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Article *in* Journal of Arid Environments · February 1997

DOI: 10.1006/jare.1996.0170

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Journal of Arid Environments (1997) 35: 341–348

Evidence of high efficiency water-harvesting by ancient farmers in the Negev Desert, Israel

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(Received 21 December 1995, accepted 9 April 1996)

Ancient stone mounds and water conduits are found on hillslopes over large areas of the Negev desert. This paper presents results from field and laboratory studies, suggesting that ancient farmers were very efficient in harvesting water. A comparison of the volume of stones in the mounds to the volume of surface stones from the surrounding areas indicates that the ancient farmers removed only stones that had rested on the soil surface and left the embedded stones untouched. According to results of simulated rainfall experiments, this selective removal increased the volume of runoff generated over one square meter by almost 250% for small rainfall events compared to natural untreated soil surfaces.

Keywords: ancient agriculture; infiltration; rainfall simulation; runoff generation; stone position; water harvesting

Introduction

Stone mounds and water conduits dating from the Nabatean, Roman and Byzantine periods (4th century B.C. to 7th century A.D.) can be found on hillslopes over hundreds of kilometres square in the Negev Desert, as well as in other parts of North Africa and the Middle East (Evenari *et al.*, 1982).

Conflicting hypotheses have been offered over the last century on the function of these features. Several investigators believed that the hillslopes in the Negev Desert were cultivated by ancient farmers and that the stone mounds found over the hillslopes in a grid-like pattern spaced 5–15 m apart (Fig. 1) were used to support grape vines (Palmer, 1871), or to increase dew which would infiltrate the soil (Reifenberg, 1955), or to plant trees within them (Mayerson, 1962; Boyko, 1966). Others came to the conclusion that the stone mounds were a byproduct of surface stones clearing which was undertaken by the ancient farmers in order to increase runoff and erosion. According to this conclusion the hillslopes only functioned as a sediment (soil) source

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Figure 1. Regularly-spaced stone mounds near Avdat, northern Negev, Israel.

(Kedar, 1957) or water source (Evenari *et al.*, 1982; Hillel, 1982) to the cultivated fields which were limited to the valley bottoms.

In other contexts, many investigators realized that in arid areas runoff is generated on rock outcrops (Yair, 1983) and as rainfall excess on sealed soil surfaces (Horton overland flow), and not as a result of soil profile saturation, and thus stones at the soil surface play a crucial role in controlling runoff generation (Yair & Lavee, 1976; Wilcox *et al.*, 1988; Abrahams & Parsons, 1991; Valentin & Casenave, 1992). In several field and laboratory experiments we demonstrated that a stone cover, thought to reduce runoff as compared to a bare soil surface (Lamb & Chapman, 1943; Grant & Struchtemeyer, 1959; Jung, 1960; Epstein *et al.*, 1966; Agassi, 1970), could increase runoff depending on the stone size and position at the soil surface (Yair & Lavee, 1976; Poesen *et al.*, 1990; Lavee & Poesen, 1991). Stones resting on the soil surface (referred to hereafter as 'on top' stones), if not very big, reduced runoff as a result of shielding the surface from direct raindrop impact and hence reducing surface sealing, whereas stones well-embedded in a sealed top layer (referred to hereafter as 'embedded' stones) increased runoff due to 'stone flow' running immediately onto the surface seal (Poesen *et al.*, 1990; Lavee & Poesen, 1991). This effect increased with increasing stone size (Lavee & Poesen, 1991). However, very big stones, even when they rest on top of the soil surface increased runoff due to the high amount of stone flow (Yair & Lavee, 1976; Lavee & Poesen, 1991).

Evenari *et al.* (1982), when they concluded that the stone removal in the Negev Desert aimed at increasing overland flow, did not pay attention to the important effect of stone size and position. They claimed that all stones were picked by the ancient farmers.

The aims of the present study were: (1) to investigate, in an ancient agricultural field, the effect of ***selective*** removal of surface stones on runoff generation, and (2) to evaluate whether or not the ancient farmers took into consideration the stone size and position when clearing the hillslope surface and building the stone mounds.

Methods

The research field site was located near Avdat, a city in the centre of an ancient agricultural area in the Negev desert, Israel.

In order to measure, in the field, the effect of selective removal of on top stones on infiltration and runoff generation, the hydrological response of plots from which the on top stones were removed was compared to that of a natural uncleared plot. Due to the presence of biogenic macropores under on top stones, runoff yield is expected to decrease immediately after such stones are removed. Increased runoff was presumably achieved, by the ancient farmers, some time after stone removal, when, after a few rainfall events, the biogenic macrophores closed up due to the high susceptibility of soil aggregates to sealing and crusting. Therefore, in order to study the runoff response of soil surface from which the on top stones were removed and the macropores sealed, two plots were chosen from which all stones were removed about 30 years ago and which, at the time of the present experiments, contained a high proportion of embedded stones at the soil surface.

The runoff response of these two plots dominated by embedded stones was compared to that of a nearby natural uncleared plot. Simulated rainfall experiments were conducted using a rotating disk rainfall simulator (Morin *et al.*, 1967). Simulated rainfall was applied over 60 min at a constant intensity of 31·8 mm h^{-1}, to the three runoff plots. The runoff plots, 1 m^2 in size, were constructed by inserting metal sheets (10 cm wide × 0·5 mm thick) about 1–2 cm into the top soil. A gutter was installed to collect overland flow at the lower part of each runoff plot. All runoff plots had similar gradients (8–10·5°). During the experiments the time to runoff was noted and runoff discharge was measured at intervals of 1–2 min.

In order to study whether ancient farmers removed only the on top stones while leaving the embedded ones untouched, the volume of stones of different sizes in six representative stone mounds was compared to that of both the on top and embedded stones in the respective surrounding areas from which stones were collected when building the mounds (referred to hereafter as 'contributing areas'). This comparison included the following procedure: (1) Mapping the location of the stone mounds; (2) Delineating the contributing area for the six stone mounds, using the Thiessen Polygon method (Thiessen, 1911); (3) Collecting the stones of each mound and from a sample of 2 m × 2 m area of the contributing area of each mound; (4) Separating the collected stones into the following size fractions; 2–4 cm, 4–8 cm, 8–16 cm, 16–32 cm, and >32 cm; (5) Separating the collected stones from the contributing areas also according to their vertical position, i.e. either on top or embedded; and (6) Measuring the total volume of the stones of each position and size fraction, using the submersion technique.

Results and discussion

Rainfall simulation experiments

Figure 2 shows the infiltration curves, calculated according to the equation developed by Morin & Benyamini (1977), for the two plots (No. 1 and No. 2) from which all stones were removed about 30 years ago and which, at the time of the present simulated rainfall experiments, contained a high proportion of embedded stones, and a natural uncleared plot (No. 3). Surface cover of embedded stones for plots 1, 2 and 3 was 28%, 48% and 31%, respectively. Surface cover of on top stones for plots 1, 2 and 3 equaled 9%, 9% and 29%, respectively. Infiltration rates are expressed as a fraction of the rainfall intensity. This figure clearly indicates that selective removal of most of the on top stones decreased the time needed to initiate runoff, and drastically reduced infiltration rates as compared to the natural plot. This is in line with other findings in laboratory experiments (Poesen *et al.*, 1990; Lavee & Poesen, 1991) and field experiments conducted in a similar climatic environment (Valentin & Casenave, 1992). The runoff yield in our field experiments is presented in Table 1. The results show that runoff yield for the treated plots increased by 245%, 83%, 48% and 45% for

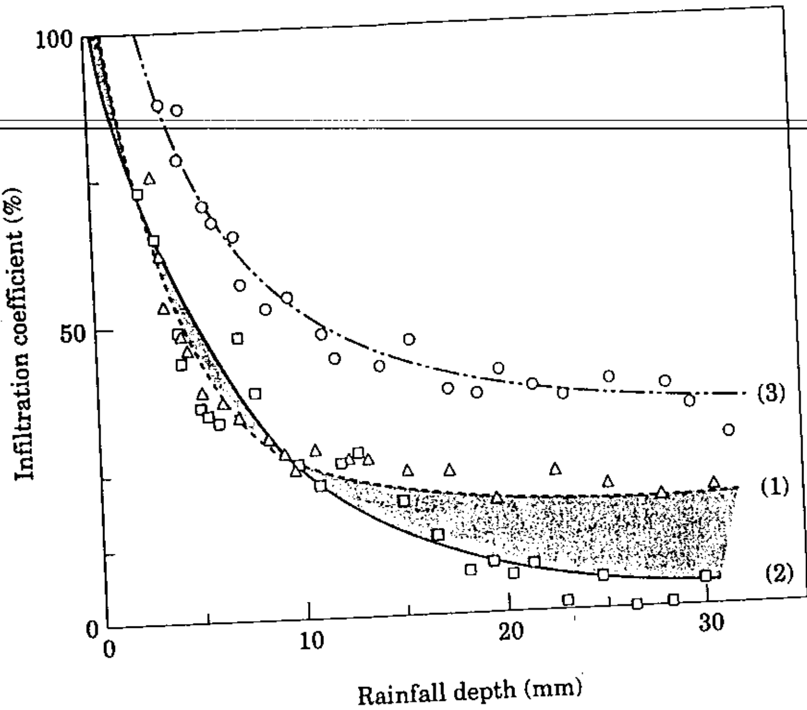

Figure 2. Infiltration curves for plots containing mainly 'embedded' stones (plots 1 and 2) *vs.* natural uncleared plot (plot 3). (△) = plot 1; (□) = plot 2; (○) = plot 3.

rainfall depths of 5 mm, 10 mm, 20 mm and 30 mm, respectively, compared to the runoff yield for the untreated plot. This means that the effect of selective stone clearing on runoff yield is most effective for short duration rainfalls, which occur frequently in the study area.

Once runoff was generated, it was intercepted by parallel conduits constructed to cross the contour lines at a slight angle and which led to the cultivated fields. Distances between consecutive conduits are typically 5 to 15 m, and up to 12 parallel conduits can be found on a single hillslope. Evenari *et al.* (1982) claimed that the conduits were built in order to prevent flash floods. Field measurements taken (Lavee & Yair, 1990) during 4 years near the present study area led to a different conclusion. Runoff plots were installed and some of the runoff yield data are presented in Fig. 3. These data are based on runoff measurements at three plots: Plot A, 65 m in length, extends from the divide to the hillslope base, while plots B and C drain the lower and upper sections of the hillslope, respectively. Plots B and C together are similar to plot A. Figure 3 shows that specific runoff yield from plot A is systematically lower than that from plots B + C together, particularly during small runoff events, i.e. specific runoff yield decreased with increased hillslope length. This is attributed to the combination of frequent very short rainshowers and the relatively high infiltration rate even at the end of a rainfall

Table 1. *Runoff yield (mm) from the treated ('on top' stones removed) and the natural runoff plots, for different rainfall amounts*

	Rainfall amount (mm)			
	5	10	20	30
Natural plot	0·275	2·30	8·20	14·40
Treated plots (average)	0·95	4·20	12·10	20·85

Under such conditions runoff flowed only over a relatively short distance downslope before infiltrating into the soil. Such a distance may range between 2 to 10 m during rainfall events which occur five to ten times per year, and 60 m during a rainfall event occurring, on average, once per year. Without water conduits most of the runoff generated at the upper part of the hillslope infiltrates before reaching the valley bottom. Accordingly, the spatial distribution of the conduits minimizes runoff discontinuity and is very efficient for water harvesting as it permits runoff collection from the upper part of the hillslope even for relatively small runoff events.

Volume and size distribution of stones

Comparison of stones in the mounds with those of the contributing areas is based on the assumption that the present stone cover in the contributing areas is similar to that which the ancient farmers found before clearing the hillslopes and constructing the stone mounds. Field evidence indicates that this assumption is justified. We determined stone distribution within the soil profile by digging four pits in the contributing areas. Each pit, one square metre in area, was dug down till bedrock was reached (about 25–30 cm). The total volume of stones and the stone size distribution were measured at depths of 0–10 cm, 10–20 cm and 20–30 cm. We found that the volume and size distribution of stones in the upper 8 cm of the soil is similar to the volume and size distribution of surface stones. This means that there are enough stones present in the subsoil for producing a new erosion pavement, similar to the present one, after clearing the surface stones. Erosion of the fine earth in the upper

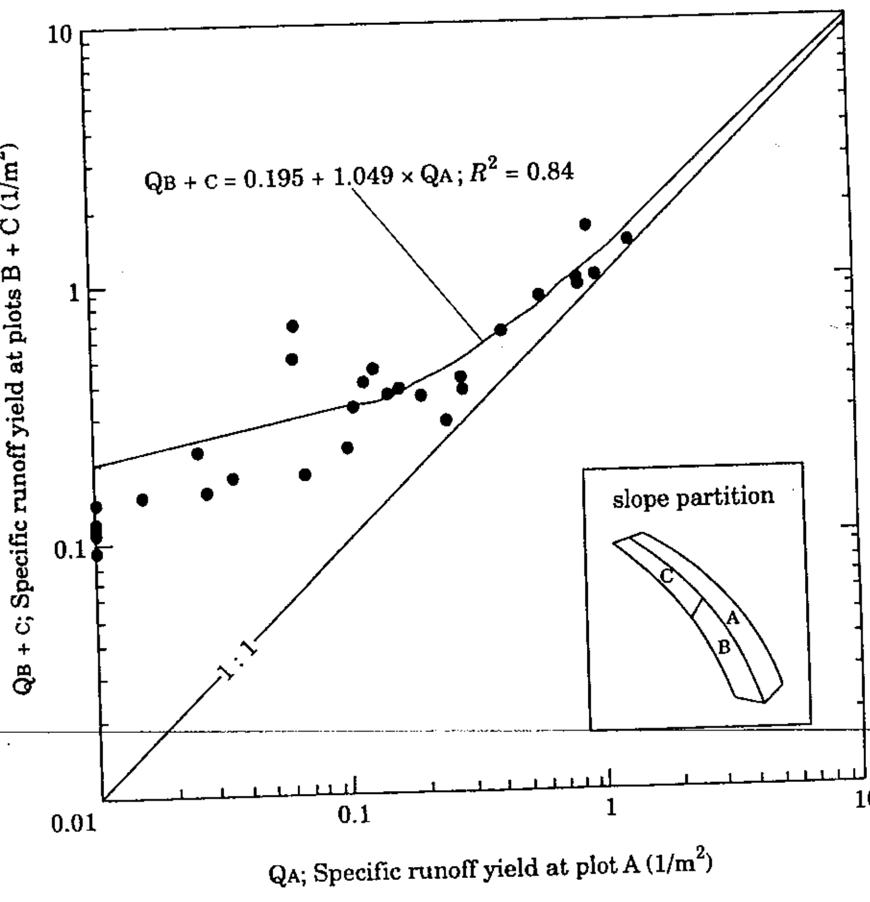

Figure 3. Specific runoff yield data from plot A against plots B + C combined.

Table 2. *Volumetric (1) size distribution of stones in mounds and in contributing areas*

	Site 11			Site 12			Site 13		
	Contributing area			Contributing area			Contributing area		
Size (cm)	On top	Total*	Mound	On top	Total*	Mound	On top	Total*	Mound
2–4	13·0	25·6	9·6	12·5	24·8	6·5	24·8	39·7	13·7
4–8	94·7	116·8	67·6	91·4	113·0	57·2	89·2	143·8	59·1
8–16	104·7	120·5	73·1	101·4	116·8	96·9	158·8	218·4	105·5
16–32	22·1	31·6	23·3	21·6	30·8	17·6	185·2	259·7	58·4
>32	44·3	44·3	0·0	43·2	43·2	0·0	73·2	73·2	0·0
Total	278·8	388·8	173·6	270·1	328·6	178·2	531·2	734·8	236·7
	Site 14			Site 15			Site 16		
	Contributing area			Contributing area			Contributing area		
Size (cm)	On top	Total*	Mound	On top	Total*	Mound	On top	Total*	Mound
2–4	60·8	71·1	99·3	16·6	40·8	19·2	12·2	29·2	13·5
4–8	61·3	122·9	68·6	63·1	165·0	35·2	44·2	115·6	46·6
8–16	179·2	261·3	202·3	87·4	252·3	61·7	51·2	166·8	39·5
16–32	143·4	759·2	147·8	140·7	368·8	110·2	98·6	258·4	63·1
>32	163·9	1150·1	178·3	0·0	786·2	65·2	0·0	550·8	27·4
Total	608·6	2164·6	696·3	307·8	1613·1	291·5	206·2	1120·8	190·1

*Total includes both 'on top' and 'embedded' surface stones.

