Modeling the effects of a partial residue mulch on runoff using a physically based approach

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Abstract

A partial covering mulch of residue on the soil strongly affects runoff dynamics, which consequently substantially reduces runoff amount. Experiments were conducted in la Tinaja (Mexico) on runoff plots (RPs) (20 m\textsuperscript{2}) of four different treatments (bare, unplanted with 1.5 t ha\textsuperscript{-1} of residue, planted with 1.5 and 4.5 t ha\textsuperscript{-1} of residue), to characterize mulch effects. During one crop cycle, rainfall and runoff flow were recorded at a 20 s time step. Soil moisture, crop leaf area index, saturated hydraulic conductivity and sorptivity were also measured. Mulch increased the infiltration rate of the topsoil layer, concentrated overland flow and slowed it down by increasing roughness and pathway tortuosity. The physically based model developed accounts for these mulch effects on runoff. The model consists of a production and a transfer module. Each RP is considered as a micro-catchment drained by a single channel. The production module accounts for rain interception by the plant and the mulch, soil retention and infiltration. The excess rainfall that cannot infiltrate defines runoff and is concentrated in the channel. The transfer module governs runoff flow out of the RP according to Darcy–Weisbach’s law. The model was calibrated on 12 events (five parameters). Fitted parameters provided high Nash efficiencies ranging from 0.721 to 0.828. Both runoff hydrographs and volumes were well simulated. A sensitivity analysis was carried out on eight parameters and a partial validation was done on 14 independent events. The model can be used as a predictive tool to assess the effect of various types of mulch on runoff. All its parameters are physical and can be measured or derived from literature. The model can also simulate inner variables of interest (water depth in the channel, infiltration in the channel and the hillslopes, etc.) at any time during rainfall.

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1. Introduction

Experimental knowledge about the effects of a mulch of vegetative residue on runoff is well established. Savabi and Stott (1994) proved that this porous media can store significant amounts of liquid water. Rutter et al. (1971) and later Scopel et al. (1998) showed that a mulch partly intercepts the rain.
and cuts down the quantity of water reaching the soil. Gilley and Kottwitz, (1994) observed an increase in soil retention capacity due to the modification of soil microtopography by mulch elements. Also, mulch elements act as a succession of barriers that block runoff and increase roughness (Gilley et al., 1991; Gilley and Kottwitz, 1992; Weltz et al., 1992). Consequently, runoff pathways are generally more sinuous, and runoff flow velocity lower on mulched soils (Abrahams et al., 1994; Poesen and Lavee, 1991). Finally, mulch tends to develop and strengthen topsoil structure through soil protection, macro-fauna activity and the incorporation of organic matter, which usually provides a high infiltration rate (Rao et al., 1998; Scopel et al., 1998; Valentin and Bresson, 1992; Zachmann and Linden, 1989).

However, very few authors have attempted to formalize or model these effects. Moreover, their models did not address all the previously listed effects but focused only on certain specific points. Gilley et al. (1991) modeled the uniform water flow on an impervious surface (7m$^2$) covered with glued residue, with the help of Darcy Weisbach’s law. Yu et al. (2000) used Manning’s equation to simulate overland flow on a mulched impervious soil (108 m$^2$), at a 1 min time step. In both cases, modeling was in good agreement with experimental data and contributed to the determination of a friction factor that varies according to the type of residue used. Bristow et al. (1986), and later Bussière and Cellier (1994) and Gonzalez-Sosa et al. (1999), developed two similar mechanistic vertical 1D models to simulate the heat and water regimes of mulched soil. They simulated rain interception by the plant and the mulch, and soil retention and infiltration. It defines runoff production as an excess of rain that cannot infiltrate or be stored, and is evacuated in the channel. Concerning rain interception, the distinction between the hillslopes and the channel was not taken into account. The plant and the mulch had a maximum water storage capacity, respectively, $R_p^\text{max}$ and $R_m^\text{max}$ (m), defined by:

$$R_p^\text{max}(t) = a_{LAI} LAI(t)$$  \hspace{1cm} (1a)$$

$$R_m^\text{max}(t) = a_{B_m} B_m(t)$$  \hspace{1cm} (1b)$$

where $t$ is time starting from the beginning of each rainfall event (s), $a_{LAI} = 2 \times 10^{-2}$, an empirical coefficient (m) derived from Brisson et al. (1998), LAI the leaf area index of the plant (m$^2$ m$^{-2}$), $a_{B_m} = 0.355 \times 10^{-3}$ an empirical coefficient (m ha$^{-1}$) derived from Arreola Tostado (1996), and $B_m$ the mulch biomass (t ha$^{-1}$). Plant and mulch water
storage are set at zero at the beginning of each rainfall. When rain starts, the plant intercepts all the rain till plant storage, \( R_p \) (m), reaches its maximum value:

\[
D R_p = 0, \quad R_p < R_{p,\text{max}}
\]

\[
(1 - \tau_c) D R_p, \quad R_p = R_{p,\text{max}} \text{ and } R_m < R_{m,\text{max}}
\]

\[
\Delta R_p = \begin{cases} 
\Delta R, & R_p < R_{p,\text{max}} \\
0, & R_p = R_{p,\text{max}} 
\end{cases}
\]

where \( R \) is the cumulative rain (m). This simplified approach causes an overestimation of the plant interception, when the plant coverage is low. However, the interception is very small for small values of LAI and this overestimation is negligible.

