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Influence of rock fragments on the water retention and water percolation in a calcareous soil

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Abstract

The water retention properties of a calcareous soil containing rock fragments have been determined in the laboratory thanks to pressure plate measurements done on both the fine earth and the rock fragments from the soil. The available water content (AWC) has been calculated from these data. We have shown that when the rock fragments are neglected, the AWC can be overestimated by 39%. When we do not neglect their volume but when their hydraulic properties are not considered, the AWC can be underestimated by 34%. By using a reservoir model, we have also calculated the effect of rock fragments on water percolation to groundwater. Depending of the climatic characteristics of the year, the underestimation of percolation when we neglect the rock fragments can reach up to 14.9% and the overestimation when we neglect their hydraulic properties can be equal to 15.8%. These findings emphasise the role of the rock fragments on the water supply in stony soils.

Keywords: Stony soil; Available water content; Water balance modelling; Infiltration

1. Introduction

Soils containing rock fragments represent about 30% of the Western Europe surface area and even 60% in the Mediterranean zone (Poesen and Lavee, 1994). Due to workability and trafficability problems, they are less used for agronomic production and, as a consequence, they have been studied less frequently. Nevertheless, the presence of rock fragments modifies (i) the soil physical properties: available water content,

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infiltration and runoff susceptibility, for example; (ii) the soil chemical properties: carbon content or nitrogen content; and (iii) the agronomical characteristics like the yields. Most studies dealing with stony soils usually do not take into account the rock fragments, even if their abundance cannot be neglected. As a consequence, the soil properties are not correctly evaluated, overestimated or underestimated, when only the fine fraction of the soil is considered (Ugolini et al., 1998).

As far as available water content (AWC) is concerned, Coile (1953) first showed that the calculated water available for plants is higher if we take into account the rock fragments, thus illustrating the water retention properties of the rock fragments themselves (Coile, 1953). However, AWC of soils containing rock fragments depends on several parameters: (i) the origin of the rock fragments, (ii) the volumetric percentage of the rock fragments, (iii) the size and the porosity of the rock fragments, and finally (iv) the position of the rock fragments. Indeed, the origin of the rock fragments has a large influence on the water holding capacity: when rock fragments come from chalk, it can be larger than 90% of the saturation range; whereas it is nearly equal to zero when the rock fragments come from basalt fragments (Poesen and Lavee, 1994). The volumetric percentage of the rock fragments in the soil usually has a negative influence on the AWC: the available water for plants generally decreases when the percentage of rock fragments increases but this is not always true, for example for soils developed on schist (Hanson and Blevins, 1979). The size and the porosity of the rock fragments play an important role in their water retention properties as well: the smaller the rock fragments, the more weathered (Childs and Flint, 1990) and the more they can store water (Hanson and Blevins, 1979; Poesen and Lavee, 1994). Finally, the position of the rock fragments, on the surface or inside the soil profile, free on the surface or embedded in the fine earth, has a large influence on the total water properties of the soil, especially because the rock fragments modify the evaporation conditions at the surface (Jury and Bellantuoni, 1976; Perez, 1998). It has been shown that a 5 cm gravel mulch can reduce the annual evaporation by 85% (Kemper et al., 1994) and that under Mediterranean conditions, the rock fragments can keep a higher water content in the soil than when they are not present (Danalatos et al., 1995). On the contrary, under strong evaporation conditions, the high calorific characteristics of the rock fragments leads to heating of the soil and therefore to a decrease of its water content.

As far as hydrodynamic characteristics of soils containing rock fragments are concerned, two types of studies have been conducted: on the one hand, some authors have discussed the effect of rock fragments on infiltration as the complementary part of runoff on erosion studies; and on the other hand, they have tried to measure or model directly the hydraulic conductivity of stony soils.

The presence of rock fragments at the soil surface can either increase or decrease infiltration (Brakensiek and Rawls, 1994). Grant and Struchtemeyer (1959) have shown in laboratory runoff experiments that the removal of rock fragments leads to a decrease in infiltration because part of the porosity has disappeared and the soil surface is not prevented from sealing by these rock fragments (Grant and Struchtemeyer, 1959). In fact, the effect of rock fragments on the soil surface strongly depends of their position: when free on the surface, they generally prevent the soil from sealing and the infiltration increases, but embedded in the surface, they participate to the establishment of a continuous crust inhibiting infiltration and reinforce runoff (Poesen and Lavee, 1994).

As for water retention properties, the size and the form of rock fragments has to be highlighted: generally, the infiltration in stony soils increases for small rock fragments but there exists a threshold (Valentin and Casenave, 1992). Above this threshold, infiltration decreases because of the less accessible surface for water flow (Valentin, 1994). Furthermore, the more spherical rock fragments are, the lower the saturated hydraulic conductivity (Dunn and Mehuys, 1984). Finally, most of the studies dealing with infiltration in soils containing rock fragments were restricted to arid or Mediterranean zones.

Laboratory experiments on disturbed soils containing rock fragments have shown that soil saturated hydraulic conductivity can be estimated from the fine earth saturated hydraulic conductivity and the volumetric percentage of the non-porous rock fragments (Mehuys et al., 1975). The presence of non-porous fragments only reduces the available area for the flow and increases the tortuosity of the water flow because pockets under the rock fragments have to be wetted (Gras, 1972). But even if tortuosity increases, the creation of new voids in the stone–earth contact, useful for water flow, can increase the saturated hydraulic conductivity with increasing rock fragments content (Ravina and Magier, 1984). Based on the heat transfer theory, a formula has been calculated for a homogeneous medium containing non-porous spherical inclusions (Peck and Watson, 1979) to calculate the hydraulic conductivity of a stony soil from the hydraulic conductivity of the fine earth and the volumetric percentage of rock fragments:

$$K_{\mathrm{soil}}/K_{\mathrm{fe}} = 2(1 - R_{\mathrm{v}})/(2 + R_{\mathrm{v}}) \tag{1}$$

