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# Exceptional Rainfall Characteristics Related to Erosion Risk in Semiarid Tunisia

S. Jebari[1*], R. Berndtsson[2], A. Bahri[3] and M. Boufaroua[4]

[1]*National Research Institute for Rural Engineering, Waters, and Forestry, Box 10, Ariana 2080, Tunis, Tunisia;* [2]*Department of Water Resources Engineering, Lund University, Box 118, S-22100 Lund, Sweden;* [3]*International Water Management Institute, PMB, CT 112, Cantonments Accra, Ghana;* [4]*Farmland Conservation and Management Department, 30, Alain Savary Street, 1002 Tunis, Tunisia*

**Abstract:** The Tunisian Dorsal area is representative of the semiarid Mediterranean region in terms of water resources availability as well as exceptional rainfall characteristics, runoff generation, and soil loss risk. In this context, soil properties, surface management practices together with highly intensive rainfall make the soils vulnerable to erosion. If the exceptional rainfall characteristics are linked to different erosion types, the erosion risk could be evaluated in a simple and straightforward way. In this regard, a short time-scale rainfall data base from the Dorsal area was analysed in the paper. The procedure used involves finding a representative duration between 1-60 min for the exceptional rainfall characteristics. Rainfall intensities of different return periods are then related to the different erosion types. The identified exceptional rainfall durations between 1-60 min were analyzed in terms of number of events, depth, average intensity and maximum intensity. Results show that the 15-min duration maximum intensity can be used to evaluate erosion risk based on soil erosion type. The developed methodology can be used to evaluate erosion risk in semiarid regions based on exceptional rainfall characteristics. In practical terms the results can be used to better manage catchments that are vulnerable to soil erosion.

## 1. INTRODUCTION

High-intensive rainfall contributes to water erosion and sediment transport (e.g., [1-5]). Consequently, strong links exist between storm rainfall characteristics on the one hand and eroded soil amount on the other hand (e.g., [6-10]). During the last decades much experimental and laboratory research work dealing with the relationship between rainfall characteristics and sediment concentration has been performed (e.g., [11-15]). Non-availability of recorded short-term rainfall data appears to be a major limitation for statistical modeling of soil erosion risk [16]. Observation of hydrological variables in small watersheds at sufficient detail is often lacking [17-19]. This is especially a drawback for areas in the semiarid Mediterranean and the Middle East, since the soil erosion is severe there [20]. These areas often display hydrological changes. The latter, are a combination of climate-induced and anthropogenic effects related to land and water management [21].

Exceptional rainfall events are responsible for most soil erosion occurring under semiarid Mediterranean conditions [5]. According to the above, the objective of this paper is to determine the erosion risk by analyzing intensive rainstorms in semiarid Tunisia. And this, considering the maximum intensity characteristics and the links to soil erosion type. The utilized data are part of a unique high-resolution rainfall data base from 28 catchments collected during an EU-funded project [22]. The paper firstly describes the data base and collection methods. After this, maximum intensities for 1-60 min durations within rainfall events are analyzed. Selected durations of these exceptional intensities are related to the risk for different soil erosion types. Finally, practical applications of the results are discussed.

*Address correspondence to this author at the National Research Institute for Rural Engineering, Waters, and Forestry, Box 10, Ariana 2080, Tunis, Tunisia; Tel: + 216 71 230 039; Fax: + 216 71 717 951;
E-mail: sihem.jebari@iresa.agrinet.tn

## 2. MATERIAL AND METHODS

### 2.1. Study Area and Observed Network

The Dorsal Mountains represent the last part of the Atlasic Mountain range toward the east (Fig. **1**). The major peaks correspond roughly to 1000 m a.m.s.l. The mountains are often described as the southern boundary of northern Tunisia. The Dorsal corresponds approximately to the 400 mm/year rainfall isohyet (Fig. **1**). Although the annual amount is small, rainfall is often characterized by intense storms during some periods of the year. Annual variation ranges from 250 to 550 mm. Both annual and monthly rainfalls are characterized by a large irregularity. The spatial characteristics of fine time-scale rainfall through the Dorsal were analyzed in a previous study [23]. This paper deals with the statistical time patterns of rainfall and links to soil erosion risk.

