same rainfall record, and that these rain events would have differing properties (duration, rain rate, etc.). One purpose of the present paper is to explore in more detail how the properties of the events identified in a single pluviograph record, and the corresponding inter-event dry intervals, vary with MIT values spanning the range of published values.

Some studies report that the MIT was selected with the goal of identifying events that could be regarded as independent. For example, Bracken *et al.* (2008) used MIT = 12 h in order that the ground could dry between runoff events, reducing the impact of antecedent soil wetness on event runoff. This led them to speculate that a different MIT value might be needed for summer and winter conditions. Likewise, in studies of canopy interception, the MIT is often selected such that there is

Table I. Range of rain MIT criteria in published studies. The values are listed in ascending order, and other criteria for event recognition employed in addition to MIT are listed. Where it was reported in the original source, the basis for selecting the value of MIT is recorded in the table

Inter-event interval	Minimum event depth	Basis for event definition	Reference
3 min		Digitiser resolution	Vilar and Burgueño (1995)
15 min		Correlation with runoff events	Cattan *et al.* (2006)
15 min	0·2 mm	Not specified	Vernimmen *et al.* (2007)
20 min		Not specified	Bidin and Chappell (2006)
30 min	0·5 mm	Not specified	Balme *et al.* (2006)
30 min		Proportion of total rainfall included in events	Cosgrove and Garstang (1995)
1 h	0·1 m	Not specified	Cutrim *et al.* (2000)
1 h	5·0 mm	Not specified	Ziegler *et al.* (2006)
2 h	5·0 mm	Not specified	Fornis *et al.* (2005)
2 h		Estimated subjectively	Klassen *et al.* (1998)
2 h	0·5 mm in 0·5 h	Not specified	Germer *et al.* (2006)
3 h		Not specified	Cuartas *et al.* (2007)
4 h		Not specified	Xiao *et al.* (2000a)
5 h		Not specified	Deguchi *et al.* (2006)
6 h		Not specified	Loukas and Quick (1996)
6 h	13·0 mm	Not specified	Agnese *et al.* (2006)
6 h		Not specified	Murakami (2006)
6 h		Judged to isolate single storm events	Manfroi *et al.* (2004)
6 h	0·5 mm	Judgement	Link *et al.* (2004)
6 h		Observed drying time for upper canopy	Tobón Marin *et al.* (2000)
8 h		Following Lloyd *et al.* (1988)	Asdak *et al.* (1998)
10 h		Sap flow measurement	Toba and Ohta (2005)
12 h (or 8 h if all in daylight)		Canopy drying time (estimated)	Silva and Okumura (1996)
12 h		Not specified	Bracken *et al.* (2008) (criterion for rain 'spell')
24 h	Measurable amount	Not specified	Levia and Herwitz (2002)
24 h	0·254 mm	Not specified	Levia (2004)

sufficient time between events for the plant canopy to dry, so re-establishing the full canopy storage capacity prior to the commencement of rain. This reduces any dependence of rain event interception losses on the time since the previous rain event or on its properties (depth, duration), and is intended to permit the data from each event to be interpreted independently. Lloyd (1990) adopted a 3 h inter-event gap on this basis, in a study of forest interception processes.

For runoff production, rain event properties affect the filling and emptying of surface depression stores. In a study of highway runoff in Switzerland, Aryal *et al.* (2007) showed that depression storage recovered fully in about 8 h without rain, and thus adopted MIT = 8 h for rain event identification in a runoff modelling study to ensure that for each studied event, these stores were empty. There appear to be no comparable studies of the part played by rain intermittency and rain event properties in plot-scale runoff yield studies, but it seems certain that the phenomenon highlighted by Aryal *et al.* (2007) would have wide application in plot studies.

A clear difficulty with the identification of rain events using a fixed MIT is that intra-storm rainless periods can be included within the event that are virtually as long as the MIT. Thus, adopting an MIT of 12 h in a study of the interception loss of rain on foliage, which arises partly from wet-canopy evaporative losses, means that a long rain event could contain intra-storm gaps of almost 12 h length. During these times, the canopy storage capacity could regenerate by drying just as it would between events separated by the MIT. In other words, although the use of a sufficiently long MIT may create independence between events, it potentially increases apparent event-based estimates of interception loss because of drying during intra-event rainless periods. Therefore, it is vital that in event-based studies of runoff production, canopy interception losses, etc., both MIT and the resulting structure of intra-event gaps be reported. Later, the effects of varying the MIT on the internal intermittency of rain events is explored using a high-resolution pluviograph record to quantify the kinds of effects that can arise. Presumably, as MIT is increased, increasingly long intra-event gaps become subsumed within the rain events that are delineated, and so the event durations themselves increase. This was argued by Restrepo-Posada and Eagleson (1982). It has in fact been shown that long rain events can include rainless gaps that amount to 75% of the total event duration (Powell *et al.* 2007, data from South Carolina). A rain event that is largely rainless poses some challenges for the interpretation of runoff or other event-based data. Indeed, as Restrepo-Posada and Eagleson (1982) suggested, although a long MIT might be useful for allowing the identification of independent events, owing to the extensive intra-event gaps, the events so recognised might not be the most appropriate or the most physically meaningful for hydrological event studies nor for exploring environmental processes.