where K_{soil} (resp. K_{fe}) represents the hydraulic conductivity of the soil (resp. of the fine earth) and R_{v} is the volumetric fraction of the rock fragments. A first comparison with experimental data has shown that this formula overestimated the hydraulic conductivity for high water content (Bouwer and Rice, 1984) and it has then be simplified to:

$$K_{\mathrm{soil}}/K_{\mathrm{fe}} = 1 - R_{\mathrm{m}} \tag{2}$$

where R_{m} represents the mass fraction of the rock fragments (Brakensiek et al., 1986). Nevertheless, whatever equations are used to estimate the saturated hydraulic conductivity in stony soils, they deal only with non-porous rock fragments and, even in that case, no general relation has been found. For soils containing porous rock fragments, Gras (1972) has pointed to the air encapsulation phenomenon inside the porous fragments which modifies the soil hydraulic conductivity. Furthermore, to our knowledge, no experimental studies has dealt with hydraulic conductivity outside the saturation range. Indeed, field experiments in stony soils are quite impossible because it is really difficult to install either tensiometers or lysimeters, for example. Direct measurement of the infiltration are still a problem. Moreover, as already mentioned by Mehuys et al. (1975), sampling of undisturbed soil cores containing rock fragments remains difficult. Laboratory measurements of unsaturated hydraulic conductivity are therefore not possible. In that context, the calculation of infiltration in a soil containing rock fragments with a deterministic model that would use explicit unsaturated hydraulic conductivity data seemingly remains elusive up to the present.

The aim of our study was to illustrate the role of rock fragments in a soil containing calcareous rock fragments, developed within a temperate climate. We first present field and laboratory experimental data that allow us to discuss the effect of the nature of rock fragments on the available water content. Then, we attempt to calculate water percolation in the same soil by using a reservoir model, in order to discuss the effect of the presence of rock fragments on water percolation.

2. Material and methods

2.1. Experimental data

The study area is located in Beauce, south of Paris, France, where we have selected a clay loam soil containing rock fragments, developed on a calcareous substratum. The depth of the soil depends on the slope orientation. Three types of soils have already been described in this area (FAO et al., 1998):

- clay loam soils developed on cryoturbated materials (Haplic Calcisol);
- clay loam soils developed on calcareous parent material (Haplic Calcisol);
- clay loam soils containing rock fragments developed on calcareous parent material (Rendzic Leptosol).

The study has been carried out on the third soil type, and two subsites within this clay loam soil containing rock fragments developed on calcareous parent material (Rendzic Leptosol) have been chosen (Coutadeur et al., 2000). The first, called site A, with a soil of 80 cm depth was cultivated with common winter wheat (*Triticum aestivum* variety: Altria) and the second one, called site B, with a soil of 55 cm thickness was cultivated with common winter wheat (*T. aestivum* variety: Soisson). In both cases, sowing was done on 19 October 1998. Nitrogen was spread for the first time on 18 February 1999 (90 kg/ha), for the second time on 23 March 1999 (90 kg/ha) and for the third time on 6 June 1999 (40 kg/ha). On site A, the wheat was irrigated with 33 mm of water on 19 June 1999.

The bulk density of the soil has been measured in the field via the membrane densitometer involving about 1 dm^3 of soil (Baize, 1993). Fine earth and rock fragments have been characterised separately for each horizon by sampling 6 kg of soil (Tables 1–3). After sieving and drying, the weight percentage of stone has been determined. Bulk density of the rock fragments has been measured on 15 replicates with the petrol method (Monnier et al., 1973) (Table 1). Total bulk density of the soil has been determined in the field. The fine earth bulk density was then calculated by comparison between the total bulk density of the soil and bulk density of the rock fragments. With these data, we have calculated the volumetric percentage of the two phases (Table 2).

Water retention data of each horizon were determined on a pressure plate apparatus for eight water potentials between -1 and -1500 kPa, according to the method described by Bruand et al. (1996). For fine earth, the water retention data have been measured on 12 replicates for each horizon with clods of about 10 cm^3 containing no rock fragments. These clods were gently separated from a large undisturbed soil block ($25 \times 25 \times 15$ cm^3)

Table 1
Bulk density and volumetric fraction of fine earth and rock fragments for the two studied soils

Horizon	Fine earth				Rock fragments			
	Bulk density (g cm^{-3})			Volumetric fraction (%)	Bulk density (g cm^{-3})			Volumetric fraction (%)
	Mean	STD	n		Mean	STD	n	
Site A								
0–27 cm	1.14	0.14	10	65.8	2.24	0.18	30	34.2
27–40 cm	1.15	0.04	3	51.2	2.04	0.08	15	48.8
40–55 cm	1.10	0.10	3	53.5	1.99	0.07	15	46.5
55–80 cm	1.27	0.10	3	43.1	1.87	0.24	15	56.9
Site B								
0–27 cm	1.11	0.23	9	78.1	2.23	0.12	30	21.9
27–50 cm	1.50	0.10		52.7	2.25	0.09	15	47.3

in order to preserve their natural structure. During this operation, rock fragments were isolated from the fine earth. They were saturated for 48 h in water and placed on a pressure plate. To assume a correct hydraulic continuity between the pressure plate and the rock fragments, we used a 0.5-cm bed of saturated kaolinite. The rock fragments were laid on the kaolinite bed on their flattest side. Ten to fifteen rock fragments were used for the measurement at each water potential. A preliminary laboratory study conducted on the calcareous rock fragments from the two soils has shown that water content reached a constant value after 2 weeks in the pressure plate. The rock fragments were therefore left in the pressure plate for 2 weeks after measurement of their water content.

