Soil loss from small rangeland plots under simulated rainfall and run-on conditions

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ABSTRACT
In order to predict and mitigate soil erosion it is necessary to understand the mechanism of detachment by raindrops and by shallow flow. The relative contribution of these drivers to the overall erosion process on arid rangelands is not well understood and field experimental data is limited. The experiment was conducted using simulated rainfall and overland flow on 56 small (2 m × 6 m) natural plots located on 7 rangeland sites in Arizona, USA. The goals of the study were (i) to compare raindrop driven and shallow flow driven erosion rates on arid rangeland, and (ii) assess the role of flow hydraulics, vegetation, and cover on attenuation of erosive impact of raindrops. A total of 520 measurements of steady state flow under two treatments (rainfall and run-on) were obtained. Flow discharge on the plots varied between 3 and 355 mm h⁻¹ and unit sediment yield varied between 0.02 and 30 g m⁻² min⁻¹. Sediment yield was best predicted by flow discharge for both rainfall and run-on treatments on all sites explaining 18% to 75% of its variability. There was statistically significant difference between two treatments. Rainfall treatment generated 2 to 44 times more sediment than run-on at the same discharge rate. We found no strong evidence of raindrop impact affecting overland flow velocity. Among 19 variables related to surface conditions a weak correlation was found between sediment yield and plant foliar cover, structure, and surface litter. However, there was no single best cover predictor common for all ecological sites tested.

1. Introduction

Arid rangelands are vulnerable environments suffering from soil erosion and degradation worldwide (Bartley et al., 2006; Chartier and Rostagno, 2006; Stavi et al., 2009). Their management and preservation require better understanding of fundamental processes of soil erosion, and its interaction with plant community (Yisehak et al., 2013). Soil erosion by water can be conceptualized as four sub-processes: detachment and transport by raindrops, and detachment and transport by surface flow (Ellison, 1944; Meyer and Wischmeier, 1969). These subprocesses typically occur simultaneously and are closely interconnected (Nouwakpo et al., 2016). Their contribution to overall soil loss is dependent on complex interaction of climatic, topographic, soil, and vegetation factors.

Overland flow on hillslopes is classified as sheet (shallow) flow over the inter-rill areas, and rill (concentrated) flow in channels. Erosion on the inter-rill areas is dominated by raindrop impact (Kinnell, 2005; Meyer and Monke, 1965) because the shear force of the flow itself is relatively small and only able to sustain transport (Proffitt and Rose, 1991). Hence, soil detachment is primarily caused by high water velocity at the points of impact (Fernandez-Raga et al., 2017; Mutchler and Hansen, 1970) where flow becomes highly turbulent (Lu et al., 2016; Young and Wiersma, 1973). Erosive power of raindrops decreases greatly with water depth (Moss et al., 1979; Mutchler and Hansen, 1970). Experiments on natural hillslopes (Gabet and Dunne, 2003; Kirkby and Kirkby, 1974; Tian et al., 2017) and in sand filled flumes (Kinnell, 1991; Moss et al., 1979) have shown that a layer of water exceeding 4 to 6 mm (or 2 to 3 drop diameters) dissipates enough of raindrop energy to inhibit much of splash detachment. Hence, in rills where flow depth and velocity are greater and raindrop penetration is limited, detachment and mobilization of particle is due almost entirely to shear force (Nearing et al., 1997).

It is important to understand relative contribution of each of these erosion mechanisms to the total soil loss from slope or watershed. A number of studies attempted to address this question. Young and Wiersma (1973) in a laboratory flume experiment on a loamy soil showed that an 89% reduction in rainfall energy at a constant rainfall rate leads to a decrease of sediment delivery by over 90%. Similar results were obtained by Walker et al. (1977) on a sandy soil where rainfall produced 5 to 10 times more sediment than equivalent amount

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of overland flow applied directly on the plot. An et al. (2012) in a flume experiment on loess soil used a fine net to dissipate rainfall energy near the surface. They reported that raindrop impact accounted for 46.5% of sediment yield from the plot. Singer and Walker (1983) built on the previous experiments by adding various levels of surface cover to different combinations of rainfall and overland flows. In their experiment a 100 mm h$^{-1}$ rain produced 10 times more sediment than the same rate of overland flow. The authors also found that the combined effect of rain, flow, and surface cover were nonlinear.