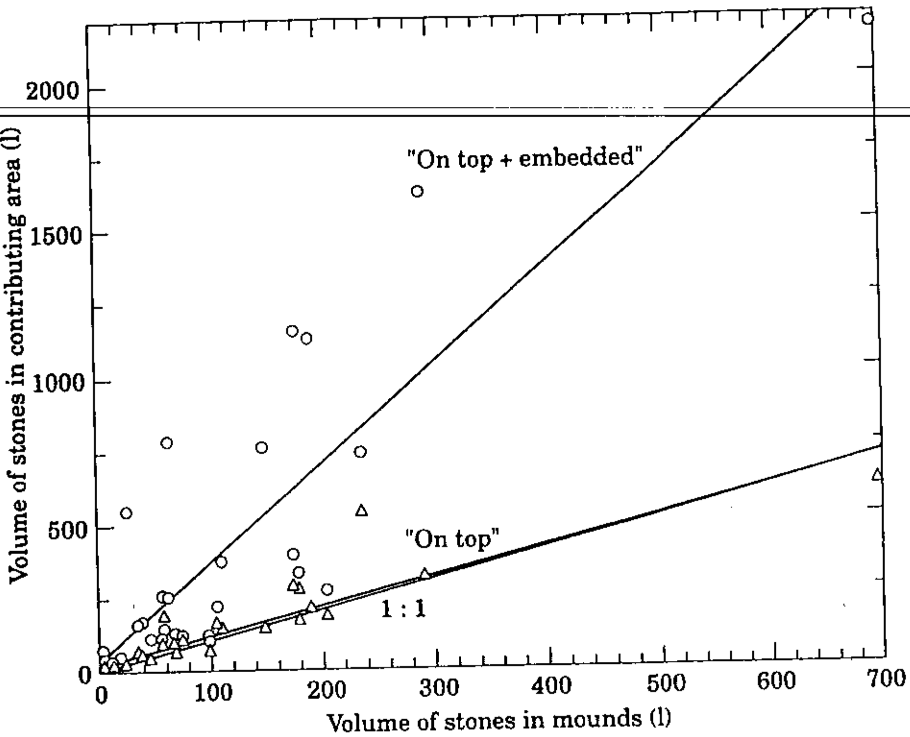

Figure 4. Volume of stones of various size classes in the mounds *vs.* volume of 'on top' stones (△) and volume of 'on top + embedded' stones (○) of the same size classes in the corresponding contributing areas.

8 cm would result in such a pavement. Additional field measurements conducted by Sharon (1962) revealed that several years are sufficient for erosion processes to develop an embedded stone cover over 75% of the area. Hence over the last 1300 years, since the decay of this ancient farming system in the Negev, a well-developed erosion pavement could be formed.

Table 2 presents the volumetric stone size distribution in the mounds and in the contributing areas. The volume of stones in contributing areas was calculated using the equation: $x = y \times z/4$, where: x = volume of stones in the contributing area, y = measured volume of stones in the 4 m^2 sampling area, and z = the contributing area (ranged between 48 m^2 and 158 m^2). The data indicate that the volumes of each stone size fraction in the mound is relatively close to the corresponding volume fraction of the on top stones in the contributing area. Figure 4 presents the volume of on top stones and the volume of on top + embedded stones of various size classes in the contributing areas *vs.* the volume of stones of the same size classes in the corresponding mound. The regression line between the volume of stones in mounds and the volume of the on top stones in the contributing areas is close to 1:1. The regression line corresponding to the volume of all surface stones is well above the 1:1 line. This strongly suggests that the ancient farmers did not remove all the stones in the contributing areas, as suggested by Evenari *et al.* (1982), Kedar (1957) and Hillel (1982), but removed only the on top stones (probably not the very big ones; see Table 2, sites 11, 12, 13) from these areas.

To sum up, the ancient farmers appear to have been well aware of the mechanisms of overland flow generation on stony soils and of overland flow continuity on arid hillslopes. It is very likely that they mainly removed the on top stones and left the embedded ones untouched not only because this provided the highest efficiency for runoff generation, but also because it consumed less labour as compared to the removal of all stones. In addition, they must have come to realize that installing closely spaced conduits running in parallel along the hillslope would increase the trapping efficiency of runoff on its way downslope.

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HYDROLOGICAL PROCESSES, VOL. 5, 345-360 (1991)

OVERLAND FLOW GENERATION AND CONTINUITY ON STONE-COVERED SOIL SURFACES

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ABSTRACT

The influence of stone cover on the generation and continuity of overland flow is a function of several variables, primarily stone size, distance (spacing) between stones, and stone position (on top of the soil surface or partially embedded). The initial hypothesis of the present study were that stone size affects overland flow generation by inducing 'concentration overland flow' and that the distance between stones affects overland flow continuity.

With respect to stone size and distance between stones, opposing results have been found in the literature. Accordingly, the present paper reports on laboratory experiments which were conducted to investigate, systematically, the effect on overland flow of stone size, distance between stones, and stone position.

The main conclusions were:

1. Stone cover tended to induce overland flow, relative to bare soil. Small stones, however, especially in a low-cover percentage setting, and when resting on top of the soil surface, produced less overland flow than bare soil.
2. Overland flow was positively related to stone size, but inversely related to distance between stones.
3. Overland flow yield was always greater when stones were embedded than when on top of the soil surface.
4. The effect of stone size on increasing the degree of overland flow was of greater significance than the effect of the distance between stones on reducing overland flow.

KEY WORDS Overland flow Stone cover Stone position Stone size Distance between stones

INTRODUCTION

Overland flow is generated when the application rate of water (rainfall and/or runoff) exceeds the infiltration rate of the soil. As a result, due to the high infiltration rates in vegetated areas, overland flow is not generated until the soil is saturated. In areas with low vegetation cover, however, a rapid decline in the infiltration rate as a function of seal formation at the soil surface induces overland flow generation even on relatively dry soil. These two mechanisms of overland flow generation are well known as 'saturated overland flow' and 'Horton overland flow'. A third mechanism might be called 'concentration overland flow'. This occurs when water is locally concentrated on relatively impermeable objects, such as stones, and when the water flow from the stone ('stone flow') to the soil surface per unit time is greater than the soil infiltration rate (Yair and Lavee, 1976). A similar effect can occur due to vegetation (e.g. stemflow).

The influence of stone cover on overland flow could be a function of several variables. The main ones are:

1. Stone size. This may have opposing effects. On the one hand, bigger stones supply more 'stone flow' than smaller ones. Therefore, a positive relation between stone size and overland flow generation might be expected. On the other hand, the stone protects the underlying soil from the impact of raindrops, thus preventing surface sealing and subsequent overland flow. Larger stones will cover and protect more of the soil surface area and will have a greater perimeter along which water can infiltrate.
2. Stone position ('on top' of the soil surface or partially embedded). This variable controls the infiltration rate of the soil near the stone edges. In the 'on top' position, and especially if the stone is rounded, the soil

0885-6087/91/040345-16$08.00

Received 10 September 1990
Revised 10 January 1991

under the edges of the stone is not in direct contact with the stone but it is still protected from surface sealing. More water may infiltrate into such an area relative to the area near the edges of a partially embedded stone (Poesen *et al.*, 1990). Thus stone position will, in part, determine which of the opposing effects caused by stone size will dominate.

3. Distance (spacing) between stones. This variable is a function of the percentage of stone cover which affects the size of the protected area, total stone perimeter, and the surface roughness. At the same time, the distance between stones will affect flow continuity. If the distance between stones is high, the 'concentration overland flow', which will be generated at the stone periphery, will infiltrate before reaching the next downslope stone.

Thus a combination of large stones, especially if embedded, and small distances between stones might lead to continuous overland flow even if the infiltration rate of the soil is relatively high.

PREVIOUS STUDIES

High stone cover is characteristic of natural landforms such as alluvial fans and terraces, scree slopes, pediments, and hamadas (Figure 1a), as well as of agricultural areas where cultivation tends to expose stones at the surface (Figure 1b).

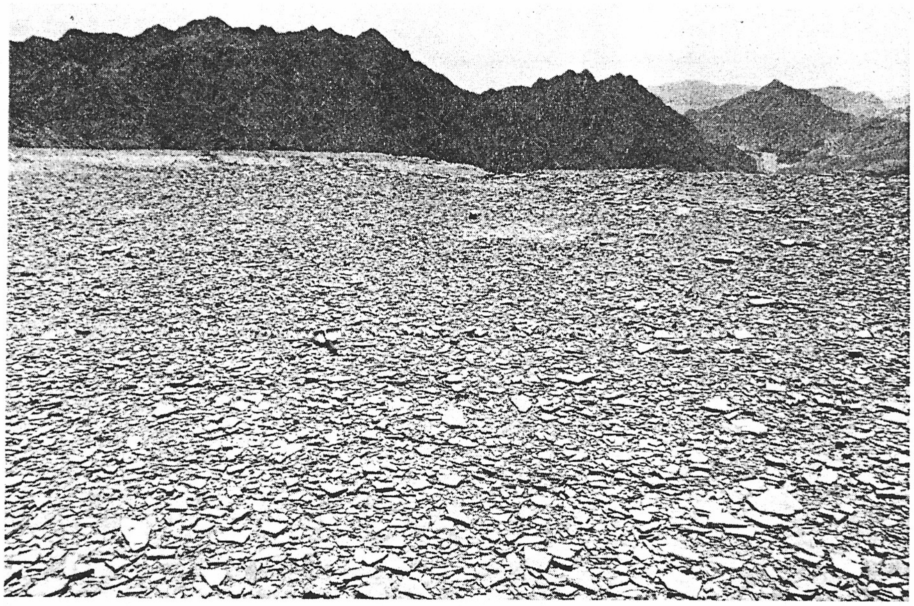
The effect of stone cover on runoff and erosion has been studied, therefore, for natural landforms (Blackburn, 1975; Yair and Lavee, 1976; Simanton *et al.*, 1984; Grinbaum, 1986; Bradford *et al.*, 1988; Parsons and Abrahams, 1989) and for cultivated areas (Lamb and Chapman, 1943; Grant and Struchtemeyer, 1959; Jung, 1960; Bertrand *et al.*, 1964; Epstein *et al.*, 1966; Box, 1981). There are a greater number of studies for cultivated areas because of the challenge agricultural engineers have faced in trying to find an optimal situation in the field for the use of stone cover. On the one hand stones can reduce overland flow and erosion but yet create an agrotechnical obstacle.

Most studies have been carried out in the field but some were based on laboratory experiments (Agassi, 1970; Koon *et al.*, 1970; Poesen, 1986). High and low slope gradients, many soil types, as well as different ranges of stone sizes and stone cover percentages were used. In many cultivated plots large stones were removed from the surface (Lamb and Chapman, 1943; Grant and Struchtemeyer, 1959; Jung, 1960; Epstein *et al.*, 1966; Box, 1981). In doing so, stone size and stone cover percentage effects could not be analysed separately.

The conclusions of the studies dealing with the hydrological response of stone-covered soil surfaces to rainfall were not always consistent. Several studies reported a negative relation between stone size and stone cover percentage, to overland flow yield (Lamb and Chapman, 1943; Grant and Struchtemeyer, 1959; Jung, 1960; Epstein *et al.*, 1966; Agassi, 1970), while others found positive relation (Bertrand *et al.*, 1964; Yair and Lavee, 1976). Yet some have presented different trends. For example, Tromble *et al.* (1974) and Bradford *et al.* (1988) found a positive correlation between cover percentage and overland flow yield for small stones, but a low correlation (or even negative) for large stones. Grinbaum (1986) found a negative relation between stone size and overland flow yield, but a positive relation between stone cover percentage and overland flow yield. Koon *et al.* (1970) found a negative correlation between the distance between stones and the overland flow yield per unit length of stone perimeter.

Several reasons have been offered to explain these results. Frequently cited is the protection of the soil by the stone from raindrop impact. Other explanations refer to the effect of water concentration by large stones (Yair and Lavee, 1976), the vesicular layers formed below the stones (Blackburn, 1975; Shanan and Schick, 1980), the improved incorporation of small stones within the soil compared to the large ones (Agassi, 1970; Bradford *et al.*, 1988), the 'effective width' and the total perimeter of the stones (Koon *et al.*, 1970), and the influence of the stones on the surface roughness as well as on the overland flow depth and velocity (Meyer *et al.*, 1972; Van Asch, 1980; Box and Meyer, 1984; Grinbaum, 1986).

Few researchers have tried to explain the abovementioned conflicting trends. Yair and Lavee (1976) claim that the different ranges of stone size and stone cover percentage of the study sites are responsible. Bradford *et al.* (1988) emphasized the difference between studies under laboratory or cultivated conditions, and those in natural conditions in arid and semiarid areas where a compacted stone pavement exists. Finally, Poesen *et al.* (1990) suggested that different stone positions (on top or embedded) was the cause.



(a)

(b)

Figure 1. Stone cover typical to (a) a natural landscape (Southern Israel), and (b) a cultivated area (Northern France)

AIM

The aim of the present study was to test the hypotheses that increasing stone size affects overland flow generation by inducing 'concentration overland flow' and that an increase in the distance between stones decreases overland flow continuity, by collecting, under controlled conditions, quantitative data on the pure effect of stone size, stone position, and distance between stones on the overland flow from stone-covered soil surfaces.

METHODS

A set of experiments was conducted with simulated rainfall, soil, and stones (Laboratory for Experimental Geomorphology, Leuven, Belgium). All rainfall, soil, and topographic characteristics controlling overland flow generation were kept constant except for three variables: stone size, distance between stones (which is a function of cover percentage), and stone position.

Rainfall

A high intensity nozzle produced, at a water pressure of 31 kPa, rainfall with an average intensity of 71·3 mm h^{-1} and a spatial uniformity coefficient of 94 per cent. Raindrop median size was 2·2 mm and fall height was 3·25 m. Hence, the kinetic energy at the soil surface reached 15·8 J m^{-2} mm^{-1} of rain. This energy approximates 60 per cent of the energy of natural rainfall with a similar rainfall intensity (Kinnell, 1987). Rainfall duration for each experiment was 60 min.

Soil and stones

Mixing an industrial silica sand and silica silt produced a loamy sand soil containing 1·8 per cent clay, 12·9 per cent silt, and 85·3 per cent fine sand. New air-dry soil material was used for each experiment. Simulated 'stones' were cut from 2 cm thick extruded polystyrene plates. This material is impervious but because of its low density (0·0338 g cm^{-3}) single pebbles were placed on top of each polystyrene element in order to prevent it from floating when overland flow is generated (Figure 2).

Plot

A plot box, 180 cm length by 127 cm width, was installed under the rainfall simulator. A soil layer, 3 cm deep, was placed on a double layer prewetted cheesecloth which was supported by a 1 cm thick perforated P.V.C. plate. The gradient of the soil surface was 4·5 per cent. The flume was cleaned after each experiment.

Variables

1. Stone size. The designed stones were squares with edges of 3, 6, 12, or 24 cm. However, in order to achieve the same cover percentages for all stone sizes, several stones were cut into smaller ones, so that the final average sizes were 3·0, 5·9, 11·7, and 22·3 cm (Figure 2),
2. Distance between stones. Four stone cover percentages were simulated: 30, 49, 70, and 88. This resulted in different distances between stones, which varied from 0·24 cm to 15·43 cm. In order to prevent straight downslope runoff flowlines the stones were arranged in a 'running bond' pattern (Figure 2).
3. Stone position. Two positions were tested: on top of the soil surface and partially embedded. In the latter case, in order to avoid soil compaction, the stones were placed on the surface of a 2 cm deep soil layer and then another 1 cm of soil was added in the interstone space.

