The effect of soil stoniness on the estimation of water retention properties of soils: A case study from central France

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The effect of soil stoniness on the estimation of water retention properties of soils: A case study from central France

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Abstract

Estimation of the water retention capacity of a heterogeneous soil requires knowledge of the hydric properties of each soil phase. Nevertheless, for stony soils, the rock fragments have often been neglected. The objective of this work was then to propose a methodology to improve the calculation of the available water content (*AWC*) of stony soils at a regional scale. On a 36,200 ha surface area in Beauce located in the Region Centre of France, the *AWC* was calculated by coupling pedotransfer classes developed for fine earth and rock fragments. When calculating the *AWC* for the first 120 cm of the soil and considering the rock fragments to be inert, the *AWC* was underestimated by 15 % and showed a high spatial variability. When both the volume and the hydric properties of the rock fragments were ignored, the *AWC* was underestimated by 20 %. This work is then the first proposal to estimate soil water properties at a regional scale by using the water storage capacity of the whole stony phase: from gravels to blocks. Results of this study will improve the calculation of water deficit on a regional scale and will aid both in regional water balance modelling and in regional assessment of irrigation needs.

Keywords: available water content; water deficit; pedotransfer functions; soil thickness; soil stoniness

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1.1. Introduction

To estimate the ability of soils to provide water to plants for their growth, soil scientists and agronomists determine the available water content (*AWC*) of the soil, which is likely to be exploited by the roots. The *AWC* is thus an important agronomic parameter for calculating soil water balance and for managing the irrigation of cultivated soils. Therefore, there is a need to explain the soil hydric characteristics to optimize crop growth and to reduce water transfer and losses deeper than the root system. As a consequence, mapping the available water content of soils at a regional scale is a key factor for evaluating land suitability and for developing models to forecast the requirements for irrigation needs and the risks to groundwater quality (Paydar et al., 2009); this mapping is especially important in the context of the climatic change that may alter water reservoir inputs and management in ways that reduce the water supply to irrigated areas (Garcia-Ruiz et al., 2011). As stated by Jensen et al. (2010), new strategies for conserving irrigation water are needed.

Nevertheless, the estimation of the soil available water content remains difficult for heterogeneous soils (Frison et al., 2009), especially stony soils, because it requires a precise knowledge of the water retention capacities of each of the main soil phases: the fine phase composed of soil particles smaller than 2 mm in diameter and the stony phase composed of rock fragments larger than 2 mm in diameter (Corti et al., 1998; Tetegan et al, 2011; Wang et al 2013). The calculation of the available water content of the fine phase can be performed through various pedotransfer classes (tables) and pedotransfer functions based on easily accessible soil characteristics such as the bulk density, carbon content and texture of fine earth (Al Majou et al., 2007, 2008a, 2008b; Bastet et al., 1999; Wösten et al., 2001). Pedotransfer classes are tables allowing to obtain the water content of the fine earth thanks to its texture, or by combining its texture and its structure (Al Majou et al., 2005; Bruand et al., 2002). The water retention properties of the stony phase have often been ignored when calculating the available water content of stony soils, although several studies have shown that rock fragments could be a significant water reserve for soil (Gras and Monnier, 1963; Poesen and Lavee, 1994). Tetegan et al. (2011) have also recently proposed new pedotransfer functions and pedotransfer classes to estimate the available water content of rock fragments in soils originating from sedimentary rocks. However, to our present knowledge, no attempt to map and globally assess the available water content of soils at a regional scale has been conducted using these new pedotransfer functions.

The objective of this paper was to use these new pedotransfer functions for estimating the contribution of rock fragments to the available water content of stony soils to i) produce a more accurate map of the available soil water content at the regional scale and, ii) assess if regional estimates of the total available soil water content using the knowledge of this contribution of rock fragments lead to substantial differences from previous approaches. Conducted on several soils of variable stoniness, for each soil type, the available water content was calculated both when considering and when disregarding the volume and the water retention properties of the rock fragments.

2. Materials and methods

2.1 Study area

The study was conducted on approximately 36,200 ha located 110 km southwest of Paris in the Patay area within "Petite Beauce". Intensive agriculture in the Petite Beauce often utilizes irrigation and 76 % of the surface area is occupied by cereals crops, mainly maize and wheat (Nicoullaud et al., 2004). The climate is temperate continental with an oceanic influence and is characterized by an evapotranspiration of approximately 780 mm calculated using the Penman-Monteith formula. The average annual temperature was 11°C from 1971 to 2000, and the average annual rainfall was 635 mm and ranged from 415 to 850 mm over the 1971 - 2000 period (Richer de Forges and Verbèque, 2003).