Sediment yield produced by rainfall and overland flow exceed the sum of sediment yields generated by these inputs occurring separately (Proffitt and Rose, 1991; Rouhipour et al., 2006; Tian et al., 2017). This is because drop impact facilitates detachment while additional overland flow provides efficient entrainment and transport. However, the interaction between these processes is complex and includes negative feedbacks. Namely, raindrop impact may retard flow velocity (An et al., 2012; Beuselinck et al., 2002; Savat, 1977) and rill development (Young and Wiersma, 1973), while increased flow depth shields the surface from raindrop detachment (Kirkby and Kirkby, 1974; Moss et al., 1979). Reynolds and Froude numbers were reported to markedly decrease while Darcy–Weisbach coefficient to increase in the absence of high energy raindrops at otherwise equal flow rates (An et al., 2012; Shen and Li, 1973).

The majority of experiments addressing the subject of relative roles of raindrop disturbance and overland flow in soil erosion were conducted in laboratory flumes on homogeneous material (Li et al., 2017; Proffitt and Rose, 1991; Rouhipour et al., 2006; Singer and Walker, 1983), or in highly controlled field environment without natural cover (Vaczi et al., 2017). On natural hillslopes researchers encounter factors and feedbacks not found on artificial plots.

Rills, which are critical transport mechanism for evacuation of the detached sediment (Young and Wiersma, 1973), are often poorly developed or absent on arid rangelands. Desert grasses form large clumps of stems, while other species tend to occupy or form micro-topographic highs. This increases flow depth and creates complex convergent and divergent non-dendritic drainage patterns. In addition, desert environment is characterized by rock pavement, which uniquely alters flow velocity (Abrahams and Parsons, 1994; Polyakov et al., 2018a) and sediment delivery dynamics (Nearing et al., 1999). Vegetation cover reduces fall velocity of raindrops, but does not affect overall discharge. Surface cover, such as litter, rocks, and plant stems protects soil from both impact, but may also accelerate bypass flow by channelization and cause localized scour.

The relative importance of all these factors is not well understood and field experimental data representing rangelands is extremely limited. The goals of the study were (i) to compare raindrop driven and shallow flow driven erosion rates on arid rangeland, and (ii) assess the role of vegetation and cover on attenuation of erosive impact of raindrops.

2. Methods

2.1. Description of the experimental sites

The experimental data for this study was collected between 2003 and 2013 on 56 long term plots located on 7 rangeland ecological sites throughout Arizona, USA (Polyakov et al., 2018b). These sites encompass a wide range of soil, climatic, and vegetation conditions found in the region (Table 1). A total of 100 rainfall simulations were conducted.

Four of the sites (ER2, ER3, ER4G, and K2) representing Loamy Uplands were located in southern Arizona in Major Land Resource Area (MLRA) 41–3 (Chihuahuan-Sonoran Semidesert Grasslands) (USDA, 2006) at elevations of 1370–1520 m. The climate there is semi-arid defined by North American Monsoon where more than half of annual precipitation occurs from July through mid-September in the form of high intensity convective storms. May and June are the driest months of the year. Mean annual temperature is 17.7°C. Sites ER2, ER3, and ER4G are located on Empire Ranch northeast of Sonoita, Arizona. The annual precipitation there ranges between 300 and 400 mm y$^{-1}$. The soil is White House (fine, mixed, thermic, Ustollic Haplargids) gravelly loam (NRCS, 2003). It was formed on alluvial fan and has a shallow A horizon underlain by deep argillic and calcic horizons. Grazing on Empire Ranch was heavy in the past but has since greatly decreased. ER2 is dominated by beard grass (Borrichiochia spp.), grama (Bouteloua spp.), love grass (Eragrostis spp.), three-awn (Aristida spp.), and native forbs. ER3 and ER4G have a mesquite-native plant community. The K2 is located on Walnut Gulch Experimental Watershed (WGEW) east of Tombstone, AZ (Renard et al., 2008). The area receives an average of 345 mm of precipitation a year. The soil is Stronghold (coarse-loamy, mixed, thermic Ustollic Calciorthids) containing 67% sand, 16% silt, and 17% clay, with 79% coarse fragments (> 2 mm) (NRCS, 2003; Osterkamp, 2008). The organic carbon content is 1.1% in the top soil. The vegetation is represented by black grama (Bouteloua eriopoda Torr.), side oats grama (B. curtipendula Torr.), three-awn (Aristida sp.), and cane beard grass (Borrichiochia barbinodis (Lag.) Herter) and forbs.