Measurements

Measurements were taken only from the central part (95·5 cm long by 60·0 cm wide) of the flume. Hence, a buffer zone of 30 to 40 cm at each side of the flume was left in order to compensate for splash losses from the central test area (Poesen *et al.*, 1990) (Figure 2). Overland flow samples were collected at 1 min to 5 min intervals and the discharge was calculated. Rainfall intensity was measured at the beginning and towards the end of each experiment and the average value was calculated. In order to collect data for four stone sizes, four stone cover percentages, two stone positions, and a control treatment, i.e. a bare soil, a minimum of 33 experiments had to be performed. In all, however, 49 experiments were actually conducted including replicates for a selected number of different stone sizes, positions, and stone cover percentages. The resuts of the replicates were similar and the average is presented in the paper.

RESULTS

Rainfall intensities (I) throughout the experiments are shown in Table I.

Figure 3 presents the calculated hydrographs for the four different stone sizes (S), four stone cover percentages (C), and two stone positions. These are standardized hydrographs for the average rainfall intensity. The original hydrographs were corrected by multiplying the runoff-rainfall ratio of each overland flow measurement with the average rainfall intensity. The following trends can be seen:

1. Stone cover was found to increase overland flow in comparison with bare soil (except in combination with the smaller stones having low stone cover percentages and in an 'on top' position).
2. Overland flow increases with increasing stone size and stone cover percentage.
3. For a given stone size and cover, overland flow was always higher for an embedded position than for the 'on top' position.

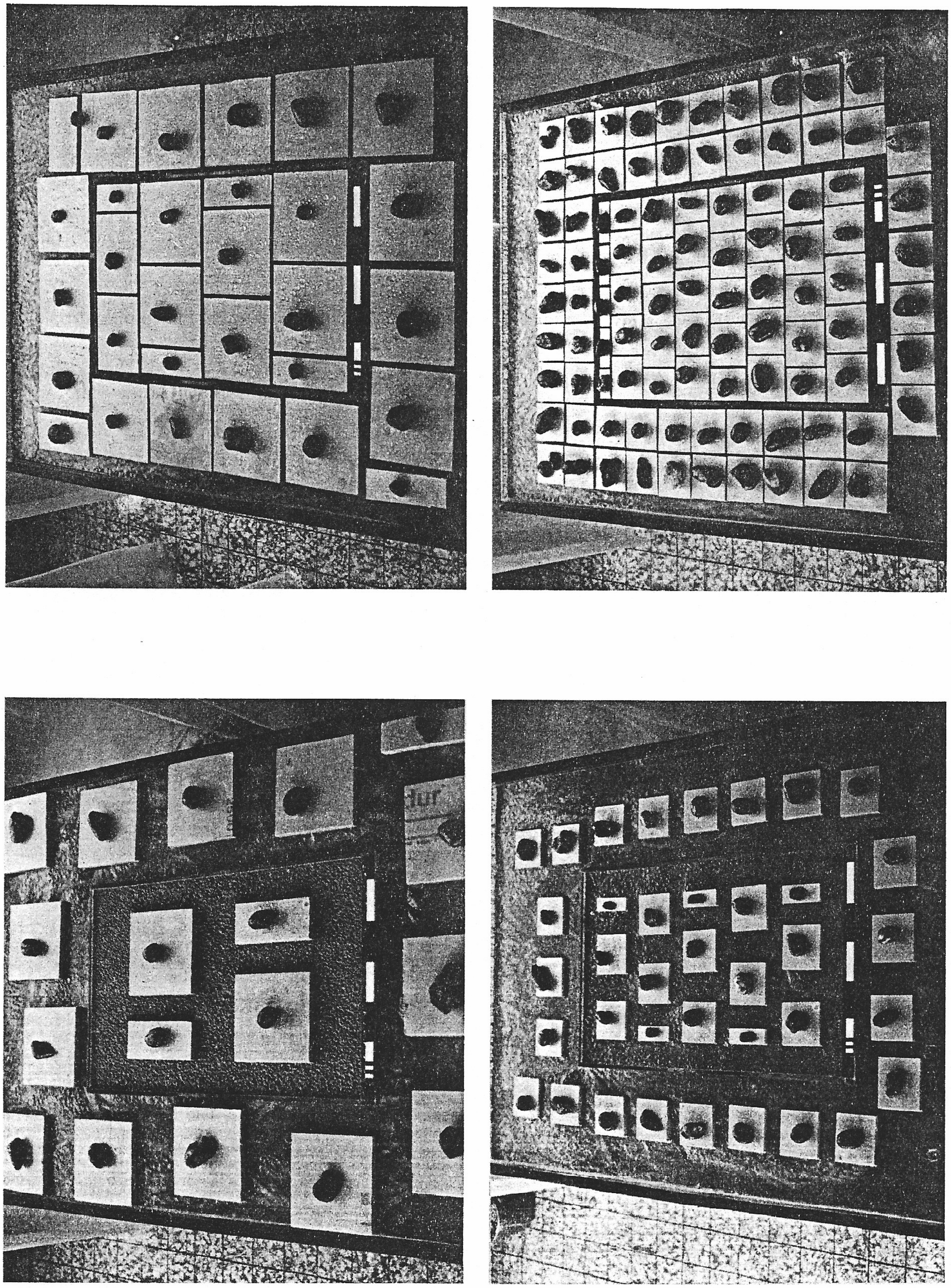
Other parameters that characterize overland flow were also calculated, and include:

1. Time to runoff (T_r, in minutes). This parameter was standardized, for comparison purposes, by dividing the initial rainfall losses (= amount of rainfall, in mm, until overland flow commenced) for each experiment, by the average rainfall intensity.
2. Initial runoff coefficient (R_i, as a percentage), which presents the runoff coefficient for the first 20 minutes of rainfall. The value of 20 minutes was chosen as most hydrographs reached steady-state by this time.
3. Final runoff coefficient (R_f, as a percentage), which is the runoff coefficient at steady-state conditions.

Table I. Stone characteristics and overland flow parameters

On top position								Embedded position							
S (cm)	C (%)	D (cm)	P (cm)	I (mm h^{-1})	T_r (min)	R_i (%)	R_f (%)	S (cm)	C (%)	D (cm)	P (cm)	I (mm h^{-1})	T_r (min)	R_i (%)	R_f (%)
22·3	88	1·00	979	70·0	1·28	34·6	43·7	22·3	88	1·00	979	70·7	0·00	56·9	60·4
	70	2·26	713	69·2	1·70	28·8	36·8		70	2·26	713	70·0	1·47	57·3	57·1
	49	7·08	516	72·2	5·82	15·2	28·0		49	7·08	516	71·7	2·01	41·9	51·6
	30	15·43	328	70·5	7·42	14·3	25·5		30	15·43	328	70·8	7·15	23·8	50·8
11·7	88	0·70	1776	72·9	7·67	20·5	32·0	11·7	88	0·70	1776	58·2	0·82	61·8	61·9
	70	1·43	1332	74·0	9·03	14·8	29·0		70	1·43	1332	69·2	1·94	49·6	53·5
	49	3·19	1027	72·7	9·89	12·3	26·1		49	3·19	1027	67·8	5·04	32·4	31·6
	30	5·72	636	69·5	10·04	8·1	23·0		30	5·72	636	71·5	7·78	15·1	27·3
5·9	88	0·46	3420	72·0	10·30	12·2	23·6	5·9	88	0·46	3420	69·3	2·05	32·1	45·3
	70	1·16	2714	70·1	10·57	12·0	26·5		70	1·16	2714	70·1	2·46	40·9	40·2
	49	2·36	1848	73·4	11·69	6·7	19·6		49	2·36	1848	74·3	7·82	23·9	26·2
	30	3·39	1160	71·8	11·48	5·2	15·0		30	3·39	1160	75·2	9·49	12·6	19·9
3·0	88	0·24	6612	72·2	12·26	5·8	17·2	3·0	88	0·24	6612	77·0	2·91	33·9	41·6
	70	0·60	5304	75·6	13·26	4·8	14·0		70	0·60	5304	70·5	5·04	24·8	32·9
	49	1·23	3696	73·4	10·82	8·3	14·3		49	1·23	3696	69·4	9·25	10·9	17·1
	30	2·41	2244	74·4	12·00	4·6	12·1		30	2·41	2244	71·3	9·76	10·8	16·8
	0			72·8	11·74	6·1	22·0								

S—Average size of stones; C—Stone cover percentage; D—Distance between stones; P—Total perimeter of stones; I—Rainfall intensity; T_r—Standardized time to runoff; R_i—Initial runoff coefficient; R_f—Final runoff coefficient.



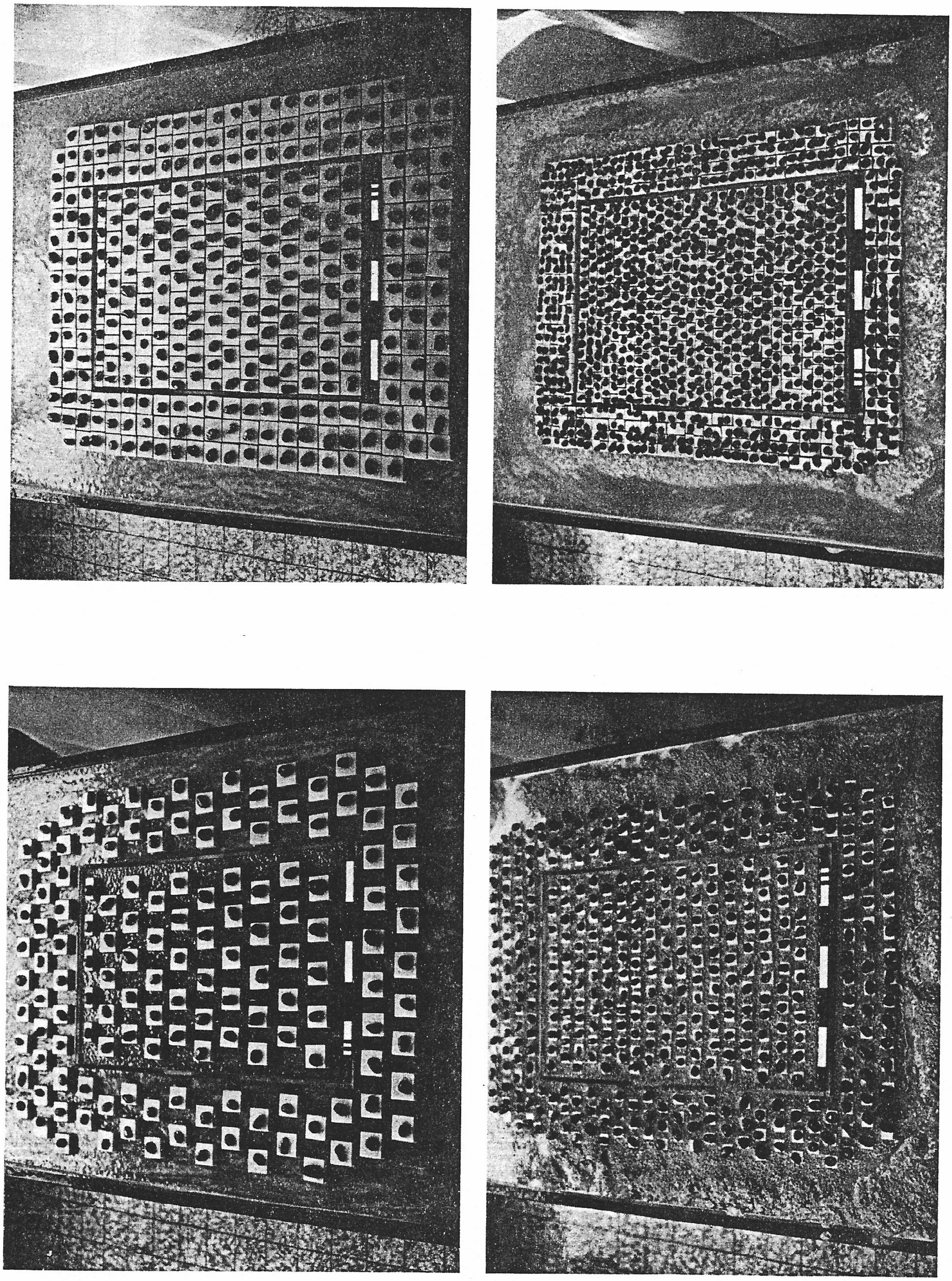


Figure 2. Simulation of different stone sizes and cover percentages in the plot box. Cover percentages are 88 per cent (on the left) and 30 per cent (on the right). Sizes (from top to bottom) are: 22·3, 11·7, 5·9, and 3·0 cm. Note the central test area and the surrounding buffer zone. Length of the measuring scale is 50 cm

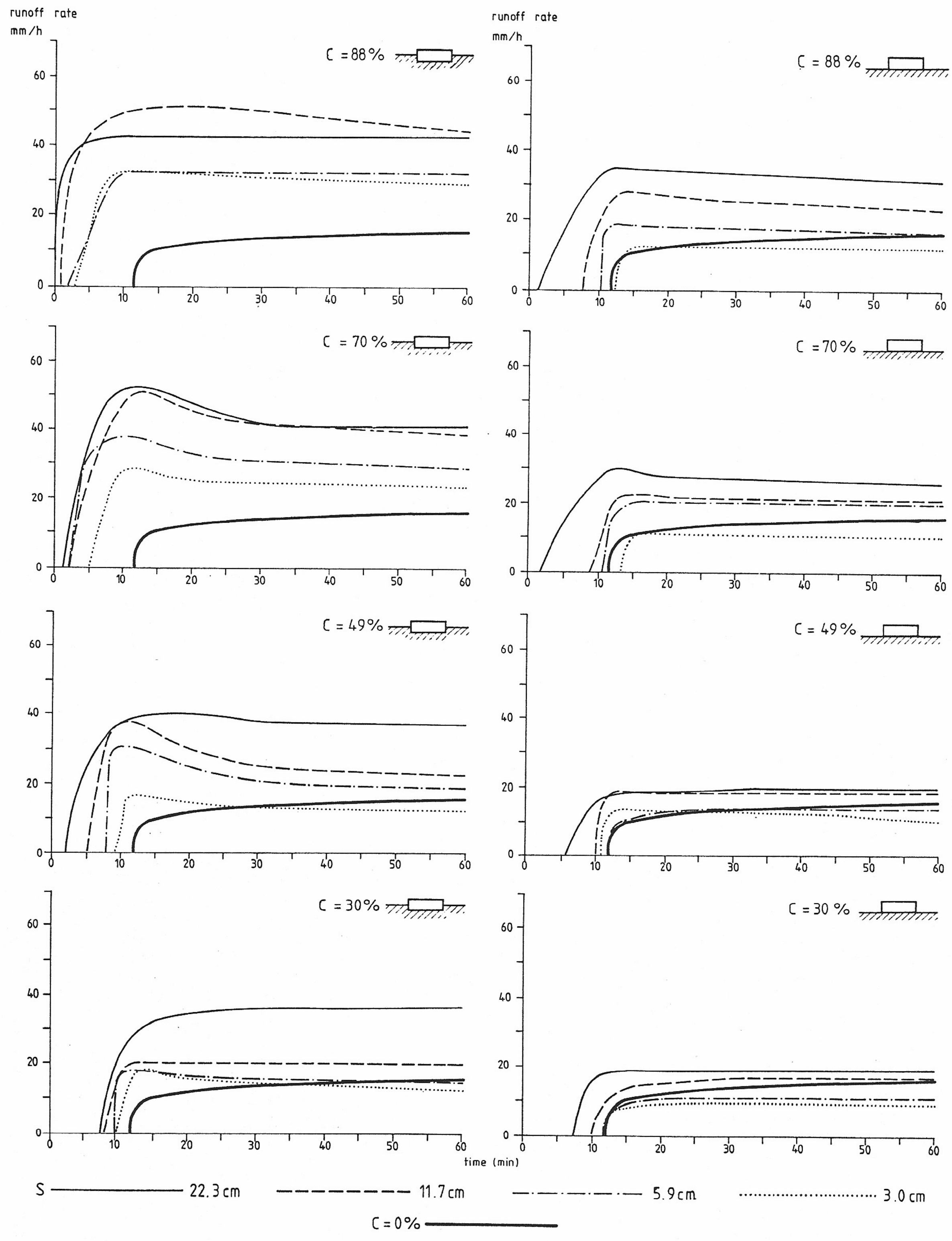


Figure 3. Standardized hydrographs for soil surfaces covered with stones of four different sizes (*S*), four cover percentages (*C*), and two stone positions ('embedded' on the left and 'on top' on the right)

Variations of the first two parameters represent differences in the first phase of overland flow generation, while the third represents the overland flow characteristic at the steady-state phase. Values, for each parameter, are shown in Table I.

