Hydrological response of Mediterranean gorse shrubland under extreme rainfall simulation event

José Carlos González-Hidalgo, Martín de Luís, Josep Ranténos, Jordi Cortina and Juan Rafael Sánchez

with 2 figures and 4 tables

Summary. Hydrological response of Mediterranean gorse shrubland under extreme rainfall simulation event. We have researched into the hydrological response and soil erosion of semi-arid Mediterranean shrub plant cover to extreme rainfall events on 12-year-old, mainly gorse (Ulex parviflorus) scrubland. Three experiments with simulated long duration rainfall (4 hours) were performed in three 2 × 2 m field plots. The rainfall volume applied was that which could be expected once in every 100 years. Soil moisture records were taken simultaneously with Time Domain Reflectometry (TDR) at different depths. The hydrological response of soil covered by semi-arid shrubs to extreme events seems to be controlled by complex processes of soil saturation that are spatially and temporally heterogeneous. These seem to be regulated by the accumulation of water in some areas and by deep flows through preferential paths. Although the run-off was variable and relatively high locally, this Mediterranean gorse scrubland was very efficient in retaining sediment, even under this extreme disturbance.


Résumé. Réponse hydrologique d’une broussée arbustive méditerranéenne à Ajoncs à des événements pluviométriques extrêmes simulés. – La recherche a porté sur la réponse hydrologique et l’érosion des sols sous une broussée méditerranéenne de douze ans (Ulex parviflorus) soumise à des événements extrêmes. Trois expériences ont été menées sur trois sites de 2 × 2 m affectés par des averse simulées de longue durée (4 heures). Le volume pluviométrique qui leur a été appliqué est de récurrence centennale. La réponse hydrologique d’un sol couvert par une broussée semi-aride à des événements extrêmes semble être contrôlée par de processus comple-
xes de saturation des sols qui sont spatialement et temporairement hétérogènes. Elle semble être régulée par l'accumulation d'eau en certains secteurs et par de écoulements le long de tra-
jets préférentiels. Quoique le ruissellement soit variable et localement relativement élevé, cette
brousse méditerranéenne s'est montrée très efficace pour retenir les sédiments, même sous ces
perturbations extrêmes.

1 Introduction

Arid and semiarid landscapes are very sensitive to erosion and desertification as well
as places where the impact of climatic change on environmental processes seems to
vary with local site conditions (YAIR 1994). Special cases are Mediterranean semiarid,
dry and sub-humid landscapes characterised by torrential rainfall, where a single and
intense rainfall event sometimes reaches values comparable to monthly totals, and
where IPCC predictions suggest an increase in rainfall torrentially.

Extreme climate events have received increased attention in the last few years
because their frequency may increase with global Climatic Change (TRENBERTH
1999) and because they favour soil erosion, instability of the slopes and floods.

The study of the effect of such events on run-off and erosion are difficult to
carry out because they occur infrequently, and most research instruments are not
usually designed to deal with their magnitudes. For that reason, rainfall simulation
experiments seem to be the best approach when analysing the hydrological conse-
quences of extreme rainfall events. Rainfall simulation experiments have been widely
applied in semiarid country, but commonly focus on regular events lasting less than
one hour (see review of CERDÀ 1999, and CROKE et al. 1999 for an exception). So, the
lack of information to extreme rainfall events means that estimations are commonly
based on extrapolations from studies of "normal events". For that reason, further
research is needed to improve our knowledge of the landscapes response under such
circumstances although logistic difficulties. In this paper, we investigate the run-off,
infiltration and erosion processes in a semiarid Mediterranean scrubland subjected to
an extreme simulated rainfall.

2 Study area and methods
2.1 Study area

The study area is located in the western coast of Mediterranean Basin (SW of the
Spain, 40–41° N, 0–2° W), and the whole area has produced some of the highest daily
maximum values very close to world maximum values (ARMENGOT-SERRANO 1994;
see table 1). Furthermore, such rainfalls develop in short time intervals of between
2 and 6 hours (National Meteorological Agency, INM).