Three experimental sites (YG1, YG2, and YG3) are located 9 km north of Young at a higher elevation (1630–1790 m) in central Arizona, in MLRA 38 (Mogollon Transition Area) on Clay Loam Upland (USDA, 2006) (Table 1). The climate associated with this area is semi-arid, characterized by cold, moist winters and warm, dry summers with large temperature variations. The driest period is from midsummer to mid-autumn. The average annual precipitation in the area is 580 mm and the mean annual temperature is 11°C. The soil is Terrarosa clay loam (fine, mixed, superactive, thermic Aridic Paleustalfs). It is deep and well drained with well-developed argillic horizon and > 1% organic matter content. The soil freezing depth in winter is 10–15 cm. Sites YG1 and YG2 are dominated by grama species (Bouteloua sp.) and cool season grasses. Site YG3 was in alligator juniper woodland state a year prior to the experiment, however, juniper was uprooted and the biomass left on site. The area where YG sites are located is prone to wildfires that occur at 10 to 15-year intervals.

2.2. Instrumentation and sampling

On each experimental site 8 replicated simulation plots were established. The plots were 6.1 m long and 2 m wide surrounded by sheet metal borders and a runoff collection trough on the down slope side. The rainfall was generated by Walnut Gulch Rainfall Simulator (WGRS). WGRS is a portable, variable intensity, computer-controlled simulator equipped with 4 spray nozzles (Paige et al., 2004). It can deliver rainfall up to 180 mm h$^{-1}$ with the energy of 204 kJ ha$^{-1}$ mm$^{-1}$. Variable speed nozzles ensure uniform coverage of the experimental plot. Windbreaks deployed around the simulator minimized the effect of wind on rainfall distribution. Run-off flow was generated by pumping water through a perforated pipe at the top edge of the plot. A strip of cloth was placed under the pipe to evenly dissipate the flow and prevent local scour.

Runoff rate was measured using a supercritical flume with electronic depth gage installed at the outlet. Approximately 30 to 50 sediment samples were collected in the course of a single simulation to quantify sediment yield during all stages of runoff event. After collection the sediments were flocculated, excess water decanted and the sediments dried at 105°C. Wet and dry samples were weighed to determine sediment concentration and soil loss rate. Flow velocities were measured using an electrolyte solution. Two liters of the solution was occluded, excess water decanted and the sediments dried at 105°C. The authors also found that the combined effect of drop, flow, and surface cover were nonlinear.
step-up sequence with in-run treatments, made in the absence of rainfall, followed the same reached a steady state for at least rates were sequentially increased after runo
during every steady state condition. Some additional runo
have peak intensities below 167 mm h
treatment. Prior to the experiment every plot was subjected to 45 min
starting conditions. Then, after 45 min hiatus, the experiment followed.
long rainfall at 65 mm h
rainfall simulation sites and their characteristics.

<table>
<thead>
<tr>
<th>Location</th>
<th>Site ID</th>
<th>Elev. m</th>
<th>MLRA</th>
<th>Vegetation</th>
<th>Soil texture</th>
<th>Precipitation mm y⁻¹</th>
<th>Slope %</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Pedro basin, Southern Arizona</td>
<td>ER2</td>
<td>1419</td>
<td>41-3</td>
<td>perennial grass</td>
<td>gravelly loam</td>
<td>300-400</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>ER3</td>
<td>1420</td>
<td>41-3</td>
<td>perennial grass</td>
<td>gravelly loam</td>
<td>300-400</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>ER4G</td>
<td>1374</td>
<td>41-3</td>
<td>perennial grass</td>
<td>gravelly loam</td>
<td>300-400</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>K2</td>
<td>1519</td>
<td>41-3</td>
<td>perennial grass</td>
<td>gravelly fine sandy loam</td>
<td>345</td>
<td>10.8</td>
</tr>
<tr>
<td>Salt River basin, Central Arizona</td>
<td>YG1</td>
<td>1632</td>
<td>38-1</td>
<td>perennial grass</td>
<td>clay loam</td>
<td>580</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>YG2</td>
<td>1632</td>
<td>38-1</td>
<td>perennial grass</td>
<td>clay loam</td>
<td>580</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>YG3</td>
<td>1790</td>
<td>38-1</td>
<td>juniper</td>
<td>clay loam</td>
<td>580</td>
<td>5.2</td>
</tr>
</tbody>
</table>

(2005). The points were identified using a laser mounted onto a frame positioned horizontally over the plot. Ground surface at thses points was characterized as plant, basal area, organic litter, rock, and bare soil. Vegetation was further classified as forbs, grass, and shrubs. In addition, the distance between plant bases (basal gap) and canopy edges (canopy gap) were measured using three lengthwise and six crosswise transects per plot. The transect data were expressed as a percentage and an average length of inter canopy and inter basal spaces.