Time to runoff values varied between 0 min for the largest stones, highest cover percentage, and embedded position, to 12 min for the smallest stones, smallest cover percentage, and an 'on top' position. The lowest initial and final runoff coefficient values, 4·6 per cent and 12·1 per cent respectively, were reached under conditions of 30 per cent stone cover, an 'on top' position, and 3·0 cm stone size, while the highest values, 61·8 per cent and 61·9 per cent respectively, were achieved for an 88 per cent cover, embedded position and, unexpectedly, at the 11·7 cm stone size rather than the 22·3 cm stone size. The initial conditions seemed to be fairly uniform spatially and fairly constant in the different experiments, owing to the facts that the soil material was unaggregated and air-dry at the beginning of each experiment. However, these anomalies cannot be explained on a theoretical basis, and are probably the result of an experimental error. Nevertheless, the values which were achieved with the largest stones are very close to those achieved with the 11·7 cm stones.

The values for the downslope distance between stones, D, (in cm) and the total perimeter of the stones, P, (in cm) are provided in Table I.

The distance between stones ranges from 0·24 cm to 15·43 cm. For the same cover percentage this distance increases with stone size. The total perimeter of the stones ranges from 328 cm for the largest stones and lowest cover percentage, to 6612 cm for the smallest stones and highest cover percentage.

DISCUSSION

The distribution of stones on the surface can be described by several variables: stone size, cover percentage, distance between stones, and stone perimeter. In order to analyse the effect of each of these variables on overland flow generation, one should keep the other three variables constant. This is not possible, however, since a change in the investigated variable leads to a change in two others. In the present study, stone size and the distance between stones were chosen for analysis. To study the effect of the distance between stones, stone size was kept constant, thus with increasing distance, both stone cover percentage and total perimeter decreased (Table I). On the other hand, increasing the stone size, while keeping the distance constant, results in an increase in stone cover percentage and a decrease in total perimeter.

The effect of distance between stones

The pure effect of distance on runoff is shown in Figure 4. For each stone size and for the two stone positions, the time to runoff (T_r) increased with increasing distance, while initial and final runoff coefficients (R_i and R_f, respectively) decreased when distance increased (these trends were obtained in spite of the fact that with increasing distance, the stone cover percentage and total stone perimeter decreased). This fits our hypothesis that an inverse relation is to be expected between the distance between stones and overland flow yield, due to the distance influence on overland flow continuity.

Koon *et al.* (1970) analysed the effect of the distance, which was assumed by them to be a logical estimation of what they defined as 'effective width'. They found, for each cover percentage, a positive relation between the distance and the infiltration rate per unit length of perimeter. This result was influenced by two factors: (1) Increasing distance with the same cover percentage can be obtained only when stone size increases. An increase in stone size (if the stones are large enough) will raise, according to our hypothesis the overland flow yield; and (2) Dividing the infiltration rate by the total perimeter. The rate of the total perimeter decrease with increasing distance is relatively high. Therefore, even if the infiltration rate using the smaller stones is greater than the infiltration rate of the larger ones, the infiltration per unit length of perimeter for the former might be lower. Figure 5a, when compared with the appropriate graph in Figure 4 (bottom, righthand graph), demonstrates the effect of the first factor mentioned above. When D increases and S does not change, as in Figure 4, R_f decreases despite the simultaneous decrease of P. When, however, there is a simultaneous increase of D and S, as in Figure 5a, the effect of S dominates and R_f increases. Comparison of the same graph

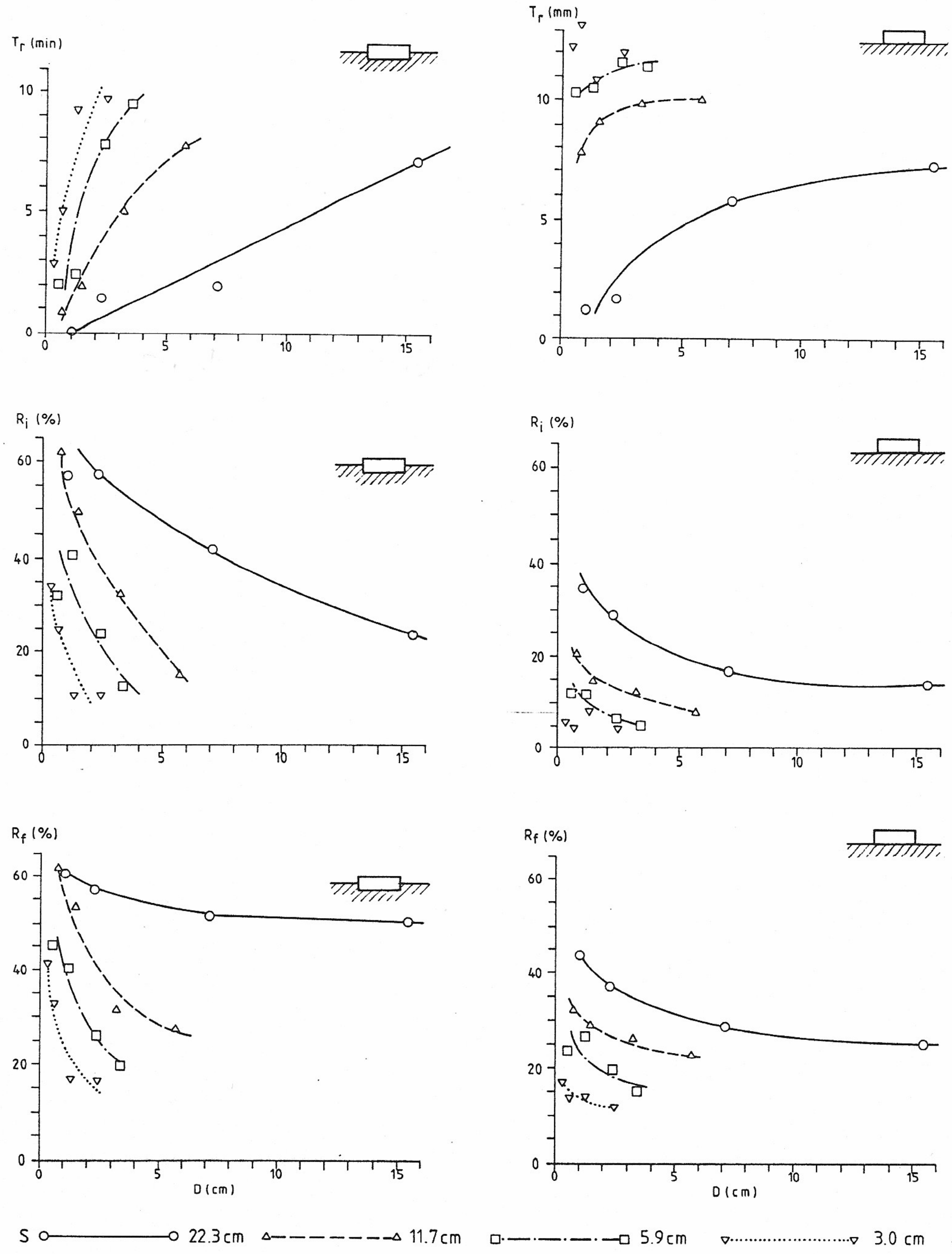


Figure 4. Runoff parameters (time to runoff (T_r), initial runoff coefficient (R_i), and final runoff coefficient (R_f)) versus distance between stones (D), for different stone sizes and two stone positions

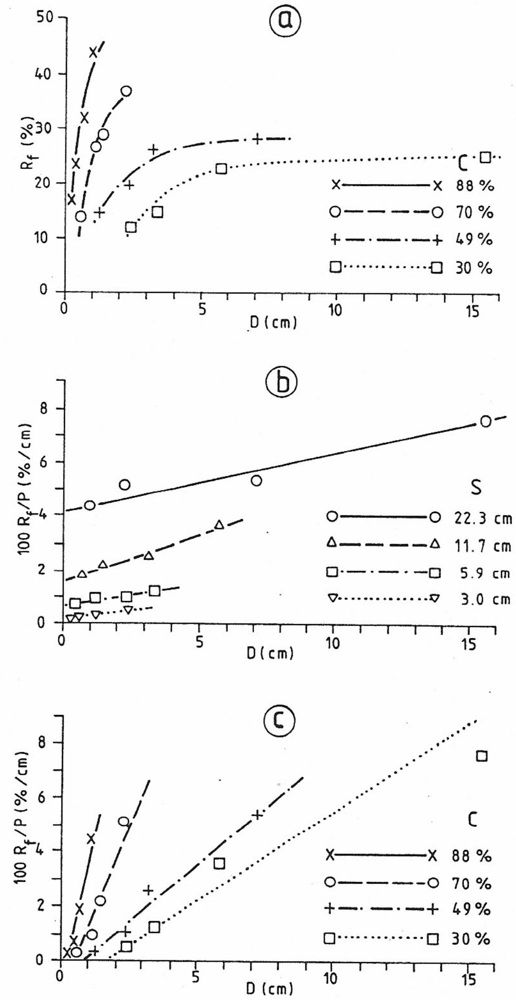


Figure 5. Final runoff coefficient (R_f) and final runoff coefficient per unit length of perimeter (R_f/P) versus distance between stones (D), for the 'on top' position and different stone sizes and stone cover percentages.

in Figure 4 with Figure 5b demonstrates the effect of the second factor mentioned above. There is a negative relation between D and R_f but a positive relation between D and R_f/P. Figure 5c shows that in the present study a positive relation exists between D and R_f/P for different stone cover percentages. This is opposite to that observed by Koon *et al.* (1970). They did not indicate which stone sizes were used. According to their infiltration pan size and the number of stones, it seems that they used relatively small stones. This may be the reason for their findings.

A distance increase in Figure 4 is accompanied by a simultaneous decrease in stone cover percentage. This indicates a positive relationship between stone cover percentage and overland flow yield. As mentioned earlier, opposing results were found by several investigators in cultivated areas. The explanation may be identical to the one offered for Koon *et al.* (1970), namely the different ranges of stone sizes.

The effect of stone size

The effect of stone size on overland flow can be seen in Figure 3. Bigger stones produce more overland flow than do smaller ones. In several cases (low stone cover percentages and an 'on top' position) the small stones

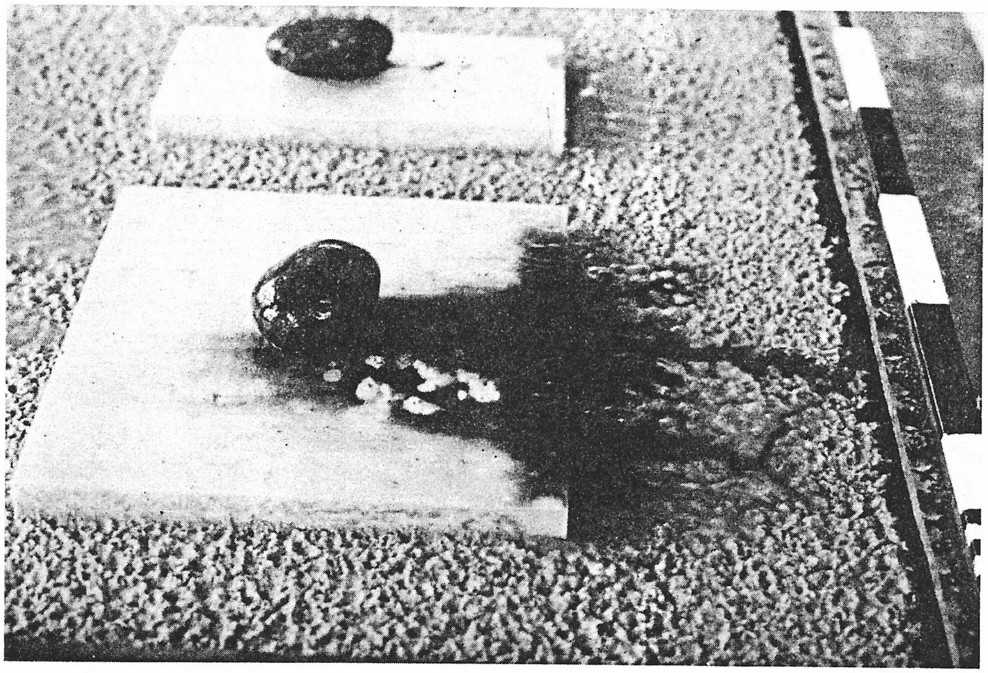


Figure 6. 'Stone flow' and 'concentration overland flow', several minutes after rainfall commenced. Stone size is 24 cm. The flow is visualized by a colour dye

produced even less overland flow than the bare soil surface. The conclusion is that for small stones and for low stone cover percentages, the protecting effect dominates the system, while for large stones and high cover percentages, the stone flow (Figure 6) and the concentration overland flow effect dominates the system. This is a quantitative validation of the concept which was suggested on a theoretical qualitative basis by Yair and Lavee (1976).

Analysing Figure 4, the pure effect of the stone size becomes clear. For the two stone positions, under any chosen distance between stones, T_r decreases with increasing S while R_i and R_f increase with increasing S.

Figure 7 presents the runoff parameters as a function of S. In this case D increases simultaneously with S. For each stone cover percentage and for the two stone positions, in spite of the increase in D, T_r decreases with S while R_i and R_f increase with S. This indicates that the importance of the stone size in controlling overland flow yield is greater, under the present study conditions, than that of the distance between stones.

Agassi (1970) investigated the effect of stone size on infiltration. As he used relatively small stones (1 and 5 cm) and low stone cover percentages (25 and 50 per cent) it is not surprising that he had opposite conclusions.

The combined effect of size and distance

Since runoff increases with stone size but decreases with distance between stones, the relationships between runoff characteristics and S^2/D were investigated (S^2 represents the area of a single stone). The results (Figure 8) show that S^2/D is a good predictor of the runoff response to rainfall for stone-covered surfaces. However, for small stones, especially in the 'on top' position, the S^2/D index is not as good as it is for the large ones. Once again, the general dominance of the stone size in controlling overland flow generation is confirmed.