Variations on the basic MIT approach to identifying rain events

The diversity of approaches to rain event identification in the literature arises not only from the wide range of MIT values. In a number of studies, additional criteria are used to supplement the MIT. These compound rain event criteria include the following:

- Specification of a minimum rain depth required for an event to be recorded. Ziegler *et al.* (2006) tallied events only if they delivered $\geq$5·0 mm, and Balme *et al.* (2006) specified 1·0 mm; other workers have adopted a minimum equivalent to one or more bucket tips (Vernimmen *et al.*, 2007 adopted a minimum depth of 0·2 mm for this reason). The 0·5 inch (12·5 mm) depth criterion of Wischmeier and Smith (1978) was mentioned earlier.
- Specification of a minimum rain event duration for an event to be recorded. For example, Fornis *et al.* (2005) specified a minimum duration of 30 min; Cutrim *et al.* (2000) used a threshold of 1 h. Tyrrell and Hasfurther (1983, cited in Powell *et al.*, 2007) required events to exceed 4 h duration.
- Specification of a minimum rain rate for a period within the event. For instance, Fornis *et al.* (2005) required an event to have a rain rate $\geq$2·8 mm h^{-1}, while Loukas and Quick (1996) specified a minimum event mean rain rate of 1·0 mm h^{-1}.
- Specification of a minimum rain rate for the start of an event to be recognised, and a minimum rain rate marking the end of an event. Kerr *et al.* (1974, cited in Powell *et al.*, 2007) identified the start of an event 1 h before the time at which the rain rate exceeded 1·3 mm h^{-1}, and the end when the rain rate fell below 0·51 mm h^{-1}.

In some studies, several of these additional criteria are adopted simultaneously, including a fixed MIT, a minimum duration, and a minimum rain depth (Balme *et al.*, 2006). Other approaches to event identification have also been developed. Staelens *et al.* (2008) defined events on the basis of 1 h of wetness indicated by leaf wetness sensors. Beyond the range of criteria and approaches just outlined, there is a range of definitions and significant variation in terminology. Croley *et al.* (1978) recognised storm events as being made up of storm 'segments', a segment being a period of consecutive rain hours, segments being separated by one or more rainless hours. They adopted a different, subjectively-defined, inter-storm gap criterion for each 2 month part of the year, the gap length ranging from 6–12 h. This work was based on a 33-year record of hourly rainfall depths, and consequently was limited to 1 h resolution in data processing. Cutrim *et al.* (2000) defined an 'event' as including both a 'storm' (1 h MIT criterion, plus at least 0·1 mm rain and 1 h duration) and the rainless 'interlude' that follows it. Consequently, low mean 'event' rain rates are reported, and the 'storm' rates would be significantly higher (and storm duration would be considerably less than event duration). Most published work appears to adopt 'event', 'storm' or 'shower' to include the primary period of active rain, only including short intra-storm gaps. Differing terminology has been used by Bracken *et al.* (2008), who used the term 'spell' to include periods of rain of up to a number of days, on the condition that there be no rainless interval of $>$12 h. Shorter periods of rain within a spell were referred to as 'storms', though these were not strictly defined. Thus, once again the mean rain rates for spells listed by Bracken *et al.* (2008), which are typically 2–5 mm h^{-1}, are lowered by the inclusion of quite long rainless intervals.

There is clearly a wide diversity in the criteria employed to identify rain events, both in the values of MIT and the use of supplementary event criteria, and this limits meaningful comparisons among published studies. The level of uncertainty is compounded when the events once defined are employed to calculate event-based runoff efficiencies, soil erosion rates, canopy interception losses, and the like. This paper aims to draw attention to this issue, and to illustrate quantitatively the magnitude of variation in event and inter-event statistics caused by altering the MIT criterion.

A note on rain event characteristics and event nomenclature

Before turning to the analysis of pluviograph data and the exploration of the effects of varying the MIT criterion, some other aspects of rain events are briefly highlighted. The terminology used in the remainder of the paper is also set out here.

The specified minimum rainless interval that must precede the start of a new rain event is referred to as the minimum inter-event time, MIT. This terminology follows Asquith *et al.* (2005). If the time lapse between the end of one period of rain and the next exceeds MIT, the two periods of rain are tallied as separate events. The actual length of time between events is the inter-event time, IET.