The experimental procedure was as follows. Four of the plots on each site were designated to receive rainfall, and four to receive run-on treatment. Prior to the experiment every plot was subjected to 45 min long rainfall at 65 mm h⁻¹ intensity to pre-wet the soil and create base starting conditions. Then, after 45 min hiatus, the experiment followed. Rainfall treatment consisted of a series of 65, 100, 125, 150, and 180 mm h⁻¹ intensities, which cover the range of natural events intensities recorded in the region. Namely, at WGEW 99% of rainfalls have peak intensities below 167 mm h⁻¹. During the experiment these rates were sequentially increased after runoff at the previous rate had reached a steady state for at least five minutes as shown on Fig. 1. The run-on treatments, made in the absence of rainfall, followed the same step-up sequence with inflow rates between 100 and 300 mm h⁻¹. At least 3 sediment samples and one velocity measurement were obtained during every steady state condition. Some additional runoff samples were collected on the rising and falling limbs of the hydrograph. On average between 30 and 40 samples were collected per experimental run. A total of 100 simulations were conducted.

In all statistical tests P = 0.05 was used, unless otherwise indicated. More details on the experimental equipment and procedures can be found in Polyakov et al. (2018b).

3. Results and discussion

3.1. Sediment yield

A total of 520 measurements of sediment discharge under two flow treatments (rainfall and run-on) were obtained. Unit flow discharge (q) on the plots varied between 5.2 × 10⁻⁶ and 601 × 10⁻⁶ m² s⁻¹ (3 and 355 mm h⁻¹) and unit sediment yield (Sy) varied between 0.003 and 2.9 g s⁻¹. All measurements were made at steady-state rate and represented a wide range of hydrologic conditions that exist on rangeland hillslopes. The total soil loss from each of the plots was small enough to assume that no major morphological changes occurred on the plot surface during the simulations. No rill development was observed. The largest sediment yield per plot per single simulation was 614 g m⁻², or an average of 0.5 mm of soil loss. All soil erosion was considered sheet erosion.

Statistical analysis showed that sediment yield was best correlated with discharge for both rainfall and run-on treatments. This is consistent with previous studies in rangeland environment (Nearing et al., 2007; Polyakov et al., 2010; Simanton et al., 1993). On all sites q explained between 5% (YG3) and 50% (ER3) of variation of Sy (Fig. 2). However, the variance of the errors of Sy in the linear model showed marked increase with increasing predictor variable q. Indeed, White’s test (White, 1980) indicated strong heteroscedasticity of the data. This warranted logarithimical transformation of q and Sy and fitting a regression of the form:

\[
\log(S_y) = \beta_0 + \beta_1 \times \log(q)
\]

where \(\beta_0\) and \(\beta_1\) are linear regression coefficients.

Separate models were used for each treatment (rainfall and run-on). The transformation of the variables improved model fit in some cases increasing \(R^2\) up to 4 fold comparing to non-transformed variables. The result of the regression indicated that q significantly predicted Sy on all
sites under both flow treatments and explained between 18% (YG3) and 75% (YG1) of its variance (Table 2). All regression slopes except for rainfall on YG3 (Figs. 2 and 3) were significantly different from 0.

Earlier studies (Osborn and Lane, 1969; Polyakov et al., 2010) demonstrated that logarithmic transformation performed poorly when applied in runoff and sediment relationship. However, those datasets represented natural events with positively skewed distributions and a small number of observations with high leverage. When log-transformed, leverage points could no longer favorably influence the coefficient of determination. In contrast, in our study the predictor variable was uniformly distributed, i.e. both high and low rates of discharge were equally well sampled.