In addition, the area is particularly prone to degradation since it is close to the
transition point from dry to semi-arid conditions, and because the steep slopes, fre-
quent wild-fires and soils (DE LUFS et al. 2001).
2.2 Field plots

We simulated an extreme rainfall event on a 12-year-old second-growth scrubland re-established after wildfire and mainly covered by *Ulex parviflorus*. To do that, we established three experimental plots 2 × 2 m on three different contiguous slopes with similar plant cover (100%). Plots were enclosed by metal sheets inserted into the soil.

The soil was sandy-silt-loam to clay-loam Typic Calcixeroll following USDA Soil Taxonomy, developed on marls inter-bedded with limestone (*De la Torre & Alías* 1996). Characteristics of soil are presented in table 2.

The slopes lie to S, NE and N for Plots 1, 2 and 3 respectively. Slope values (measured by a Pitty pantometer) were 26%, 26% and 27%, for Plots 1, 2 and 3.

We also established another set of plots, which had been burnt for experiment. The burnt plots were located at several meters distance from each vegetated plot, on the same three slopes and under the same soil conditions. These runs were performed only to check the scrubland plots (as control), and not will be analysed in detail in this paper.

2.3 Rainfall simulation

The rainfall simulator consisted of a 3.5 m high metallic structure supporting a nozzle (Spraying System™) that produced a homogeneous 7 m diameter rainfall cone.
Table 2  Texture, bulk density (BD), Stoniness (> 2 mm, % by weight) and CaCO₃ content at different depths on the three experimental slopes. In GARCÍA CANO (1998).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Clay (&lt;2 μ)</th>
<th>Silt (2–50 μ)</th>
<th>Sand (&gt;50 μ)</th>
<th>BD (g/cm³)</th>
<th>Stoniness (%)</th>
<th>CaCO₃ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
</tr>
<tr>
<td>0–2</td>
<td>14</td>
<td>12</td>
<td>14</td>
<td>38</td>
<td>46</td>
<td>39</td>
</tr>
<tr>
<td>2–5</td>
<td>15</td>
<td>13</td>
<td>15</td>
<td>48</td>
<td>39</td>
<td>43</td>
</tr>
<tr>
<td>5–10</td>
<td>13</td>
<td>14</td>
<td>12</td>
<td>49</td>
<td>37</td>
<td>44</td>
</tr>
<tr>
<td>10–20</td>
<td>13</td>
<td>15</td>
<td>12</td>
<td>36</td>
<td>39</td>
<td>46</td>
</tr>
</tbody>
</table>
Rainfall intensity was 2.59 mm min\(^{-1}\) (155 mm h\(^{-1}\)). The total volume of rainfall applied during the simulations (more than 3,000 litres per run) corresponded to that of a rainfall occurring once in every one hundred years (De Luis 2000). Rainfall intensity agrees with extrapolations from empirical adjustments proposed by Camarasa & Segura (2001).

In vegetated plots rainfall duration was 4 hours and run-off was collected at 1-minute intervals. In burnt plots rainfall simulation was only 2 hours, and run-off and sediment were collected at 2-minute intervals. The weight of the sediment was evaluated after sieving and oven drying at 105°C in the laboratory.

### 2.4 Soil moisture

Changes in soil water content were recorded throughout the simulation by using Time Domain Reflectometry (TDR) and data logger after calibration of probes in the laboratory. Probes were inserted parallel to the surface after digging a lateral trench outside each plot. The trenches were then refilled with soil and covered with a plastic film during simulation, to reduce disturbance as much as possible. Rainfall simulations were performed one month later.

Soil moisture measurements were taken every 15 minutes at different depths. Results were expressed as percentage of saturation to standardise the measurements taken at different depths and plots.