2.2 The Patay soil map and the soil database

A soil map (scale: 1/50,000) was designed by Richer de Forges and Verbèque (2003) with a mean density of observations equal to 1 auger-hole per 17 hectares. Quantitative data used to create the soil map (granulometry, carbon content, pH, etc…) were measured on approximately 100 soil profiles, using standard analyses, and stored in an associated database. Upper horizons were affected by peri-glacial winds that largely redistributed the fine material (Macaire, 1971, Bourennane et al., 1996), resulting in a rather homogeneous particle-size distribution of the fine earth (i.e., values of silt, clay, sand, etc...). Most of the soils consisted then of a silty-clay layer (approximately 60% silt and 30% clay) developed on a lacustrine limestone substrate, which was locally cryoturbated. King et al. (1999) and Bourennane et al. (1998) indicated that the soil units that formed on cryoturbated limestone deposits or on soft limestone deposits had the deepest silty-clay layer (up to 0.8 m deep), whereas the shallowest soils (approximately 0.3 m deep) were developed directly on hard calcareous bedrock. This latter bedrock is cracked (Lorain 1973), which could allow a root proliferation of cultures. The study area was classified into 23 main map units (MUs) according to i) the spatial variability of the soil characteristics, ii) the depth and type of limestone where the soil horizons have been developed, and iii) the thickness of the silty-clay layers. Non-stony soils were mainly arenosols, cambisols, fluvisols, luvisols, haplic planosols and vertisols (IUSS Working Group WRB, 2006). Stony soils were mainly rendzic leptosols, haplic calcisols and calcaric cambisols, with various quantities of rock fragments of different sizes, from gravels to blocks (IUSS Working Group WRB, 2006).

The MUs of the soil map consisted of one or several soil units corresponding to a synthetic soil profile defined in terms of soil and agronomic characteristics observed in the field (Legros, 2006). The information on the soil units was stored in the "DoneSol" soil database (Gaultier et al., 1993; Grolleau et al., 2004). From this database, we used the following soil characteristics to estimate the available water content of both the stony and non-stony soils:

- the volume proportion and the texture of the fine phase,
- the volume proportion, the lithological class (limestone, quartz, or flint, on the studied area) and the bulk density of the whole stony phase (gravels, pebbles, stones and blocks),
- the thickness of the horizons
- the nature of the underlying parent material
- the surface proportion of each soil unit in each of the 23 MUs of the map of Patay.

To be comparable with the pedotransfer functions developed by Tetegan et al. (2011) for the estimation of the contribution of rock fragments to the available water content, the bulk density of the rock fragments located within the soil profile was used, rather than the bulk density of the bedrock, the latter that could be slightly different.

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2.3 Calculation of the available water content at different scales

2.3.1. Choice of a definition and units for the available water content

We define the available water content as the quantity of water that can be used by plants for their growth, and we assume that it is equal to the difference between the water content at field capacity, and the water content at permanent wilting point, with the units $cm^3.cm^{-3}$, as calculated in equation (1). Nevertheless, for practical reasons, it is also expressed as a depth (expressed in mm): it represents the available water within a soil horizon (see equation (2)) or within a soil profile (see equation (3)) and can be directly used in a water balance model.

2.3.2. Method used to calculate the available water content

The available water content for both the fine phase and the stony phase (AWC_i) was calculated using equation (1):

$$AWC_i = \theta_{fc,i} - \theta_{wp,i} \quad (1)$$

where AWC_i represents the available water content of the phase i in $cm.cm^{-3}$, $\theta_{fc,i}$ represents the volumetric soil water content at field capacity for phase i in $cm.cm^{-3}$, and $\theta_{wp,i}$ is the volumetric soil water content at the permanent wilting point for phase i in $cm.cm^{-3}$. For both the fine phase and the stony phase, the volumetric soil water content at field capacity was set equal to the soil water content at a matric potential of -100 hPa, as suggested by Bruand et al. (2004) and Al Majou et al. (2008a, 2008b) for the fine earth, and by Tetegan et al. (2011) for the stony phase. For both the fine and the stony phase, the volumetric soil water content at permanent wilting point was set equal to the soil water content at a matric potential of -15850 hPa, as typically required. For the fine phase, the volume soil water contents at -100 hPa and -15850 hPa were calculated from the pedotransfer classes of Bruand et al. (2004). These authors used the soil texture (Baize et al., 2009) from the French texture class triangle of Jamagne (1967) and separated topsoil and subsoil horizons in the soil profile. For our study, the dominant texture of the fine phase for each horizon of each soil unit was collected from the soil database and the position of each horizon in the soil profile was simplified by distinguishing only between topsoil and subsoil horizons. Table 1 presents the AWC_i for the fine phase. For the stony phase, the volumetric soil water contents at -100 hPa and -15850 hPa were calculated using the pedotransfer classes proposed by Tetegan et al. (2011), who used informations only on the lithological class of the rock fragments and the bulk density of each rock fragment. In our study, the dominant lithological class of the rock fragments was collected from the soil database for each soil horizon. The bulk density of the rock fragments of each lithological class was taken from Tetegan et al. (2011). The AWC_i for the stony phase is presented in Table 2.

From the AWC_i of both the fine and the stony phases given by Eq. (1), the available water capacity of a horizon n (AWC_h^n) was calculated in millimetres by using the equation Eq. (2) proposed by Cousin et al. (2003):

$$AWC_h^n = \left(\sum_{i=1}^{i=2} AWC_i \times P_i^n \right) \times T_h^n \quad (2)$$

where P_i^n — collected from the soil database — represents the volume proportion of phase i (fine phase or stony phase) in horizon n and T_h^n represents the thickness in millimetres of the horizon n.

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Table 1
The pedotransfer classes used in Eq. (1) for the calculation of the available water content (AWC_i) of the fine phase as a function of both the position of the horizon in the soil profile and the texture of the fine earth texture.
From Bruand et al. (2004).