There was statistically significant difference between two input treatments at each of the sites (Figs. 2 and 3). Rainfall treatment generated approximately 2 (YG1) to 4 (ER3) times more sediment than run-on at the same discharge rate. This difference between the treatments, particularly on ER and K2 sites was within the range of what was previously reported. Namely, various studies attributed between 85% and 95% of sheet flow sediment yield to rainfall impact (An et al., 2012; Guy et al., 1987; Singer and Walker, 1983; Walker et al., 1977; Young and Wiersma, 1973). Most of the prior research, however, was conducted on artificial plots with no vegetation and non-cohesive soils.

3.2. Soil, surface, and cover effects

Multiple regression analysis was used to test whether sediment yield ($S_v$) was affected by vegetation or surface cover variables. A total of 19 secondary predictors were used. Means and standard deviations of several of these variables are presented in Table 3. A weak but statistically significant correlation was found between $S_v$ and either canopy, rock, bare soil cover, or canopy gap, which explained between 3 and 31% of its variation. However, there was no best secondary predictor common for all the sites. This was likely due to the heterogeneity of the data set. Namely, large inter-site variability, moderate intra-site variability (Table 3) and differences in soil texture (Table 1). In addition, erosion rates on rangelands are low in comparison with croplands. Hence, systematic trends are more difficult to identify.

It is well established that inter-rill erosion is dominated by splash detachment occurring at the point of drop impact (Gabet and Dunne, 2003; Kinnell, 2005; Meyer and Monke, 1965; Parsons et al., 1994). However, its effect and interaction with surface flow on rangelands is complex. Rock and litter cover minimize the area susceptible to splash but also concentrate overland flow. There appears to be a feedback between cover and erosion rate where increase in surface protection diminishes splash, but increases localized flow scour. Singer and Walker (1983) reported peak soil loss at 40% ground cover. Water depth of more than 2–3 drop diameters can effectively inhibit splash detachment (Kinnell, 1991; Kirky and Kirky, 1974). The median drop size produced by the simulator (2.9 mm) and the range of observed flow depth of 2 to 12 mm (Buono, 2009) suggest that considerable portions of our experimental plots could have been effectively shielded from splash by overland flow (Figs. 4 and 5).

Canopy is a major factor that dissipates kinetic energy of raindrops diminishing potential detachment. However its efficiency greatly depends on canopy height (Khun et al., 1988) and structure. This might explain the weak correlation between erosion rate and canopy despite considerably variability in cover area, namely 29% to 55%.

Examination of the plots shows that rangeland vegetation tends to grow in patches, with bare areas in between (Fig. 5). This arrangement leads to formation of isolated micro elevations surrounded by depressions. As shown in Fig. 5, these depressions, highlighted by runoff with dye, provide hydrologic connectivity. Similar flow patterns were also present on other rangeland sites. During the experiments, run-on was initially applied across the entire width of the plot. However, the flow became more concentrated downstream. It did not form rills or headcuts, and on occasions the pattern was divergent. As seen on Fig. 5 the flow under run-on treatment interacted with only a fraction of the total plot area (indicated by green dye). In contrast, under rainfall treatment raindrops impact the entire surface and surface flow occurs on the entire plot area. This difference between affected areas adds to the contrast between sediment yields under rainfall and run-on.

Erosion rates on Salt River ecological sites (Table 1) differed significantly from those on San Pedro sites. Overall the former had lower unit sediment yields (<0.7 g m$^{-2}$ s$^{-1}$) and were less responsive to variation in precipitation or run-on as indicated by the smaller slopes of the regression lines (Fig. 3, YG1–YG3). In addition, on Salt River sites the difference between the two treatments was also less pronounced. Namely, rainfall generated 1.5 to 6 fold more sediments than run-on at the same flow rate, while on the other sites this difference was 7 to 42 fold. Two features that distinguish Salt River sites from other locations was vegetation and soil type. The area is located at higher elevation with greater annual precipitation (580 mm) and lower mean annual temperatures (11 °C). This allows growth of perennial sod grasses with ground biomass estimated at 1600 kg ha$^{-1}$ and effective rooting depth of 70 cm. A denser near surface root structure provides better binding of the soil particles and decreases susceptibility to erosion. The soil, Terrarosa (Fine, mixed, superactive, thermic Aridic Paleustalfs), is a more cohesive clay loam with low (6–12%) rock content. It is prone to compaction by livestock when moist. Cohesive soil with greater root penetration was likely responsible for the difference in erosion rates between Salt River sites and the rest, more so than variation in surface litter or canopy cover and structure. Debris dams consisting of litter mobilized by overland flow were sometimes observed on YG sites (Fig. 4). These dams induced ponding that further retarded splash detachment.