Event average rain rate R_e is defined by the relation

$$R_e = d/E_d$$

where d is the event rain depth (mm), and R_e is the mean event rain rate. This is the equivalent rain rate that would provide the observed event depth at a constant intensity. However, it is known that fluctuations in intensity characterise many rain events even when rain is continuous. Following an analysis of rainfall records for Illinois, Huff (1967) introduced the classification of rain events into four groups, which he referred to as quartiles, depending upon whether the first, second, third, of fourth quarter of the rain event had the greatest rain depth and hence, rain rate. (The most common events were those of first and second quartiles; fourth quartile events were the least common.) The method has also been adopted by Tsubo *et al.* (2005), who found that for sites in South Africa, about half the events fell in the first quartile, about 25% in the second quartile, and the remainder were spread across the third and fourth quartiles. Distinctive patterns have been reported elsewhere. The temporal spread of rain within an event has been termed the 'event profile' (Acreman, 1990), and this may be a rain event parameter that is controlled by the mechanism of rainfall (convective, stratiform, frontal, etc.) in particular cases. Often, rainfall depth is low toward the end of an event (perhaps in the last hour, or last quartile) and sometimes also in the first hour (Acreman 1990). More resolution than is provided by quartile analysis may be needed to resolve a low-rain-rate commencement or ending within a rain event. The literature appears to provide relatively few instances where rain event profiles have been reported, although there is increasing awareness that event profiles may affect the operation of landscape processes, and varying profiles have been adopted in some rainfall simulation experiments to explore this further.

Various studies have confirmed the relevance of event profile in catchment runoff (Aron and Adl 1992), and many approaches to developing temporal storm rainfall profiles have been developed (see reviews in Pilgrim *et al.*, 1969 and Pilgrim and Cordery, 1975). Growing evidence of the importance of event profile and intra-event fluctuations in intensity comes primarily from rainfall simulation experiments programmed with varying event profiles. An example is provided by the rainfall simulation experiments on soil trays carried out by Frauenfeld and Truman (2004). In runs that were otherwise identical, they employed either constant rainfall rate (57 mm/h) or a variable rate delivering an intensity of about 160 mm h^{-1} at a peak in the second quartile of the storm duration, preceded by rising intensity and followed by declining intensity. Both treatments delivered the same total water depth, and although the event profiles were based upon data for natural storms in the field area, all events were held to a fixed duration of 70 min.

Although the varying rain event profiles did not change total infiltration or runoff volumes, they did result in changes in the amount of soil lost from the sample trays. The changes were related to differences in the time and extent of surface seal formation among the steady or variable rain rate events. Interrill erodibility was found to vary with the properties of the rain event.

Large intensity bursts within a rain event exhibiting a lower R_e are significant in terms of both production of overland flow and sediment entrainment (Parsons and Stone 2006). Likewise, studies are progressively demonstrating that rain rate fluctuations significantly affect nutrient and agrochemical runoff arising in rainfall simulation studies (Potter *et al.*, 2006; Frankline *et al.*, 2007; Truman *et al.*, 2007). For example, using simulated storms with a pattern of changing rain rate matched to generalised local storm characteristics, Truman *et al.* (2007) demonstrated that sediment and carbon losses in a variable rain rate event were considerably larger than arose in constant-rain-rate events of the same total rain depth. Runoff rates peaked earlier in the runoff event, and at a higher flow rate.

In contrast to these findings, Elsenbeer *et al.* (1994) found an increase of only 1·7% in interception amounts in events with multiple rain rate peaks over those with only a single peak. However, these results were not standardised for event depth, and the population of events was reduced by the elimination of events with a maximum 10 min rain rate of $<2{\cdot}5$ mm h^{-1}.

This growing body of evidence highlights the need for a wider and more systematic consideration of the methods used to identify rain events, and of the potential impact of MIT and other criteria in the data reduction process. If a larger value for MIT yields longer rain events, then it seems inevitable that intra-event variability of the kind just described would also increase with MIT. This is explored quantitatively below, where a pluviograph record with high temporal resolution is analysed to reveal the consequences of a variation in the MIT criterion for rain event properties, intra-event variability in rain rates, and for the behaviour of the inter-event dry intervals.

ANALYSIS OF A 5 YEAR PLUVIOGRAPH RECORD

The rainfall record analysed here is a 5 year record collected at the Fowlers Gap Arid Zone Research Station, located in far western NSW, Australia. Year-to-year variation in annual rainfall in this part of Australia is strongly affected by the El Niño—Southern Oscillation (ENSO) phenomenon. The long-term mean rainfall is about 200 mm. The record analysed was collected with a 0·5 mm capacity tipping-bucket pluviograph equipped with an event logger. Bucket tip events were logged as calendar dates with a 0·5 s resolution. The record analysed here contains 1797 bucket tips, representing 898·5 mm of rain (average annual rainfall was therefore approx. 180 mm). The pluviograph was mounted at 1 m above the ground in low chenopod shrubland, remote from any hills or trees, and was regularly inspected.