In order to estimate the respective roles of rock fragments and fine earth in water transfer in stony soils, we have measured the water content in the soil at different specific dates. We have collected fine earth and rock fragments three times throughout the whole soil profile to determine the partition of water between these two particle size fractions. The dates for this complete characterisation have been chosen to be representative of three phenological stages of the wheat. The first date corresponded to the end of winter (10

Table 2
Physico-chemical characteristics of the two soil profiles

	Soil texture (fine earth)					$CaCO_3$ (%)	pH water	Organic matter (%)	Total nitrogen (%)
	Clay <2 μm (%)	Fine silt 2–20 μm (%)	Large silt 20–50 μm (%)	Fine sand 50–200 μm (%)	Large sand 200–2000 μm (%)				
Site A									
0–27 cm	37.9	22.2	15.0	6.7	18.2	44.6	8.3	3.82	0.242
27–40 cm	24.2	25.2	5.3	2.0	43.3	82.6	8.8	2.34	
40–55 cm	16.3	23.0	3.4	4.2	53.1	93.6	9.1	0.36	
55–80 cm						95.0			
Site B									
0–27 cm	38.4	22.8	25.7	3.9	9.2	9.1	8.2	3.35	0.226
27–50 cm	37.7	22.0	20.0	6.7	13.6	27.7	8.4	2.32	

March 1999), the second one to the beginning of spring (8 April 1999) after the dormant season, and the third one to the end of the crop cycle (21 June 1999). The rooting pattern of wheat has been described at these three dates using the method of Tardieu and Manichon (1986).

Furthermore, we have measured the water content in both fine earth and rock fragments in the surface horizon. The surface horizon has been separated into three sub-horizons (0–5, 5–20 and 20–27 cm) and 10 rock fragments have been collected from each of these sub-horizons. Water content in both fine earth and rock fragments was measured each 2 weeks from 10 March 1999 to 21 July 1999 in the three sub-horizons.

2.2. Available water content

Available water content (AWC), i.e. water disposable for plant growth, has been calculated for the studied soil. These results yield insights about the influence of rock fragments on the total available water content. Moreover, AWC is an input for the model that we used in this study to discuss the role of rock fragments on infiltration in the soil.

The available water content is determined by the following equation:

$$\mathrm{AWC}_i = (W_{\mathrm{fc}_i} - W_{\mathrm{wp}_i})d_i\mathrm{th}_i \tag{3}$$

where AWC_i represents the available water content of phase i (mm cm^{-1}), W_{fc_i} is the water content at field capacity (g 100 g^{-1}), W_{wp_i} is the water content at permanent wilting point (g 100 g^{-1}) (measured as 15,800 kPa), d_i is bulk density of the phase i (g cm^{-3}), th_i is thickness of the horizon (dm).

The total available water content of the soil is therefore equal to:

$$\mathrm{AWC} = \sum_i \mathrm{AWC}_i p_i \tag{4}$$

where p_i represents the volumetric fraction of phase i.

Water content at permanent wilting point has been determined via pressure plate measurements. Water content at field capacity has been estimated by an expert analysis from the field water content data at the end of winter: sampling of rock fragments and fine earth at the first date (10 March 1999) has been carried out when soil was considered at field capacity, after gravimetric water has drained.

2.3. Modelling of water percolating at the soil base

In order to discuss the effect of water use by plants in stony soil, whether or not take into account the role of rock fragments, we have calculated the water percolation at the base of the soil profile by using the STICS model (Brisson et al., 1998, 2002). It is a crop model that enables the calculation of water and nitrogen balances in a soil–crop system. Known for its robustness and easy access to inputs, it was initially developed for wheat and corn but calculations with several new crops are now available. For our study, we were interested in the water balance module on bare soils. It works as a reservoir model: the soil is discretized into horizons with various thicknesses (corresponding to the actual thicknesses of the simulated soil), each horizon being defined by its water content at field capacity, its water content at permanent wilting point and its bulk density. For the surface horizon, albedo, clay content, calcareous content, organic nitrogen content, potential evaporation limit and humification depth are used as well. Each horizon is then cut into 1-cm layers, and when the actual water content of a layer exceeds the field capacity water content, water is transferred to the layer below. As far as climatic data are concerned, the precipitation (and irrigation) and the reference evapotranspiration calculated through the Penman's formula are needed. The model operates at a daily time step. For the water balance module, the output data are the daily water content of each horizon (on a mass basis) and the daily water percolation at the lower horizon limit.

3. Results and discussion

3.1. General characterisation of the two phases

The volumetric percentage of rock fragments is high in the surface horizon (0–27 cm) of the two sites: 34.2% in site A and 21.9% in site B (Table 2). This percentage is higher in the lower horizons and reaches 56.9% at 55–80 cm depth in site A. In site B, the proportion reaches 47.3% in the last soil horizon at 50 cm depth. Nevertheless, the size distribution of rock fragments varies on the two sites: at the soil surface, rock fragments belong mainly to the 2–20 mm fraction in site A, whereas they belong mainly to the 20–75 mm fraction in site B (Table 3). But for both soils, the diameter of the rock fragments increases with depth. The bulk density of the rock fragments ranges from 1.9 to 2.2 (Table 2) and is of the same order of magnitude as the one measured by Gras (1972) on calcareous soils. In contrast, bulk density of the fine earth, ranging from 1.1 to 1.2 on site A is low, compared to the results of Gras (1972).

3.2. Water retention properties of the rock fragments and the fine earth

The water retention properties of fine earth and rock fragments have been measured by experiments on pressure plates apparatus. For the three first horizons of site A and for the two horizons of site B, the water content (determined on a mass basis) in fine earth is about

Table 3
Particle size distribution of rock fragments in the two soils

	2–4 mm (%)	4–8 mm (%)	8–20 mm (%)	20–75 mm (%)	>75 mm (%)
Site A					
0–27 cm	22.9	8.8	28.7	28.7	10.3
27–40 cm	22.8	10.3	27.8	27.7	11.8
40–55 cm	17.4	8.3	28.5	32.1	14.8
55–80 cm	13.7	7.2	21.2	39.1	19.2
Site B					
0–27 cm	15.1	5.5	12.4	39.2	27.8
27–50 cm	16.7	4.6	11.9	10.9	56.0

30% at a water potential of -1 kPa and decreases with depth to about 15% or lower (Fig. 1). The water content, whatever the water potential, is about 10% lower in the last horizon of site A.