When throughfall onto the soil and the mulch begins, mulch interception, \( R_m \) (m), is proportional to mulch coverage, \( t_c \) (m² m⁻²), till it reaches its maximum value:

\[
D R_m = 0, \quad R_p < R_{p,\text{max}}
\]

\[
(1 - \tau_c) D R_p, \quad R_p = R_{p,\text{max}} \text{ and } R_m < R_{m,\text{max}}
\]

\[
\Delta R_m = \begin{cases} 
\tau_c \Delta R, & R_p = R_{p,\text{max}} \text{ and } R_m < R_{m,\text{max}} \\
0, & R_p = R_{p,\text{max}} \text{ and } R_m = R_{m,\text{max}} 
\end{cases}
\]

The amount of rain, which is not intercepted by the mulch, is transmitted to the soil. This transmission is total when mulch storage reaches its maximum value. The cumulative amount of rain reaching the soil, \( R_s \) (m), is governed by:

\[
\Delta R_s = \begin{cases} 
0, & R_p < R_{p,\text{max}} \\
(1 - \tau_c) \Delta R_p, & R_p = R_{p,\text{max}} \text{ and } R_m < R_{m,\text{max}} \\
\Delta R, & R_p = R_{p,\text{max}} \text{ and } R_m = R_{m,\text{max}} 
\end{cases}
\]

Infiltration rate in the soil, \( q_i \) (m s⁻¹), is defined:

\[
q_i = (1 - \alpha_i) q_{ih} + \alpha_i q_{ic}
\]

where \( q_{ih} \) and \( q_{ic} \) are the hillslopes and channel contributions, respectively (m s⁻¹). Infiltration rate is controlled by a potential infiltration rate \( q_{i,\text{pot}} \) (m s⁻¹), defined by the law of Philip (1957):

\[
q_{i,\text{pot}}(t) = \frac{S(\theta_0, \theta_s)}{2\sqrt{t}} + \frac{1}{3}(1 + \mu)K_s
\]

where \( S \) is the soil sorptivity (m s⁻¹/²) for initial and saturated water content, respectively, \( \theta_0 \) and \( \theta_s \) (m³ m⁻³), \( \mu \) is a parameter ranging from 0 to 1 (Haverkamp et al., 1999) and set to 0, \( K_s \) is the soil water conductivity at saturation (m s⁻¹), and \( t \) is the elapsed time from the beginning of rain (s). Hydraulic properties and initial conditions are supposed to be the same for hillslopes and channel, which lead to a single value for \( q_{i,\text{pot}} \). When the water cannot infiltrate totally into the soil on hillslopes (Fig. 1), a residual amount
\( h_h \) (m), remains on the surface:

\[
q_{ih} \Delta t = \min[h_h + \Delta R_e; q_i^{\text{pot}} \Delta t]
\]

(7a)

\[
\Delta h_h = \Delta R_e - q_{ih} \Delta t
\]

(7b)

This amount is stored till it reaches the soil surface retention capacity \( h_s \) (m), and is later infiltrated. The potential excess, \( h_{h, \text{excess}} = \max[h_h - h_s; 0] \) (m), is concentrated in the central channel with a one time step delay (20 s) (Eq. (13)), which is in good agreement with the concentration law of Gregory (1982) for a hillslope length of 1 m, a slope of 0.05, a Manning’s roughness coefficient of 0.01, and a typical rainfall intensity of 6 mm h\(^{-1}\) (Table 1). In the channel, infiltration is governed as on the hillslopes and the potential residual amount of water, \( h_c \) (m), is calculated from the amount of rainfall and infiltration:

\[
q_{ic} \Delta t = \min[h_c + \Delta R_e; q_i^{\text{pot}} \Delta t]
\]

(8a)

\[
\Delta h_c = \Delta R_e - q_{ic} \Delta t
\]

(8b)

Runoff transfer begins if water depth in the channel exceeds zero and water is evacuated from the plot. The runoff flow is described in Section 2.2.

### 2.2. Runoff transfer

The transfer module deals with runoff flow in the channel (Fig. 1), and takes into account pathway tortuosity and soil and mulch friction. It is based on

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition and main characteristics of the 26 rain events used for modeling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rain event</th>
<th>Day of year (d)</th>
<th>Duration (h)</th>
<th>Amount (mm)</th>
<th>Intensity (mm h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>Validation</td>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>1c</td>
<td>1v</td>
<td>184</td>
<td>2.41</td>
<td>16.9</td>
</tr>
<tr>
<td>2c</td>
<td>1v</td>
<td>187</td>
<td>0.34</td>
<td>1.6</td>
</tr>
<tr>
<td>3c</td>
<td>2v</td>
<td>187</td>
<td>0.30</td>
<td>3.2</td>
</tr>
<tr>
<td>4c</td>
<td>2v</td>
<td>188</td>
<td>0.16</td>
<td>2.0</td>
</tr>
<tr>
<td>5c</td>
<td>210</td>
<td>0.43</td>
<td>7.8</td>
<td>18.2</td>
</tr>
<tr>
<td>6c</td>
<td>213</td>
<td>2.87</td>
<td>8.0</td>
<td>2.8</td>
</tr>
<tr>
<td>7c</td>
<td>220</td>
<td>0.88</td>
<td>4.6</td>
<td>5.3</td>
</tr>
<tr>
<td>8c</td>
<td>224</td>
<td>0.88</td>
<td>4.8</td>
<td>5.5</td>
</tr>
<tr>
<td>9c</td>
<td>237</td>
<td>0.59</td>
<td>4.8</td>
<td>8.1</td>
</tr>
<tr>
<td>10c</td>
<td>238</td>
<td>1.41</td>
<td>7.4</td>
<td>5.3</td>
</tr>
<tr>
<td>11c</td>
<td>239</td>
<td>0.51</td>
<td>4.5</td>
<td>8.8</td>
</tr>
<tr>
<td>12c</td>
<td>239</td>
<td>0.76</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>13c</td>
<td>243</td>
<td>0.76</td>
<td>3.6</td>
<td>4.8</td>
</tr>
<tr>
<td>14c</td>
<td>245</td>
<td>0.53</td>
<td>2.0</td>
<td>3.8</td>
</tr>
<tr>
<td>15c</td>
<td>249</td>
<td>1.41</td>
<td>4.1</td>
<td>2.9</td>
</tr>
<tr>
<td>16c</td>
<td>252</td>
<td>2.25</td>
<td>5.6</td>
<td>2.5</td>
</tr>
<tr>
<td>17c</td>
<td>254</td>
<td>1.48</td>
<td>6.9</td>
<td>4.6</td>
</tr>
<tr>
<td>18c</td>
<td>254</td>
<td>0.47</td>
<td>3.2</td>
<td>6.8</td>
</tr>
<tr>
<td>19c</td>
<td>255</td>
<td>1.53</td>
<td>6.4</td>
<td>4.2</td>
</tr>
<tr>
<td>20c</td>
<td>261</td>
<td>0.42</td>
<td>1.6</td>
<td>3.9</td>
</tr>
<tr>
<td>21c</td>
<td>262</td>
<td>1.87</td>
<td>2.0</td>
<td>1.1</td>
</tr>
<tr>
<td>22c</td>
<td>272</td>
<td>1.08</td>
<td>7.6</td>
<td>7.1</td>
</tr>
<tr>
<td>23c</td>
<td>272</td>
<td>1.17</td>
<td>3.6</td>
<td>3.1</td>
</tr>
<tr>
<td>24c</td>
<td>274</td>
<td>1.25</td>
<td>4.1</td>
<td>3.2</td>
</tr>
<tr>
<td>25c</td>
<td>278</td>
<td>0.63</td>
<td>3.0</td>
<td>4.7</td>
</tr>
<tr>
<td>26c</td>
<td>285</td>
<td>0.23</td>
<td>2.6</td>
<td>11.3</td>
</tr>
</tbody>
</table>