In processing the pluviograph record, the logged events were converted to Modified Julian dates, using double-precision FORTRAN routines from the International Astronomical Union's 'SOFA' (Standards of Fundamental Astronomy') algorithm collections (see URL http://www.iau.org/Standards_of_Fundamental_Astro.481·0.html). The use of Modified Julian Days, which begin at midnight rather than noon as for Julian days, facilitated the tallying of daily totals, and Julian dates in general allow the length of rain events to be found simply by subtracting the starting and ending Julian date. The Modified Julian day number subroutine from SOFA (iau_CAL2JD) was modified to include time with a resolution of $\ll 1$ s as well as day number. In turn, the file of Julian dates was passed to a FORTRAN routine that grouped these into 'events' on the basis of a user-defined MIT. The MIT was varied from 15 min to 24 h, to include the range commonly reported in the published literature (Table I). Statistical measures generated included

Table II. Rain event properties derived from a 5-year pluviograph records resulting from varying the MIT parameter in the range 15 min to 24 h. NB: single-tip events are included in the count of events, but were excluded when calculating mean event durations, depths, and rain rates. All means are geometric means, owing to positive skew in the distributions (see text for explanation)

MIT (min)	No. events N	Mean event duration (h)	Mean event depth (mm)	Mean event rain rate (mm/h)	Mean gap between events (h)
15	550	0·66	0·87	2·04	2·9
30	363	0·75	1·11	2·14	8·9
60	271	0·92	1·39	2·08	21·5
120	224	1·08	1·62	1·99	38·2
180	203	1·26	1·77	1·83	51·1
360	170	1·69	2·06	1·53	83·1
720	141	2·51	2·66	1·25	134·0
1440	118	3·98	3·27	0·94	201·9

mean event durations, rain depths, and rain rates, and distributions of inter-event times. Isolated single-tip events were tallied separately. Once the rain events had been identified, the temporal distribution of pluviograph tip events within each rain event was analysed using a third FORTRAN routine. The expectation here was that longer events would involve the incorporation of longer intra-event dry intervals, and that this would result in greater variance of inter-tip times). Parameters generated for each event, and then averaged across all events for each value of MIT, included the mean inter-tip time, and the variance of the inter-tip times. This was done in order to produce data to evaluate any effects of changing the MIT on the internal variability of the events. In examining the variance of inter-tip times within defined rain events, only events with at least five tips (2·5 mm rain depth), 20 tips (10 mm rain) and 30 tips (15 mm rain) were employed. For rain events with only one or a few tips (which are very common in the record—discussed later) the measures of variance would be of little significance.

RESULTS

The pluviograph record revealed a mean rain-day amount of 5·6 mm (standard deviation 7·62 mm). The largest daily rain total was 29·0 mm. Only 8·9% of days recorded rain, which is the equivalent of about 33 rain days per year on average.

Variation of the MIT resulted in considerable variation in rain event parameters (Table II). For instance, MIT = 15 min resulted in the identification of 550 rain events, but this declined by 78·5% to 118 events for MIT = 24 h. Correspondingly, a much smaller proportion of the total record length (~5 years) was included within rain events defined using a 15 min MIT (0·24% of the record), compared with a 24 h MIT (2·63% of the record included in rain events). A longer MIT also generated events with larger event depths but reduced mean event rain rates, as detailed later.

Published studies have established that the distributions of event depth, duration, and rain rate, and the durations of inter-event rainless periods, are all strongly positively skewed (Acreman, 1990; Guo, 2006), and analyses (Figure 1) confirmed this for the present data. Therefore the geometric mean was adopted as a more appropriate descriptor than the arithmetic mean in describing these event characteristics.

Geometric mean event duration rose from 0·66 h for MIT = 15 min to 3·98 h for MIT = 24 h, an increase of >6 times.

In terms of the dry intervals between rain events (IET), there were again clear variations relating to the choice of MIT. For MIT = 15 min, the mean IET was 2·9 h (4·4 times longer than the mean event length), but this rose 69·6 times to 201·9 h (nearly 8·5 days, or about 51 times the mean event duration) for MIT = 24 h. The shortest IET was always close to the specified MIT (e.g. it was almost exactly 15 min for a 15 min MIT; for a 12 h MIT, the minimum actual gap between defined rain events was 12 h 14·5 min; for MIT = 24 h, it was 26·1 h). In all cases the longest inter-event gap was a rainless interval of nearly 102 days. Long periods with no rain are expected in this arid location.

Events comprised of a single pluviograph tip were quite common. In the analysis using MIT = 15 min, single tip events amounted to 64% of all rain events, and contributed 19·6% of all measured rain. Using a 24 h MIT, single tip events amounted to 19·5% of all rain events, but only contributed 1·28% of all measured rain. Clearly in this arid location, single tip events become of concern when short values of MIT are adopted. Given the 0·5 mm bucket capacity of the pluviograph, some of these events might have approached 1 mm, with rain ceasing before a second tip was triggered, so that there can be less confidence in both the timing and depth of events that deliver a very low rain amount than in larger events.

