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# RUNOFF FROM SOILS ON MARLS UNDER SEMI-ARID MEDITERRANEAN CONDITIONS

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Abstract. In semi-arid Mediterranean regions the pressure on natural resources such as water and soil is increasing. In the Maghreb, soil degradation and reservoir sedimentation are serious problems, particularly in catchment areas with a high proportion of marls. As part of an Algerian-German project of scientific-technical cooperation, the runoff from soils on marls was studied, using modem rain simulators. A description of the rainfall experiments is followed by the presentation of a simple and appropriate mathematical approach to the modelling of runoff from soils on marls, and by a discussion of the influence of cultivation on water infiltration and runoff of these soils.

Keywords: semi-arid Mediterranean climate, marls, infiltration, runoff, modelling

## INTRODUCTION

In arid and semi-arid regions water supply for irrigation and consumption is becoming increasingly difficult, as the quantity and quality of ground water is often insufficient. It is therefore necessary to create new storage reservoirs. In the past, in Algeria (North Africa) these were often established in areas with a high proportion of marly soils. These marly soils proved to be extremely susceptible to runoff, and were therefore under grave threat of erosion. The thus induced sedimentation of reservoirs and the subsequent problem of distributing decreasing amounts of water to those living downstream, led to frequent frictions between the authorities responsible for water supply and small-scale farmers in the catchment areas, who for a long time were mistakenly regarded as the principal cause of soil erosion.

Therefore the objective of a scientific-technical Algerian-German cooperation project was to develop sustainable farming systems for catchment areas with marls in North Africa. It was mainly based on the investigation of runoff processes from marly soils and on the determination of the influence of soil cultivation on runoff and erosion for several years. The 'Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH' commissioned intensive measurements and observations in small catchment-areas, both under natural conditions and involving the use of rainfall simulators. The investigations revealed interesting peculiarities regarding the hydrological properties of marly soils.

## THEORY

Soils developed on marls with a high clay content have no stable porespace. Instead, characteristics such as vigorous swelling and shrinking, to some extent combined with pronounced vertisolic processes, give them a structure which is highly variable and therefore only to a very limited degree susceptible to a mathematical description of its hydrological behaviour.

Investigations in Algeria demonstrated that the top soils on marls which had not been cultivated were intensively crusted and clogged. It is known from Literature that surface sealing is an extremely dynamic process, which is of great importance to the description of surface runoff and soil erosion. This has been documented in detail in a number of publications [8,10]. Surface sealing, which, after drying is known as surface crusting, causes a reduction in the permeability of the surface soil. In the literature, the following factors are cited as relevant to this process:

- aggregate breakdown caused by raindrop impact, wetting and surface runoff in combination with other physical and chemical factors in both water and soil [9],
- the displacement of fine materials in deeper soil horizons and the clogging of pores by its deposition,
- the deposition of fine materials on top soils on topographically suitable surfaces (e.g., in depressions, foot slopes etc.), thus smoothing the microrelief of top soils.

The thickness and the morphometry of these seals vary with the physicochemical characteristics of the soil, the precipitation and the local topography. They are also time-dependent, as crusts, especially when thin, tend to break up very quickly in dry periods. Therefore both aggregate breakdown and crust-formation may change during a rainfall event. Le Bissonnais and Singer [7] showed that the antecedent moisture content of the surface soil is among the factors exerting a strong influence on the aggregate breakdown and the crust-forming process.

According to Roth [9] aggregate breakdown due to raindrop impact may be the most important process in the clogging of aggregated soils in humid climatic zones. Also in dry and semi-humid zones, aggregate stability is cited as a major factor in determining soil erodibility. However, aggregate stability in these regions depends much more on specific soil properties than on the soil type. For example, Farres (quoted in [9]) divided those soil parameters into static factors (texture, type of clay and oxides) and dynamic factors (content of organic matter, water and salts). It has been demonstrated by Shainberg and Letey [10] and Mualem *et al.* [18], that besides physical conditions, chemical properties are of particular significance under semi-arid conditions. As the exchangeable sodium proportion (ESP) rises, the influence of the chemical composition on the infiltration behaviour of soils increases. Therefore, it was essential to distinguish the soils of the project area according to their physicochemical properties; even for extensive catchment areas this could be carried out in great detail by remote-sensing methods [12].