- Minimum: 0.16, 1.5, 1.1, 2.3
- Maximum: 2.87, 16.7, 18.2, 108.0
- Average: 1.02, 4.7, 6.0, 34.6
- Median: 0.82, 4.1, 4.8, 36.0
the semi-empirical law of Darcy–Weisbach (Gilley et al., 1991):

\[ v = \sqrt{\frac{8gS_o h}{f}} \]  

(9)

where \( v \) is the horizontal runoff flow velocity (m s\(^{-1}\)), \( g \) the acceleration of gravity (m s\(^{-2}\)), \( S_o \) the slope of the rough surface (—), \( h \) the thickness of the flowing water (m), and \( f \) the Darcy–Weisbach friction factor (—).

The presence of mulch on the soil increases the length and tortuosity of runoff pathways. The flow occurs with lateral movements along an apparent shallower slope in the channel (Findeling, 2001). This effective flowing slope \( S_e \) (—) is derived from soil surface slope \( S_o \) (—), with the help of a trigonometric calculus:

\[ S_e = \frac{\sin \alpha}{\sqrt{\tau^2 - \sin^2 \alpha}} \text{ with } S_o = \tan \alpha \]  

(10)

where \( \alpha \) is the angle between horizontal and soil surface (rad), and \( \tau \) the pathway tortuosity (—), defined as the ratio between real length of a trajectory and direct length between the top and the bottom of this trajectory. The similar effect on the hillslopes is neglected.

Mulch elements also acts as a succession of physical obstacles that block runoff and delay its flow (Findeling, 2001). These complex mulch effects may be considered to be greater roughness on mulched soil than on bare soil, and are included in the model as a friction factor \( f \) that increases with mulch biomass. Allowing for mulch specificity and assuming that the channel has a negligible retention capacity, we define the potential runoff flow velocity in the channel as \( v^\text{pot} \) (m s\(^{-1}\)):

\[ v^\text{pot} = \sqrt{\frac{8gS_o h_c}{f}} \]  

(11)

The runoff flow per unit surface \( q \) (m s\(^{-1}\)) is then derived from \( v^\text{pot} \) by assuming a uniform flow in the central channel and respecting the limitation of the amount of available water in the channel:

\[ q\Delta t = \frac{\alpha_l h_c}{L} \min[v^\text{pot} \Delta t; L] \]  

(12)

where \( L = 10 \) m is the length of the RP. The residual amount of water in the channel is actualized before starting the following iteration, by accounting for runoff discharge and hillslopes inflow:

\[ \Delta h_c = -\frac{1}{\alpha_l} q\Delta t + \frac{1 - \alpha_l}{\alpha_l} h_{c,\text{excess}} \]  

(13)

where \( 1/\alpha_l \) and \( (1 - \alpha_l)/\alpha_l \) are concentration factors of the water in the channel depending on the relative width of the latter. An example of the dynamics of most variables of the model is given in Fig. 2, for a typical rain event.

3. Material and methods

Experimental data (rain and runoff dynamics), soil, mulch and plant properties, and parameters describing runoff flow were required to calibrate and validate the model. This information was obtained from measurements on different plots and is described in the subsections below. The methodology adopted for modeling consisted of three steps: (1) calibration of runoff production and transfer modules by means of an iterative procedure; (2) sensitivity analysis; (3) validation of the model.

3.1. Experiments

Experiments were performed from July to October 1998 (crop cycle) in la Tinaja (Mexico-State of Jalisco) on 4 RPs, under natural rain in a semi-arid climate. It was surrounded by metal plates and runoff water was collected in a drum (180 l) located at its outlet. When the first drum was full, a partitioning device extracted one fifth of the excess runoff, which was then stored in a second drum. Each RP formed a single replication of a specific treatment (Table 2), identically repeated since 1995: direct drilling of corn with 4.5 t ha\(^{-1}\) of corn residue mulch (RP4.5P), direct drilling of corn with 1.5 t ha\(^{-1}\) of corn residue mulch (RP1.5P), no tillage and no plant with 1.5 t ha\(^{-1}\) of corn residue mulch (RP1.5), and bare soil (RP0). Crop LAI was measured on RP4.5P and RP1.5P every week with a radiation interception measuring device (picqhelios model). The mulch was composed of vegetative corn residue (canes, leaves, etc.) from the previous crop, which were brought in from adjacent plots and spread out homogeneously on the soil.
Mulch elements were left at the surface and decomposed along the crop cycle. We assumed a mulch biomass degradation based on a decreasing exponential law with extinction factor \( a_{Bm} = 7.02 \times 10^{-3} \text{ d}^{-1} \) (Arreola Tostado, 1996). Mulch coverage was derived from previous measurements (Arreola Tostado, 1996).