Horizon position in the soil profile	Texture of fine earth	AWC_i of the fine phase ($cm \cdot cm^{-3}$)
Topsoil	Clay loam	0.136
	Sandy clay	0.173
	Silt loam	0.173
	Silt	0.167
	Loam	0.143
	Silty clay loam	0.213
	Clay loam	0.183
	Sandy loam	0.162
	Sandy clay	0.128
	Loamy sand	0.131
	Sand	0.060
Subsoil	Silty clay	0.113
	Sandy clay	0.095
	Clay	0.093
	Silt loam	0.149
	Silt	0.148
	Loam	0.127
	Silty clay loam	0.207
	Clay loam	0.196
	Sandy clay	0.103
	Loamy sand	0.116
	Sand	0.073

Table 2
Available water content (AWC_i) of the stony phase calculated from the pedotransfer classes of Tetegan et al. (2011).

Lithological classes of rock fragments	Bulk density of rock fragments ($g \cdot cm^{-3}$)	AWC_i of the stony phase ($cm \cdot cm^{-3}$)
Quartz	2.65	0.00
Flint	2.22	0.01
Limestone	2.18	0.03

The available water content of a soil unit *m* (AWC_{SU}^m) was calculated for its soil profile as the sum of the AWC_h^n of each horizon (Eq. (3)). From the available water content of each soil unit (AWC_{SU}^m), the available water content of each map unit (AWC_{MU}^t) was calculated according to the equation Eq. (4).

$$AWC_{SU}^m = \sum_{N=1}^{N} AWC_h^n \quad (3)$$

$$AWC_{MU}^t = \sum_{N=1}^{N} (AWC_{SU}^m \times S_{SU}^m) \quad (4)$$

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In the equation Eq. (3) *N* represents the number of horizons of the soil unit *m*. In the equation Eq. (4) *N* is the number of soil units composing the map unit *t* and S^m_{SU} is the surface proportion of the soil unit *m* in the map unit *t*.

2.3.3 Choice of a value of soil depth to calculate the AWC

A fundamental parameter in the estimation of the available water content is the soil depth. In our study, we calculated two values of the *AWC* to accommodate two definitions of the soil depth:

- For a soil scientist, the soil depth is the thickness of all the soil layers from the surface to the bedrock. The depth of the bedrock, designated here as the "real soil depth" was known from the soil database. The available water content map calculated using the real soil depth (AWC_{soil}) can be used to generate a generic map that is useful for many environmental applications.

- For an agronomist, the soil depth corresponds to the rooting depth, which varies considerably with the plant type. In our study, we will focus our calculations on the maize crop because i) it is known for its high water requirement (to reach a maximum production, maize needs from 500 to 800 mm of water, depending on the climate) (Doorenbos et al., 1978) and ii) it is cultivated over much of the Patay area and typically requires irrigation. The average rooting depth of maize is equal to 120 cm (B.S.I. Standards., 1988). Therefore, knowing that: i) at the study area, the shallow stony soils are draining soils lying on a cracked calcareous bedrock (Lorain 1973) enabling a storage of the drained water and giving enough spaces between cracks for root proliferation, ii) calcareous bedrock can provide nutrients to plants (Abou-el-Seoud and Abdel-Megeed, 2012; Korboulewsky et al., 2010a; Korboulewsky et al., 2010b), iii) maize roots have a remarkable plasticity by increasing their root length, allowing to capture nutrient resources (Li et al., 2012), a soil depth of 120 cm was used to calculate the AWC in this second case (AWC_{maize}), regardless of the soil unit and the "real soil depth".

Depending on their locations, soil units exhibited different real soil depths, from a few centimeters to more than one meter (Fig. 1). For the AWC_{soil} and AWC_{maize} calculations, soils thicker than 120 cm were truncated to 120 cm. This truncation ranged from 2 to 31 cm.

For the AWC_{maize} calculations, soils less than 120 cm thick were extended to 120 cm. This extension for soils shallower than 120 cm was mainly necessary for soils that were developed on limestone (cracked calcareous bedrock). This extension ranged from 1 to 109 cm with a median value of 38 cm. From the depth observed in the field to the depth of 120 cm, we accounted for the rocky parent material and hypothesized that its hydric properties were close to those of the rock fragments in the soils of Patay. This hypothesis was supported by experimental measurements of the water content in soil rock fragments at different depths in the soil profile and at different degrees of alteration (Tetegan et al., 2011).

2.4 Evaluation of the role of rock fragments in the calculation of the available water content

The available water contents estimated for two soil depths (AWC_{soil} and AWC_{maize}) were calculated according to three scenarios.

- Scenario 1- Under this scenario, the stony soils were considered to contain active rock fragments; we accounted for both the volume proportion of the rock fragments and their hydric properties, which were estimated with the pedotransfer classes proposed by Tetegan et al. (2011). This scenario is considered the reference scenario, where soil contains porous rock fragments that may store water.

- Scenario 2- All soils were considered to be 100 % fine earth; the volume of the rock fragments in each soil horizon was replaced by an equivalent volume of fine earth. This scenario is similar to actual scenarios when the available water content is calculated over large scales, for example to create regional maps. In this situation, both the quantity and properties of rock fragments are neglected, and the proportion of rock fragments is replaced by an equivalent quantity of fine earth.
- Scenario 3- The stony soils contained inert rock fragments; we accounted for the volume of the rock fragments but assumed that they could not to store water. This scenario is an intermediate scenario between scenarios 1 and 2; the proportion of rock fragments is high enough that it is usually not neglected in available water content calculations. Nevertheless, their hydric properties, especially their contribution to the available water content, are unknown. In this situation, the proportion of rock fragments is not neglected, but the rock fragments are replaced by nothing (not by the fine earth).