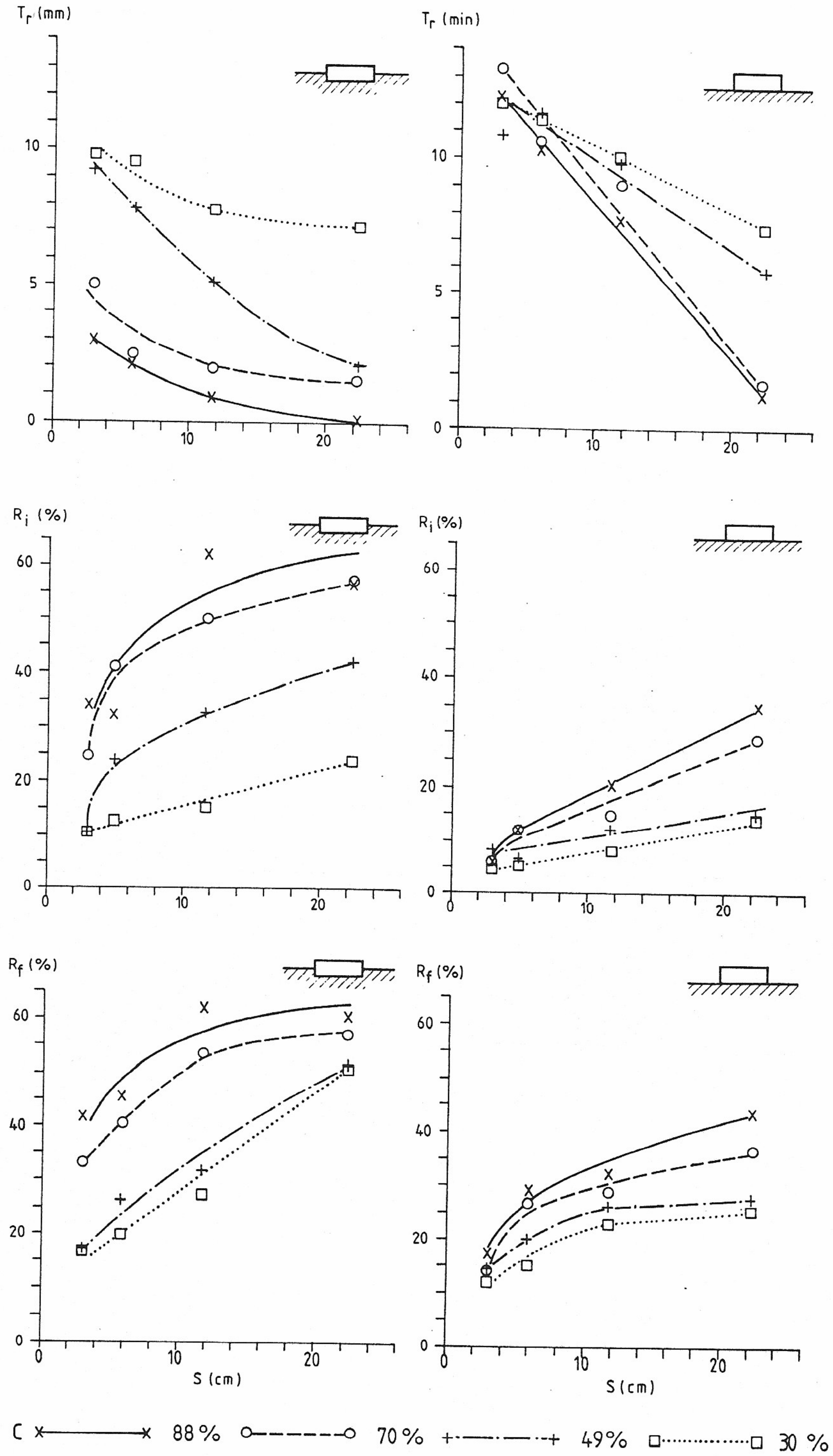


Figure 7. Time to runoff, initial runoff coefficient, and final runoff coefficient versus stone size (S), for different cover percentages and two stone positions

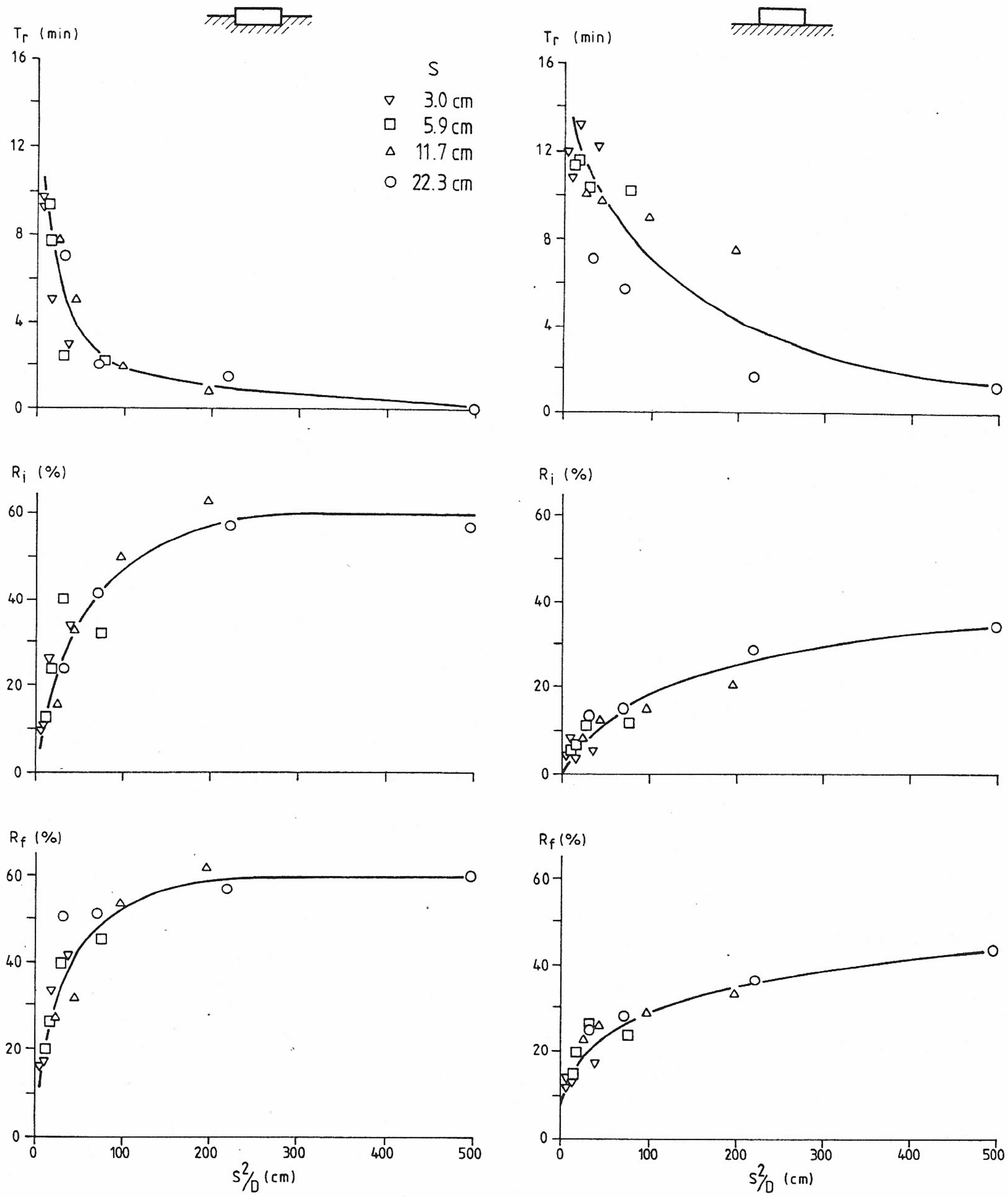


Figure 8. Time to runoff, initial runoff coefficient, and final runoff coefficient versus S^2/D

The effect of stone position

Throughout all the experiments, overland flow generation was more rapid and runoff yield was higher for embedded stones relative to the 'on top' position. This can be clearly seen in Figure 3. Figures 4 and 7 demonstrate that for different stone sizes, different distances between stones, and different stone cover percentages, the time to runoff is always shorter and runoff coefficients are always higher for the embedded position than for the 'on top' position. The explanation for this fact is that in the embedded position the surface seal joins the stone, while in the 'on top' position a discontinuity exists between the surface seal and the stone. This was shown by micromorphological analysis by Poesen *et al.* (1990). Accordingly, more water can infiltrate near the stone edges in the 'on top' position.

The stones in the present study had a rectangular vertical cross-section, while natural stones often have an ellipsoidal cross-section. Thus in the case of the 'on top' position, the possibility of water to infiltrate near the stone edges in the present study was smaller than that in the case of natural stones. This explains the larger difference between runoff coefficients, for the embedded and 'on top' positions which were found by Poesen *et al.* (1990) for rounded natural stones.

SUMMARY AND CONCLUSIONS

1. Laboratory measurements of overland flow on stone-covered soil surfaces established that under certain conditions of rainfall, soil properties and slope gradient, the stone size, distance between stones, and stone position are dominant factors in controlling the overland flow yield. Stone cover usually activates overland flow relative to bare soil. Small stones, however, especially in low cover percentages and when in an 'on top' position, produce less overland flow than bare soil. Overland flow is positively related to stone size, but negatively to distance between stones. If the stones are partially embedded in the soil, the overland flow yield is greater than in the case of stones resting on top of the soil surface. These results confirm the initial hypothesis that stone size affects overland flow generation, and that distance between stones affects overland flow continuity.
2. It was shown that, under the present study conditions, the effect of stone size on increasing overland flow is more important than the effect of the distance between stones on decreasing overland flow. Stone size plays an important role as it affects the 'stone flow' volume. Such stone flows are delivered to the periphery of the stone and, if the delivery intensity exceeds the infiltration rate of the soil, a 'concentration overland flow' is generated. Below a certain stone size the stone flow is incapable of generating concentration overland flow. This critical stone size varies in different conditions and depends on the rainfall and soil properties, slope gradient, antecedent soil moisture, stone position, and stone shape. Further investigation is needed to examine the effect of both stone size and distance between stones on overland flow generation and continuity under the above-mentioned differing conditions.
3. Under natural field conditions, many other variables (in addition to those analysed in the present paper) control overland flow generation and yield. In cultivated fields, where many stones rest on top of the soil surface, where the slope gradient is low, and where the soil is very permeable, only very large stones may be able to overcome the protective effect. Such large stones usually do not exist in cultivated fields. Therefore, stones in agricultural areas usually reduce overland flow generation. On the other hand, in natural landscapes, where large and even very large stones are partially embedded in the soil, and where the soil itself is relatively compacted, the stones play an important role in triggering overland flow generation.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support for this study which was obtained through Fellowships within the framework of the Exchange of Researchers Israel–Belgium (Flemish Community) 1989/1990, and from the Commission of the European Communities, D.G. XII (contract no. EV4V-0112-C).

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Rock fragments in top soils: Significance and processes

Article *in* Catena · September 1994

DOI: 10.1016/0341-8162(94)90050-7

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Rock fragments in top soils: significance and processes

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Abstract

This introductory paper reviews various aspects of rock fragments in top soils. Such information is required for various reasons and in particular for predicting the impact of climatic or landuse changes on the response of these soils. Particular attention is paid to the definition and measurement of rock fragment content in top soils, the density of soils containing rock fragments, the spatial distribution and movement of rock fragments in top soils, the effects of rock fragments on some key hydrological processes, thermal properties of top soils, physical soil degradation, soil erosion and soil productivity.

1. Introduction

In the literature on soils, considerable attention has been paid to the study of the role played by the finest particles (i.e. the clay fraction) in conditioning a soil's behaviour. Much less attention has been devoted to the effects of the coarsest soil fraction, i.e. rock fragments.

Over the last decade, there has been a growing interest in soils containing considerable amounts of rock fragments for several reasons. First of all, these soils are widespread, particularly in the Mediterranean area where they often occupy more than 60% of the land (Poesen, 1990, Fig. 1). Soils rich in rock fragments are found on erosional as well as on depositional landforms. In some cases, high rock fragment contents in top soils can be attributed to intensive cultivation (Fig. 2). Secondly, soils with large amounts of rock fragments represent a significant portion of our land resources to be increasingly used for food and fibre production (Miller and Guthrie, 1984) as well as for recreation with the ever present potential of undesirable soil degradation. Information on the behaviour of these soils is especially needed because of their potential benefits or limitations for landuse (Nichols et al., 1984). Finally, there is a growing need for more quantitative information on the effects of

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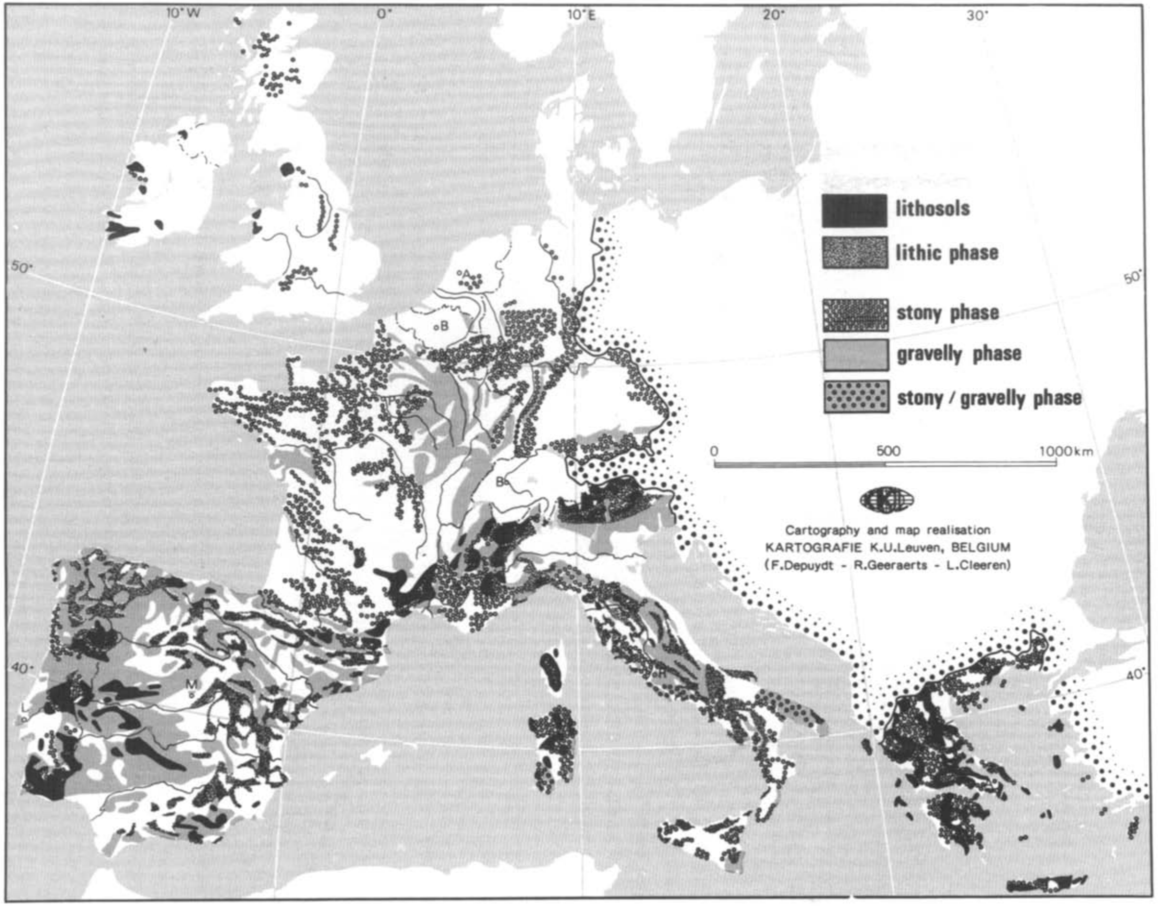

Fig. 1. Spatial distribution of soils containing significant amounts of rock fragments in Western Europe (based on the soil map of the European Communities and CORINE data base (Commission of the European Communities, 1985)). Lithosols: hard rock occurs at less than 10 cm depth; lithic phase: continuous coherent and hard rock occurs within 50 cm of the surface; stony phase: presence of stones (rock fragments with a diameter larger than 7.5 cm), boulders or rock outcrops in the surface layer or at the surface; gravelly phase: presence of more than 35% of gravels (rock fragments with a diameter up to 7.5 cm) in the surface layer.

Fig. 2. Tillage erosion and water erosion under wheat cultivation have resulted in the formation of this lithosol (hard rock occurs at less than 10 cm depth) on schist in southeastern Portugal (Baixa Alentejo, see also Fig. 1). Rock fragment content of these cultivated top soils is highest on profile convexities as well as on plan convexities due to tillage erosion. Length of scale equals 50 cm.

rock fragments on various hydrological and soil degradation processes. Such information is required in order to improve process-based models aiming at predicting the effects of climatic or landuse changes on the response of these soils.

This paper as well as the following papers of this volume are an attempt to elucidate the role played by rock fragments in hydrology, soil degradation and soil productivity by drawing together results of recent process research. This introductory paper reviews the significance of rock fragments for a number of earth surface processes. Topics not represented in the following papers will be developed in greater detail in this introductory paper. Particular attention will be paid to the definition and measurement of rock fragment content, density of soils containing rock fragments, spatial distribution and movement of rock fragments in soils and at the soil surface, effects of rock fragments on hydrological processes, thermal properties of top soils, physical soil degradation, soil erosion both by water as well as by wind and soil productivity.