Mean event rain rates were low, varying from $R_e = 2{\cdot}04 \text{ mm h}^{-1}$ (MIT = 15 min) to $R_e = 0{\cdot}94 \text{ mm h}^{-1}$ (MIT = 24 h). This is a decline of about 54% as MIT increases through the range tested. Maximum mean event rain rates in the 5 year record fell from 54·7 mm h^{-1} for MIT = 15 min to 49·7 mm h^{-1} for MIT = 24 h. This is a decline of 9·1%. Using the rain rate classification of Tokay and Short (1996), the mean event lies in the 'moderate' category at MIT = 15 min but shifts to the 'very light' category for MIT = 24 h. The maximum event rain rates fell into the 'extreme' category.

Highest mean event rain rates were associated with short events. For an MIT of 15 min, the highest event rain rate (54·7 mm h^{-1}) was for an event lasting 3·8 min. For an MIT of 24 h, the highest event rain rate (49·7 mm h^{-1}) was for an event of 6·0 min. Within the pluviograph record, therefore, quite short events but having relatively high rain rates are bounded by much longer dry intervals.

All geometric mean rain event parameters correlate significantly with the value of MIT with which they were identified. The relationships established in the analysis of

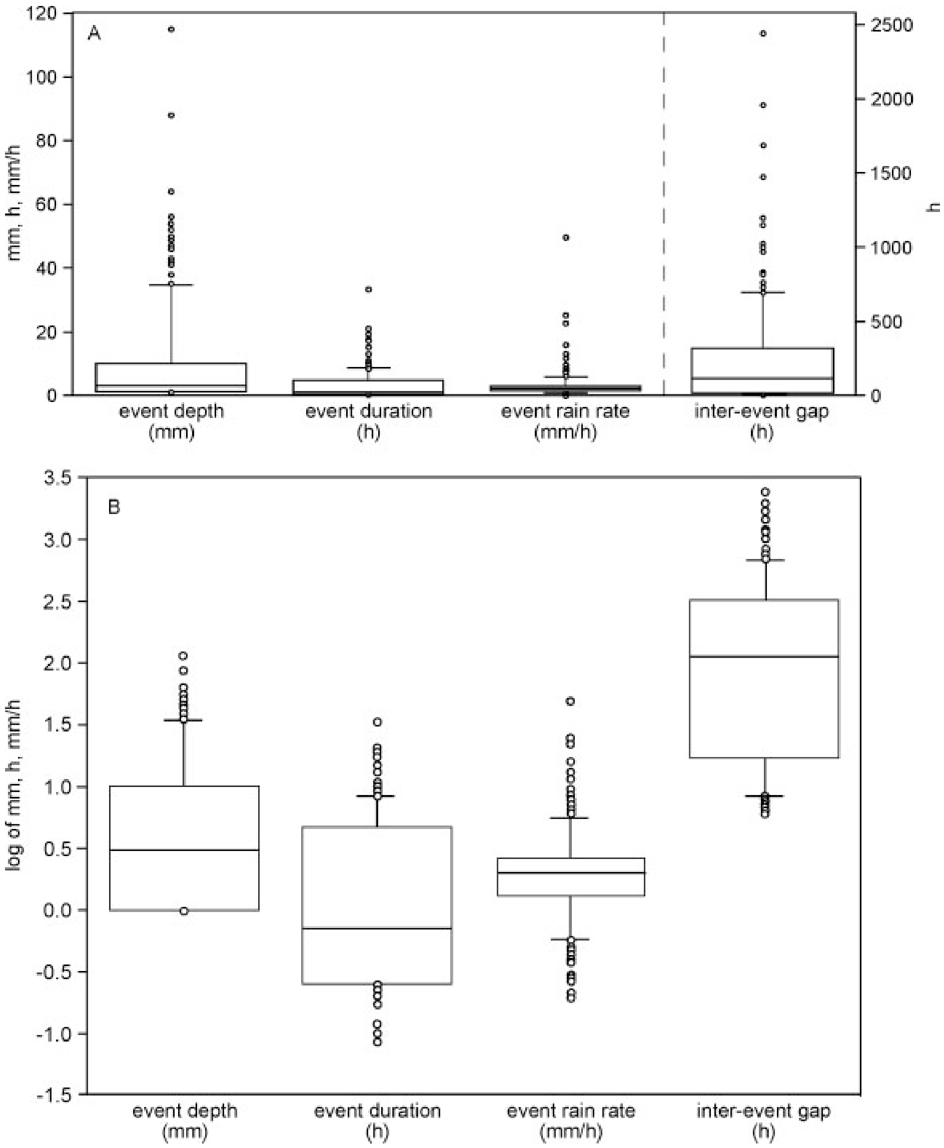

Figure 1. Distributions of rain event properties for the 170 events identified using MIT = 6 h. (A). Box plots of untransformed data. Positive skew, with unbalanced patterns of outliers, is evident. Note that the scale on the right hand axis applies to the inter-event gap length only. (B). Box plots of log10 transformed data for the same 170 events, exhibiting greater symmetry. Geometric means were consequently adopted in preference to arithmetic means in describing the distributions of rain event properties. See text for details

the 5 year pluviograph record, varying MIT in the range 15 min to 24 h, are as follows:

Number of rain events: $N = 1107{\cdot}3\mathrm{MIT}^{-0{\cdot}318}$ $(r^2 = 0{\cdot}99)$ (1)

Mean event duration (h): $E_d = 0{\cdot}771 + 0{\cdot}002\mathrm{MIT}$ $(r^2 = 0{\cdot}99)$ (2)

Mean event depth (mm): $d = 0{\cdot}422(\mathrm{MIT})^{0{\cdot}279}$ $(r^2 = 0{\cdot}99)$ (3)

Mean even rain rate (mm h^{-1}) : $R_e = 3{\cdot}89\mathrm{MIT}^{-0{\cdot}169}$ $(r^2 = 0{\cdot}81)$ (4)

Mean inter-event time (h): $\mathrm{IET} = 17{\cdot}37 + 0{\cdot}138\mathrm{MIT}$ $(r^2 = 0{\cdot}96)$ (5)

All symbols are as previously defined, and MIT is expressed in minutes. Equations (1), (3), and (4) are power function models, while (2) and (5) are linear. All relationships are significant at $P < 0{\cdot}001$.

Variability of tip intervals within rain events

It was hypothesised that longer events, delimited using a larger MIT, would be associated with a greater variability in rain rate arising from the inclusion of rainy and rainless intervals. This was assessed using the mean standard deviation, S, of the time between pluviograph tips within every defined rain event. In order to generate meaningful estimates of variance, S was evaluated using all values of MIT and for defined rain events having more than 2·5 mm, 10 mm, and 15 mm rain depth (see Tables III, IV, and V).

Table III. Rain event properties and intra-event variability for the subset of rain events having depth ≥2·5 mm, for MIT varied in the range 15 min to 24 h

MIT (min)	No. events >2·5 mm rain depth	Mean event depth (mm)	Mean of event mean time between pluviograph tips (min)	Mean of the event standard deviation of time between pluviograph tips, S (min)
15	81	7·1	5·26	2·43
30	86	8·0	8·22	4·37
60	83	9·0	10·90	7·69
120	80	9·8	13·46	12·74
180	79	10·1	15·86	17·21
360	73	11·1	21·61	31·04
720	73	11·4	44·17	67·28
1440	69	12·3	69·02	122·55

Table IV. Rain event properties and intra-event variability for the subset of rain events having depth ≥10·0 mm, for MIT varied in the range 15 min to 24 h

IEG (min)	No. events >10·0 mm rain depth	Mean event depth (mm)	Mean of event mean time between pluviograph tips (min)	Mean of the event standard deviation of time between pluviograph tips, S (min)
15	14	17·0	3·83	2·39
30	24	17·7	5·57	4·66
60	26	18·4	6·39	6·31
120	29	18·7	9·36	11·89
180	29	19·4	10·03	14·75
360	28	21·4	12·29	23·49
720	28	22·0	14·65	33·68
1440	29	22·6	27·02	78·9

Table V. Rain event properties and intra-event variability for the subset of rain events having depth ≥15·0 mm, for MIT varied in the range 15 min to 24 h

MIT (min)	No. events >15·0 mm rain depth	Mean event depth (mm)	Mean of event mean time between pluviograph tips (min)	Mean of the event standard deviation of time between pluviograph tips, S (min)
15	9	20·3	3·28	2·45
30	15	21·3	5·38	4·21
60	16	22·7	6·61	6·18
120	18	23·1	9·05	13·06
180	19	23·6	9·86	17·15
360	19	26·1	12·68	25·77
720	20	26·3	14·72	35·12
1440	20	37·3	21·56	67·21

Set of all rain events >2·5 mm depth

For MIT = 15 min (81 events), the mean time between tips was 5·26 min (S = 2·43 min). However, for MIT = 24 h (69 events), the mean time between tips rose to 69·0 min (S = 122·6 min). For MIT ≤ 2 h, the mean in all cases exceeded S. However, for MIT ≥ 3 h, S exceeded the mean. The value of S thus rose by 50·4 times as MIT was increased from 15 min to 24 h. The fitted regression model linking S and MIT was

$$S = 2{\cdot}187 + 0{\cdot}085\mathrm{MIT} \quad (r^2 = 0{\cdot}99) \qquad (6)$$