As far as rock fragments are concerned, water content in site A decreases from 7% to 4% in the upper horizon and from about 12% to 5% in the lower horizon. We observe that water content is always lower in rock fragments than in fine earth but this water content, usually not far from 10%, can a priori not be neglected. In site B, the water content is more or less equal to 5% whatever the water potential and the horizon. Nevertheless, in the two sites, these data are mean data calculated from 10 or 15 replicates. The standard errors are usually high (e.g., it is equal to 5.4% for water content at -1 kPa in site A, 0–27 cm) and demonstrate the large heterogeneity of the properties of rock fragments.

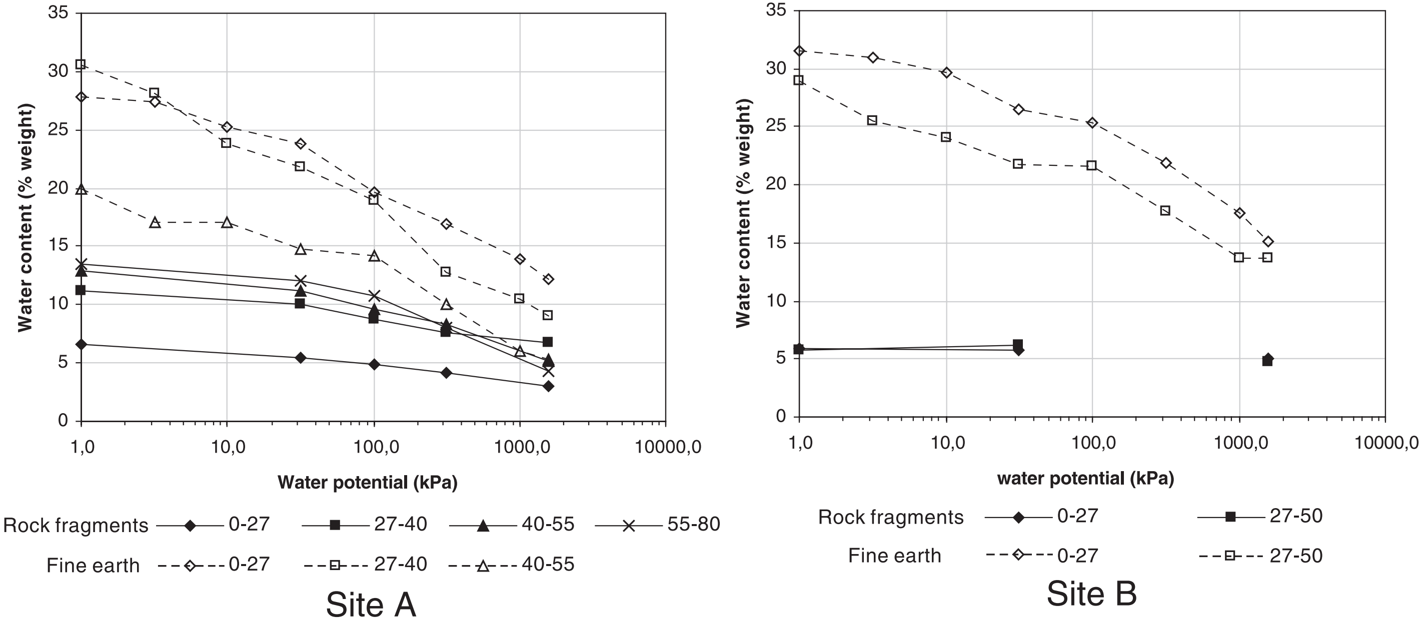
Due to its role in the calculation of AWC, let us focus on the measurement of water content at the permanent wilting point. In site A, the water content at permanent wilting point is equal to 3.4% and 12.2% in the upper horizon for rock fragments and fine earth, respectively (Fig. 2). It decreases with depth for fine earth to reach a value of 5.3%, which is not far from the value obtained for rock fragments. In site B, water content at permanent wilting point is constant in the whole profile for rock fragments, with a value of 5.2%. For fine earth, the water content at permanent wilting point is equal to 15.1% in the upper horizon and 13.8% at 35 cm depth, and is always substantially larger than the value for rock fragments. The difference in water content for fine earth in the two sites is probably related to the difference in texture for the two soils (Table 1).

As far as rock fragments are concerned, the difference in water holding characteristics can be explained by the variation in parent material origin and degree of alteration. Limestone is more porous at site A and can be more weathered. As a consequence, porosity is lower from rock fragments sampled in the surface horizon than from deeper areas because relatively large rocks (larger than 20 mm) are cut into smaller more resistant ones (Table 3), with larger bulk density (Table 1) and then lower porosity. Water content at field capacity is then lower at the surface horizon than deeper areas at site A. In a lesser extent, that effect can be seen for the water content at permanent wilting point, too. In contrast, at site B, the calcareous parent material is less porous and can be less weathered, and the soil thickness is smaller. Rock fragments that reach the surface are therefore not different from the ones near the parent material, with the same bulk density (Table 2). Water content at field capacity and permanent wilting point is also nearly the same all along the soil profile.

3.3. Available water content

For site A, the AWC of the stone phase is equal to 0.6 mm cm^{-1} at the surface and increases to up to 1.4 mm cm^{-1} in the last horizon (Fig. 3). It is lower and more constant for site B, with a constant value of 0.25 mm cm^{-1}.