2. Definition of rock fragments

Rock fragments are particles 2 mm or larger in diameter and include all sizes that have horizontal dimensions less than the size of a pedon (Miller and Guthrie, 1984). Generally, the area of a pedon is about 1 m^2 and is thick enough to represent all soil horizons to a depth of about 2 m. Soil materials with a diameter smaller than 2 mm are referred to as *fine earth materials.*

In this paper, the term "rock fragment" is used rather than the term "stone" since the latter refers to a particular rock fragment size class with class limits depending on the classification system used. For instance, stones refer to rock fragments 75 to 250 mm in size in the F.A.O. classification, 2 to 600 mm in size for British soil scientists and 250 to 600 mm in size for U.S. soil scientists (Fig. 3).

A rock fragment must meet a slaking test to qualify as a rock fragment. If a "field"

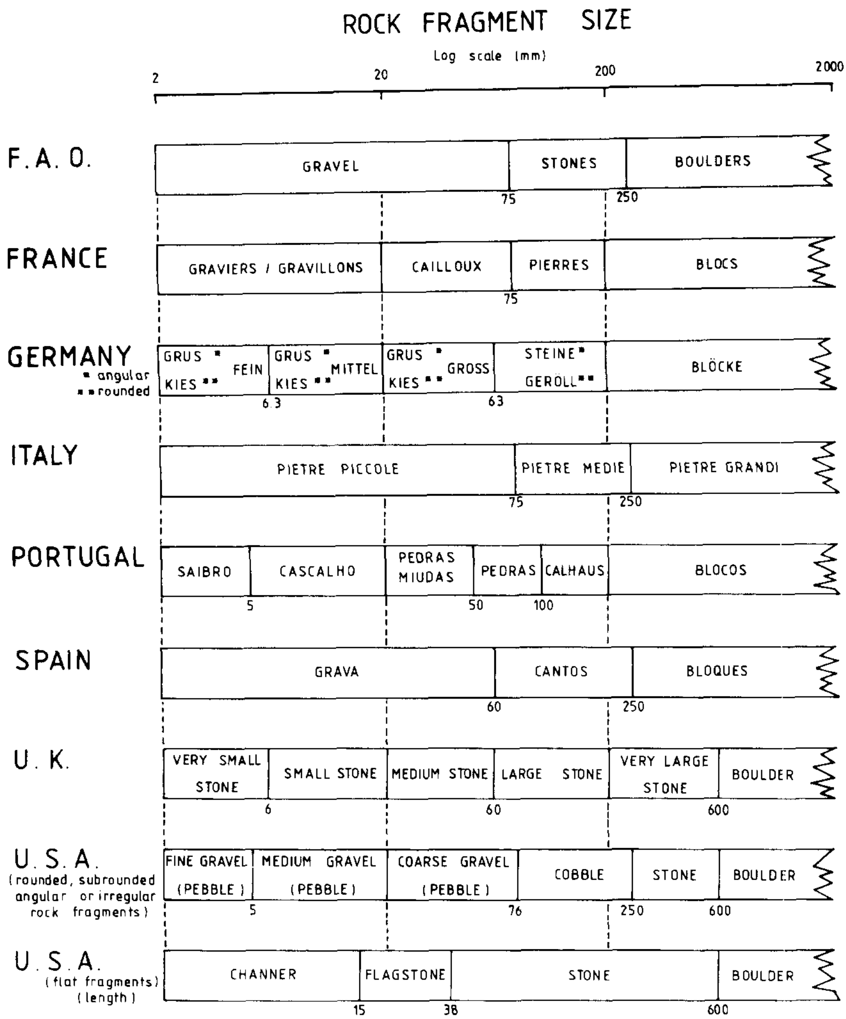

Fig. 3. Some classification systems of rock fragments in soils by size and shape used by F.A.O. (F.A.O., 1977) and used in France (Casenave and Valentin, 1989), Germany (Schachtschabel et al., 1989), Italy (Sanesi, 1977), Portugal (Hodgson, 1978), Spain (Ministerio de Agricultura, Pesca y Alimentacion, 1983), UK (Hodgson, 1978) and USA (Miller and Guthrie, 1984).

rock fragment — i.e. what appears to be a rock fragment in the field — breaks down or desintegrates when shaken overnight in a sodium hexa-metaphosphate solution it will not be qualified as a "laboratory" rock fragment (Munn et al., 1987).

Rock fragments in soils are classified by size and shape and various classification systems have been proposed (Fig. 3).

3. Measuring rock fragment content of top soils

At least three different parameters are used to express the (relative) amount of rock fragments in the top soil: (1) rock fragment coverage of the soil surface (R_c), (2) rock fragment content by volume (R_v), and (3) rock fragment content by mass (R_m).

Rock fragment cover can be assessed by visual estimates (by comparing with area charts), by transecting, or by the point-count method. Visual estimates are also used for determining rock fragment content by volume since the relative area of a soil component in a vertical exposure is proportional to its relative volume in a soil horizon or pedon (Alexander, 1982). This method is most effective for rock fragments >76 mm. For small rock fragments, however, visual estimates are much more difficult and become sometimes unreliable. Sieving and weighing of this rock fragment fraction is a much more accurate means of estimating their content.

Conversion from mass to volume percentage can be accomplished using the equation (Childs and Flint, 1990):

$$R_v = R_m \cdot BD_t / BD_{rf} \tag{1}$$

with R_v = rock fragment content by volume [(volume of rock fragments)/(total volume)], R_m = rock fragment content by mass [(mass of rock fragments)/(total mass of rock fragments and fine earth)], BD_t = total soil bulk density [(total mass)/(total volume)], and BD_{rf} = bulk density of a rock fragment [(mass of a rock fragment)/(volume of a rock fragment)]. Alternatively, the nomogram proposed by Torri et al. (1994) can be used to transform R_v into R_m and vice versa using an appropriate ratio between fine earth bulk density for rock fragment-free soils and BD_{rf}.

Caution is required when converting data on R_m to R_v and vice versa. Using a particle density value between 2650 and 2750 kg/m^3 for BD_{rf} is allowed only if the rock fragments have no porosity. Published data demonstrate that the density of weathered rock fragments is lower than this figure because of the existence of an internal porosity due to surface weathering (Table 1). In general, rocks with the lowest bulk density (and therefore the highest porosity) are smaller, essentially because of their high surface to volume ratio (Childs and Flint, 1990).

4. Density of soils containing rock fragments

For the interpretation of the behaviour of a soil containing rock fragments, two density values are commonly required: total bulk density of the soil (BD_t) and bulk

Table 1
Bulk density (BD_{rf}) for fragments of different rock type

Rock type		BD_{rf} (kg/m^3)	Source
Andesite			
– bedrock		2200–2300	Farmer (1968)
		2240	Gras (1972)
– rock fragm.	(2–4.8 mm)	1840 (±150)	Childs and Flint (1990)
Basalt			
– bedrock		2800–2900	Farmer (1968)
– rock fragm.	(2–4.8 mm)	1950 (±280)	Childs and Flint (1990)
Granite			
– bedrock		2600–2700	Farmer (1968)
– rock fragm.	(2–4.8 mm)	2240 (±100)	Childs and Flint (1990)
– rock fragm.		2170	Ingelmo et al. (1994)
Limestone			
– bedrock		2200–2600	Farmer (1968)
– Miolacea limestone		1610	Gras (1972)
– rock fragm.		2080	Alberto (1971)
– rock fragm.	(4–20 mm)	2380	Poesen and Lavee (unpublished)
	(20–40mm)	2540	
	(40–80 mm)	2550	
Sandstone			
– bedrock		2000–2600	Farmer (1968)
– rock fragm.	(5–35 mm)	2350	Hanson and Blevins (1979)
	(25–76 mm)		
	– fresh	2560 (±40)	Childs and Flint (1990)
	– weathered	2090 (±90)	
	(150–400 mm)	2355	Poesen and Torri (1989)
Shale			
– bedrock		2000–2400	Farmer (1968)
– rock fragm.	(5–25 mm)	2070	Hanson and Blevins (1979)
Siltstone			
– rock fragm.	(45 mm)	1970	Montagne et al. (1992)
Quartzite			
– rock fragm.		2430	Ingelmo et al. (1994)

density of the fine earth [BD_{fe} = (mass of fine earth)/(total volume – volume of rock fragments) or BD_{fe} = (mass of fine earth)/(volume of fine earth + volume of textural and structural pores)]. Fig. 4 illustrates the relation between R_m and BD_{fe} as well as between R_m and BD_t for two different soils. With increasing rock fragment content, total bulk density increases to reach a maximum between 40% and 50% beyond which it decreases. Contrary to BD_t, BD_{fe} decreases monotonically with increasing R_m.

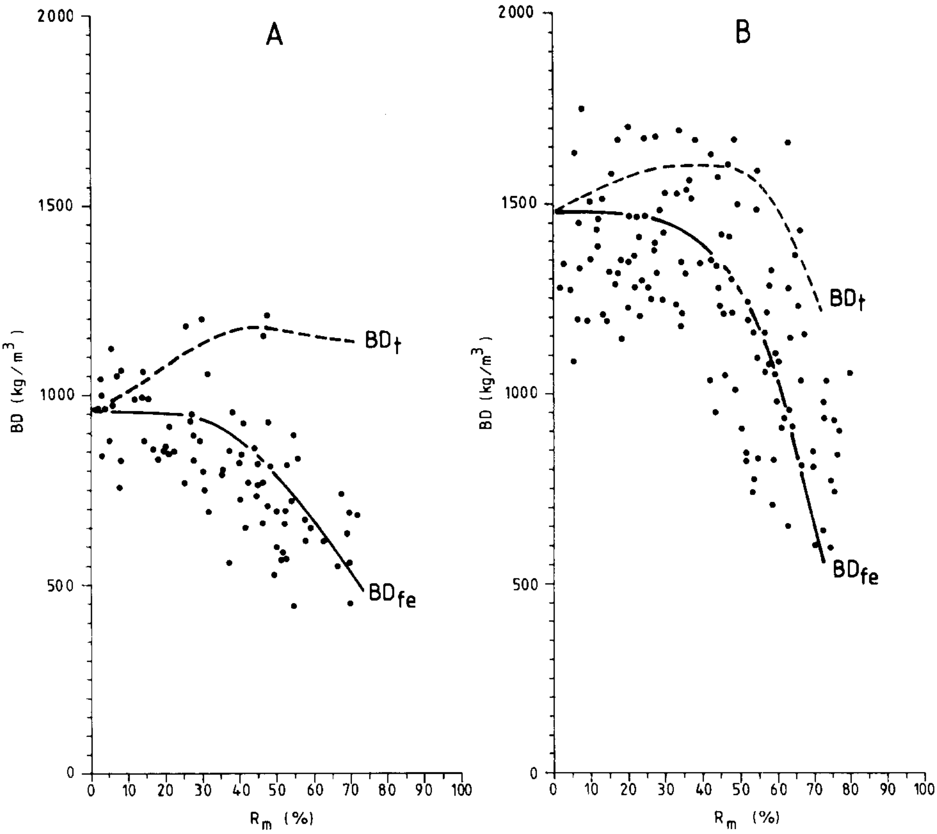

Fig. 4. Relation between rock fragment content by mass (R_m, %) and fine earth bulk density (BD_{fe}, indicated by dots and solid line) and total bulk density of the soil (BD_t, indicated by dashed line) for two different soils: (A) forest soil on Silurian mudstone (Wales, UK) and (B) Brown cultivated soil with limestone fragments developed on a river terrace (Ebro basin, Spain). Data on BD_{fe} were extracted from scatter diagrams published by (A) Stewart et al. (1970) and (B) Alberto (1971). BD_t was calculated using the equation $BD_t = (1)/[(1 - R_m)/BD_{fe} + R_m/BD_{rf}]$ where BD_{rf} = bulk density of the rock fragments (= 2300 kg/m^3 for mudstone fragments (estimated using Table 1) and 2080 kg/m^3 for limestone fragments (Alberto, 1971)) and R_m is expressed as a fraction.

There are a number of possible reasons why a negative relationship between BD_{fe} and R_m might occur.

(1) At high rock fragment contents a situation will be reached where there is insufficient fine earth to fill the voids in between the rock fragments resulting in lower BD_{fe} values.

(2) In a mixture of two particle size grades, the presence of even small numbers of large particles has a negative effect on the bulk density of the smaller particles because the smaller particles cannot pack as closely to the larger particles as they can with each other (Stewart et al., 1970). Also, fine earth and rock fragments react in a different way when expanding and contracting (e.g. during the process of wetting

and drying or of freezing and thawing). This might cause voids to form at the contact between rock fragments and fine earth.

(3) The presence of rocks in the soil changes the nature of the fine earth fraction. With increasing rock fragment content, decaying organic matter, fertilizer inputs, rain water, etc. are concentrated in a decreasing mass of fine earth (Childs and Flint, 1990). Hence, an increased input per mass of fine earth will affect other soil properties such as soil structure. In particular, an increase in organic matter content of the fine earth fraction (corresponding to an increase in R_m) will lead to a decrease of the BD_{fe} value since the average bulk density of organic matter equals 224 kg/m^3 (Rawls, 1983). In addition to this effect, an increase in organic matter content also often leads to a better (i.e. with a higher porosity) and a more stable structure of the fine earth fraction.

Fig. 4 illustrates that even at high total soil bulk density, according to traditional standards, fine soil bulk densities are not excessively high. This has important implications for plant growth: if plant growth is related to the soil physical properties of the fine soil fraction, high total soil bulk density in skeletal soils (i.e. soils with $R_v > 35\%$ in a specific subsurface zone) does not necessarily indicate a poor root growth environment.

5. Spatial distribution of rock fragments in soils

Spatial variability of rock fragment content in soils can be very large (Childs and Flint, 1990). However, under particular conditions, concentrations of rock fragments occur both vertically in the soil profile as well as laterally in the top soil.

In many parts of the world researchers have reported higher concentrations of rock fragments at the soil surface compared to the soil horizons below (e.g. Shaw, 1929; Lowdermilk and Sundling, 1950; Rohdenburg, 1977; Mabbutt, 1979; Nettleton et al., 1989; Parsons et al., 1992; Cooke et al., 1993). These rock fragment concentrations have been described as stone pavements (Fig. 5) and are due to either removal of fine earth (by wind or by overland flow) and/or upward migration of rock fragments to the surface (by freezing and thawing or by cycles of wetting and drying) (Cooke et al., 1993). If the stone pavement is only due to the removal of fine earth by sheet and rill erosion, this feature is also termed an erosion pavement (Shaw, 1929).

Soil horizons with a greater proportion of rock fragments than the horizons above and below them have been described in both temperate and tropical areas as stone lines (i.e. a single layer of rock fragments) or stone zones (i.e. a layer more than one rock fragment thick, Fig. 6) (e.g. De Ploey, 1964; Faniran and Jeje, 1983; Alexandre and Symoens, 1989; Johnson, 1990). These (continuous or discontinuous) horizons vary in thickness from about 10 cm to more than 50 cm and they occur at various depths from the surface down to 6 m (Faniran and Jeje, 1983).

With respect to the lateral distribution of rock fragment content in the top soil, specific patterns (i.e. "stone polygons" or "sorted nets" (Fig. 7), and "stone stripes") resulting from the size-sorting of rock fragments and fine earth have been widely reported in different (climatic) environments: at high latitudes and high altitudes

Fig. 5. Stone pavement consisting of well-rounded limestone fragments both resting on the soil surface as well as partly embedded in the top layer (Avdat, Israel). Rock fragment cover at the soil surface ranges between 50 and 60% while at 5 cm depth rock fragment cover varies between 10 and 30%. Total length of scale is 1 m.

due to frost action and solifluction (e.g. Pissart, 1972; Gleason et al., 1986), and in deserts due to wetting and drying and to solution and recrystallization of salts (Cooke et al., 1993). Stone stripes resembling periglacial features have been reported to form during high-intensity storms (Kelletat, 1985). A theoretical model developed by Ahnert (1994) demonstrates that stone polygons can develop on any piece of unobstructed ground surface (with little or no gradient) if it bears a loose, discontinuous cover of pebble-sized rock fragments and if these fragments are moved in any direction with equal probability.