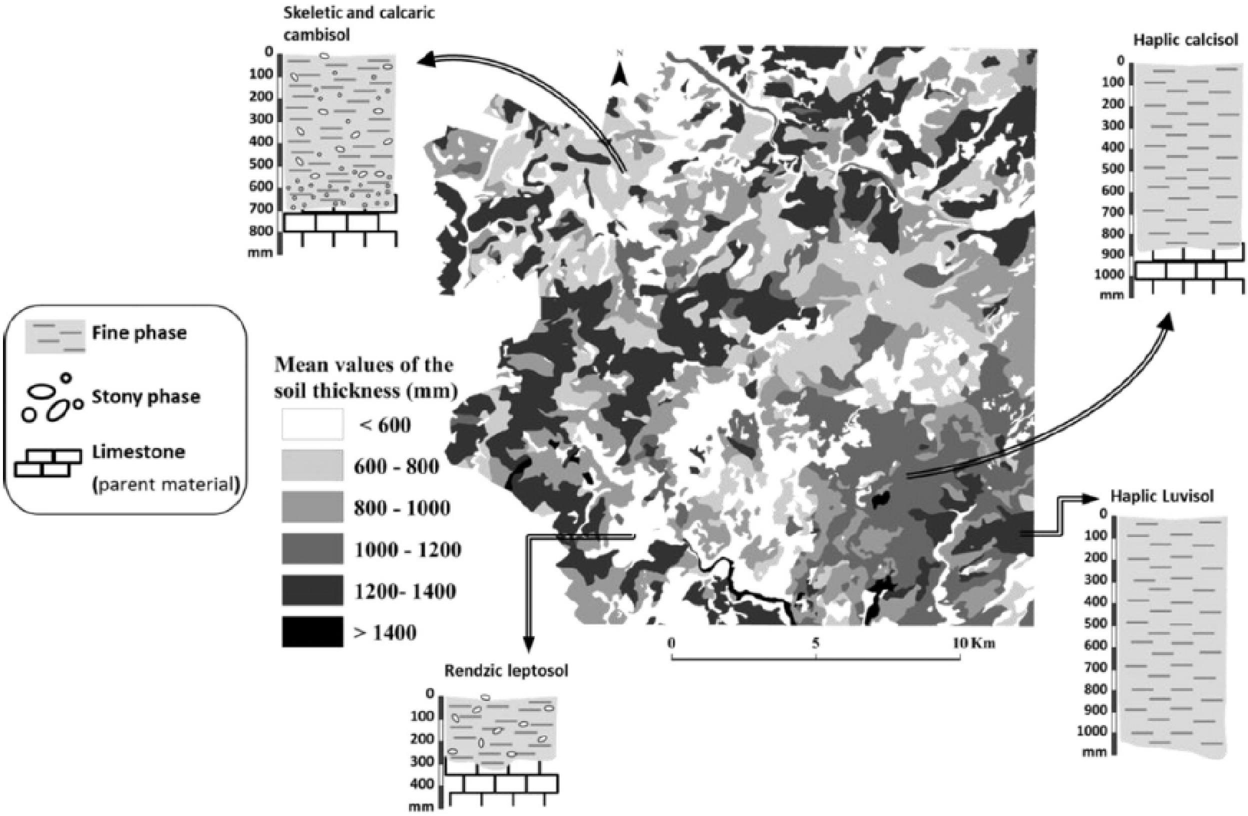

Fig. 1. Map of the soil thickness in the area of Patay. Four synthetic characteristic soil profiles are represented. From Richer de Forges and Verbèque (2003).

Scenarios 2 and 3 were each compared with the reference scenario: for each map unit, we have computed the difference between the reference scenario and another scenario with the following equation:

$$\Delta AWC = AWC_j - AWC_{jref}$$

where AWC_j represents the available water content calculated using scenario 2 or scenario 3 and AWC_{jref} represents the available water content calculated using scenario 1. Negative

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values represent under-estimations of the real available water content, whereas positive values represent over-estimations.

To evaluate the global differences between these scenarios at the regional scale, we have also computed the Mean Error (*ME*), the Mean Absolute Error (*MAE*) and the Root Mean Square Error (*RMSE*), using the following equations:

$$ME_{AWC} = \frac{1}{N}\sum_{j=1}^{N}(AWC_j - AWC_{jref}) \quad (6)$$

$$MAE_{AWC} = \frac{1}{N}\sum_{j=1}^{N}\left(\left|AWC_j - AWC_{jref}\right|\right) \quad (7)$$

$$RMSE_{AWC} = \sqrt{\left(\frac{1}{N}\sum_{j=1}^{N}(AWC_j - AWC_{jref})^2\right)} \quad , \quad (8)$$

where AWC_j represents the available water content calculated using scenario 2 or scenario 3 and AWC_{jref} represents the available water content calculated using scenario 1.

Exclusively related to the difference between scenarii on the AWC-calculation and not including the errors linked to parameters provided by "DoneSol" soil database, these ME, MAE and RMSE give a theoretical estimate of the quantitative relevance of the contribution of the hydric properties of the stony phase in those of stony soils.

The maps showing the available water content maps were designed with the ArcGis9® software.

3. Results and discussion

3.1 Soil stoniness and soil thickness

The real soil thickness in the study area varied from 11 cm to 151 cm (Fig. 1). The shallowest soils (thickness less than 50 cm, typically Rendzic leptosol) occupied 17% of the surface of the map. The largest area of the soil map (81%) was represented by soils with a thickness between 50 and 150 cm. The deepest soils (thickness greater than 150 cm, typically Haplic luvisol) represented only 2% of the surface of the map and were mainly situated in a band oriented from southwest to northeast (Fig. 1).