To discuss the influence of rock fragments on the calculation of soil AWC, we have considered three hypotheses. In the first case, AWC is calculated using Eq. (4). This means that the AWC of the rock fragments and their volume are taken into account (case 1). In the second case, we have taken into account the volume of the rock fragments but we have



Site A

Site B

Fig. 1. Water content versus water potential for all horizons of the two studied sites.

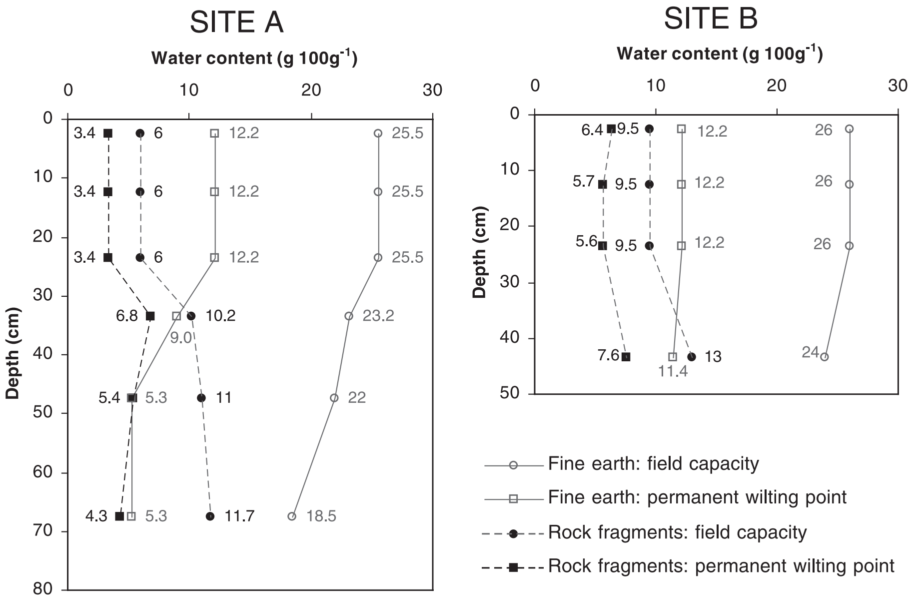


Fig. 2. Evolution of the water content at field capacity and permanent wilting point for the fine earth and for the rock fragments versus depth in the profile.

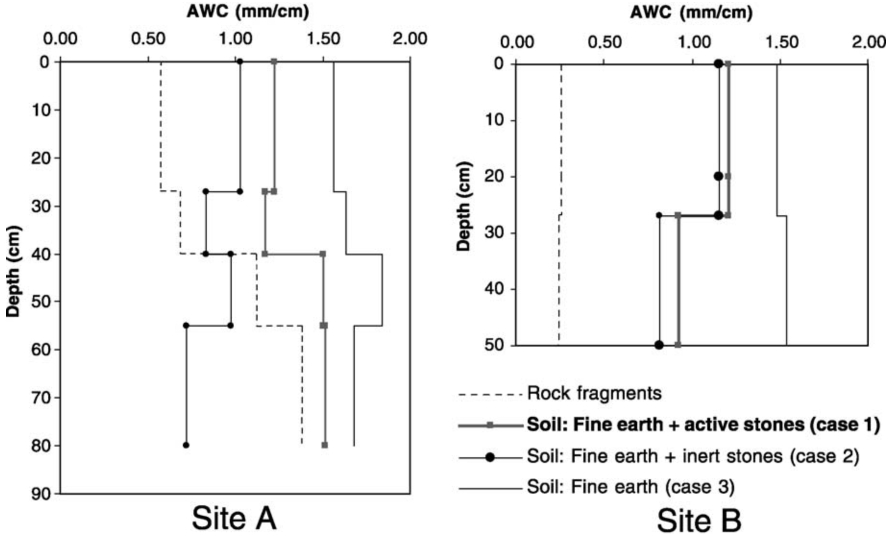


Fig. 3. Available water content (AWC) calculated for rock fragments and fine earth, and for the soil defined with three hypotheses.

considered that they do not contain water, meaning that they do not participate in water transfers (case 2). In the third case, we have not taken into account the rock fragments at all and we have considered that the soil consists only of fine earth (case 3).

For site A, the actual AWC (case 1) is equal to 1.23 mm cm^{-1} from the surface to 40 cm depth and it increases up to 1.50 mm cm^{-1} for the deeper horizons (Fig. 3). This high value of AWC for a clay loam soil is related to the relative high water retention properties for rock fragments compared to the water retention properties of fine earth at this depth. In case 2, when we take into account the volumetric part of rock fragments but not their water retention properties, the AWC in the soil is underestimated by 0.2 mm cm^{-1} in the upper horizon and by 0.8 mm cm^{-1} in the deeper horizons. In contrast, when we totally neglect the rock fragments (case 3), the AWC is overestimated by 0.3 mm cm^{-1} in the upper horizon and by 0.15 mm cm^{-1} in the deeper horizon.

For site B, the AWC of the soil in case 1 is equal to 1.23 mm cm^{-1} at the surface and decreases down to 0.93 mm cm^{-1} from 27 cm depth. In case 2, the AWC in the soil is underestimated by 0.05 mm cm^{-1} in the whole profile. The difference between case 1 and case 2 is lower for site B than for site A because the AWC of rock fragments in site B is really low (equal to 0.25 mm cm^{-1}). This is due to their low porosity (see the bulk density values on Table 2). In contrast, if we completely neglect the rock fragments and if we consider that the soil consists only of fine earth, the AWC of site B is overestimated by 0.25 mm cm^{-1} in the surface horizon and by 0.61 mm cm^{-1} from 27 cm depth. This high discrepancy between case 2 and case 3 for site B is due to the volumetric percentage of the rock fragments, equal to 47.3% in the deep horizon (Table 2), which cannot be neglected. For site B, the volumetric percentage of rock fragments is high, meaning that it is important to take its volume into account. Nevertheless, due to their low porosity, the rock fragments do not store a considerable quantity of water and their water retention properties can be overlooked.