## METHODS AND RESULTS

### Rainfall experiments

17 measurement plots were set up on 6 different soils in the project area (see Table 1) and 54 experiments were carried out with both small and large-scale rainfall simulators. The soils were developed on tertiary clay marls of the Miocene, Oligocene and Eocene. The terrain was extremely steep, with average inclinations of 29° to 37°, and very rough surface structure. (cf. Fig. 1).

### Small-scale experiments: layout, procedure and results

The first stage in establishing measurement plots was to place the infiltration frames of 1 $m^2$ into undisturbed soil. The rainfall simulator could then be set up over this 1 $m^2$ measurement area without stepping on it. On the lower edge of each infiltration device, a drain allowed the measurement of surface runoff, using a covered collection channel leading to a float infiltrometer. Infiltrometer readings were both analogous (with the output of a water-level graph over the time axis) and digital (water-level display). Before each experiment, rainfall intensity had to be determined by measuring runoff from the plot while it was completely

**Table 1.** Physico-chemical soil parameters

| Soil according to Vogt *et al.* [11] | Soil depth (cm) | pH | C org. (%) | Texture classes in (mm), values in (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | <0.002 | 0.002-0.02 | 0.02-0.05 | 0.05-0.20 | 0.20-2.00 | >2.00 |
| Vertisols with high clay contents | 0-50 | 7.48 | 1.26 | 62 | 13 | 3 | 10 | 8 | 4 |
| | 50-80 | 7.89 | 0.90 | 69 | 13 | 3 | 9 | 3 | 3 |
| Red mediterranean soils on calcretes | 0-23 | 7.7 | 0.80 | 24 | 15 | 7 | 49 | 4 | 1 |
| Vertisols with coarse fragments | 0-12 | 7.66 | n.d. | 46 | 23 | 12 | 18 | 1 | 0 |
| | 12-120 | 7.74 | n.d. | 47 | 21 | 11 | 17 | 1 | 3 |
| Vertisols on terraces, moderately saline | 0-30 | 7.50 | n.d. | 58 | 27 | 9 | 6 | 0 | 0 |
| | 30-100 | 7.50 | n.d. | 68 | 25 | 3 | 2 | 2 | 0 |
| Saline vertisols with high clay contents | 0-12 | 7.60 | 0.60 | 50 | 32 | 9 | 7 | 2 | 0 |
| | 12-95 | 7.70 | 0.36 | 54 | 33 | 5 | 7 | 1 | 0 |
| Silty - clayey saline vertisols | 0-9 | 7.30 | 0.41 | 41 | 31 | 9 | 16 | 3 | 0 |
| | 9-24 | 7.34 | n.d. | 39 | 32 | 10 | 16 | 3 | 0 |
| | 24-100 | 7.44 | n.d. | 45 | 33 | 9 | 10 | 3 | 0 |
| Badlands on marls | 0-10 | n.d. | 0.09 | 43 | 37 | 12 | 6 | 1 | 1 |
| | >10 | n.d. | 0.03 | 32 | 48 | 10 | 8 | 2 | 0 |

**Fig. 1.** General view in project area.

covered, because the wind and the different inclinations made it impossible to determine it indirectly with any degree of precision.

Before and after each experiment the water content in the top soil (down to a depth of about 10 cm), at the edge of the plot but outside the measurement area, was determined volumetrically.

After an initial experiment with a dry top soil, for each series of measurements at each site, at least one further experiment was conducted on one of the following days (depending on the weather and the logistical situation) with a consequently higher antecedent moisture content.

Under these conditions it was possible to describe a linear precipitation-runoff relationship according to Eq. (1):

$$A_r = \varphi_r N_h - c_r \qquad (1)$$

where $A_r$ - runoff depth (cum.) (mm), $N_h$- rainfall depth (cum.) (mm), $\varphi_r$- runoff coefficient (-), $c_r$ - threshold factor (mm), at least for the experiments with moist initial conditions (Fig. 2), while runoff behaviour with dry initial conditions (Fig. 3) could not be described as accurately in this simple form.