The soil stoniness was highly variable in space (Fig. 2a and 2b). The rock fragments were mainly limestone (78 %), quartz (13%) and flint (9%) (Fig. 2a). The southeast part of the map was occupied by soils containing the smallest percentage of rock fragments (less than 10%), and was surrounded by rockier soils. Sixty-seven percent of the surface was covered by soils with a mean stoniness less than or equal to 10%, and 31% was covered by soils with mean stoniness values between 10% and 30% (Fig. 2b). Only 2% of the soil surface of the Patay area demonstrated stoniness above 30%.

The soil stoniness and the thickness were weakly correlated (R = 0.34) (Fig. 3). The thickest soils (thicker than 100 cm) were not systematically located in areas with the lowest proportion of rock fragments. However, as expected, the shallowest soils (thickness less than or equal to 30 cm) were located in areas with high rock fragments proportions, i.e., between 10% and 20% of the soil volume (Figs. 1 and 2). The southwest to northeast band of the map was an area where the soil stoniness and thickness were approximately 20 - 30 % and 100 - 140 cm respectively.

After substituting the maize rooting depth for the real soil depth, we recalculated the stoniness values for all the MUs (Fig. 2c). In this case, 98 % of the surface area of the Patay map was represented by soils containing rock fragments. Over 50 % of the surface contained

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soils with mean values of stoniness greater than or equal to 35%. The southeast part of the map remained the area containing soils with the fewest rock fragments (composing less than 20 % of the soil volume).

3.2 Estimation of the soil available water content for the 3 scenarios

3.2.1. Overview of the available water content calculated for the two depths and the 3 scenarios

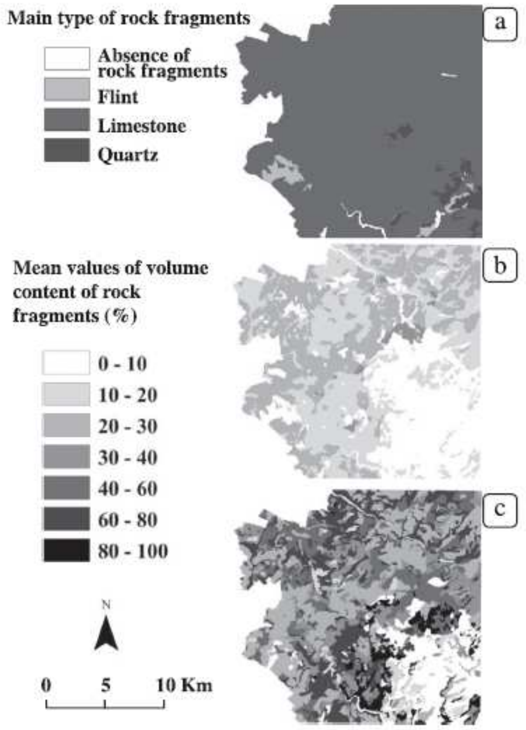

Fig. 2. Rock fragment content and types in the area of Patay. a) Primary of rock fragment type; b) rock fragment content observed in the field (information stored in the soil database; c) rock fragment content recalculated for a soil thickness of 120 cm.

The available water content of the soils in the area of Patay was calculated for each map unit using the two soil depths (AWC_{soil} and AWC_{maize}) and the three scenarios defining the degree to which soil stoniness was considered in the calculations. For the real soil depth neither the range of the AWC_{soil} values nor the mean or median AWC_{soil} values varied significantly with the scenario (Table 3). As expected, however, the lowest values were recorded for scenario 3, which ignored the water retention properties of the stony phase. The lowest median value (scenario 3) was equal to 105 mm of water, which corresponded to 1.12 mm of water by cm of soil (Table 3). This value is close to 1 mm/cm, the *AWC* value usually used for loamy soils developed on loess (Jamagne et al., 1977). The highest median AWC_{soil} value was recorded for scenario 2: it was equal to 109 mm of water which corresponded to 1.20 mm of water by cm of soil.

When the maize rooting depth was used as the soil depth to calculate the available water content (AWC_{maize}), the range of AWC_{maize} values and the mean and median AWC_{maize} differed with the scenario (Table 3). The highest mean value of the AWC_{maize} was recorded for scenario 2 and was equal to 124 mm. The range of AWC_{maize} values was larger for the scenario 2 than for the reference scenario.

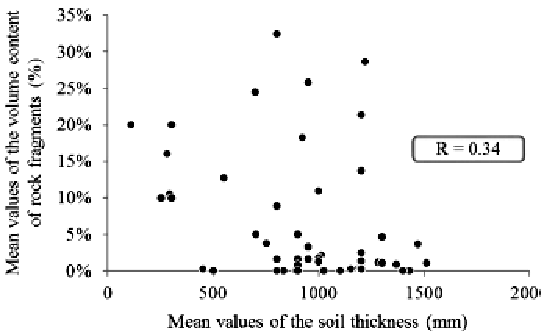

Fig. 3. Relationship between the mean values of rock fragment content and the mean soil thickness for each map unit.