Webster (1985) observed that the semi-variograms of rock fragment content in the top soil were not the same in all directions and concluded that rock fragment content varied anisotropically for the investigated field. The top soil at points along the strike of a sequence of sedimentary rocks is more likely to be similar than at points the same distance away in the direction of the dip. Finally, Simanton et al. (1994) found surface rock fragment cover to increase non-linearly with ground slope along catenas in semiarid Arizona and Nevada. This spatial distribution of rock fragment content should be considered when looking at the effects of rock fragments on hydrological processes or on soil degradation.

6. Movement of rock fragments in the top soil

Study of processes leading to vertical or lateral rock fragment movement in soils

Fig. 6. Stone zone (Zaïre). Total length of the handle of the hammer is approximately 30 cm (photo J. De Ploey).

Fig. 7. Stone polygon (Green Lakes Valley, CO, USA). Diameter of lens cap equals 5 cm.

Table 2
Processes leading to vertical or lateral movement of rock fragments in top soils as reported by various authors. Classification of these processes is according to Hole's (1961) classification of pedoturbations which has been expanded to include anthropopedoturbation

Process	Source
1. Faunalpedoturbation	
– burrowing, tunnelling or mounding by	
– earthworms	Webster (1965), Johnson et al. (1987), Ponomarenko (1988)
– pocket gophers	Murray (1967), Johnson et al. (1987)
– desert beetles	Haff (1986)
– ground squirrels	Johnson et al. (1987)
– mole rats	Cox et al. (1987)
– trampling by sheep and goats	Poesen (field observations in the Mediterranean region)
2. Floralpedoturbation	
– tree uprooting	Johnson (1990)
3. Cryoturbation	
– freezing and thawing	Pissart (1969), Manikowska (1982), Mackay (1984), Van Vliet-Lanöe (1985), Pérez (1987)
4. Argillipedoturbation	
– swelling and shrinking of clays	Springer (1958), Cooke et al. (1993)
5. Gravipedoturbation	
– mass wasting	
– soil settling	Moeyersons (1978)
– creep	Schumm (1967), Williams (1974), Moeyersons (1978, 1989)
– debris flow	Van Steijn et al. (1988)
6. Aeropedoturbation	
– wind erosion	De Ploey (1980), Wilshire et al. (1981)
– eolian accumulation	McFadden et al. (1987)
7. Aquapedoturbation	
– splash creep	Moeyersons (1975)
– runoff creep	De Ploey et al. (1976)
– surface wash	Kirkby and Kirkby (1974)
– hydraulic erosion	Abrahams et al. (1984), Poesen (1987)
8. Crystalpedoturbation	
– growth and wasting of crystals	Cooke et al. (1993)
9. Seismipedoturbation	
– earthquakes	Clark (1972)
10. Anthropopedoturbation	
– trampling	Barton (1987)
– tillage	Kouwenhoven and Terpstra (1979)
– off-road vehicle traffic	Elvidge and Iverson (1983), Pérez (1991)

have been conducted for various reasons: for engineering studies, for geomorphological–pedological process interpretations, and for accurate archaeological and paleoecological reconstructions. These processes can be grouped according to the dominant soil mixing vector. Table 2 lists the most important processes classified according to Hole's (1961) classification of pedoturbations which has been expanded to include anthropopedoturbation. Processes leading to vertical or lateral movement of rock fragments often control the spatial distribution of rock fragments in the soil profile (see section 5). In addition, many of these processes control the position of rock fragments at the soil surface, which, under certain conditions, determines the hydrological (e.g. Poesen et al., 1990; Valentin, 1994) and erosion (e.g. Poesen et al., 1994) response of the top soil.

7. Effects of rock fragments on hydrological processes

When discussing the effects of rock fragments on the intensity of hydrological processes, a distinction should be made between rock fragments at the soil surface and rock fragments below the surface (Fig. 8). Rock fragments resting on the soil surface or partly incorporated in the top soil affect rainfall interception, rock flow (i.e.

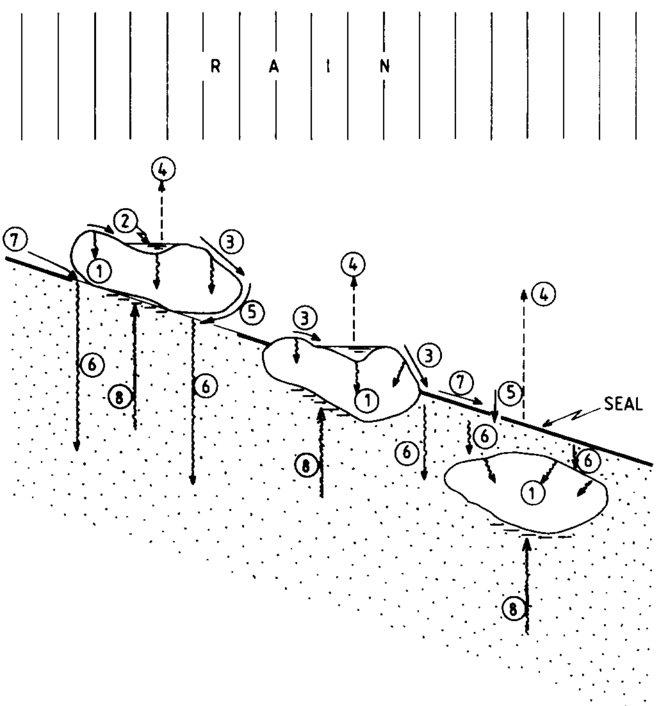

Fig. 8. Sketch to illustrate different hydrological subprocesses occurring on topsoils containing rock fragments having various positions: 1 = water absorption, 2 = interception and depression storage, 3 = rockflow, 4 = evaporation, 5 = infiltration, 6 = percolation, 7 = overland flow, 8 = capillary rise.

runoff generated by the rock surface), infiltration, overland flow (generation and hydraulics), as well as evaporation. Rock fragments situated below the soil surface affect percolation rate and thus also infiltration rate as well as runoff generation.

During rainfall, rock fragments at the soil surface intercept raindrops. This rainwater will either (1) be stored at the rock surface, or (2) penetrate the rock fragment (absorption), or (3) evaporate, or (4) flow on the rock fragment as rockflow (Fig. 8). Rain interception by non-porous surface rock fragments of different sizes was studied by El Boushi and Davis (1969). They found that water retained at contact points between adjacent rock fragments accounts for most of the water storage on rock fragments with diameters smaller than about 3 cm. For rock fragments larger than 10 cm, however, most water is held as puddles on the rock surface. The amount of rainwater absorbed by porous rock fragments depends on the water-holding capacity of the rocks (MC, expressed as a gravimetric moisture content at saturation) which in turn is determined by rock type and size (Table 3). While flintstone, for instance, has a MC of only 0.2%, it can be as high as 91.7% for chalk. Since in natural soils small rock fragments usually are more weathered and hence more porous than larger fragments (Childs and Flint, 1990) small rock fragments can absorb larger quantities of water per unit of rock mass. Effects of rock fragment content on hydric properties of Spanish soils developed over various lithologies have been studied by Ingelmo et al. (1994).

The effects of rock fragments on infiltration rate and percolation rate are discussed in detail by Brakensiek and Rawls (1994) and Valentin (1994). Recent studies have shown that rock fragment cover at the soil surface has an ambivalent effect on infiltration rate and on overland flow generation. On the one hand, rocks prevent direct infiltration of (intercepted) raindrop water into the soil and in some cases even produce rock flow resulting in an increase of overland flow volume. On the other hand, however, rock fragments cause an increase of water intake rates by protecting the soil surface against raindrop impact forces. This prevents soil surface sealing and crusting. Whether the total volume of infiltration is finally increased or decreased by the presence of rock fragments depends on various factors such as position (Poesen, 1986; Poesen et al., 1990; Valentin, 1994), size (e.g. Yair and Lavee, 1976; Lavee and Poesen, 1991; Valentin, 1994) and cover (e.g. Poesen et al., 1990; Valentin, 1994) of rock fragments as well as structure of the fine earth (Poesen and Ingelmo-Sanchez, 1992). Poesen and Lavee (1991) and Lavee and Poesen (1991) investigated systematically the effect of different combinations of rock fragment size, cover and position on infiltration rate and on overland flow production. They found that the size and position of rock fragments are important factors at the microscale, controlling overland flow generation near the edge of the rock fragment. They also found that rock fragment cover percentage (which determines the distance between rock fragments) is an important factor at the meso-scale, controlling the continuity of overland flow along a hillslope.

Once overland flow is generated at the soil surface, rock fragments affect its hydraulics. Abrahams and Parsons (1994) discuss in great detail the hydraulics of interrill overland flow on desert surfaces covered by rock fragments.

A layer of rock fragments at the soil surface acts as a mulch. This implies that it

Table 3
Moisture content at saturation (MC, by mass) for fragments of different rock type and size

Rock type	MC (%)	Source
Basalt	0.4	Gras and Monnier (1963)
Chalk	91.7	Gras (1974)
Flintstone	0.2	Gras and Monnier (1963)
Granite		
- bedrock	0.4	Gras and
- weathered	5.3	Monnier (1963)
- (100–300 mm)	0.8–0.9	Yair and Lavee (1976)
Igneous rock		
- (2–5 mm)	22.0–25.5	Coile (1953)
- (5–12.5 mm)	7.5–17.9	Coile (1953)
- (12.5–19.0 mm)	5.7–10.3	Coile (1953)
- (20.0–40.0 mm)	0.8	Yair and Lavee (1976)
Limestone		
-	2.6–7.9	Gras and Monnier (1963)
- (50–120 mm)	1.1	Yair and Lavee (1976)
Sandstone		
-	0.3–43.7	Gras and Monnier (1963)
- (80–140 mm)	5.7	Yair and Lavee (1976)
- (2–5 mm)	14.9	Hanson and
- (5–20 mm)	7.7	Blevins
- (20–35 mm)	6.1	(1979)
Shale		
- (2–5 mm)	49.6	Hanson and
- (5–20 mm)	32.6	Blevins
- (20–25 mm)	19.7	(1979)
Siltstone		
- (45 mm)	12.3	Montagne et al. (1992)
Slate		
- (2–5 mm)	10.5–27.0	Coile (1953)
- (5–12.5 mm)	9.5–14.1	Coile (1953)
- (12.5–19.0 mm)	7.2–11.9	Coile (1953)

may change the soil's radiation balance, water balance and temperature regime among other factors. A pure rock fragment layer has a very low unsaturated hydraulic conductivity at low suctions. Consequently, if such a layer is present at the soil surface, it decreases the amount of water that can be transported to the surface by capillary rise. As a result, water transport upward through the rock fragment layer is by vapour diffusion only. As this quantity is usually low, total evaporation losses are low. Various studies have demonstrated the reduction in evaporation rate by a cover of rock fragments (e.g. Corey and Kemper, 1968; Unger, 1971a; Ingelmo-Sanchez et al., 1980). As with other mulch materials, a rock fragment cover has its greatest inhibiting effect upon evaporation the first few days after a rainfall event. The long-term beneficial effect of such a mulch depends very much upon the frequency and amount of rainfall. For instance, a rock mulch is less effective in situations where only very small rain amounts occur at long intervals of time because most of this water might evaporate in spite of the mulch (Corey and Kemper, 1968).

8. Effects of rock fragments on thermal properties of top soils

Although a surface layer of rock fragments may have only a modest effect upon evaporative losses from the soil, it has a profound effect upon the temperature regime of the surface horizon.

Heat transfer in a soil can be characterized by *thermal diffusivity* (Childs and Flint, 1990) which is defined as the ratio of thermal conductivity to heat capacity. *Thermal conductivity* (i.e. the rate of heat transfer along a unit temperature gradient) increases progressively faster with increasing rock fragment content (Fig. 9). *Heat storage capacity* (i.e. the amount of heat required to raise the temperature of a volume of

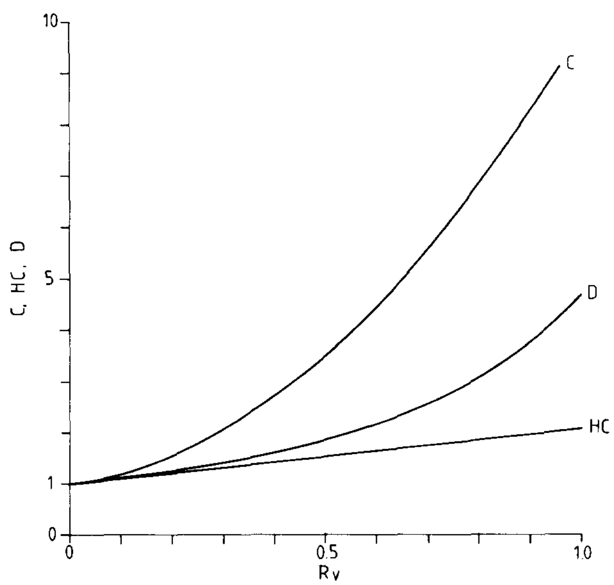

Fig. 9. Effect of rock fragment content by volume (R_v) in a dry soil on relative thermal conductivity (C, i.e. the rate of heat transfer along a unit temperature gradient), on relative heat storage capacity (HC, i.e. the amount of heat required to raise the temperature of a volume of soil one degree) and on thermal diffusivity (D, i.e. the ratio of thermal conductivity to heat storage capacity). Based on data published by Childs and Flint (1990).

soil one degree) increases linearly with rock fragment content for a dry soil. For a saturated soil, the opposite is true. As a consequence, thermal diffusivity increases non-linearly with rock fragment content in a dry soil (Fig. 9). Therefore, rocky soils have been observed to warm more rapidly than rock free soils in early spring while during late summer soil temperature can become dangerously high and stay high for considerable duration in dry soils. Also, a higher thermal diffusivity for rocky soils compared to non-rocky soils means a higher total heat flux into the soil as well as a deeper penetration of the daily heating cycle (Childs and Flint, 1990).

Rock fragments can also induce a lateral movement of heat which in turn can cause migration of moisture. During the heating period, temperatures beneath isolated rock fragments are lower than in adjacent air-dry soil (Mehuys et al., 1975; Evenari et al., 1982). Temperatures are dependent on colour and dimension of the rock fragment (Larmuth, 1978). A white rock fragment at the soil surface may be as much as 13°C cooler on its under surface when compared with a grey rock fragment of the same thickness (2 cm) and an increase in rock fragment thickness by a factor of 5 only halves this difference. Provided that the soil is sufficiently dry so that water moves mainly in the vapour phase, both heat and water vapour move, during the heating period, from the adjacent soil towards the underside of the cooler fragments where moisture condensation can occur. Such a heat and moisture flux towards the cylinder of soil under the rocks (due to horizontal temperature gradients induced by a rock cover) has been observed by Jury and Bellantuoni (1976). The lower temperatures during the heating period as well as the moisture accumulation under rock fragments can be of significance to flora (seedlings) and fauna in dry and hot periods/areas.

9. Effects of rock fragments on physical degradation of top soils

Physical degradation of the soil refers to adverse changes in soil physical properties, including porosity, permeability, bulk density and structural stability (F.A.O., 1979). The most important processes of physical degradation are surface sealing, crusting and compaction.

Rock fragments *at the soil surface* protect the latter against aggregate breakdown, surface sealing and crusting insofar as these processes result from physical dispersion of soil aggregates by raindrop impact and filtration of dispersed soil particles transported in infiltrating water. Valentin (1994) reports on field studies dealing with the influence of rock fragments on surface sealing.

Rock fragments *below the soil surface* support the existing soil structure and, hence, they have a negative effect on the susceptibility of the soil to compaction (compactibility). This has been demonstrated by several investigators. Saini and Grant (1980) reported that when applying a dynamic load to a loamy soil, the presence of rock fragments reduced compaction of the fine earth. For a given rock fragment content, the smallest fragments were most effective in reducing compactibility of the fine earth fraction. Ravina and Magier (1984) found in laboratory experiments that the rock fragment content in clay soils had a positive effect on their resistance to compaction. Larger volumes of large pores were found after a compaction of soils with increasing coarse fragment content. These results are along the same lines as the relations between rock fragment content and bulk density of the fine earth fraction (Fig. 4).