The rainfall threshold value was determined by finding the intersection point of the

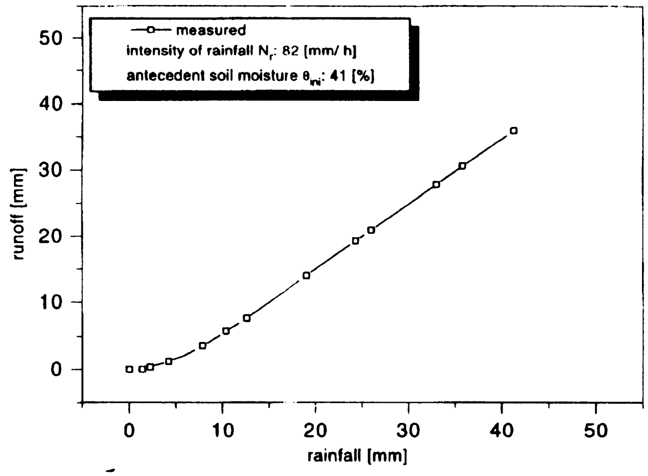

**Fig. 2.** Typical runoff behaviour with moist initial conditions.

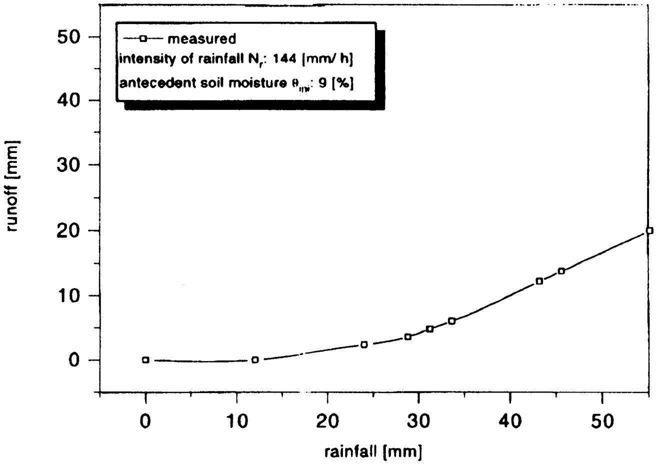

**Fig. 3.** Typical runoff behaviour with dry initial conditions.

straight lines with the rainfall axis in accordance with Eq. (2):

$$S_r = -\frac{c_r}{\varphi_r} \qquad (2)$$

where $S_r$ - rainfall threshold (mm).

In these soils which have a very high content of clay minerals with a high swelling potential [1], as expected, the rainfall threshold depended strongly on the antecedent soil moisture (see Table 2). Furthermore, each precipitation led to increased surface homogenisation due to an aggregate breakdown and thus to a reduction in concave forms as the surface microrelief was levelled out. Saline soils with poor vegetation cover proved to be significantly more susceptible to runoff than soils with less salt content. This confirms the theory that saline soils show less aggregate stability and are therefore extremely susceptible to surface sealing under the given boundary conditions (see Table 1).

In all infiltration experiments on deep soils (plots 9 and 10 in Table 2) the runoff coefficient was strikingly low, even after heavy rainfall with a high antecedent moisture content. These deep, regularly cultivated soils on marls were clearly distinct from the other soils investigated.

The soils in plots 1-3 were pedologically very similar to those of plots 9 and 10. Test plots 1-3 of these uncultivated soils were clearly more susceptible to runoff than those of plots 9 and 10, the runoff coefficient tending towards 1.0 under a high antecedent moisture content.

The saline soils (test plots 4 - 8) were the ones most susceptible to runoff. With a low antecedent moisture content and a low hydraulic conductivity, these compact soils were infiltrated by very little rainwater. With a higher antecedent moisture content and a theoretically higher hydraulic conductivity, surface sealing prevented higher infiltration rates, with the result that extremely high runoff coefficients were reached very soon.