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3.2.2. Spatial variability of the available water content calculated for the two depths and the 3 scenarios

The spatial variability of the available water content on the Patay map is presented in Figure 4. For the reference scenario (scenario 1), whatever the depth of calculation, the available water content ranged mainly from 50 to 150 mm for more than 70 % of the map surface (Figs. 4a and 4a'). The main spatial feature of the AWC_{maize} map was its relative homogeneity of the map, whereas the AWC_{soil} map was more heterogeneous. For the AWC_{soil} map, the minimum values - lower than 50 mm - were located in the south-central portion of the area, whereas the maximum values - larger than 150 mm - were rare (Fig. 4a). For scenarios 2 and 3, the minimum values of AWC_{soil} and AWC_{maize} - lower than 50 mm - were also in the south-central area. Regardless of the location, the available water content calculated when the rock fragments were considered to be inert (scenario 3) was systematically less than or equal to the available water content calculated when the soil was considered to contain fine earth only (scenario 2) (Figs. 4b, 4c, 4b'and 4c').

Table 3
Ranges of the soil available water content according to the different calculation scenarios. The scenario 1 is the reference scenario.

	Minimum values (mm)		Mean values (mm)		Median values (mm)		Maximum values (mm)	
	AWC_{soil}	AWC_{maize}	AWC_{soil}	AWC_{maize}	AWC_{soil}	AWC_{maize}	AWC_{soil}	AWC_{maize}
Scenario 1	13	56	104	124	108	127	190	170
Scenario 2	14	15	107	105	109	153	191	182
Scenario 3	11	12	101	99	105	102	189	169

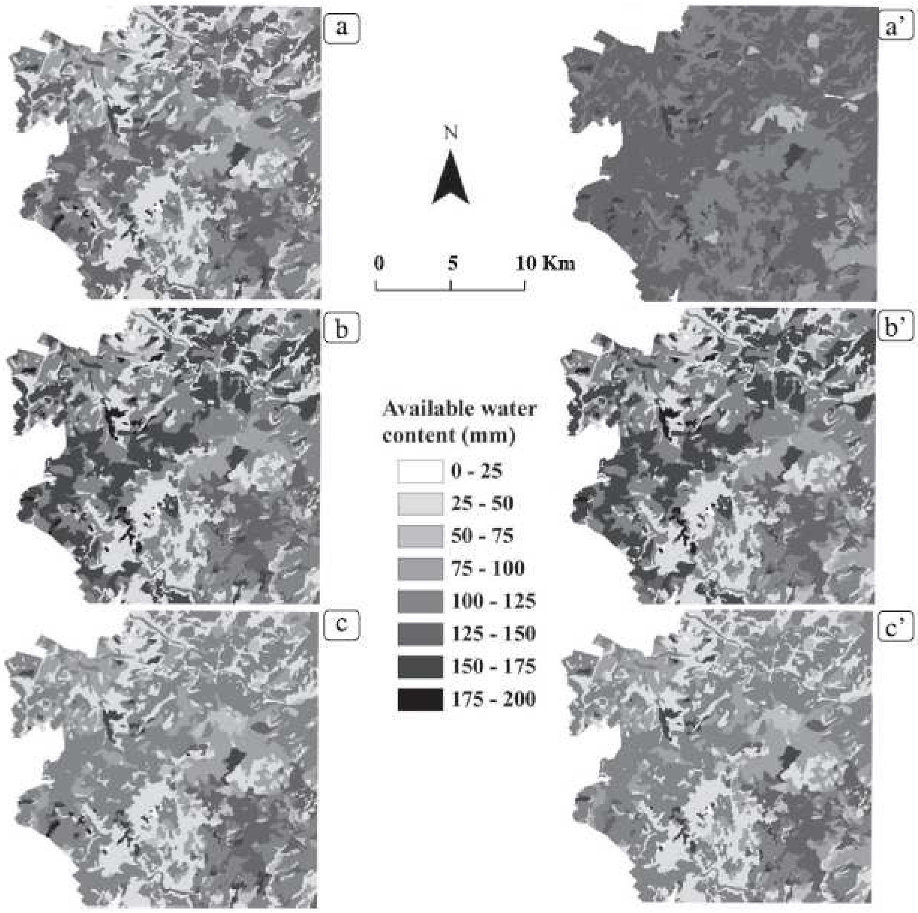

Fig. 4. Maps of the soil available water content (mm) calculated for the two soil depths and the three scenarios. a) AWC_{soil} calculated for scenario 1 (reference scenario); b) AWC_{soil} calculated for scenario 2; c) AWC_{soil} calculated for scenario 3. a') AWC_{maize} calculated for scenario 1 (reference scenario); b') AWC_{maize} calculated for scenario 2; c') AWC_{maize} calculated for scenario 3.