The RPs were on a sandy-silt soil (16.5% clay, 23.9% silt and 59.5% sand) with a bulk density of 1500 kg m\(^{-3}\). The soil was assumed to possess homogeneous hydraulic properties within each RP. As RPs were small and thus very sensitive to invasive measurements, soil hydraulic properties were roughly estimated by measurements on adjacent plots with the same treatments. Water content at saturation \( \theta_s \) (m\(^3\) m\(^{-3}\)), hydraulic conductivity at saturation \( K_s \) (m s\(^{-1}\)), and intrinsic soil sorptivity \( S(\theta_s, 0) \) (m s\(^{-1/2}\)) were measured with the help of the 1D Beer–Kan method (de Condappa, 2000; Haverkamp et al., 1998), with 10 averaged replications (Table 2). Since this method ignores 3D fluxes and so gives rise to a slight overestimation of \( K_s \), the measured values of Table 2 were taken as upper bound values. Soil moisture was measured every week in the 0–20 cm layer of the RPs with buried TDR probes (four replications per plot). These measurements were not continuous enough to constraint the model but permitted to assess the initial soil water content \( \theta_0 \) of each event.

Rainfall and runoff dynamics were measured with an electric pluviograph and pressure sensors located at the bottom of each drum. These instruments were connected to a Campbell CR10 datalogger operating

![Fig. 2. Dynamics of some intermediate variables of the runoff-infiltration process simulated by the model for rain event 5c (Table 1) and plot RP4.5P (Table 2).](image)

<table>
<thead>
<tr>
<th>Plot</th>
<th>Plant</th>
<th>Maximum LAI (m(^2) m(^{-2}))</th>
<th>Mulch</th>
<th>Soil(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td></td>
<td>Initial biomass ( R_m ) (t ha(^{-1}))</td>
<td>Coverage rate ( \tau_c ) (−)</td>
</tr>
<tr>
<td>RP4.5P</td>
<td>Corn</td>
<td>3.1 (0.5)</td>
<td>4.5 (0.2)</td>
<td>0.70 (0.05)</td>
</tr>
<tr>
<td>RP1.5P</td>
<td>Corn</td>
<td>2.7 (0.5)</td>
<td>1.5 (0.2)</td>
<td>0.30 (0.05)</td>
</tr>
<tr>
<td>RP1.5(^c)</td>
<td>None</td>
<td>0.0 (0.0)</td>
<td>1.5 (0.2)</td>
<td>0.30 (0.05)</td>
</tr>
<tr>
<td>RP0</td>
<td>None</td>
<td>0.0 (0.0)</td>
<td>0.0 (0.0)</td>
<td>0.00 (0.00)</td>
</tr>
</tbody>
</table>

\(^a\) Soil parameters were estimated on adjacent plots.

\(^b\) At saturation (\( \theta_s = 0.420 \text{ m}^3 \text{ m}^{-3} \)).

\(^c\) This plot had direct drilling of corn with 3.0 t ha\(^{-1}\) of mulch from 1995 to 1997.
at a 20 s time step. Water temperature in the drums was measured (thermocouple) to correct thermal drift of the sensors according to previously performed laboratory calibration. When measuring pressures, allowances were made for sediment deposit on the sensors and at the bottom of the drums. Technical problems due to the erratic working of the partitioning device prevented us from using rain events that produced more runoff than the first drum capacity, which corresponded to a runoff amount of about 9 mm. We included only the small or medium rain events for this work.

A specific runoff experiment was designed to provide an in situ estimation of some key runoff parameters of the model. These measurements were performed to confirm the assumption of the model and to initialize the calibration procedure of the latter. They were carried out at the beginning of the cycle (day 187). Two artificial and constant water flows \( Q_{\text{low}} = 5.13 \pm 0.50 \times 10^{-3} \text{ m}^3 \text{ s}^{-1} \) and \( Q_{\text{high}} = 2.14 \pm 0.29 \times 10^{-4} \text{ m}^3 \text{ s}^{-1} \) which corresponded to a runoff amount of about 9 mm. We included only the small or medium rain events for this work.

### 3.2. Modeling

#### 3.2.1. Calibration of the model

From the 26 rain events used (Table 1), 12 events produced a significant runoff volume on the four RPs. All these events were necessary to explore satisfactorily the high variability of the hydrological regime of la Tinaja (rain amount, maximum rain intensity, duration, temporal structure of the rain intensity). Besides, these events had the highest signal amplitude (rain and runoff intensity) and thus the lowest sensitivity to measurement errors. The model was calibrated with these 12 events to maximize the scope of the calibration. The remaining events were used for validating the model. The observed variables were the runoff flow per unit surface, \( q_{\text{obs}} \) (m s\(^{-1}\)) and the cumulative runoff volume per unit surface, \( V_{\text{obs}} \) (m). The former was used in the calibration procedure of the model and the latter was eventually used for comparison with the model outputs.