This trend where rainfall is responsible for generating most of sediment will likely hold true in a broader range of climatic and soil conditions. Similar tendencies have been observed in field and laboratory experiments elsewhere (An et al., 2012; Li et al., 2017; Rouhipour et al., 2006). However, the difference between the two regimes might be less pronounced in the environment with greater potential for rill and channel development. These would include areas with silty soils, low rock content, sparse vegetation, poor root structure, or periodic tillage.

3.3. Velocity effects

Overland flow velocity is related to shear stress and stream power, which are used to predict sediment detachment rates (Lafiten et al., 1997; Nearing et al., 1999; Rose et al., 1983). Hence, when comparing sediment detachment and yield under two flow treatments, the velocities under these treatments also need to be evaluated. Previous studies
conducted in laboratory conditions showed that raindrop impact reduces velocity of shallow flow through increased turbulence (An et al., 2012; Beuselinck et al., 2002; Savat, 1977). This reduction appears to be limited to the top water layer (Beuselinck et al., 2002) and tend to decrease with increasing discharge or flow depth (Savat, 1977).

In our study a total of 404 velocity measurements were obtained, ranging between $6.6 \times 10^{-3}$ m s$^{-1}$ and $61.1 \times 10^{-3}$ m s$^{-1}$. The dynamics of shallow flow generated by rainfall and run-on differ from

Table 3
Mean values of selected cover characteristics of the experimental plots. Standard deviation is shown in parentheses.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ER2</th>
<th>ER3</th>
<th>ER4G</th>
<th>K2</th>
<th>YG1</th>
<th>YG2</th>
<th>YG3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy cover, %</td>
<td>55.7</td>
<td>42.9</td>
<td>32.7</td>
<td>43</td>
<td>45</td>
<td>37.8</td>
<td>29.6</td>
</tr>
<tr>
<td>Rock, %</td>
<td>23.9</td>
<td>28.6</td>
<td>13</td>
<td>19.9</td>
<td>12.3</td>
<td>6.2</td>
<td>9.4</td>
</tr>
<tr>
<td>Litter, %</td>
<td>50</td>
<td>40</td>
<td>54.6</td>
<td>50.6</td>
<td>65.9</td>
<td>77.4</td>
<td>19.9</td>
</tr>
<tr>
<td>Basal area, %</td>
<td>8</td>
<td>11.3</td>
<td>3.8</td>
<td>4.3</td>
<td>11.1</td>
<td>10.1</td>
<td>16.5</td>
</tr>
<tr>
<td>Bare soil, %</td>
<td>18.1</td>
<td>20.1</td>
<td>28.6</td>
<td>25.2</td>
<td>5.7</td>
<td>10.1</td>
<td>6.4</td>
</tr>
<tr>
<td>Soil inter-canopy</td>
<td>13.1</td>
<td>13.6</td>
<td>20.4</td>
<td>14</td>
<td>9.2</td>
<td>4.9</td>
<td>46.3</td>
</tr>
<tr>
<td>Basal gap, m</td>
<td>0.24</td>
<td>0.22</td>
<td>0.05</td>
<td>0.43</td>
<td>0.25</td>
<td>0.2</td>
<td>0.46</td>
</tr>
<tr>
<td>Canopy gap, m</td>
<td>0.16</td>
<td>0.23</td>
<td>0.23</td>
<td>0.22</td>
<td>0.2</td>
<td>0.16</td>
<td>0.33</td>
</tr>
</tbody>
</table>
each other. If the soil is saturated and infiltration is steady, the discharge increases linearly downslope under rainfall treatment, while it decreases under run-on treatment. During the experiment discharge was measured at the outlet and represented a point value. On the other hand, velocity was measured over the lower half of the plot and represented a mean value over the corresponding 3 m length. In order to compare velocities under two treatments and relate them to unit discharge we calculated mean unit discharges \( (q_m, \text{m}^2 \text{s}^{-1}) \) for the lower half of the slope and regressed it against mean velocities \( (v_m, \text{m} \text{s}^{-1}) \) for the same distance.