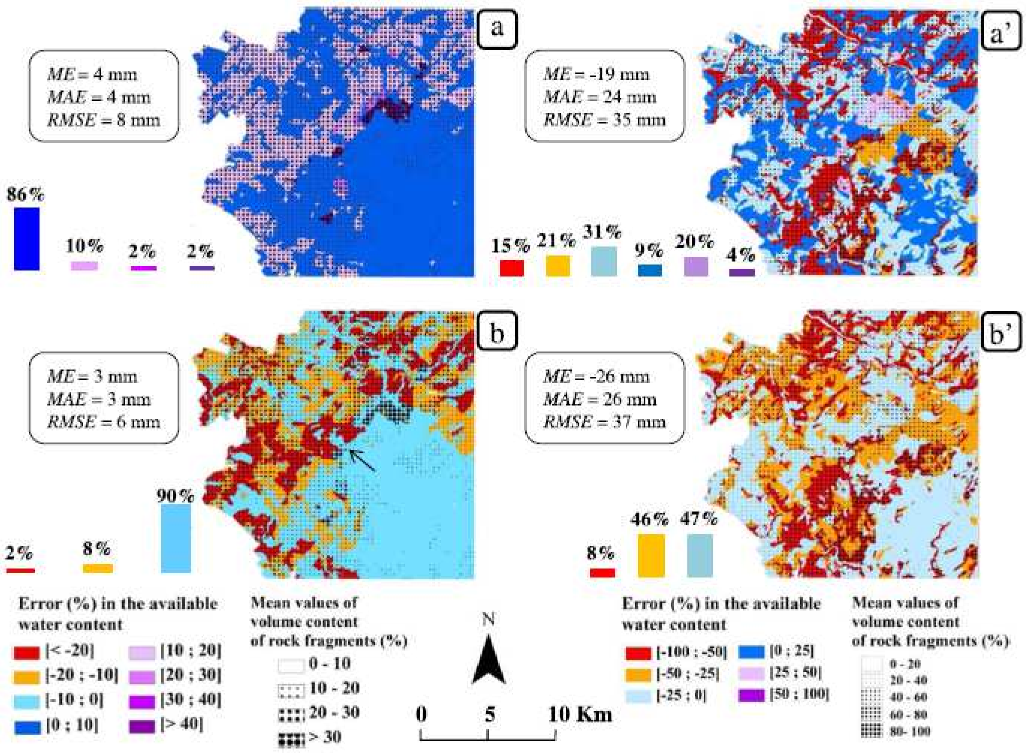

Fig. 5. Maps of the errors in the estimation of the soil available water content calculated for the two soil depths. a) Difference in AWC_{soil} calculated for scenario 2 compared with scenario 1; b) difference in AWC_{soil} calculated for scenario 3 compared with scenario 1; a') difference in AWC_{maize} calculated for scenario 2 compared with scenario 1; b') difference in AWC_{maize} calculated for scenario 3 compared with scenario 1.

3.2.3. Mapping differences in available water content estimates

The differences in available water content between scenarios 2 or 3 and the reference scenario are presented in figure 5. The AWC_{soil} was systematically overestimated using scenario 2 compared with scenario 1 (Fig. 5a). By contrast, scenario 2 either underestimated or overestimated AWC_{maize} compared with scenario 1 (Fig. 5a'). The overestimation, which covered 33 % of the surface area, was usually located in areas with a low stoniness, for example in non-stony soils of the southeast part of the map or in deep soils with a low stoniness, as in the southwest-northeast band. Nevertheless, the AWC_{maize} was overestimated in some highly stony areas, presumably when rock fragments could store only a small quantity of water, less than that stored in the fine earth (see in the central part of the map on figure 5a'). Figure 5a' also shows that the AWC_{maize} was underestimated on 67 % of the surface of the map. Depending on the texture of the fine earth and the lithological class of the rock fragments, the stony phase can store more water than the fine earth can. This situation occurred when the fine earth had a low available water content - sandy fine earth for example -, and when the rock fragments had a high available water content - porous limestone for example. In some stony areas, the AWC_{maize} was underestimated by more than 50 % (Fig. 5a'). These areas had thin soils, and the AWC_{maize} was calculated by assuming that much of the subsoil explored by the maize roots consisted of parent material. As explained in the materials and method sections, we have hypothesized that the available water content of the subsoil was the same as that of the rock fragments in the soil.

For the scenario 3, in which the stony phase was considered to be inert, the available water content (both AWC_{soil} and AWC_{maize}) was systematically underestimated. In areas with low rock fragments content (the southeast part of the soil map on Figs. 5b and 5b', for example), the differences between scenario 1 and scenario 3 were minor (less than 10 %), as expected. In some very stony areas (see the black arrow in Fig. 5b), the difference between scenarios 3

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and 1 for AWC_{soil} was minor as well (less than 10 %): in these areas, the rock fragments were quartz or flint, which are rock fragments with a quasi-null water retention capacity. By contrast, large surface areas characterized by highly rocky soils exhibited AWC_{soil} and AWC_{maize} values that were lower in scenario 3 than in 1: in these cases, rock fragments can retain significant quantities of water and must not be neglected when evaluating the available water content of soil.

3.2.4. Effect of soil thickness and soil stoniness on the estimation of the available water content

The relationships between the thickness and soil stoniness of soils and the errors in the AWC_{soil} values estimated using scenarios 2 and 3 compared with 1 are presented in Figures 6a and 6b. As might be expected, the errors were the lowest not only for soils with a low stoniness, but also for the shallowest soils. No obvious relationship between the errors on the AWC_{soil} estimation and the thickness or stoniness was observed.

3.3. Assumptions used to estimate the available water content at a regional scale

We have defined the available water content as the quantity of water that can be used by plant for their growth. It is typically defined as the difference between the water content at field capacity, and the water content at permanent wilting point. In our calculations, we have determined that the water content at field capacity could be considered equal to the water content at -100 hPa, as demonstrated by Bruand et al. (2004) for fine earth, and by Tetegan et al. (2011) for rock fragments. Nevertheless, this value of water potential at field capacity, that has been shown to be true in our study could be changed and should be adapted in other contexts: for example, it could be adjusted to -330 hPa (Bruand et al., 2004) for more clayey soils, or, even -500hPa, as suggested by Whalley et al. (2005) for some crops, when available water contents are used in crop models.