Both the volumetric percentage and water retention properties have to be considered when one wants to estimate the role of rock fragments on water transfer in stony soils. In our case, the total AWC for the whole soil profile can be overestimated by 22–39% when we do not take into account the rock fragments properties, and underestimated by 8–34% when we take into account the volume of the rock fragments but not their retention properties.

3.4. Temporal evolution of the water content in the soil profile for both the rock fragments and the fine earth

The water content of fine earth and rock fragments has been measured at three dates for the whole soil profile. Data are presented as water storage, which we define as the percentage of available water capacity in each horizon (Fig. 4).

10 March 1999: At site A, the rate of water storage is maximum for the whole profile and the water content is larger than the water content at field capacity for all horizons.

8 April 1999: After the dormant period of wheat, water storage has decreased in the surface horizon and we notice that the water used by plants and/or the evaporation comes mainly from fine earth. At this date, root pattern analysis has shown that the roots are mainly located in the surface horizon and they are not specifically in direct contact with rock fragments (Coutadeur et al., 2000). In the lower horizons (40–55 cm and 55–80 cm), water storage has likewise decreased but the used water comes from rock fragments.

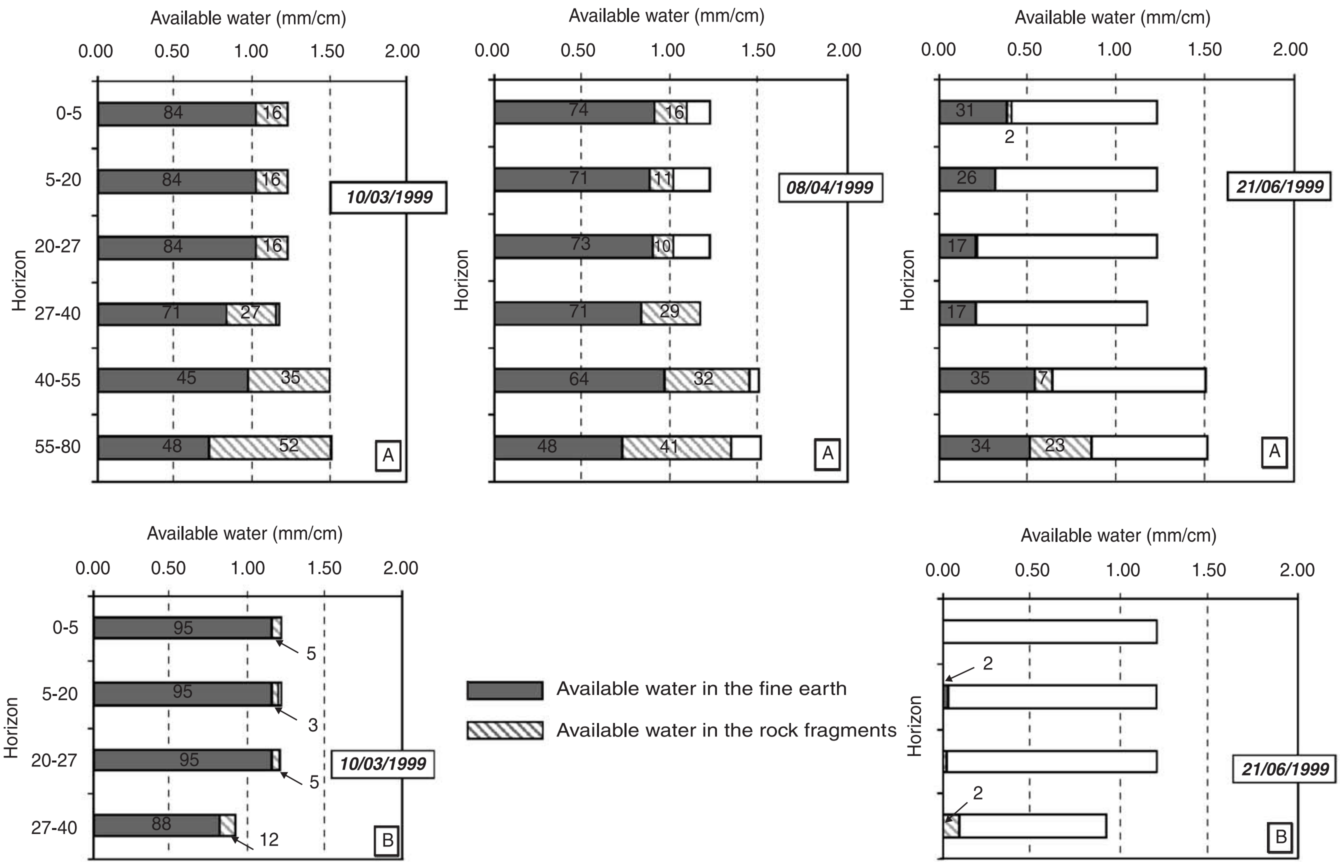


Fig. 4. Evolution of water storage in the two soil profiles at three dates for site A and two dates for site B.

21 June 1999: Water storage is really low but is not totally empty because of irrigation (on wheat) on 19 June 1999. At this date, the rock fragments do not provide any water to the soil (except a very low quantity in the upper horizon) for the 0–27 cm horizon. In the deeper horizons, water storage has decreased but it is still equal to half of the water storage capacity in the 55–80 cm horizon where rock fragments provide 41% of the water to the soil. Observation of the roots' position shows that many of them are directly stuck on rock fragments. In this horizon, the decrease in water content is due to both a decrease of water content in fine earth and in rock fragments.

At site B, the water content in fine earth and in rock fragments was measured only on two dates (Fig. 4). On 10 March 1999, water storage is full for the whole profile and the fine earth provides 96% (resp. 87%) of the total water in the 0–27 cm (resp. 27–50 cm) horizon. For 21 June 1999, water storage is empty in the surface horizon and only the rock fragments still contain water in the deep horizon. This low contribution of rock fragments to the water dynamics is due to their low porosity, as measured by their bulk density (Table 2).