Due to specific bioclimatic conditions of the Mediterranean climate, the soils are better characterized by the degradation of rock material rather than their organic matter content. Consequently, they are not well developed and often quite shallow. Moreover, soil erosion is a serious problem throughout the Dorsal area. The soil degradation that characterizes the Dorsal has led to serious soil erosion causing a thinner and uneven soil cover, that display the underlying bare bedrock. It has been estimated that 7% of the area are badly damaged by erosion and 70% are moderately damaged. During the decadal strategies, the Dorsal area man-

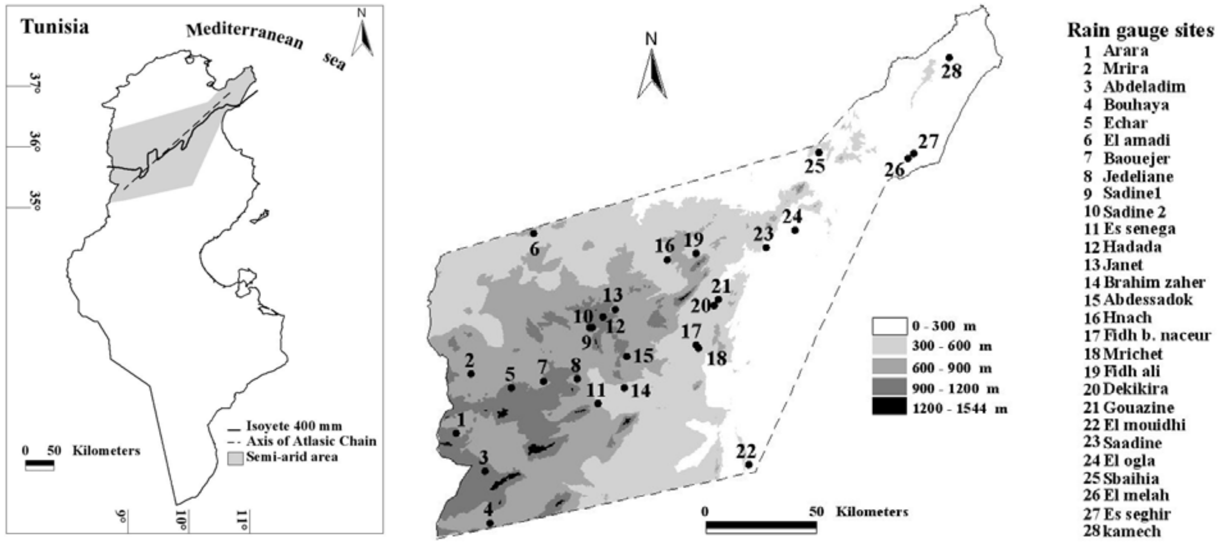


**Fig. (1).** Study area and observation network.

agement was based on water and soil conservation practices that covered about 20% of the total area.

In general, the mean annual soil loss in semiarid Tunisia is about 11.5 metric tons/ha/year. This figure was determined according to the deposited sediment volume in the bottom of reservoirs. Wischmeier and Smith [24], amounted soil loss tolerance to 12 tons/ha/year. This value is defined as "the maximum level of soil erosion that will permit a level of crop productivity to be sustained economically and indefinitely". Experiments throughout the Tunisian semiarid area have determined the average tolerable soil loss [25]. This is estimated to be respectively about 2.5, 5, and 10 tons/ha/year for thin, average and thicker soil. With a very slow rate of soil formation in some parts of the Mediterranean region, any soil loss more than 1 ton/ha/year can be considered as irreversible within a time span of 50-100 years [26].

The rainfall gauge monitoring network covers 28 experimental catchments (Table **1**). The observation network was set up through the EU-funded Programme HYDROMED (Research program on hill reservoirs in the semiarid Mediterranean periphery, 1992-2002; [22, 27]. At present it is managed by the Tunisian Farmland Conservation and Management Department (DG/ACTA). Each catchment discharges into a small reservoir. An automatic rain gauge is located at each site on the dike itself, as well as an automatic water level recording.

### 2.2. Rainfall Characteristics and Soil Erosion Processes

Raindrop impact initiates detachment of soil particles (rain splash) and causes crust formation [28-30] which seals the surface and limits the infiltration. Once the rainfall intensity exceeds the infiltration rate of the soil, overland flow of water occurs across the land surface, generating hydraulic forces that erode and transport sediments in a down-slope direction [31]. In the Mediterranean areas, very low values of saturated hydraulic conductivities are often found after 10 min of simulated rain [32]. As a consequence of weak aggregate stability of the soil surface, rainfall is often laterally distributed by Hortonian overland flow even for low intensity rainfall [33]. Runoff is the most important direct driver of severe soil erosion [28]. It often occurs at catchment scale, when rainfall intensities reach a minimum threshold of about 25 mm/h in 10 min [e.g., 34]. For other semiarid areas, observations have shown that about 15 mm rain may be needed to produce 1 to 2 mm of runoff [2]. High-intensity rainfall events affect runoff generation and erosion processes which are known to be highly non-linear [35]. This is also considered as the major contributor to long-term soil loss [36-38]. The lowest rainfall intensities leading to runoff on humid soil range from about 2 to 23 mm/h in Tunisian semiarid areas [39].