Set of all rain events >10·0 mm depth

For MIT = 15 min (14 events), the mean time between tips was 3·83 min (S = 2·39 min), rising to 27·0 min (S = 78·9 min) at MIT = 24 h (29 events). The mean value of S thus rose by 33·0 times as MIT was increased from 15 min to 24 h. The fitted regression model linking S and MIT was

$$S = 3{\cdot}427 + 0{\cdot}051\mathrm{MIT} \quad (r^2 = 0{\cdot}99) \qquad (7)$$

Set of all rain events >15·0 mm depth

For MIT = 15 min (9 events), the mean time between tips was 3·28 min (S = 2·45 min), rising to 21·56 min

(S = 67·21 min) at MIT = 24 h (20 events). The value of S thus rose by 27·4 times as MIT was increased from 15 min to 24 h. The fitted regression model linking S and MIT was

$$S = 5{\cdot}522 + 0{\cdot}043\mathrm{MIT} \quad (r^2 = 0{\cdot}98) \qquad (8)$$

All of these regression models were significant at $P < 0{\cdot}0001$.

This analysis shows that in all cases, increasing the MIT results in an associated increase in the mean of the standard deviation of the inter-tip times, S, with an approximate doubling for each doubling of the MIT. That is, the intra-event variability in tip rates increases linearly with increasing MIT. The longer events that are identified in the pluviograph record when using a large value of MIT are confirmed to exhibit more intra-event variability. However, there is a tendency for this effect to be reduced when only larger rain events being analysed. This effect is especially noticeable for the largest MIT values (6, 12, and 24 h). For example, for MIT = 24 h, the average standard deviation, S, of intra-event tip intervals is 122·55 min for all events >2·5 mm, falls to 78·9 min for events >10·0 mm, and to 67·21 min for events >15·0 mm.

DISCUSSION

The results presented above illustrate the range of consequences for rain event properties that arise from altering the value of the MIT criterion in one 5 year pluviograph record.

There is a marked dependency of the number of events on the value of MIT used to delimit them. In the 5 year record analysed, more than 400 additional rain events were recognised using MIT = 15 min than when MIT = 24 h. This is a decrease of 78·5%. Correspondingly, mean event rain rates were larger when using short MIT, since breaks in rain are excluded from the events (i.e. there is less intermittency of rain within an event). For MIT = 24 h, the mean event rain rate was consequently about 54% lower than for MIT = 15 min. Clearly, attempts to detect changes in rain rates associated with ongoing global environmental change must in some way be standardised in order to eliminate confounding with this effect. Likewise, data on event soil loss, runoff ratio, canopy interception loss, etc., made in studies using different values of MIT cannot be directly compared unless the data are standardised to eliminate the effect of MIT. The dependence of rain event numbers and rain rates reported here is likely to be distinctive to some extent owing to the mechanisms yielding rainfall in an arid environment, and therefore similar investigations of other climatic environments would be informative, and may yield contrasting results.

Measures of the length of rain events are strongly affected by the MIT criterion. The total duration of rain events identified was 103·4 h with MIT = 15 min, but rose to 1126·8 h with MIT = 24 h, an increase of about 11 times. This is a sizeable difference, amounting to about 51-fold increase in total event duration.

Another large effect of varying the MIT criterion is seen in the intra-event variability in rain rates, as expressed by the standard deviation of the time between pluviograph tips within rain events. As noted earlier, this variability grows very rapidly with increasing MIT for all categories of event size examined. The increase is smaller as the events analysed are restricted to those with increasingly large rain depths. For all events larger than 2·5 mm, S rose by more than 50-fold as MIT was increased from 15 min to 24 h. In other words, as increasingly long MIT values are used to seek independence among the events so defined, those events exhibit increasing levels of intra-event variation in rain rate. This means that various modifications to surface hydrologic and geomorphic processes are probable in events defined using large MIT but would be much more muted in events defined using small MIT. For instance, in studies of canopy interception loss, events defined using large MIT would have intervals of reduced rain rate during which canopy drip and evaporation could partially empty leaf and stem storages. Thus, interception losses would tend from this cause to be larger in events defined using large MIT values, other factors being constant. Likewise, in studies of the generation and behaviour of overland flow, in rain events defined using large MIT, infiltration from ephemeral ponds, evaporative drying of the soil surface, etc., would be enhanced in comparison with rain events defined by small values of MIT, other factors being constant. Overall runoff ratios on an event basis would then tend to be reduced in events defined using a large MIT, other factors remaining constant. The results show that the effects of changing MIT on intra-event variability in rain rates is substantial, and this confirms that studies adopting different MIT criteria can only be compared with considerable uncertainty.

A range of parameters can be erected for describing rain events (Merz *et al*., 2006), including measures of depth, duration, rain rate (intensity), and the distribution of rain within the event (the event profile). The latter can include both key aspects of rain intermittency, with dry intervals within a longer period of rain, as well as the distribution of depth, rain rate, etc. within the event. Only some aspects of rain events have been explored here, and only the use of the MIT criterion has been explored.