In conclusion, it can be stated that rock fragments help preserving favourable soil structures either at the soil surface by acting as a mulch or in the soil as a skeleton by preventing the soil from being compacted. Hence, the presence of rock fragments will usually reduce the intensity of physical degradation in fine textured soils.

10. Effects of rock fragments on soil erosion

The role of rock fragments in soil erosion by water at various spatial scales is discussed by Poesen et al. (1994). Abrahams and Parsons (1994) investigate how rock fragments affect the hydraulics of interrill overland flow and the implications for sediment transport modelling.

It is generally assumed that a high surface cover by rock fragments reduces the wind erodibility of soils by protecting the soil surface immediately below the rock fragments against deflation. However, individual roughness elements at the soil surface, such as rock fragments, increase the turbulence intensity of the air flow and, hence, affect critical wind velocities for soil particle motion (Lyles et al., 1971). Therefore, rock fragments have an ambivalent effect on soil erosion by wind. At low cover percentages rock fragments reduce the critical wind velocity at which erosion starts (= deflation threshold) compared to a bare soil surface, and therefore activate wind erosion. At high cover percentages, rock fragments increase the deflation threshold and, hence, shelter the soil surface from wind erosion. For each rock fragment size and shape, a minimum value for rock fragment cover (R_c) exists above which rock fragments will protect the soil surface against wind erosion. This minimum R_c value increases linearly with rock fragment size (Logie, 1982).

The previous section illustrates that, under certain conditions of rock fragment cover and size, the intensity of wind erosion can be activated by the presence of rock fragments. This is similar to water erosion (Poesen et al., 1994). The increased deflation due to a (low) cover of rock fragments will last until more subsurface rock fragments are exposed and the cover (stone pavement) exceeds the minimum cover percentage.

The effects of rock fragments on the deposition of airborne dust is discussed by Goossens (1994).

11. Effects of rock fragments on soil productivity

In this section we investigate how rock fragments affect the capacity of a soil in its normal environment to produce a specified plant or sequence of plants under a specified management system (= soil productivity, Soil Conservation Society of America, 1982).

11.1. Effects of rock fragments on soil properties affecting plant growth

When assessing the effects of rock fragments on soil quality, the prevailing assumption is that rock fragments decrease the total volume of fine earth (i.e. the effective soil). This is expressed by (Childs and Flint, 1990):

$$D_{eff} = D_{tot}(1 - R_v) \tag{2}$$

with D_{eff} = effective soil depth, D_{tot} = total soil depth, and R_v = rock fragment content by volume. In some instances this concept may be valid. Often, however, this concept leads to errors in interpretation because rock fragments affect soil behaviour in other ways.

This is well illustrated by observations made by Gras (1972). In an area of the Rhone valley where annual evaporation exceeds annual precipitation by 25O mm, no significant difference in peach tree productivity was observed between sites with no rock fragments and sites having up to 60% (R_m) rock fragments. Similar observations from other regions in France characterized by soils containing rock fragments were reported (Gras, 1972). From this striking observation he concluded that rock fragments are not simply inert material diluting the fine earth volume but that they contribute to the water-holding capacity of a soil.

Various researchers have reported important contributions to plant available water by rock fragments (Table 4). Available water for plants, expressed by available water capacity (AWC, in %), is the amount of water stored between a "field capacity" value and a dry or "unavailable water" volume. This water content is affected by rock type, degree of weathering and rock fragment size as illustrated in Table 4. Hence, although rock fragments reduce the overall water-holding capacity of the soil, they can still contribute to available soil water. Particularly chalk fragments can supply considerable amounts of water to plants (Table 4). Burnham and Mutter (1993) reported that even very shallow soils on chalk, such as those affected by severe erosion, will grow nearly as heavy a cereal crop as a deeper soil, provided that the soil is saturated with water at some time during the winter and that adequate fertilizer is applied.

Besides plant available water, rock fragments in soils have also been reported to contribute significantly to the nutrient content and cation exchange capacity (Munn et al., 1987). This is remarkable given the current view which attributes the cation exchange capacity of soils to their clay and organic matter fractions.

From the preceding it can be concluded that the rock component of a soil is not inert but may contribute in varying degrees to soil properties affecting plant growth in a positive way.

In addition, rock fragments themselves change the nature of the fine earth fraction. This can be easily understood if one considers the fact that increasing rock fragment content in a soil decreases the fine earth fraction but does, in most cases, not affect the amount of inputs to the soil (Childs and Flint 1990). These inputs (e.g. decaying organic matter and fertilizer) are concentrated on the fine earth fraction. This, then, will affect other soil properties, soil development and soil productivity. For instance, rock fragment content affects BD_{fe} (Fig. 4) and macroporosity, which in turn affects root development.

Table 4
Plant available water capacity (AWC, %) for selected fragments of different rock type, size and degree of weathering

Rock type	Degree of weathering or size	AWC (%) (* by mass, ** by volume)	Source
Basalt		0 *	Gras and Monnier (1963)
Chalk		24.7 *	Gras and Monnier (1963)
		20.0 *	Burnham and Mutter (1993)
Diorite			
	– fresh	3 **	Childs and Flint (1990)
	– slight	3 **	
	– moderate	3 **	
Flintstone		0 *	Gras and Monnier (1963)
Limestone		5–8 *	Gras and Monnier (1963)
Pumice		91–124 *	Munn et al. (1987)
Sandstone			
	–	10.3 *	Gras and Monnier (1963)
	– (2–5 mm)	5.6 *	Hanson and Blevins (1979)
	– (5–20 mm)	4.8 *	
	– (20–35 mm)	3.6 *	
	– fresh	4 **	Childs and Flint (1990)
	– slight	11 **	
	– moderate	15 **	
	– high	13 **	
Schist			
	– fresh	3 **	Childs and Flint (1990)
	– moderate	5 **	
	– high	10 **	
Shale			
	– (2–5 mm)	12.9 *	Hanson and Blevins (1979)
	– (5–20 mm)	5.9 *	
	– (20–35 mm)	6.2 *	
Siltstone	– (45 mm)	10 **	Montagne et al. (1992)

11.2. Effects of rock fragment content on plant growth

Few studies have been devoted to the effects of rock fragments in the surface and subsurface horizons on plant productivity. The scarce results indicate that the effects of rock fragment content on plant growth vary with fine earth properties, vegetation type and climate.

11.2.1. Fine earth properties

Lutz and Chandler (1946) reported that reasonable amounts of rock fragments in heavy-textured soils have to be regarded as favourable for tree growth while as in sandy soils rock fragments appear to have an unfavourable effect on plant growth. Babalola and Lal (1977b) found that the inhibitory effect of rock fragments on root development of maize (*Zea mays* L.) seedlings was more pronounced for sandy fine earth than for a sandy loam or a clay fine earth. From these observations it can be concluded that the vegetation response to rock fragment content is, at least partly, conditioned by the texture and the nutritional properties of the fine earth fraction.

11.2.2. Vegetation type

Different relations between rock fragment content and soil productivity have been observed for different plant species (Fig. 10): i.e. negative, positive, ambivalent or no relationships.

A *negative effect* of rock fragment content on plant growth has been reported by several investigators. Most studies of forest soils conclude that rocky soils are less productive than similar soils without rock fragments because rock fragments decrease the soil volume for nutrient supply (Childs and Flint, 1990). Voiculescu et al. (1983) found that walnut growth in Romania was restricted in soils containing more than

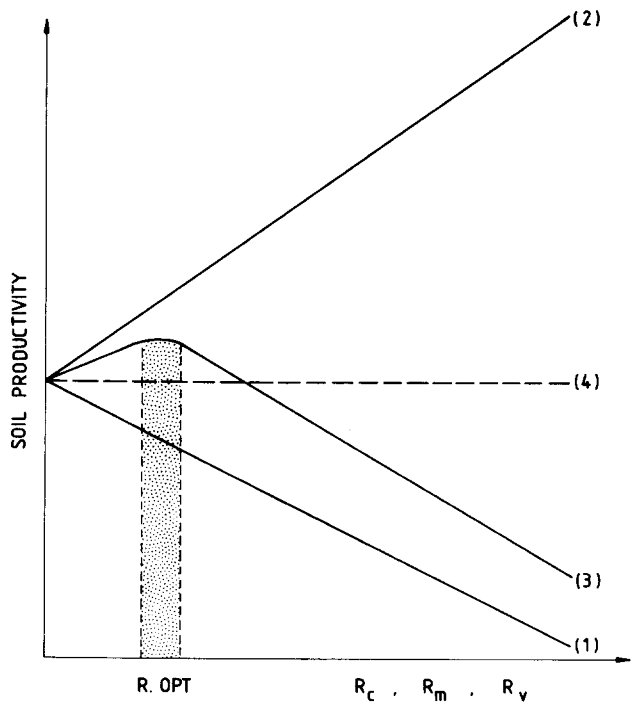

Fig. 10. Sketch to illustrate the typology of relations between rock fragment content in soils (*R*c, *R*m or *R*v) and productivity. *R*.OPT equals the optimal rock fragment content. 1 = negative relation, 2 = positive relation, 3 = ambivalent relation and 4 = no relation.

20% rock fragments. Research on irrigated reclaimed sites in Colorado (U.S.A.) showed a negative effect of rock fragment content on grass production (Munn et al., 1987). Babalola and Lal (1977b) observed root development of maize seedlings to be adversely affected by rock fragments when R_m exceeded 10–20%. Adams (1967) found that the application of a rock mulch in Texas had a detrimental effect on sorghum yields. He concluded that high temperature due to rock fragments next to the plant stems may have adversely affected certain physiological functions of the plant. Finally, Kongsrud (1978) reported a negative relation between content of rock fragments (with diameters between 2 and 6 mm) and strawberry yield.

Several studies also demonstrated a *positive effect* of rock fragment content on soil productivity. Experiments conducted by Jackson et al. (1972) indicate that soil associations with a high rock fragment content provide the conditions most favourable to the emergence, growth and development of blueberry seedlings (*Vaccinium angustifolium* Ait.) because in these soils a greater amount of root branching was obtained than in similar rock-free soil. A study on the effects of rock fragment content on reclaimed sites in Colorado on the growth of shrubs, forbs and grasses revealed that the highest productivity of fourwing saltbush (*Atriplex canescens*) occurred on a site with 85% rocks in the surface horizon (Munn et al., 1987). Albaladejo (1990) reported for southeastern Spain that thyme bushes (*Thymus*) prefer soils with a high rock fragment content in the top layer. Unger (1971b) demonstrated that the use of a rock mulch had a beneficial effect on sorghum (*Sorghum vulgare*) yields in Texas because of a reduction in evaporation and a higher water storage from small precipitation events. Similar results were obtained in Colorado for corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.M.), tomatoes (*Lycopersicon* sp.) and soybean (*Glycine max* L.M.) yields (Fairbourn, 1973) and were attributed both to soil water conservation as well as to higher soil temperatures due to the rock fragment mulch. The higher soil temperatures promoted early season growth. Finally, soils containing rock fragments are also known to produce high quality grapes for wine-making because of the rock fragments' effects on permeability, water-holding capacity and the temperature regime (Seguin, 1971).

Ambivalent effects of rock fragment content on soil productivity have also been reported. Rutherford (1983) found that surface rock cover in South Africa could increase or decrease herbaceous standing crop in non-wooded parts of savanna and in desert grassland. The type of relationship strongly depended on subsurface rock weathering patterns. Several researchers observed a positive effect of rock fragment content on plant growth up to an optimal rock fragment content (*R*.OPT, Fig. 10). Above this *R*-value, the trend reversed.

Wollny (1897–98) was the first to report that R_v.OPT equalled 10–20% for a number of crops (i.e. cereals, root crops, vegetables) in southern Germany. He attributed this to rock fragment effects on soil moisture and soil temperature regime. Lutz and Chandler (1946) reported a R_v.OPT-value of 20% for tree growth. Above this value, unfavourable effects, i.e. restricted root space, too high temperature extremes, and decreased field capacity of the soil body, begin to outweigh the favourable ones. Saini and Grant (1980) found a R_v.OPT-value of 12% for potato (*Solanum tuberosum* L.) yield. The positive effect of rock fragment content on soil productivity, below this R_v.OPT value, was attributed to higher soil temperature, higher soil moisture content, less soil compaction, and reduced water erosion. Babalola and Lal (1977a,b) concluded from their experiments that R_m.OPT equalled 10–20% for the growth and development of maize roots. Magier and Ravina (1984) reported a R_v.OPT-value of 25–30% for apple tree (*Pyrus Malus*) development and yield in Israel.

Finally, Gras (1972) did *not observe any significant effect of rock fragment content ($0\% < R_m < 60\%$) in soils on the growth of peach trees in southern France.*

11.2.3. Climate

From an extensive literature review, Munn et al. (1987) concluded that the effects of rock fragment content on soil productivity varied along a moisture gradient from humid to arid climates. In *humid climates*, crop productivity generally is higher on fine-textured, non-rocky soils. As precipitation declines, the relationship generally continues to hold but the difference in productivity potential diminishes and eventually is reversed in areas of very low precipitation (< 300 mm). In *arid and semi-arid regions*, the deeper penetration of limited precipitation and greater availability of water at low moisture contents in coarse-textured soils and soils containing rock fragments in surface horizons often result in these soils being more productive than finer textured soils in comparable upland topographic positions. Kadmon et al. (1989) reported a positive effect of rock fragment content on the abundance of woody perennials in the northern Negev (170 mm of annual rainfall) and attributed this to the favourable effects of rock fragment content on water availability.

Similar results were recently reported by Kosmas et al. (1994) in Greece. In a wet year, i.e. with 663 mm of rain during the growing season, they observed that biomass production of rainfed wheat along catenas on shale-sandstone soils containing 40 to 65% of rock fragments was 60 to 80% of the biomass production on marl soils which had no rock fragments at all. However, in a dry year, i.e. with only ±95 mm of rain in the growing season, they found that biomass production on the shale-sandstone soils was 5 to 10 times the biomass production on marl soils. The different behaviour of these two soil types could be attributed to differences in clay mineralogy, soil structure and rock fragment content.

Along the same lines, Yair and Shachak (1987) came to the conclusion that in arid areas the ratio of bare bed-rock outcrop to soil cover decreases the ecological aridity of the area. Rocky slopes were found to maintain a more favourable environment for plant growth than non rocky slopes because of the positive effects of rock outcrops on runoff frequency and magnitude, and therefore water availability, as well as on soil desalination.

From this review we conclude that the relation between rock fragment content and plant productivity is fairly complex. Some general statements, however, can be made:

(1) Rock fragments seem to be more beneficial for plant growth in clay soils than in sandy soils.

(2) Some shrubby deep rooting plants seem to be better adapted to soils containing rock fragments than shallow rooting grassy plants or trees.

(3) Moderate rock fragment contents can beneficially affect the moisture and

temperature regime of soils. However, beyond an optimal rock fragment content varying between 10 to 30%, the abundance of rock fragments starts to adversely affect plant productivity by restricting rooting space and the nutritional capacity of the soil, and by increasing soil temperature extremes above plant tolerable values.

(4) In dry climatic conditions rock fragments seem to create favourable conditions for plant growth. Consequently, degradation of the vegetative cover due to climatic change might be less severe on soils rich in rock fragments compared to rock-free soils.

12. Conclusions

From this literature review we conclude that the presence of rock fragments can significantly affect the behaviour of a soil. More particularly, rock fragments alter soil properties such as bulk density, water-holding capacity, infiltrability, erodibility, soil temperature, and rooting volume, and therefore influence the hydrological response of a soil as well as soil degradation and soil productivity.

Acknowledgements

This research was conducted as part of a collaborative research project funded by the Commission of the European Communities (DG XII) and this support is gratefully acknowledged. The help of Dr. M. Jamagne and Dr. Y. Le Bissonais (I.N.R.A., Orléans) and of Dr. F. Depuydt in producing Fig. 1. is acknowledged. Dr. Jan Moeyersons, Dr. Dirk Goossens, Dr. Bas van Wesemael and Dr. Kristin Bunte are thanked for their comments on an earlier draft of this paper.

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