Rainfall characteristics determine the erosive action of raindrops and overland flow. They also define the most common water erosion processes namely, interrill, rill, and gully erosion. Interrill erosion concerns uniform removal of soil and is assumed to be the first phase of the erosion process. It affects the largest areas and is of main importance in the erosion process [15, 28]. When overland flow is concentrated in well defined incisions in the soil surface, turbulent flow occurs and small rivulets are formed. This is known as rill erosion. The rill erosion amount increases with growing water inflow rate and slope [40]. Under extreme storms, rill erosion progresses to gully erosion. the latter, results in large incisions which cause severe damage to the landscape [31] [41, 42]. Gullies increase the connectivity of the drainage system, and seem to be a main component in sediment delivery [43].

Return period intervals that characterize the rainfall events are crucial in describing the erosion impacts on the landscape. Bull [44] and Hooke [1], showed that important events transporting sediments have a return period of more than 1 to 7 years. Garcia-Ruiz *et al*. [45] and Coppus *et al*. [2] described 1-year return period events as mobilizing bed load and 5-year return period events as mobilizing small rock avalanches and channelizing debris flows. According to [46], events with an occurrence of 5 to 15 years considerably change the valley floor. Harvey [47] showed that 25-year event rainfall can modify the channel morphology. Finally, the 100-year return period rainfall shows reactivation of large, deep mass movements and exceptional events with a return period that exceeds 100 years are considered to be a catastrophic geomorphic process [2, 45].

**Table 1. Description of Observed Rainfall Events for the Dorsal Experimental Rainfall Network (1993 to 2003)**

| Rainfall Gauge | Events/Year | Mean Event Depth (mm) | Mean Event Duration (min) | Mean Event Int. (mm/h) | Max. Event Depth (mm) |
|---|---|---|---|---|---|
| 1. Arara | 100.7 | 2.1 | 77 | 4.0 | 40.0 |
| 2. Mrira | 126.1 | 2.4 | 77 | 7.3 | 84.5 |
| 3. Abdeladim | 116.6 | 2.4 | 74 | 3.8 | 52.0 |
| 4. Bou Haya | 76.8 | 2.7 | 72 | 5.6 | 38.0 |
| 5. Echar | 133.8 | 2.4 | 76 | 4.3 | 53.5 |
| 6. El Amadi | 180.7 | 3.6 | 94 | 3.8 | 113.0 |
| 7. Baouejer | 155.2 | 2.1 | 75 | 6.4 | 31.0 |
| 8. Jédéliane | 100.0 | 2.9 | 80 | 4.1 | 79.0 |
| 9. Sadine1 | 165.9 | 2.7 | 86 | 4.8 | 107.5 |
| 10. Sadine 2 | 150.6 | 2.6 | 91 | 3.4 | 64.5 |
| 11. Es Senega | 88.8 | 3.0 | 76 | 4.3 | 58.0 |
| 12. Hadada | 170.5 | 2.2 | 84 | 3.5 | 33.5 |
| 13. Janet | 144.2 | 2.7 | 84 | 3.8 | 65.5 |
| 14. Brahim Zaher | 77.7 | 2.6 | 73 | 4.5 | 36.0 |
| 15. Abdessadok | 106.5 | 3.0 | 82 | 4.2 | 78.0 |
| 16. Hnach | 120.1 | 2.6 | 84 | 3.5 | 59.5 |
| 17. Fidh b. naceur | 83.2 | 2.9 | 78 | 5.9 | 42.0 |
| 18. Mrichet El Anze | 136.3 | 2.9 | 89 | 3.5 | 73.0 |
| 19. Fidh Ali | 84.7 | 3.1 | 77 | 7.7 | 55.0 |
| 20. Dekikira | 96.3 | 3.0 | 84 | 6.7 | 72.5 |
| 21. El Gouazine | 103.1 | 3.0 | 83 | 4.8 | 84.5 |
| 22. El Mouidhi | 68.7 | 3.5 | 81 | 5.3 | 53.5 |
| 23. Saadine | 103.8 | 3.3 | 81 | 4.6 | 74.5 |
| 24. El Ogla | 107.9 | 3.2 | 84 | 3.5 | 84.5 |
| 25. Sbaihia | 135.6 | 2.9 | 85 | 3.5 | 78.0 |
| 26. El Melah | 132.3 | 3.4 | 88 | 3.7 | 56.0 |
| 27. Es Seghir | 135.3 | 3.1 | 85 | 2.9 | 91.0 |
| 28. Kamech | 174.4 | 3.1 | 78 | 5.2 | 125.5 |