The model was calibrated on five parameters (Table 3): (i) soil water conductivity at saturation, \( K_s \), and soil intrinsic sorptivity, \( S(\theta, 0) \), which were roughly estimated on adjacent plots, (ii) soil surface retention capacity, \( h_s \), which was not measured, and (iii) proportion of the plot width occupied by the flow, \( \alpha_l \), and friction factor, \( f \), which were difficult to assess accurately. A direct calibration of all the parameters with the help of an automatic non-linear optimizer does not always provide a relevant solution. The minimum of the error function may indeed be poorly defined for so many parameters. To avoid this eventuality we split the parameters into two sets: (i) \( K_s \), \( S \) and \( h_s \), and (ii) \( \alpha_l \) and \( f \). Both sets were calibrated with a controlled iterative procedure. Each iteration had two steps. In the first step, \( \alpha_l \) and \( f \) were kept constant and \( K_s \), \( S \) and \( h_s \) were optimized. In the second step, temporary best values of \( K_s \), \( S \) and \( h_s \) were used, and \( \alpha_l \) and \( f \) were optimized. Best values of the latter parameters were then used to start the next iteration. For the first iteration, \( \alpha_l \) and \( f \) were set to measured values of Table 4. For each step, optimization consisted in maximizing a Nash efficiency criterion, \( E_q \) (\( \alpha \)):

\[
E_q = 1 - \frac{\sum_{i=1}^{N} \left[ q(i, t) - q_{\text{obs}}(i, t) \right]^2 \, dt \} \right] \]

where \( N \) is the number of considered rain events (\( \alpha \)), \( q \) the simulated runoff flow per unit surface (m s\(^{-1}\)),...
and \( q_{\text{obs}}(t) \) the average measured runoff flow per unit surface for a given event \( i \) (m s\(^{-1}\)).

In practice, we defined a calibration range for each parameter and each RP (Table 3). The ranges of \( K_s \) and \( S \) were based on the upper bound values obtained from measurements and the usual spatial variability of one order of magnitude for such parameters. The range of \( \alpha_l \) was imposed by its physical limits. The range of \( f \) was based on measurements and plausible extreme values (Weltz et al., 1992). The range of \( h_s \) was derived from literature (Kamphorst et al., 2000).

For step one, we scanned the 3D matrix defined by the ranges of parameters \( K_s; S \) and \( h_s \) and calculated the corresponding values of \( Eq. (11) \) simulations. The best triplet of parameters was manually determined with the help of contour maps. For step two, the same method was applied to \( \alpha_l \) and \( f \) (102 simulations). The procedure was repeated until convergence, which was reached after three iterations and provided a set of five adjusted parameters for each RP.

### Table 3

Definition of the ranges used for the calibration of the model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>Unit</td>
</tr>
<tr>
<td>( K_s )</td>
<td>( 10^{-6} \text{ m s}^{-1} )</td>
</tr>
<tr>
<td>( S(u_s, 0) )</td>
<td>( 10^{-2} \text{ m s}^{-1/2} )</td>
</tr>
<tr>
<td>( h_s )</td>
<td>mm</td>
</tr>
<tr>
<td>( \alpha_l )</td>
<td>–</td>
</tr>
<tr>
<td>( f )</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 4

Experimental characterization of runoff flow for two artificial and constant water flows (uncertainty in brackets)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>RP4.5P</th>
<th>RP1.5P and RP1.5</th>
<th>RP0</th>
<th>RP0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{\text{low}} )</td>
<td>( Q_{\text{high}} )</td>
<td>Mean value</td>
<td>( Q_{\text{low}} )</td>
<td>( Q_{\text{high}} )</td>
<td>Mean value</td>
</tr>
<tr>
<td>Tortuosity ( \tau )</td>
<td>–</td>
<td>1.54</td>
<td>1.38</td>
<td>1.46 (0.08)</td>
<td>1.31</td>
</tr>
<tr>
<td>Eff. slope ( S_e )</td>
<td>%</td>
<td>4.5</td>
<td>5.0</td>
<td>4.8 (0.3)</td>
<td>5.3</td>
</tr>
<tr>
<td>Flow depth ( h )</td>
<td>mm</td>
<td>3.50</td>
<td>8.25</td>
<td>–</td>
<td>3.00</td>
</tr>
<tr>
<td>Velocity ( v )</td>
<td>m s(^{-1})</td>
<td>0.07</td>
<td>0.12</td>
<td>0.09 (0.03)</td>
<td>0.17</td>
</tr>
<tr>
<td>Friction ( f )</td>
<td>–</td>
<td>2.63</td>
<td>2.26</td>
<td>2.45 (1.50)</td>
<td>0.43</td>
</tr>
<tr>
<td>Occupation ( \alpha_l )</td>
<td>NM(^a)</td>
<td>0.15</td>
<td>0.15 (0.15)</td>
<td>NM</td>
<td>0.20</td>
</tr>
</tbody>
</table>

\( a \) Not measured.

#### 3.2.2. Sensitivity analysis

A one-at-a-time analysis of the sensitivity of the model was carried out on the five calibration parameters plus three additional parameters: the effective slope \( S_e \), the coefficient of rain interception by plant \( a_{\text{LAI}} \), and by mulch \( a_{\text{Bm}} \) (Table 5). The relative variation of the parameters \( \delta_{k,l} \) was defined as:

\[
\delta_{k,l} = \frac{p_{k,l} - p_k}{p_k} \quad \text{if } p_k \neq 0 \quad (15a)
\]

\[
\delta_{k,l} = \frac{p_{k,l} - p_k}{p_k^*} \quad \text{otherwise} \quad (15b)
\]

where \( k \in \{1; \ldots; 8\} \) is the index of parameter \( - \), \( l \in \{1; \ldots; l_k\} \) the index of current value of the considered parameter \( - \), \( l_k \) the number of values taken by parameter number \( k \) \( - \), \( p_k \) and \( p_{k,l} \) the optimum value and current value \( l \) of parameter number \( k \), respectively, and \( p_k^* = \min \{|p_{k,l}| \} \) the smallest non zero value of parameter \( k \) in absolute...
where \( j \in \{ \text{c, d, e, f} \} \) is the type of variable, and \( i \in \{ \text{p, s, a} \} \) is the index of \( \text{RP} \).

3.2.3. Validation of the model

Using optimized parameters, the model was tested as a predictive tool on the 14 rain events that were not used for calibration (Table 1). It was noted that this validation was only partial as validation events had light rain amount and intensity. The model could therefore not be tested in conditions of substantial runoff production, especially for RP4.5P. However, the validation permitted to estimate roughly the scope of the calibrated model.