### 3 Results

#### 3.1 Run-off

Run-off began within 5 minutes after the start of the simulation in all the scrubland plots (fig. 1a, b, c), and quickly increased to relatively high rates (c. 0.5 mm min\(^{-1}\)), gradually decreased thereafter. Later, the three plots behaved differently. In Plot 1, after a relatively stable run-off rate of 0.2 mm min\(^{-1}\), it increased to 0.5 mm min\(^{-1}\) after the plot had received a rainfall volume of c. 300 mm (fig. 1a). In Plot 2, the initial run-off rate (0.07 mm min\(^{-1}\)) increased twice at 300 and 400 accumulated rainfall, corresponding to run-off rates of 0.10 y 0.25 mm min\(^{-1}\) respectively (fig. 1b). Run-off rate in Plot 3 was close to 0.10 mm min\(^{-1}\) throughout the simulation (fig. 1c). Accumulated run-off was 75.5 mm, 33 mm and 22 mm in Plots 1, 2 and 3 respectively, representing a global run-off coefficient of 12%, 5% and 4%.

Run-off on burned soil plots was different. Run-off started in the first minute, then rose and stabilised, with final rates being 0.38 mm min\(^{-1}\), 0.82 mm min\(^{-1}\) and 0.56 mm min\(^{-1}\), respectively on slopes 1, 2, 3, and total run-off representing a run-off coefficient of 16%, 32% and 16%. Table 3 shows run-off accumulated at 50 mm, 100 mm, and 200 mm intervals for burned and vegetated soil. Accumulated run-off on vegetated plots until the end of the simulation is included.

#### 3.2 Soil erosion

Sediment yield from the three vegetated plots was very low (ranging between 2 and 6 g m\(^{-2}\)). Concentration decreased exponentially after the beginning of the simulation...
Fig. 1. Run-off versus accumulated rainfall. Dotted line corresponds to rainfall intensity. (a) Plot 1; (b) Plot 2; (c) Plot 3.
and thus most of it occurred shortly after the onset of the rainfall. On burned plots, soil erosion was higher, and the sediment showed a marked decrease as the rainfall simulation progressed. Table 4 shows the sediment accumulated at various intervals throughout the simulation.

3.3 Soil moisture evolution

The increase in soil water content during the simulation did not occur gradually from the top to the bottom of the soil profile. Thus, we recorded significant increases in moisture content at deep soil layers when accumulated rainfall was only 200 mm in Plot 3. Saturation of the whole profile occurred at 300, 400 and 200 mm in Plots 1, 2 and 3, respectively. The results are shown in a set of different profiles at selected rainfall accumulated values (see fig. 2 a, b, c).

Table 3  Accumulated run-off (in mm) at different rainfall intervals. Vegetated and bare (burned) plots.

<table>
<thead>
<tr>
<th>Rainfall (mm)</th>
<th>Accumulated runoff (mm)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Slope 1</td>
</tr>
<tr>
<td></td>
<td>Vegetated</td>
</tr>
<tr>
<td>50</td>
<td>5.5</td>
</tr>
<tr>
<td>100</td>
<td>9.3</td>
</tr>
<tr>
<td>200</td>
<td>14.9</td>
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<tr>
<td>300</td>
<td>22.1</td>
</tr>
<tr>
<td>622</td>
<td>75.5</td>
</tr>
</tbody>
</table>

Table 4  Accumulated sediment yield (g m⁻²) at different accumulated rainfall values. Vegetated and bare (burned) plots.

<table>
<thead>
<tr>
<th>Rainfall (mm)</th>
<th>Accumulated sediment yield (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope 1</td>
</tr>
<tr>
<td></td>
<td>Vegetated</td>
</tr>
<tr>
<td>10</td>
<td>0.15</td>
</tr>
<tr>
<td>50</td>
<td>0.29</td>
</tr>
<tr>
<td>100</td>
<td>0.67</td>
</tr>
<tr>
<td>200</td>
<td>1.78</td>
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</tbody>
</table>
Fig. 2. Soil moisture profile evolution (% over saturation) during rainfall simulated experiment at selected accumulated rainfall values (mm). (a) Plot 1; (b) Plot 2; (c) Plot 3.
4 Discussion

4.1 Run-off development and soil erosion

The rapid generation of run-off under shrub cover contrasts with previous research in similar conditions (Francis & Thornes 1990, Cerdà 1995), in some of which run-off was not generated even after 30 to 45 minutes. In our case, run-off volumes during the first 4–5 minutes were very high, representing instantaneous run-off coefficients of 11% to 21%. Differences in early run-off volume can be attributed to the rainfall intensity used in the present study (Evans et al. 1999, Robichaud 2000), and hydrophobic qualities of the surface soil layers probably favoured an early run-off.