## 2.3. Rainfall Data and Treatment

Twenty eight rainfall gauges from the hydrological network were used in this study (Fig. **1**). Missing data were less than 1% and the gauging density corresponds to approximately 1 gauge per 24 $km^2$ catchment area. Table **1** gives descriptive statistics for recorded rainfall events during the analyzed 10-year period (1993-2003). The rain gauges are fully automatic and provide an accuracy of ±4% up to 250 mm/h intensity for a 5-min time step. However, observed rainfall intensity is available down 1-min values [48]. Rainfall intensities could be computed with great accuracy for the range of durations used in the current study. Rain gauges are of tipping bucket type connected to a logger recording data every minute. A total of about 27000 station rainfall events were included in the present analysis. A rainfall event was defined as separated from another event if a rain gauge showed less than one tip per hour. For each rainfall event, duration, accumulated depth, average, and maximum intensity for 1, 2, 5, 10, 15, 20, 25, 30, 45, and 60-min durations were determined. Corresponding maximum intensities are hereafter named $I_1$-$I_{60}$. The events with maximum intensities corresponding to a return period superior to one year were kept for further analyses. These events are called exceptional rainfall events. It should be noted that exceptional events of

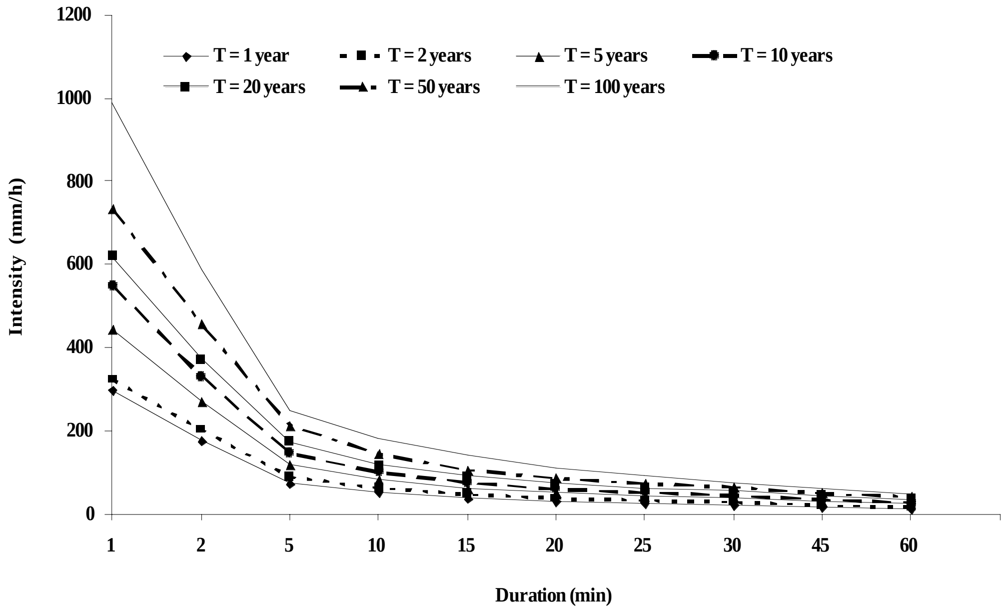


**Fig. (2).** Intensity-duration-frequency (IDF) curves for short-term rainfall in the Tunisian semiarid region (1964 – 2003).