4. Results

4.1. Experiments

The results of the artificial runoff experiment are presented in Table 4. Tortuosity increased almost linearly with mulch biomass, its average from 1.09 on RP0 to 1.46 on RP4.5P (Table 4). Corresponding effective slope decreased from 0.064 to 0.048. Friction factor, derived from velocity and flow depth (Eq. (11)), was strongly affected by mulch biomass and increased on average from 0.20 on bare soil to 2.45 on RP4.5P. Width occupation varied from about 0.15 on mulched plot to approximately 0.40 on bare soil. Unsubmerged mulch elements acted like micro-dams and tended to concentrate the flow, whereas bare soil let it spread more widely.

We present the runoff coefficients (RC) for 26 rain events distributed over the 1998 crop cycle on Fig. 3. These experimental results showed that the four treatments were separated event per event and on average at the cycle scale (RC = 0.05 for RP4.5P, RC = 0.16 for RP1.5P, RC = 0.22 for RP1.5, and RC = 0.44 for RP0). The differences between RC were highly significant (\( p = 0.001 \)) for all the treatments, except for RP1.5 and RP1.5P (\( p = 0.18 \)). RP0 recorded the greatest RC ranging from 9 to 80% throughout the experiment. This plot was bare and crusted (Table 2) and had no rain interception. A strong mulch effect was observed when comparing RP1.5 with RP0. The small amount of residue in RP1.5 dramatically cut down runoff (0% \( < \) RC \( < \) 57%). Mulch intercepted up to 5% of the rain and increased friction and pathways tortuosity (Table 4), which slowed the flow down. It also improved infiltration rate by soil protection. A comparison of RP4.5P and RP1.5P showed that mulch biomass had an important impact on runoff. RC was seldom greater than 0% and never exceeded 23% for RP4.5P, whereas it was often substantial for RP1.5P (0% \( < \) RC \( < \) 48%). An increase in mulch biomass enhanced the mulch effects (interception of up to 16% for RP4.5P). Finally, a slight plant effect was observed when comparing RP1.5P with RP1.5, especially in the second part of the cycle when the crop was well developed. Soil protection and rain interception by the plant (up to 5%) were probably the main factors that contributed to the decrease of RC by 5–15%.

Cumulative and instantaneous hyetograph and runoff hydrographs were obtained for every event given in Table 1. Measured runoff dynamics showed general common characteristics that can be represented by the event 5c (Fig. 4). Curves of Fig. 4a

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Parameter</th>
<th>Number of values</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_s )</td>
<td>m s(^{-1} )</td>
<td>( \delta )</td>
<td>7</td>
<td>([0.1 \cdot p_1(j); 10 \cdot p_1(j)])</td>
</tr>
<tr>
<td>( S(t_s, 0) )</td>
<td>m s(^{-1/2} )</td>
<td>( \alpha_t )</td>
<td>10</td>
<td>([0.05; 0.99])</td>
</tr>
<tr>
<td>( h_s )</td>
<td>m</td>
<td>( \alpha_s )</td>
<td>7</td>
<td>([0; 10 \cdot p_1(j)])</td>
</tr>
<tr>
<td>( \alpha_{AM} )</td>
<td>m</td>
<td>( a_{\delta_{m}} )</td>
<td>8</td>
<td>([0; 10 \cdot p_1(j)])</td>
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<td>m s(^{-1} )</td>
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<td>([0.1 \cdot p_1(j); 10 \cdot p_1(j)])</td>
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<td>m s(^{-1/2} )</td>
<td>( \alpha_t )</td>
<td>10</td>
<td>([0.05; 0.99])</td>
</tr>
<tr>
<td>( h_s )</td>
<td>m</td>
<td>( \alpha_s )</td>
<td>7</td>
<td>([0; 10 \cdot p_1(j)])</td>
</tr>
<tr>
<td>( \alpha_{AM} )</td>
<td>m</td>
<td>( a_{\delta_{m}} )</td>
<td>8</td>
<td>([0; 10 \cdot p_1(j)])</td>
</tr>
</tbody>
</table>
were ordered like cumulative runoff and never crossed, which proved that at any time during a rain event runoff followed the previously observed pattern. The general shape of the cumulative hydrographs did not vary significantly with treatment (except RP4.5P which sometimes had no runoff). They were similar to rain dynamics and may be deduced from the latter by means of a storage threshold and a reduction factor according to the treatment used. Ponding time varied significantly according to rain intensity but were also generally ordered (Fig. 4b): the quickest pondings were observed in RP0 (no interception and low infiltration rate), while RP1.5 and RP1.5P had intermediate ponding times, and RP4.5P, which had the highest interception (mulch and plant) and infiltration rate, recorded the highest ponding time (sometimes infinite). Instantaneous runoff flow was the highest on RP0, medium on RP1.5P and RP1.5 (with values slightly greater for RP1.5) and the lowest on RP4.5P, which was consistent with all the previous results.

4.2. Modeling

4.2.1. Calibration of the model

Calibrated parameters are given in Table 6. Except for RP4.5P, calibrated $K_s$ and $S(\theta, 0)$ followed
the same trend as measurements with mulch application rate (Table 2). The low value of calibrated $S(\theta_s, 0)$ for RP4.5P was due to the high ratio $K_s/S(\theta_s, 0)$, which provided the highest sensitivity to $K_s$ and the lowest sensitivity to $S(\theta_s, 0)$, through the linkage between $K_s$ and $S(\theta_s, 0)$ in Eq. (6). This mathematical artifact does not mean that sorptivity was low in RP4.5P. A simulation was carried out with $K_s = 1.25 \times 10^{-5}$ m s$^{-1}$ and $S(\theta_s, 0) = 2.40 \times 10^{-4}$ m s$^{-1/2}$, which respect the experimental trend of Table 2. This simulation provided an efficiency of 0.707, only 2.5% lower than the maximum efficiency (Table 6). Calibrated $h_s$, $\alpha_j$, and $f$ were sound in spite of high values of friction factor that will be analyzed in the discussion.