The hydrophobic quality of the soil has been related to plant species with a high oil, resin and wax content, to low water content in the leaf litter and the surface mineral level of the soil, and with soils with low clay or high sand content (DeBano 1981, Soto et al. 1993, Dörr et al. 2000). Litter accumulation in the experimental plots (mostly O₃ and O₄ layers, USDA) was between 400 to 600 g m⁻² and it was mainly composed of recently shed Cistus albidus leaves and fragments of Ulex parviflorus stems. On the other hand, soil water content was relatively low at the beginning of the rainfall simulation (less than 25%). All of these aforementioned factors together with relatively high sand content are likely to generate hydrophobia in the surface soil layers. A simple index of hydrophobia (Water Repellence Index, WRI), induced by natural conditions indicated values of 15.7% for Plot 1, 8.1% in Plot 2 and 8.3% in Plot 3, very close to values observed by Pierson et al. (2001). No repellence was apparently observed in burned plot.

After the initial phase, run-off rates decreased and stabilised in vegetated plots. The relationship between run-off rate in burned soil and soil with cover was 2:1, 10:1 and 3:1, for Plots 1, 2 and 3 respectively, very similar to those reported by Soto et al. (1993) and Castillo et al. (1997). Finally, run-off showed very different dynamics in the three plots at the end of experiment. Although the run-off coefficient was variable and relatively high locally (Plot 1), this Mediterranean gorse scrubland was very efficient in retaining sediment and soil particles, even under this extreme disturbance (table 4).

4.2 Soil moisture

Saturation of soil profiles were reached in the three plots, but process seems to be spatially high heterogeneous. Soil water profiles under shrubs did not produce a gradual advance of a wetting front, and this suggests the existence of preferential paths (macropores) formed by plant growth, root networks and animal activity (Heppell et al. 2000). Furthermore, it is well known that they affect infiltration (Bochet et al. 1999, Geddes & Dunkerley 1999, Cerdà et al. 1998), and that their effects are noticeable under extreme rainfall events (Amin et al. 1998, Heppell et al. 2000). Also stemflow may have favoured the rapid transport of water to deep soil layers by funnelling rainwater (De Ploey 1984, Tanaka et al. 1990). In this research we have not measured stemflow in gorse, but in accordance with studies on other Mediterranean shrubs and on Ulex europaeus (a very similar species to Ulex parviflorus, Soto & Díaz-Fierros 1997), it is reasonable to assume that it was close to 25% of incoming rainfall. The
water repelling quality of superficial layers in the early phases of the simulation may also have favoured the concentration of water on the surface and channelisation to deep soil strata (Doerr et al. 2000).

If we accept these assumptions, the rapid saturation of soil profiles in the field plots seems to respond to a local saturation and could be in agreement with the run-off model suggested by de Ploey (1984) under plant canopy on an individual spatial scale caused by the effect of stemflow, or related to the hydrophobic qualities of the soil in accordance with the model suggested by DeBano (1969 as quoted by Doerr et al. 2000: 50). Under such conditions, surface run-off was not produced uniformly in each plot.

5 Conclusions

When Mediterranean gorse scrubland is subjected to an extreme simulated rainfall event, infiltration processes does not seen to be neither spatially homogeneous processes nor generate a gradual advance of wetting front in a uniform way, but rather to follow preferential paths. Thus saturation of the soil profile does not occur gradually from top to bottom. This has important implications on the storage of water in deep soil layers and the dynamics of the generation of run-off. The complexity of water fluxes in the profile is reflected in a high spatial heterogeneity of run-off dynamics and volume. By the other hand, Mediterranean gorse scrubland behaves as extremely efficient factor in controlling soil erosion, even under extreme torrential rainfall event.

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References


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