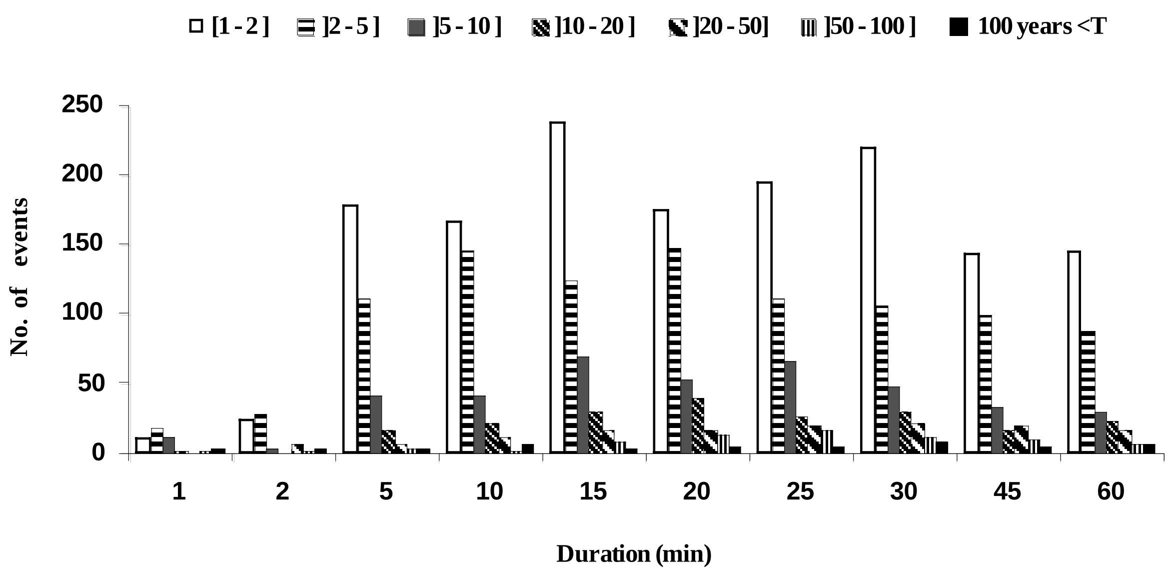


**Fig. (3).** Identified exceptional rainfall events depending on duration and return period (in total 3350 station events).

certain duration often contain exceptional events with shorter duration.

In order to evaluate the representativity of the observation period as compared to long-term rainfall conditions a number of comparisons were made, particularly in terms of mean rainfall depth and maximum intensities. The longest and most reliable long-term records are from 10 nearby stations in the Dorsal Mountains. The mean annual rainfall for the longer period (1969–2003) was about 406 mm (standard deviation was 124 mm). The same value for the period 1993-2003 was 365 mm (standard deviation was 102 mm). Maximum rainfall intensity for the investigated period was compared to long-term values for different time steps and return periods [49]. Fig. (**2**) shows intensity-duration-frequency (IDF) curves for the period 1964-2003. As seen in Fig. (**3**), even if the investigated period was short (1993-2003), it is still representative of longer periods in terms of maximum intensities corresponding sometimes to more than a 100-year return period.

### 2.4. Methods

The erosive characteristics of rainstorms and the resulting soil erosion process for the Tunisian semiarid area bring up many questions. For example, what is the importance of exceptional rainfall (rainfall intensities corresponding to a return period superior to 1 year) for the erosion risk? What time step is the most important when estimating the erosive potential of rainfall events? Which lower or upper limits of rainfall intensity characteristics could trigger erosion events? What is the most active erosion process in small catchments? Several aspects of the rainfall may be important to define events that lead to soil erosion. Different rainstorm characteristics, such as return period, duration, maximum short-term intensity, and rainfall depth may be significant for the soil erosion risk. Many studies during recent years have shown that rainfall return period is one of the most important characteristic indicating soil erosion amount and type. The following relationships are an attempt to summarize important soil erosion research concerning return period and soil erosion type for semiarid areas in general as well as semiarid Mediterranean regions in particular (using the following references in alphabetical order; [50,44,34,2,51,3,45,1,47,52-54,46,37,55-56,38,57-58,7,59,14].

1) Interrill erosion: $1 \le T < 5$

2) Rill erosion: $5 \le T < 10$

3) Gully erosion: $10 \le T$

where $T$ is rainfall return period in years and the duration of rainfall is 1 to 60 min.

The above relationships can be used in a simplified way, to estimate erosion risk based on short-term rainfall characteristics. It has to be remembered that the relationships are in general only valid for semiarid areas similar to the Atlasic catchments. The return period intervals should also be seen as an approximation for a large number of samples.