The simulation was satisfactory for the 12 contrasted events with efficiencies ranging from 0.721 for RP1.5 to 0.828 for RP0 (Table 6). Regression between simulated and observed runoff flow gave slopes in the range of 0.832–1.064 with origins always lower in absolute terms than 0.25 mm h$^{-1}$, and determination coefficients in 0.736–0.865. Residual standard deviation never exceeded 2.6 mm h$^{-1}$. The total amount of observed and simulated runoff (respectively, $\sum V$ and $\sum V$), and the bias on runoff volume ($\sum [V - V_{obs}]$) are given in Table 6, for the whole crop cycle. The total amount of runoff was well simulated for unplanted plots and somewhat underestimated for planted plots (up to 5.6 mm). Observed and simulated runoff hydrographs of two contrasted events (1c and 5c) are represented in Fig. 5. We generally observed a good agreement between simulation and observation for both events. For event 1c (Fig. 5a–d), intensity peaks were well reproduced even at the beginning when intensity was low. However, intensity was underestimated for RP1.5 (10 mm h$^{-1}$). Event 5c had a lighter rain intensity (Fig. 5e–h). Its intensity peaks were correctly reproduced with discrepancies lower than 5 mm h$^{-1}$. The advance of the model for RP1.5 and RP0 (3 min) was due to a model structural imperfection that will be debated in the discussion.

### 4.2.2. Sensitivity analysis

For all the parameters except for the third ($k \neq 3$), relative variation $\delta_{ij}$ was defined by Eq. (15a). For parameter $h_s$ ($k = 3$), $\delta_{ij}$ was defined using Eq. (15a) for RP0 and Eq. (15b) with $p_3 = 0.2$ mm for the other plots. Model sensitivity $\xi$ is presented in Fig. 6 for both output variables $q_m$ and $V$ against the relative variation of each parameter. General behavior of the model proved consistent: $\xi$ was an increasing function of $S_a$ and a decreasing function of all other parameters. The highest sensitivity was observed for
Fig. 5. Comparison of observed and simulated runoff hydrographs for two calibration events (1c on the left and 5c on the right).
KS and S for both output variables. For output variable qm, the model had a substantial sensitivity to f and S that governed runoff flow dynamics. Sensitivity was intermediate for h, αB, and α which accounted for rain retention, rain interception and relative width of the flow. As αAI had the lowest incidence, it justified the use of an approximate value obtained from literature. For output variable V, parameters h, αB, and α had the second highest impact on sensitivity. This is logical because these parameters quantified rain interception and thus runoff production. Sensitivity was moderate for αAI and α, which characterized the interception of rain by the plant and the proportion of the plot surface generating runoff, respectively. The lack of precision on α had consequently a small impact. Finally, f and S, which mainly affected runoff propagation had a small impact on runoff volume sensitivity.

4.2.3. Validation of the model

Main characteristics of validating simulations are given in Table 7. Statistical results of RP4.5P proved poor because runoff dynamics were very small. The difference between observed and simulated runoff amount was small in absolute terms (1.2 mm). For RP1.5P and RP1.5, efficiencies were higher (~0.5) and linear regression between observation and simulation gave slopes in the range of 0.452–0.492 with origins lower in absolute terms than 0.03 mm h⁻¹ and determination coefficients within the 0.499–0.527 range. Residual standard deviation remained lower than 0.7 mm h⁻¹. Small slopes meant an underestimation of runoff flow which led to a slight underestimation of runoff amount (~3 mm). For RP0, efficiency was the highest (0.661) and linear regression was closer to the y = x axis, with a determination coefficient of 0.721 and a residual standard deviation of 1.6 mm h⁻¹. The total runoff amount was well simulated.

Observed and simulated runoff hydrographs of two validation events (4v and 5v) are represented in Fig. 7. Flows in RP4.5P are very small and thus difficult to reproduce. The model proved sensitive enough to respond to event 4v but did not simulate runoff for

![Fig. 6. Model sensitivity on maximum runoff flow (a–b) and runoff volume (c–d) for the four RPs.](image-url)
event 5v. For the other treatments, we observed a good agreement between simulation and observation for both events. Intensity peaks were all qualitatively reproduced even if some discrepancies of about 5–10 mm h$^{-1}$ appeared, especially for event 4v (Fig. 7a–d). The advance of the model was observed for RP1.5 and RP0 as during the calibration of the model.

### 5. Discussion

In this work, specific experiments were designed to assess quantitatively the main effects of a partial covering mulch of corn residue on runoff. Measurements showed that runoff was dramatically cut down by mulch, even for a small amount of residue. Runoff coefficient was reduced by 50% on average by applying only 1.5 t ha$^{-1}$ of residue. This behavior was due to both short-term and long-term effects. At the cycle scale, the mulch stored up to 1.6 mm by rain interception, which reduced runoff production. Runoff was concentrated in channels, which were more sinuous and rougher when mulch biomass was high. Pathway tortuosity and friction significantly slowed down runoff flow (Table 4) and delayed runoff propagation. These phenomena were in agreement with previous investigations (Abrahams et al., 1994; Gilley et al., 1991; Savabi and Stott, 1994; Scopel et al., 1998). At the four-cycles scale (1995–1998), the decomposition of the successive mulches, even with small amounts of residue, provided a continuous organic cover made of small pieces of residue, which protected efficiently the physical topsoil structure (Findeling, 2001). Besides, this structure was also stabilized by an increase in the soil organic matter content and a higher macrofauna activity (Scopel and Findeling, 2001). Consequently, mulched soil developed higher water conductivity and sorptivity than bare soil (Table 2), and had a higher potential infiltration rate.