It has been shown that the velocity of overland flow over eroding surface can be predicted by unit discharge alone (Abrahams et al., 1996; Govers, 1992; Nearing et al., 1997; Takken et al., 1998). This empirical relationship lead to formulating of slope-velocity equilibrium hypothesis (Nearing et al., 2017), which suggests the presence of dynamic feedback between overland flow and surface roughness. According to the hypothesis increased flow velocity accelerates the formation of rougher surface on rangeland slopes, primarily due to creation of rock pavement. This in turn acts to impede the velocity. A power model proposed earlier for the same dataset (Polyakov et al., 2018a) was used to describe this relationship for two water application treatments on each site:

\[
v_m = \alpha \cdot q_m^{\beta_i}
\]

where \( \alpha_i \) and \( \beta_i \) are empirical regression coefficients, and \( i \) indicates treatment (1 or 2).

The results of the regression analysis are presented in Table 4. To test the null hypothesis \( (H_0: \alpha_1 = \alpha_2, \ \beta_1 = \beta_2) \) we used sum of squares reduction test (Schabenberger and Pierce, 2001) with reduced model nested within a full model and computed \( F_R \) statistic (Table 4). The analysis showed that overland flow velocity was not affected by water input treatment on ER2 (Fig. 6), ER4G, and YG1 sites. On ER3, K2, YG2, and YG3 sites run-on and rainfall regressions were statistically different, however there was no consistent trend indicating that one treatment produced higher velocities than the other at the same level of discharge.

Possible reasons for this could be relatively high discharge rates and partially channelized flow patterns, which increase flow depth negating raindrop impact effect. In addition, vegetation cover found on natural plots acts to partially dissipated raindrop energy that contributes to flow turbulence. Indeed, Buono (2009) found the flow under rainfall on

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**Table 4**

Coefficients of the regression equation \( v = \alpha \cdot q^\beta \) for flow velocity under two water application treatments.

<table>
<thead>
<tr>
<th>Application treatment</th>
<th>Parameter</th>
<th>ER2</th>
<th>ER3</th>
<th>ER4G</th>
<th>Site K2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \alpha_1 )</td>
<td>3.20</td>
<td>2.60</td>
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**Fig. 4.** Debris dams formed from surface organic litter on a clay loam upland site (YG2) on 8% slope at 125 mm h\(^{-1}\) rainfall intensity. The flow direction on the photograph is left to right.

**Fig. 5.** Run-on flow treatment at 12 L min\(^{-1}\) rate on clay loam upland site (YG3). The flow followed inter-vegetation micro depressions. The flow direction on the photograph is left to right.

**Fig. 6.** Overland flow velocity on ER2 site under rainfall and run on treatments. Shown trends are similar and do not fit the data significantly better than the reduced model.
San Pedro sites plots to be within the laminar flow regime (185–1280) with Darcy–Weisbach friction factor ranging from 7 to 329. The slope-velocity equilibrium phenomena (Nearing et al., 2017) observed previously on the study sites (Polyakov et al., 2018a) might have implications for generation of sediment yield. Decreased overland flow velocity caused by greater roughness results in decreased detachment. Hence the difference between detachment by raindrop and by shallow flow on rangeland slopes may become more pronounced.

4. Conclusions

Sediment yield on rangeland hillslopes was best predicted by discharge rate for both rainfall and run-on flow conditions (R² = 18% to 75%). There was statistically significant difference between two input treatments. Rainfall generated 2 to 44 times more sediment than run-on at the same discharge rate. This was attributed to several interacting factors. Overland flow was channeled and did not form rills with dendritic topology. Instead, it followed micro depressions between vegetated micro-topographic highs, and was often divergent. As a result it interacted with only a fraction of the plot area. In contrast, raindrops affected larger-topographic surface providing greater capacity to mobilize sediment. Flow velocity tended towards slope-independent equilibrium due to evolution of surface roughness. This also became a limiting factor for detachment by shear stress of overland flow. While increase in surface cover mitigates raindrop impact and diminishes splash, it may increase flow tortuosity and localized scour as water makes its way around obstacles. If surface organic litter is abundant it could be mobilized by overland flow to create debris dams, pond water and thus further diminish detachment. Other factors, such as canopy, rock, bare soil cover, or canopy gap, significantly affected sediment yield. However, there was no single secondary predictor common across all ecological sites in the study. This was likely due to the heterogeneity of the data set, and low magnitude and large variability of sediment yields. There was no evidence of rain drop impact affecting flow velocity on rangeland slopes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