## 3. RESULTS

### 3.1. General Rainfall Characteristics

Table **1** shows a summary of nearly 27000 identified station rainfall events during the observation period. The number of more or less independent rainfall events per year corresponds to between 70 and 180. The average number of rainy days is about 22% (80 days/year) for the entire rain gauge network with a maximum of 30% at Kamech and a minimum of 13% at Mouidhi. More than 80% of the events appear as afternoon rains. This is consistent with the convective storm system. The rainfall event duration does not exceed 1 hour in 70% of the cases. Rainfall events with duration of less than 6 hours represent about 28% and events superior to 6 hours only 2%. Because of this, the majority of events can be categorized as small meso-scale rainfall according to House [60]. Only 25% of the events exceed 3 mm in depth. This value is the threshold to evaluate the kinetic energy of rainfall [61]. They hold about 70% of the total rainfall depth and represent 90% of the rainfall erosivity potential.

### 3.2. Exceptional Rainfall Event Characteristics

The observed rainfall data during the studied period displayed a maximum rainfall event of 125.5 mm that lasted about 12 hours (Table **1**). This corresponds to a daily return period of about 50 years and the highest return period of 20 years for $I_{45}$ and $I_{60}$. Among notable events the maximum values during 10, 15, and 20 min duration were respectively 24, 60, and 74 mm. For 30 and 60 min duration, 82 and 98 mm, were recorded. These values correspond to about 25% of the highest recorded rainfall intensity in the world for a duration of 15, 20, 30, and 60 min [62].

The exceptional events represent about 12% of the annual rainfall station events in semiarid Tunisia (about 10-20 events per year). Exceptional events less than a 10-year return period, represent several hundred station events, while, larger than a 10-year return period corresponds to about 10-20 events. According to Fig. (**3**), the number of exceptional events is unevenly distributed over the 1-60 min durations. One and 2-min duration exceptional events are rare. The 15-min duration displays a peak representing about 15% of all exceptional events. For instance, it displays 130, 45 and 171 more exceptional events than what is noted for the 5, 30 and 60 min durations, respectively. In general, the events occurring throughout the different durations seem to be nearly identical. If we have to choose representative durations for exceptional rainfall events, the 15-min duration, presents some advantages. When using, e.g., the universal soil loss equation (USLE; [24]). The rainfall and runoff erosivity is expressed by the so-called $R$ factor. The $R$ factor is calculated as a product of the total energy of rainfall, $E$ and its maximum 30-min intensity, $I_{30}$. Consequently, the identified $I_{30}$ exceptional intensities could be used to calculate the $R$ factor. However, the $I_{15}$ also displays possibilities to further elaborate on intensity variations within the 30-min duration. Compared to other durations it also displays the lowest stan-

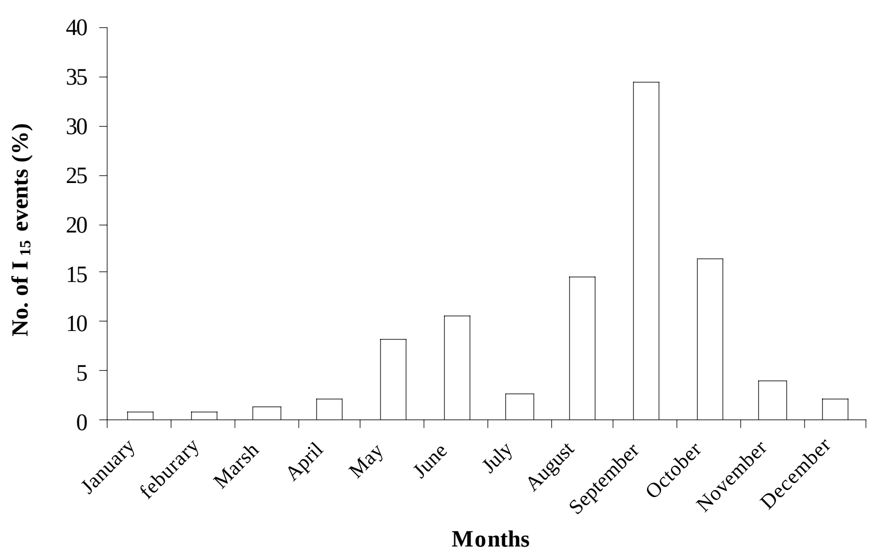


**Fig. (4).** Seasonality of the identified exceptional rainfall events with 15-min duration (average of about 500 station events).