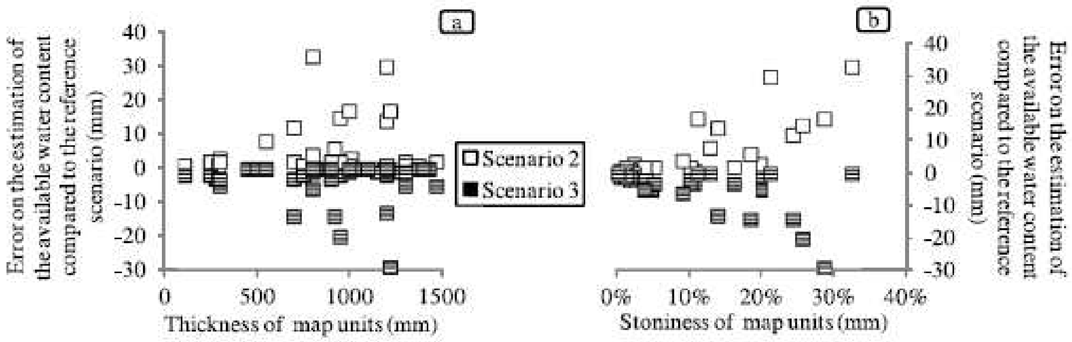

Fig. 6. Relationship between the errors in estimation of the available water content (AWC_{soil}) and a) the soil thickness and b) the soil stoniness.

For the permanent wilting point, we have used the classic value of water potential equal to -15850 hPa that can be calculated by pedotransfer functions and is commonly used by soil scientists. This value can be used with mature plants; however, it is known that the real value of permanent the wilting point depends on both the soil (especially the soil texture) and the physiological characteristics of the plant, as demonstrated by Czyz and Dexter (2012). Plants from humid zones would not survive such low pF values and their permanent wilting point would be lower. In contrast, desert plants, if we choose an extreme, will survive extremely low pF values (about – 163,000 hPa for Artemisia Herba Alba (Gobat et al., 2003) The results obtained here at a regional scale, where all the crops are considered to be maize, could then be different for other crops where the water potential at field capacity may be different for physical reasons, and both the water potential at the permanent wilting point and the soil depth could be different for agronomic and/or ecophysiological reasons.

4. Conclusions

The available water content of the stony soils of Patay was calculated using pedotransfer classes proposed by Bruand et al. (2004) for the fine earth and Tetegan et al. (2011) for the rock fragments. We demonstrated that the *AWC* calculated by assuming that the stony soil was completely composed of fine earth led either to overestimations or underestimations of the real *AWC* calculated when both the proportion and the water –holding capacities of the stony phase are taken into account. We also demonstrated that the *AWC* calculated by assuming that the stony soils considered to consist of fine earth and non -porous rock fragments led to systematic underestimation (up to 20%) of the real *AWC*. Estimation of the available water content, and thus of the soil water deficit, was strongly dependent on value of the soil thickness which was considered in the calculations.

From these maps and the associated databases, the water demand of crops in the study area can be calculated. In the context of climate change, which is expected to intensify droughts and increase the need for irrigation, this will enable a more accurate calculation of the water deficit and will be beneficial for farmers and regional planning of irrigation needs. If these maps are to be used as spatial data input for regional water balance modelling, our results demonstrate that failing to account for the rock fragments may lead to erroneous conclusions and unappropriated recommendations.

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Figure captions:

Figure 1: Map of the soil thickness in the area of Patay. Four synthetic characteristic soil profiles are represented (from Richer de Forges and Verbèque, 2003).

Figure 2: Rock fragments content and types, in the area of Patay. a) Primary of rock fragments type; b) Rock fragments content observed in the field (information stored in the soil database ; c) Rock fragments content recalculated for a soil thickness of 120 cm.

Figure 3: Relationship between the mean values of rock fragment content and the mean soil thickness for each map unit.

Figure 4: Maps of the soil available water content (mm) calculated for the two soil depths and the three scenarios. a) AWC_{soil} calculated for the scenario 1 (reference scenario); b) AWC_{soil} calculated for the scenario 2; c) AWC_{soil} calculated for the scenario 3. a') AWC_{maize} calculated for the scenario 1 (reference scenario); b') AWC_{maize} calculated for the scenario 2; c') AWC_{maize} calculated for the scenario 3.

Figure 5: Maps of the errors in the estimation of the soil available water content calculated for the two soil depths. a) Difference in AWC_{soil} calculated for scenario 2 compared with scenario 1 ; b) Difference in AWC_{soil} calculated for scenario 3 compared with scenario 1; a') Difference in AWC_{maize} calculated for scenario 2 compared with scenario 1 ; b') Difference in AWC_{maize} calculated for scenario 3 compared with scenario 1.

Figure 6: Relationship between the errors in estimation of the available water content (AWC_{soil}) and a) the soil thickness and b) the soil stoniness.

List of tables:

Table 1: The pedotransfer classes used in the equation Eq. (1) for the calculation of the available water content (AWC_i) of the fine phase as a function of both the position of the horizon in the soil profile and the texture of the fine earth texture (From Bruand et al., 2004).

Table 2: Available water content (AWC_i) of the stony phase calculated from the pedotransfer classes of Tetegan et al. (2011).

Table 3: Ranges of the soil available water content according to the different calculation scenarios. The scenario 1 is the reference scenario.