Only plots 9 and 10 had a thin plant groundcover. The other plots on fallow land showed almost no vegetation, because of the climatic and socio-economic boundary conditions.

## Large-scale experiments: layout, procedure and results

With modern rainfall simulators, working on the principle of Foster *et al.* [3], heavy rainfall can be simulated with considerable accuracy, as regards the intensity cycle and precipitation energy.

Large-scale rainfall experiments were conducted either at a constant intensity of about 30 mm/h or with intensities varying with time (rainfall model). The pattern of this 'rainfall model', also with a precipitation of 30 mm, was determined empirically. The actual amount of precipitation in each experiment was determined by repeated totalisator control in the test area in order to take account of any extraneous factors.

The large-scale plots, roughly 100 $m^2$ in area were each delineated with sheet-metal strips set in the soil, and the outflow from the lower end of the plot was channelled via a calibrated measuring weir into a totalisator container. The temporal runoff and erosion pattern was determined by taking regular level-readings at the measuring weir and by taking samples. As it was impossible to measure the infiltration rate directly it was calculated from the difference between the rates of rainfall and of runoff.

With changing intensities, the series of rainfall experiments showed that the infiltration rate was clearly dependent on rainfall intensity both in the rising and falling limbs of the precipitation curve (Fig. 4). At every stage of intensity, the infiltration rates seemed to settle at a certain level. It was also of interest that when the antecedent moisture content was high, runoff started at very low precipitation levels with relatively low intensity, but that the infiltration rate and the runoff coefficient followed very closely all changes in precipitation intensity.

## Modelling

The hydrological model of Horton [6] and other approaches derived from it are very suitable for describing soil infiltration influenced by clogging and crusting, as many authors have already demonstrated. However, instead