**Table 2. Description of Identified 15-min Duration Exceptional Rainfall Events. Depth, Intensity, and Return Period Refer to the Maximum Observed Intensity**

| Rainfall Gauge | Events/ Year | Mean Event Depth (mm) | Max. Int. (mm/h) | Return Period (Years) |
|---|---|---|---|---|
| 1. Arara | 1.0 | 28.5 | 60 | 2–5 |
| 2. Mrira | 1.4 | 53.5 | 80 | 10–20 |
| 3. Abdeladim | 1.7 | 44.0 | 68 | 5–10 |
| 4. Bou Haya | 1.9 | 31.0 | 76 | 5–10 |
| 5. Echar | 1.6 | 53.5 | 94 | 20–50 |
| 6. El Amadi | 3.2 | 80.5 | 240 | 100 |
| 7. Baouejer | 1.4 | 31.0 | 70 | 5–10 |
| 8. Jédéliane | 2.3 | 79.0 | 84.6 | 10–20 |
| 9. Sadine1 | 2.4 | 107.5 | 186 | .>100 |
| 10. Sadine 2 | 1.8 | 38.0 | 100 | 20–50 |
| 11. Es Senega | 1.6 | 58.0 | 112 | 50–100 |
| 12. Hadada | 1.9 | 33.5 | 71 | 5-10 |
| 13. Janet | 2.1 | 63.0 | 96 | 20–50 |
| 14. Brahim Zaher | 1.5 | 36.0 | 110 | 50–100 |
| 15. Abdessadok | 2.4 | 78.0 | 140 | >100 |
| 16. Hnach | 1.7 | 27.0 | 86.6 | 10–20 |
| 17. Fidh b. naceur | 1.6 | 42.0 | 80 | 10–20 |
| 18. Mrichet El Anze | 2.2 | 73.0 | 98 | 20–50 |
| 19. Fidh Ali | 2.3 | 50.0 | 100 | 20–50 |
| 20. Dekikira | 2.2 | 72.5 | 94 | 20–50 |
| 21. El Gouazine | 2.5 | 84.5 | 88 | 10–20 |
| 22. El Mouidhi | 2.2 | 53.5 | 134 | 50–100 |
| 23. Saadine | 2.5 | 74.5 | 180 | >100 |
| 24. El Ogla | 3.7 | 84.5 | 102 | 50–100 |
| 25. Sbaihia | 1.9 | 66.5 | 116 | 50–100 |
| 26. El Melah | 3.6 | 56.0 | 110 | 50–100 |
| 27. Es Seghir | 2.5 | 91.0 | 152 | >100 |
| 28. Kamech | 3.5 | 125.5 | 102 | 50–100 |

dard deviation (15.8 mm) for rainfall depth and the smallest coefficient of variation (37.8%) linked to the maximum intensity values. In short, the 15-min duration, seems to be the most homogeneous sub-sample of exceptional rainfall intensities and also the most representative duration for erosive rainfall in the Dorsal area.

### 3.3. $I_{15}$ Characteristics and Erosion

Fig. (**4**) shows inter-annual variation of $I_{15}$ events. As shown in the figure, the majority of exceptional events occur with a major peak during the start of the rainy period in Tunisia between August September and October. During this specific period, the soils are the most vulnerable for rainfall erosion since they usually lie bare after the long dry period.

The average depth and duration for all identified 15-min exceptional events are respectively 25 mm and 105 min,. Corresponding average and maximum intensity are 23 and 56 mm/h. Table **2** shows a summary of the $I_{15}$ maximum event characteristics depending on station. As seen in the table the return period for these events are often much larger than the 10-year recording period and in several cases larger than 100 years. Consequently, the observation period may well represent a much longer period in statistical terms. The