A gap was observed in the literature between experimental knowledge on mulches and modeling the effects of mulch on runoff. Models in literature only partially take mulch effects on runoff into account (Yu et al., 2000; Gonzalez-Sosa et al., 1999). We proposed a physically based model to account for the observed mulch effects. Its originality lies in the representation of pathway tortuosity by an effective slope and the concentration of runoff flow in a main channel, whereas the usual models are generally based on a homogeneous flow taking up the whole width (Gilley et al., 1991; Yu et al., 2000). All the model parameters have a physical meaning. They can consequently be measured or estimated, which is a big help when using the model as a predictive tool in different contexts (soil, mulch, slope, etc.).

The sensitivity analysis showed that soil hydraulic properties ($K_s$ and $S$) had a determining effect on runoff, which is in accordance with the modeling assumption of a system controlled mainly by

### Table 7

<table>
<thead>
<tr>
<th>Runoff flow</th>
<th>RP4.5P</th>
<th>RP1.5P</th>
<th>RP1.5</th>
<th>RP0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>-</td>
<td>-0.013</td>
<td>0.499</td>
<td>0.527</td>
</tr>
<tr>
<td>Slope</td>
<td>0.096 (0.004)</td>
<td>0.452 (0.007)</td>
<td>0.492 (0.008)</td>
<td>0.824 (0.012)</td>
</tr>
<tr>
<td>Origin</td>
<td>0.002 (0.003)</td>
<td>-0.030 (0.011)</td>
<td>-0.009 (0.016)</td>
<td>0.226 (0.041)</td>
</tr>
<tr>
<td>$\sigma_{tr}$</td>
<td>0.142</td>
<td>0.456</td>
<td>0.661</td>
<td>1.623</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.200</td>
<td>0.681</td>
<td>0.665</td>
<td>0.721</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Runoff amount</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sum V$</td>
<td>mm</td>
<td>0.2</td>
<td>1.7</td>
<td>3.2</td>
</tr>
<tr>
<td>$\sum V_{obs}$</td>
<td>mm</td>
<td>1.4</td>
<td>4.4</td>
<td>6.6</td>
</tr>
<tr>
<td>$\sum [V - V_{obs}]$</td>
<td>mm</td>
<td>-1.2</td>
<td>-2.8</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

* Slope, origin, residual standard deviation and determination coefficient derive from linear regression between $q$ and $q_{obs}$ of the 14 calibration events (1898 values per RP).
Fig. 7. Comparison of observed and simulated runoff hydrographs for two validation events (4v on the left and 5v on the right).
the potential infiltration rate of the topsoil layer. Although the sensitivity to $S$ was higher, $K_c$ remains the main parameter that drives runoff because its natural variability is far higher than that of $S$ (Table 2). The physical and geometrical properties of the flow ($f$, $S_c$ and $a_l$) had a slighter impact but contributed to improving simulation of runoff dynamics. Parameters characterizing water storage and interception ($h_s$, $a_{Rm}$, and $a_{t,Aij}$) mainly affected production processes, and thus, runoff volume.

The physical structure of the model made it possible to monitor meaningful intermediate variables at any time during any rain event. Fig. 2 shows the behavior of six key variables on RP4.5P, which includes plant and mulch effects. The rain event 5c was broken up in five periods named (a) to (e). During period (a), the rain began and was completely intercepted by the plant, till plant storage, $R_p$, reached its maximum value. During period (b), the plant could not intercept more water and let rain fall to the soil. The mulch intercepted rain proportionally to its coverage and let rain fall to the soil. The mulch intercepted rain, thereby leading to an underestimation of potential infiltration and an overestimation of runoff. A time compression approach that adapts the time variable to the temporal evolution of the rain intensity (Corradini and Melone, 1992) should partially solve this problem. However, a more detailed analysis that takes into account infiltration as a soil-limited and rainfall-limited process (Swartzendruber, 1974) appears necessary to significantly improve modeling. Finally, no time lag was assumed for simulating the time necessary for water flowing in the channel to reach the plot outlet, which led to an early estimation of runoff. This bias was partially counterbalanced by an overestimation of the calibrated friction factor $f$, on average 5–10 times greater than usual friction (Weltz et al., 1992; Yu et al., 2000). A quick calculation showed that for current velocities, time lag to flow from the center of the channel to the plot outlet was approximately 15 s for RP0 and 75 s for RP4.5P, while advance of simulated runoff ranged on average from 80 s for RP0 to 220 s for RP4.5P. This difference between time lags may be explained by a longer hillslope to channel time lag. Accounting for the latter in the model would probably improve the modeling significantly.
6. Conclusion

The objective of this work was to quantify and model the main effects of residue mulch on runoff processes. The experimental layout showed that runoff was dramatically cut down by mulch, even for a small amount of residue. In the short run (0–1 year), mulch intercepted rain, enhanced water flow concentration by dam effect, and slowed down runoff flow by increasing roughness and pathway tortuosity. In the long run (4 years), mulch ensured high topsoil water conductivity and sorptivity. Measurements did not permit us to tackle the dynamics of hydraulic properties evolution. A physically based model was developed to account for these effects on runoff in terms of dynamics and volume. Its parameters have a physical meaning and can be measured either directly ($K_s$, $S$, $\tau$ and $\alpha_l$), or indirectly ($a_{LAI}$, $h_s$ and $f$). The model was successfully calibrated on 12 events. A sensitivity analysis showed that soil hydraulic properties ($K_s$ and $S$) had the greatest impact on runoff for our plots. Although it was only partially validated, the calibrated model simulated satisfactorily the runoff dynamics in the four studied plots.

Acknowledgements

Financial and technical support from Centro Internacional de Mejoramiento del Maíz y Trigo (CIMMYT) as well as Institut National de la Recherche Agronomique (INRA) is gratefully acknowledged. Special thanks to Jean-Claude Gaudu for his efficient technical assistance.

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