**Table 2.** Rainfall and runoff data of small test plots, campaign 1989/90 and 1990/91

| Plot | Soil according to Vogt *et al.* [12] | Runoff coefficient | Intensity (mm/h) | Rainfall (mm) | Antecedent soil moist (%) | Ponding (mm) |
|---|---|---|---|---|---|---|
|  |  |  |  | 1989/90 |  |  |
| 1 | Vertisol with coarse fragments | 0.52 | 144.0 | 55.2 | 9.9 | 17.8 |
|  |  | 0.92 | 82.0 | 40.3 | 40.8 | 3.1 |
| 2 | Vertisol with coarse fragments | 0.83 | 93.6 | 233.2 | 9.8 | 23.6 |
|  |  | 0.99 | 72.0 | 72.0 | 44.0 | 3.6 |
| 3 | Vertisol with coarse fragments | 0.30 | 64.8 | 64.8 | 9.8 | 27.3 |
|  |  | 0.92 | 40.2 | 10.1 | 39.7 | 1.4 |
| 4 | Saline vertisol with high clay content | 0.48 | 69.8 | 17.5 | 7.2 | 4.4 |
|  |  | 0.89 | 69.8 | 23.3 | 16.3 | 1.5 |
|  |  | 0.83 | 50.0 | 16.7 | 24.1 | 5.2 |
| 5 | Vertisol on terrace, mod. saline | 0.48 | 37.1 | 27.5 | 9.8 | 7.7 |
|  |  | 0.68 | 43.0 | 14.3 | 28.9 | 2.2 |
| 6 | Vertisol with high clay content | 0.52 | 81.2 | 27.1 | 7.2 | 8.0 |
|  |  | 0.52 | 68.6 | 25.6 | 19.2 | 0.6 |
| 7 | Saline vertisol with high clay content | 0.60 | 49.7 | 20.7 | 7.2 | 6.6 |
|  |  | 0.85 | 49.7 | 12.4 | 17.3 | 1.5 |
| 8 | Saline vertisol with high clay content | 0.53 | 51.8 | 17.3 | 7.2 | 5.3 |
|  |  | 0.70 | 51.8 | 12.9 | 16.1 | 3.3 |
| 9 | Vertisol with high clay content | no runoff | 52.7 | 33.4 | 9.9 | >33.4 |
|  |  |  |  | 1990/91 |  |  |
| 1 | Vertisol with coarse fragments | 0.54 | 33.0 | 49.5 | 26.4 | 17.4 |
|  |  | 0.91 | 26.4 | 75.0 | 40.5 | 2.2 |
| 2 | Vertisol with coarse fragments | 0.39 | 28.2 | 33.4 | 21.7 | 11.8 |
|  |  | 0.89 | 28.8 | 55.2 | 37.6 | 5.7 |
|  |  | 0.94 | 30.0 | 19.0 | 38.9 | 0.8 |
| 3 | Vertisol with coarse fragments | 0.64 | 30.0 | 52.5 | 26.5 | 14.5 |
|  |  | 0.83 | 30.0 | 30.0 | 45.7 | 3.8 |
|  |  | 0.88 | 33.0 | 35.8 | 39.2 | 2.0 |
| 4 | Saline vertisol with high clay content | 0.76 | 31.2 | 28.6 | 23.3 | 7.0 |
|  |  | 0.87 | 25.8 | 55.0 | 29.7 | 0.9 |
| 5 | Vertisol on terrace, mod. saline | 0.43 | 18.0 | 36.0 | 22.9 | 15.9 |
|  |  | 0.55 | 31.2 | 31.0 | 41.6 | 2.9 |
|  |  | 0.99 | 24.0 | 14.0 | 40.4 | 0.5 |
| 6 | Silty - clayey saline vertisol | 0.44 | 28.2 | 14.5 | 15.5 | 3.0 |
|  |  | 0.89 | 28.2 | 50.0 | 25.9 | 0.5 |
| 7 | Saline vertisol with high clay content | 0.72 | 30.0 | 37.3 | 13.2 | 5.3 |
| 8 | Saline vertisol with high clay content | 0.67 | 27.0 | 29.0 | 13.2 | 4.3 |
|  |  | 0.91 | 30.0 | 18.7 | 17.7 | 1.5 |
| 9 | Vertisol with high clay content | 0.23 | 36.6 | 45.6 | 15.2 | 14.0 |
|  |  | 0.29 | 37.8 | 37.5 | 35.7 | 3.7 |
|  |  | 0.49 | 31.8 | 18.7 | 46.0 | 1.9 |
| 10 | Vertisol with high clay content | 0.16 | 37.8 | 57.0 | 9.7 | 14.8 |
|  |  | 0.28 | 30.0 | 30.0 | 40.4 | 1.8 |
| 11 | Silty - clayey vertisol | 0.40 | 30.0 | 30.0 | 12.5 | 5.4 |
|  |  | 0.78 | 30.0 | 17.5 | 40.7 | 1.7 |

of the functional dependence between infiltration rate and time chosen by Horton [6], Gomer [4], following Roth [9], Gunnink [5] and others, contrasted the cumulated kinetic energy with the infiltration rate. For the absolute infiltration rate $f_{(E\,kin)}$:

$$f(E\,kin) = (V_{init} - V_{final})\,e^{-W\,E_{kin}} + V_{final} \quad (3)$$

is valid, where $f_{(E\,kin)}$ - infiltration rate depending on cum. kinetic energy, $V_{init}$ - initial infiltration rate, $V_{final}$ - final infiltration rate, $W$ - curve-determining factor, $E_{kin}$ - cumulated kinetic energy of precipitation [2].

Both, the results of the small-scale infiltration experiments and of the large-scale rainfall experiments matched very well with an exponential pattern.