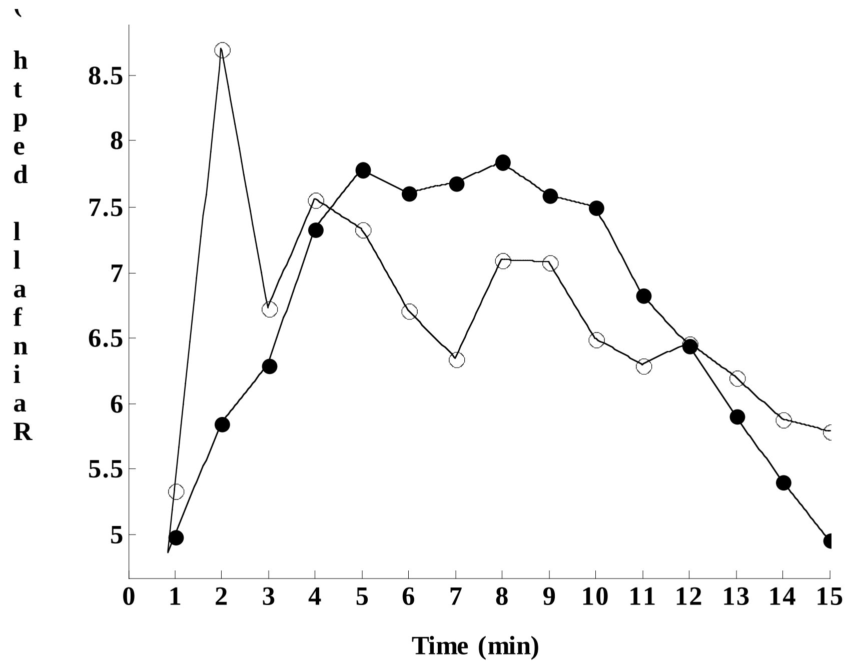


**Fig. (5).** Temporal distribution of the identified 15-min duration exceptional rainfall events. Line connecting filled circles shows average properties and line connecting empty circles shows standard deviation (about 500 station events).

28 different rainfall stations display varied number of exceptional 15-min duration events. Ogla, Amadi, and Kamech show more than 3 exceptional events per year while Arara only has one single exceptional event per year. The largest observed $I_{15}$ was recorded at Amadi and Sadine 1 with a return period larger than 100 years. The corresponding intensities were 240 and 186 mm/h that correspond to respectively 450 and 200 year return period. Largest maximum intensities occur most often east of Mouidhi to Kamech. The western parts usually have the lowest maximum intensities.

Fig. (**5**) shows the average temporal distribution for the 15-min duration exceptional rainfall events. The distribution appears somewhat skew with a centre of gravity towards the first half of the events. The intensity maximum occurs after about 5-10 min. The standard deviation displays a large variation for the first minutes that then gradually decreases. This indicates that some rainfall events may have large intensities right from the start which can cause great raindrop impact initiating detachment of soil particles.

The erosion types are linked to the different return periods (cf. Methods). Consequently, the risk of erosion appears to be related to specific exceptional 15-min intensities. This yields the following relationships:

1) Interrill erosion: $38 \leq I_{15} < 65$

2) Rill erosion: $65 \leq I_{15} < 75$

3) Gully erosion: $75 \leq I_{15}$

where $I_{15}$ is the exceptional rainfall intensity in mm/h.

The above relationships should be regarded as a simplified way to estimate the occurrence of different erosion types depending on the maximum 15-min duration rainfall intensity. As such, the intensity boundaries should not be seen as fixed but rather indicative. Together with additional information on a particular catchment´s situation in the soil degradation cycle [63], the relationships can be used to estimate the risk for different types of erosion in the Dorsal region. The results can be used to better manage erosion-prone catchments and also give input to erosion modelling.

## 4. CONCLUSION AND DISCUSSION

Semiarid regions are especially vulnerable to erosion due to a combination of geomorphological conditions, soil management, and the high-intensive character of rainfall. Due to this, there are needs to better develop methods and estimate the erosion risks in a simple way. The most rational means to do this is to start from the rainfall characteristics. About 12% of all rainfall events in the Tunisian semiarid region are erosive and can be categorized as being exceptional (return period equal and superior than 1 year). A literature survey of pertinent soil erosion research for semiarid regions shows that type of erosion can in a general way be related to rainfall return period. A combination of these results with the conclusions herein show that the 15-min exceptional rainfall intensity can be used to characterize erosive rainfall. And this leads forward to a simplified general relationship for the occurrence of a certain type of erosion. The relationship links erosion type with the 15-min exceptional rainfall intensity. The results can be used to estimate the risk of certain type of erosion in a simplified way based on short-term rainfall characteristics. Together with information on a certain catchment´s location in the soil degradation cycle. Results can be used as input to erosion modeling but also to better manage erosion risks in catchments with water erosion problems.


## ACKNOWLEDGEMENTS

Sihem Jebari and Akissa Bahri thank Mr Habib Farhat, head of the Tunisian Farmland Conservation and Management Department (DG/ACTA) for providing data and all his staff for valuable time and discussions allocated to this work.

Ronny Berndtsson is supported by the Swedish Research Council.

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Received: March 11, 2008 Revised: April 01, 2008 Accepted: April 02, 2008