The delimitation of rain events using a specified MIT was referred to by Bonta and Ramchandra Rao (1988) as an 'arbitrary separation' process of event recognition. As noted earlier, one objective for undertaking such a separation is to delimit events of differing properties and which can be regarded as independent of one another. If this condition is achieved, then it may be that the runoff from an event, or the resulting soil loss from an experimental plot, can be analysed in terms of event characteristics without having to evaluate the effects of antecedent conditions (e.g. the extent of soil wetness). On the other hand, the effects of one rain event may remain in the landscape in the form of soil surface seals, proto-rills, or other features, and thereby influence runoff production and other surface processes even in subsequent rain events whose properties are statistically independent. Given the objective of identifying independent rain events, slightly more complex methods for delimiting these, that explicitly employ serial autocorrelations, can be used, with the MIT being increased until the serial correlation levels fall to a pre-set threshold (Morris, 1984 and Bonta and Ramchandra Rao, 1988 provide examples and additional commentary). An example of this procedure, using hourly rainfall records from 449 stations in Texas USA is provided by Asquith *et al.* (2005). They show that autocorrelations among hourly values decline steeply to about 0·02 for lag times of about 8–9 h or longer. They therefore adopt 8 h as the MIT in an analysis of storm events. The autocorrelation data of Asquith *et al.* (2005) showed no evident spatial trends for sites across Texas, suggesting that the single value of MIT should be applicable across the whole region.

The identification of independent events was explored by Restrepo-Posada and Eagleson (1982). They argued that whilst an identification of storms, on the basis of a knowledge of the atmospheric processes accounting for storm development, is in principle desirable, a simpler statistical approach is more readily achievable. Given that the distribution of the time intervals between Poisson events (which notionally are of zero duration) is distributed exponentially, Restrepo-Posada and Eagleson (1982) derived values of the time between events that yielded the most acceptably exponentially-distributed inter-event times. They began with short intervals and successively increased these whilst examining goodness-of-fit. Testing this approach with hourly and daily data, they derived optimal inter-event gaps that ranged from 132 h (5·5 day) (rainfall data from Al Wajh, Saudi Arabia) to 1·0 h (0·04 day) (for Santa Rita, Colombia). In general, the optimal inter-event time was inversely related to the mean annual rainfall, being greatest in arid conditions. This suggests that a single fixed value is not appropriate for partitioning all rainfall records into events. Moreover, despite analyses such as this suggesting that quite long MIT may be required for identification of independent events, most published studies (Table I) adopt MIT values of <24 h.

The foregoing discussion suggests several issues relating to the identification of rain events using a fixed MIT that warrant further exploration:

1. Can the method be applied meaningfully to rain events having different origins and atmospheric processes? An example is the delimitation of relatively intense convective showers from stratiform rain (Llasat, 2001).
2. Can the method be applied meaningfully to events in different seasons (such as summer vs winter events)? In the published literature, most studies adopt a fixed value of MIT that is used for all times of day and all seasons.
3. Can the method be applied meaningfully at different geographical locations, e.g. drylands vs wet tropics?

Investigating these issues requires data from many regions, and is not attempted here, though more work in this direction would undoubtedly yield valuable insights.

CONCLUSIONS

The results presented in this paper show that changing the value of the MIT criterion substantially changes both the number and the properties of rain events identified in a pluviograph record. Therefore, studies based on the analysis of rain events will be more informative if they include an explicit reporting of the criteria used to define events. As noted earlier, there is a wide range in the values adopted for MIT (15 min to 24 h). Indeed, in many published studies where rain event properties have been reported, no mention was made of the criteria by which events were defined. It is hoped that the findings presented here will lead more workers to consider event identification as an issue that needs consideration.

An important issue highlighted here is the compromise between independence of rain events and intra-event variability in rain rates that is involved when selecting a value for the MIT criterion. This seems not to have been explored previously in the literature, but it does have implications for many kinds of hydrologic study, such as the instances of runoff generation or canopy interception loss cited earlier. Rain events that exhibit marked variation in rain rate, and/or which contain significant rainless periods, may yield less explanatory power in studies of overland flow, erosion rate, and other processes. Given that the influence of varying the MIT criterion is quite straightforward to explore, as done in the present paper, it would be valuable if hydrological studies using rain event data explored further the most appropriate value in different areas of application.

The extent to which the findings outlined here from an arid zone rainfall record can be generalised is however unclear. It may be that in humid environments, the dependence on MIT might be different. However, increasing the value of MIT seems likely to lengthen defined rain events in all environments, and therefore to have the effect of increasing intra-event variability in rain rates, as demonstrated in the analyses presented here. Further exploration of these effects using data from a wide range of rainfall climates would be informative. In addition, exploration of the seasonal variability in rain event properties, and the detection of changes related to regional and global environmental change, require that the effects of varying MIT criteria be better understood and more widely reported.

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