The experiments with low antecedent moisture contents demonstrated that in all soils the infiltration rates dropped significantly more slowly than when the antecedent moisture content was high. In the latter case, the final infiltration rate was also reached very rapidly. In contrast to the

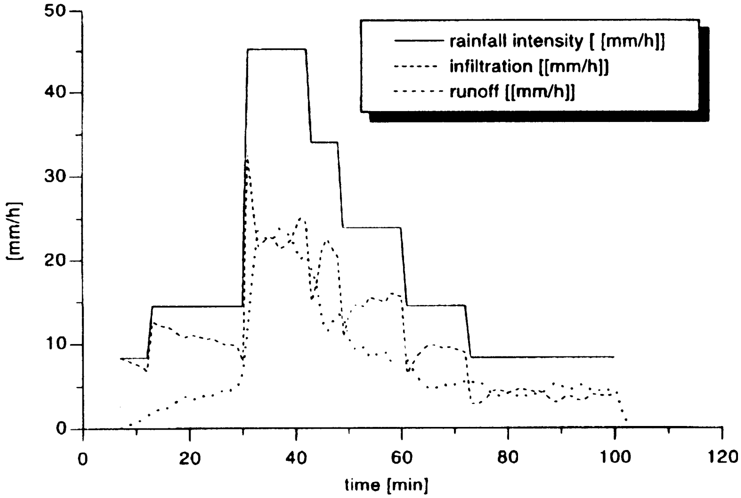

**Fig. 4.** Dependence of infiltration on rainfall intensity.

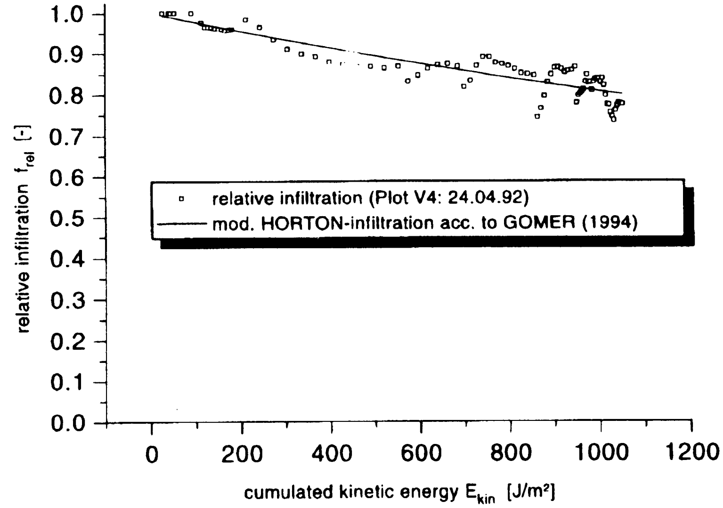

**Fig. 5.** Relation of relative infiltration $f_{rel}$ on cumulated kinetic energy of rainfall $E_{kin}$.

findings of Gunnink [5] regarding semi-arid Mediterranean soils in southern France, where the level of precipitation intensity apparently had only a negligible effect on the absolute infiltration rate, here a clear dependence on precipitation intensity could be found.

Gomer [4] thus took a different approach (Eq. (4)), relating the infiltration rate $f$ to the rainfall intensity $N_r$, and with this relative infiltration $f_{rel}$ was able to describe the behaviour of marly soils very accurately with few parameters (Fig. 5).

Instead of explaining all parameters dependent on antecedent soil moisture $\theta_{ini}$ and rainfall intensity, when matching the actual infiltration rate, it was thus possible to treat the relative initial and final infiltration rates as soil-specific and keep them constant, so that only the curve-determining parameter $W$ exhibited any dependency on antecedent soil moisture $\theta_{ini}$:

$$f_{rel.\,(E_{kin})} = \frac{f_{(E_{kin})}}{N_{r\,(t)}}$$

$$= (V_{rel.,\,init} - V_{rel.,final})\, e^{-W E_{kin}} + V_{rel.,final} \quad (4)$$

where $f_{rel.\,(E_{kin})}$ - relative infiltration rate = $f_{(E_{kin})} / N_r$, $V_{rel.,\,init}$ - relative initial infiltration rate = $V_{init}/N_r$, $V_{rel.,final}$ - relative final infiltration rate = $V_{final} / N_r$ [2].

Gomer [4] showed that the functional connection between heavy precipitation and infiltration or runoff (depending on the soil type and antecedent moisture content), which was described in Eq. (4), could be reliably extrapolated to small catchment areas. In doing so it was also necessary to take account of the absolute value of the final infiltration rate, as otherwise no further infiltration would have taken place after the cease of precipitation.

