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Water balance for different land use and crop sequences under semiarid environment

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SUMMARY

In semiarid agrosystems, improving management of soil and water resources requires developing reliable means for characterizing the temporal dynamics of soil water balance in a spatially distributed manner. The purpose of this study is to analyze soil water balance in relation to natural drivers (i.e. rainfall and soil properties) and anthropogenic forcing (i.e. land use and crop successions). We focus on a hilly watershed devoted to rainfed agriculture, so-called the Kamech watershed, which is located in the Cap Bon Peninsula, north-eastern Tunisia. The soil moisture analysis is based on in-situ data collected in different fields and during various crop growth cycles under the common cereals/legumes/pasture cropping systems. In-situ data include water balance components and vegetation parameters. The results show that annual rainfall is mainly converted into evapotranspiration during the growing cycle for different land uses. The runoff amounts, for most of the sites, correspond to less than 10% of the rainfall amount. The evapotranspiration ratio significantly differs in relation to soil properties and cumulated rainfall. We observe large differences in soil water dynamics among the legumes (fababean and chickpea) and cereals (wheat, oat, and triticale). Soil water is larger for legume crops, despite substantial plant growth during winter-spring. This is ascribed to the shallow root systems of fababean and chickpea that induces a restricted access to deep water. Despite drought conditions during summer, bare soil following annual pasture and legumes corresponded to larger amounts of soil water as compared to cereals. The amount of available water observed ranges from 0 mm to nearly 100 mm.

Keywords: Water balance, land use, crop sequences, semiarid environment.

RESUME

Dans les agrosystèmes semi-arides, l'amélioration de la gestion des ressources en sols et en eau exige l'élaboration de moyens fiables pour caractériser spatialement la dynamique temporelle du bilan hydrique du sol. Le but de cette étude est d'analyser le bilan hydrique du sol en lien avec le milieu physique (i.e. pluies et propriétés du sol) et le forçage anthropique (i.e. utilisation des terres et successions de cultures). Nous nous concentrons sur un bassin versant collinaire dédiée à l'agriculture pluviale, nommé le bassin versant Kamech, qui est situé dans la péninsule du Cap Bon, au nord- est de la Tunisie. L'analyse de l'humidité du sol est basée sur des données in-situ recueillies dans différents parcelles et pendant différents cycles de croissance végétale pour des systèmes de cultures céréales / légumineuses / pâturages. Les mesures in situ comprennent des composantes du bilan hydrique et les paramètres agronomiques. Les résultats montrent que les précipitations annuelles sont principalement converties en évapotranspiration au cours du cycle de croissance pour diverses occupations des terres. Pour la majeure partie des parcelles, le ruissellement annuel correspond à moins de 10% des précipitations annuelles. Le taux d'évapotranspiration diffère de manière significative selon les propriétés du sol et les précipitations cumulées. On observe de grandes différences dans la dynamique de l'eau du sol entre les cultures de légumineuses (fèves et pois chiches) et les cultures de céréale (blé, avoine et triticale). Le contenu en eau du sol est plus élevée les cultures de légumineuses, en dépit de la croissance des plantes substantielle durant la période hiver - printemps. Cela est attribué aux systèmes racinaires peu profonds pour les fèves et les pois chiches, induisant un accès restreint à l'eau plus profonde. Malgré des conditions de sécheresse durant l'été, nous observons des contenus en eau du sol élevés pour les sols nus qui suivent les pâturages et les cultures de légumineuse, en comparaison aux cultures de céréales. La quantité d'eau disponible observée varie de 0 mm à 100 mm.

Mots-clés: Bilan hydrique, occupation des sols, successions de cultures, agrosystèmes collinaires.

1. INTRODUCTION

Soil moisture is one of the main limiting factors for plant growth and crop production in semiarid agrosystems (Qiu et al. 2001). Improving management practices, for soil and water resources at different spatiotemporal scales, relies on increasing the use efficiency of rainfall and root zone water, as well as on predicting watershed hydrological processes, among others. This requires developing reliable means for characterizing the temporal dynamics of soil water balance in a spatially distributed manner. When characterizing water balance under cultivated areas, errors in estimating the different terms are mainly driven by spatiotemporal changes in soil water content, where the latter results from different agricultural practices and different water extraction regimes by rooting systems (Fu et al., 2003; Lenssen et al. 2007; Chen et al. 2008).