3.5. Influence of the rock fragments on the water percolation in the soil

3.5.1. Input data and conditions for the use of the model

We calculated the water infiltration rate on sites A and B. Since the soil depth on site B is equal to 50 cm, we calculated the percolation at this depth for both sites, to be able to discuss the effect of different rock fragments types on infiltration. We calculated percolation at site A at the 80 cm depth, which corresponds to the depth of the soil at this site and which enables us to discuss the effect of depth for percolation at site A. Similar to AWC calculations, three cases were calculated: fine earth and active rock fragments (case 1), fine earth and inert rock fragments (case 2) and fine earth alone (case 3). The calculations were done for 7 years, from 1994 to 2000. To be able to compare the results without the effect of different crops, we calculated the percolation on a bare soil. The initial date was the 20 July (corresponding to a typical wheat harvesting date in that region) and the final date was 30 April.

3.5.2. Comparison of the model results with experimental data

We have compared the calculated water content in each horizon and the measured water content on site A for the period 20 July 1998–25 April 1999. We used the experimental data of the water content in fine earth and in rock fragments to calculate an equivalent horizon water content in each horizon. Comparisons between experimental and simulated data were carried out for the period 10 March 1999–24 April 1999. During this period, water retention was measured in the field when wheat was still in its dormant phase. Comparisons between measured and experimental data in a soil under wheat and simulated data on a bare soil are therefore possible. Due to the reservoir method calculation, water content larger than field capacity cannot be determined by the STICS model (Fig. 5), whereas some measured water contents were higher than field capacity during the winter season. This explains some discrepancies between some experimental data and the corresponding calculated values at high water content. Nevertheless, for each of the three cases, when the measured water content is lower than the field capacity water content, the

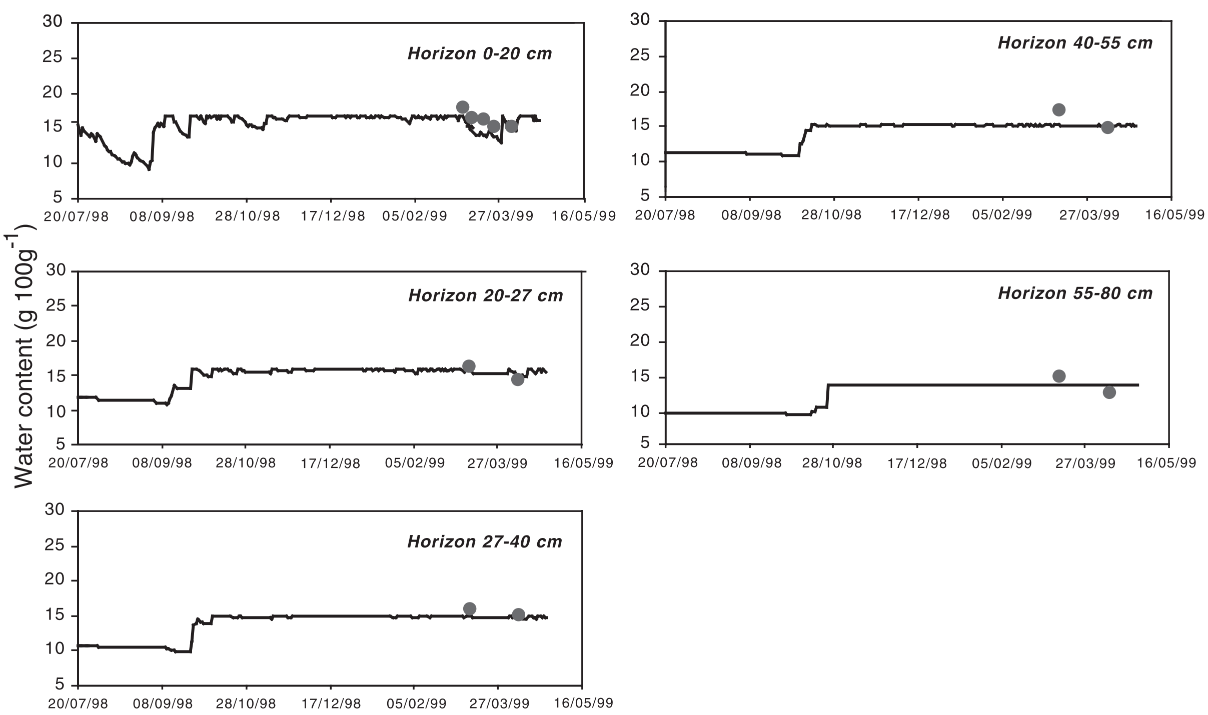


Fig. 5. Water content (on a mass basis) calculated in each horizon for site A with the STICS model for the 20/07/1998–25/04/1999 period (black line). The dots correspond to experimental data and the plain lines correspond to simulated data.

simulated data are in accordance with the measured data. Whereas we have only two measured data for most of the horizons, this reasonable fit between simulated and observed data allows us to use the model to discuss the percolation evolution.

3.5.3. Effect of rock fragments on the percolation in stony soils

In site A, for the whole soil profile (80 cm depth), the highest percolation value, linked to the earliest percolation date, is related to case 2 (fine earth + inert rock fragments) and the lowest percolation value, linked to the most recent percolation date is related to case 3 (Fig. 6). Total percolation is equal to 206 mm in case 1, 230 mm in case 2, and 191 mm in case 3. The 7.3% difference between case 1 and case 3 points to the influence of the volumetric percentage of rock fragments, whereas the 11.7% difference between case 1 and case 2 points to the effect of the water retention properties of rock fragments (Fig. 7). Both cannot be neglected for this soil type.