The curve-determining parameter $W$, which depends on antecedent soil moisture $\theta_{ini}$, was determined by Gomer [4] by matching the function to the empirical curve derived from the individual experiments (Fig. 6). The curve-determining factor $W$ increased much faster with soil moisture in saline soil types than in soil types suitable to cultivation, with the effect that the final infiltration rate is reached more quickly in saline soils unsuitable to cultivation than in agriculturally used soils.

## The effect of cultivation on infiltration

The effect of cultivation on infiltration was demonstrated by the results of the large-scale experiments on the 'Mehallet' measuring plot. Like all areas under cultivation, this plot had been cultivated by local farmers. The rainfall experiments on this plot were conducted some 3 months after cultivation. The first treatment with a constant intensity of approximately 30 mm/h, lasting slightly more than an hour resulted in a continuous reduction of infiltration, as the kinetic energy increased. The second experiment, which took place 5 days after the first one, continued the relative infiltration-rate pattern of the first experiment (after compensation for initial ponding) (Fig. 7). A similar behaviour was observed in all the soils investigated here, particularly (of course) when there was only a brief interval between the experiments.

After the 2nd rainfall experiment on the 'Mehallet' plot it was once more hoed by the farmers and four parallel V-shaped channels dug in it, each arm of the V being about 10 cm long, in order to investigate erosion behaviour with channel runoff. But despite intensive rainfall - again about 30 mm/h - in a third experiment, no perceptible surface runoff took place until more than an hour had passed (Fig. 8). From this it may be concluded that soil cultivation can have a very significant effect on infiltration. Taking into account the clogging and crusting mechanisms discussed above, however, the positive effect of soil cultivation on infiltration must be expected to decrease after a few rainfall events.

## CONCLUSIONS

Depending on the properties of the soil, runoff from marly soils is very strongly dependent

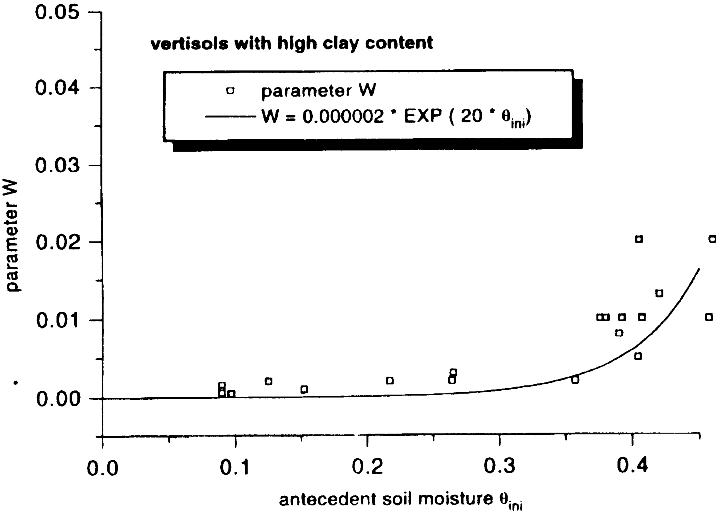

**Fig. 6.** Dependence of parameter $W$ on antecedent soil moisture.

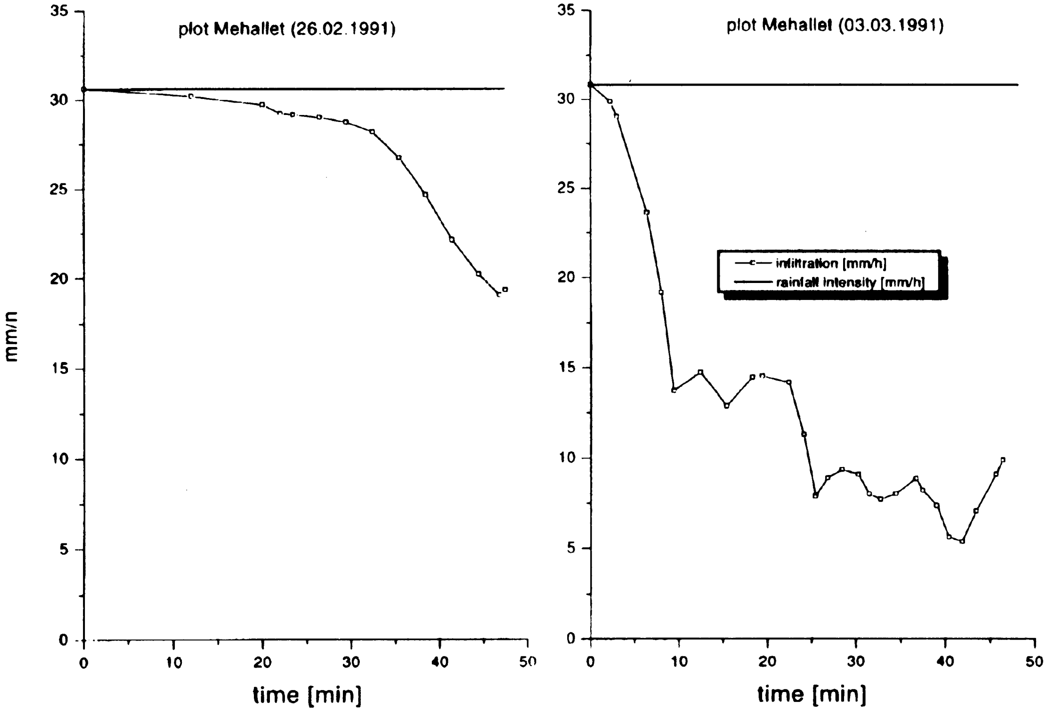

**Fig. 7.** Infiltration on plot 'Mehallet' at simulation No. 1 and 2.

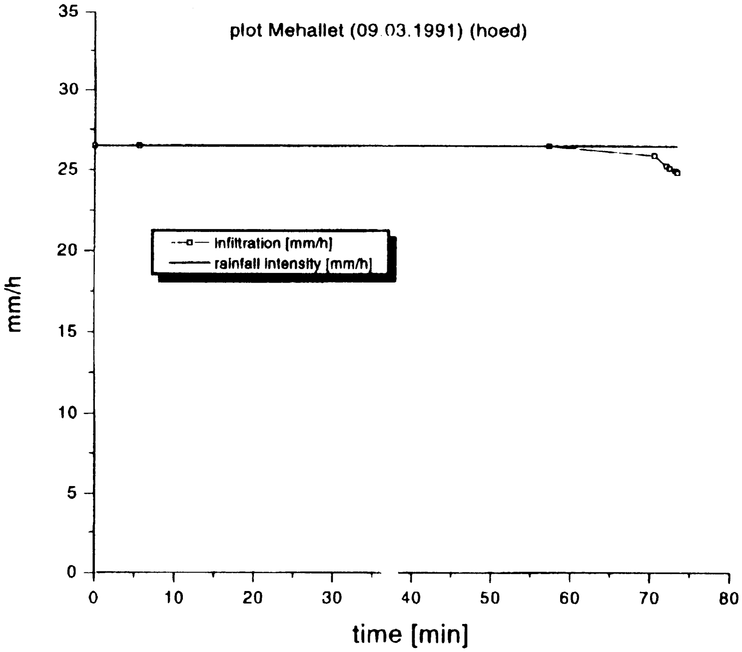

**Fig. 8.** Infiltration on plot 'Mehallet' at simulation No. 3.

on the intensity of precipitation and the antecedent soil moisture content. For a semi-arid Mediterranean climate, it can be very accurately described and modelled using the methods presented. Only very few parameters need to be determined, and these are easy to measure. Point measurements can be extrapolated to catchment areas if reliable and detailed information is available on soil-distribution, antecedent soil moisture content and topography, as shown by Gomer [4]. If the soils are properly cultivated, runoff is substantially reduced and surface sealing inhibited.

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