Calculation of the annual percolation was done for several years with various rainfall and evapotranspiration characteristics. The results were analysed as differences between the percolation for case 1 and for other cases (Fig. 7). The difference in percolation is always higher for case 2 than for case 1, and always lower for case 3 than for case 1. For the two sites, at 50 cm depth, percolation is underestimated for case 3 because the storage capacity of fine earth is larger than its counterpart in active rock fragments. The difference in percolation for case 3 is higher for site B than for site A at 50 cm depth, because of the higher volumetric percentage of rock fragments. For the two sites, at 50 cm depth, percolation is overestimated for case 2 because we neglected the storage capacity of rock fragments. The overestimation of percolation for 50 cm depth is generally lower at site B than at site A, because of the lower storage capacity of rock fragments. In that case (case 2), the difference in percolation for site A is higher for 80 cm depth than for 50 cm depth, and the error in estimating the percolation rate can reach 15.8% for 80 cm depth. This strengthens the effect of the volumetric percentage of the rock fragments.

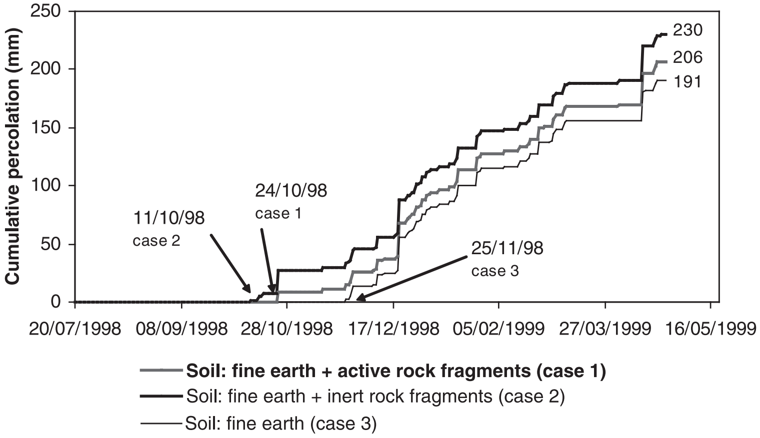


Fig. 6. Cumulative percolation (mm) calculated by the STICS model for the 3 cases on the site A with a 80 cm depth. The arrows refer to the dates when percolation starts.

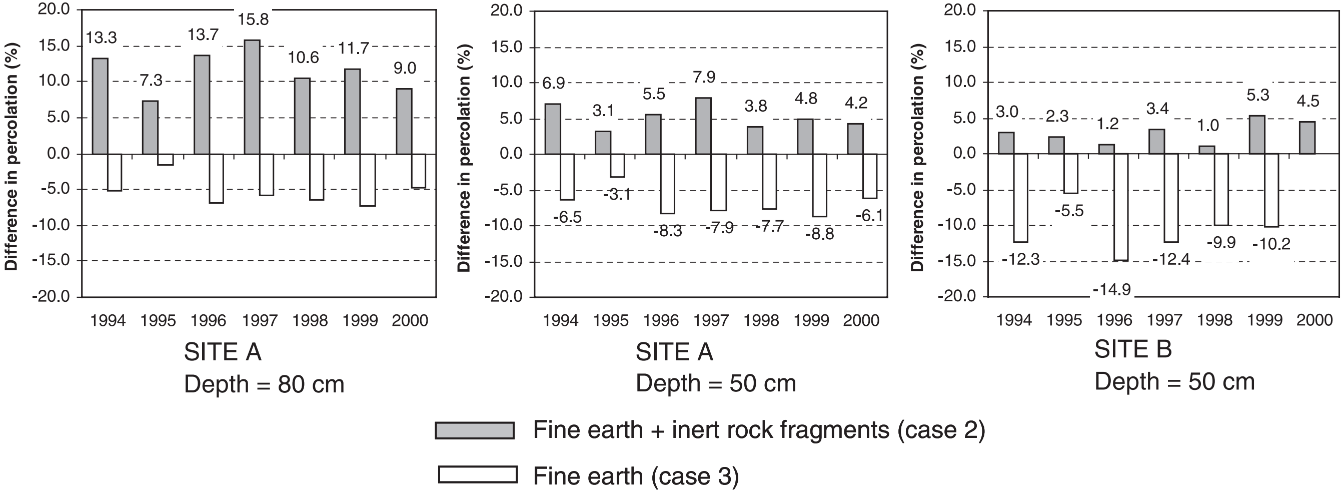


Fig. 7. Difference in percolation between the case 1 and the other cases calculated from the percolation data estimated by the STICS model. Annual data for several years.

4. Conclusion

Our experimental and modelling work has shown the effect of rock fragments in a calcareous stony soil from France. The use of a reservoir model has enabled us to discuss the influence of rock fragments in stony soils.

When the rock fragments are neglected and the soil is considered only as fine earth, the available water content is overestimated and, as a consequence, percolation is underestimated. This percolation underestimation can reach values larger than 10%, depending on the actual volumetric percentage of rock fragments in the soil. On the other hand, when this volumetric percentage is taken into account and when the rock fragments are considered as inert, meaning they do not exhibit any specific water retention characteristics, the available water content is underestimated and, as a consequence, the percolation value is overestimated, by values of up to 15%, depending on the water retention characteristics of the rock fragments and of the annual climatic characteristics.

These results may have an impact on water management, from the agricultural and environmental points of view. When available water content is underestimated, irrigation demands from groundwater should be increased to compensate a possible lack of water for plant growth. At the same time, percolation is overestimated, meaning that the actual water quantity reaching the groundwater is lower than the calculated one. As a consequence, groundwater level will decrease, for two additive reasons: (i) because water recharge is lower and (ii) because pumping for irrigation is higher. This emphasises the necessity to take into account all the parameters influencing water percolation, and in our case, the role of rock fragments. Because of their usual large heterogeneous distribution in the field, an improvement in water management in stony soils should probably require the use of precision farming techniques.

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