With the increasing demands on water resources for agricultural purposes, there is a growing need to characterize the spatiotemporal variability of soil moisture, as well as its magnitude in relation to land use. Three decades ago, McGowan and Williams (1980) reports large spatial changes in soil water content within rainfed wheat crops, which was ascribed to spatial heterogeneity of rainfall distribution within the soil, and to changes in drainage and root water extraction. Further, little attention has been paid to this topic, with since studies only have focused on the impact of land use characteristics on soil moisture patterns (Qiu et al. 2001, Fu et al., 2003; Lenssen et al., 2007; Chen et al. 2008).

The main purpose of the present study is to increase our knowledge on the spatiotemporal variability in soil water content and in water balance for different land uses and crop successions. This is conducted by analyzing soil water balance parameters throughout several growth cycles for different crop on different soils, and for different locations within hillslopes.

2. MATERIALS AND METHODS

2.1. Study site

The experimental site, so-called the Kamech watershed, belongs to the long-term collaborative environmental research observatory labeled OMERE for "Mediterranean observatory of water and rural environment". It is located in the Cap Bon Peninsula, northeastern Tunisia. It is an agricultural hilly watershed, with a 2.6 km² size.

The climate is typically semi-arid Mediterranean, including a hot and dry summer and a mild and rainy winter. The mean annual precipitation ranges from 400 to 650 mm, with a marked winter dominance since 75% of the total annual rainfall occurs between October and April. Average annual potential evapotranspiration is 1250 mm (Zitouna Chebbi, 2009).

Four major soil types mostly used for annual crops were distinguished and mapped according to the FAO classification (FAO, 1998). The predominant soils are Cambisols, and cover about 46% of the watershed. Luvisols and Vertisols cover about 26 and 10%, respectively. Regosols, which are thin and commonly associated with pasture and shrubs, cover about 18%.

The watershed is characterized by an intensive agricultural activity and high spatiotemporal variation in land uses and agricultural practices (Mekki et al., 2006). Agricultural land use includes eight classess: six cropping systems for 171 ha (cereals, legumes, market gardening, vineyards, orchards and fallow), and two pasture systems for 91 ha (pastures-annual and pastures-shrubs).

During the experimental periods, all crops followed summer bare soil. Wheat was sown in November and harvested in late June. Fababean was sown in November and harvested in May. After cereal harvest in June, farmers set field fallow until the beginnning of the rainy season that drives the tillage operations (i.e. between September to October).

2.2. Measurements

Soil water balance parameters and vegetation parameters were collected within the Kamech watershed throughout four crop growth cycles: January 2001 to August 2001, January 2002 to May 2002, and April 2006 to July 2006 and January 2013 to June 2013. Soil water content profiles was monitored on about weekly basis on different fields. The field experimental and the resulting datasets are detailed in Mekki (2003); Mekki et al. (2006); Zitouna Chebbi (2009) and Zitouna Chebbi et al. (2012).

For the period [10 January - 03 August 2001] and the period [10 january - 25 may 2002], soil water content profiles were collected using a neutron probe (Solo 25, Nardeux, St-Avertin, France). Volumetric water content was calculated from gravimetric water content using bulk density measured with a gamma-density probe (Solo 40, Nardeux, St-Avertin, France), which was measured along the soil profile at the same location.

For the 2006 growing season, measurements of soil moisture were conducted on five different types of land use plots. The latter were selected according to soil type and topographic position. Gravimetric sampling was performed at different moisture states. Soil samples were taken with an auger. Gravimetric water content was obtained by weighing before and after oven-drying at 105 °C for 24 hours. For the period [02 January - 05 June 2013], soil water content profiles were collected using a neutron probe (Campbell Pacific Nuclear (CPN®), 503 DR).

3. RESULTS AND DISCUSSION

3.1. Temporal variation of soil water content

The temporal variations of mean soil water content (SWC) for the period January 2001 to August 2001 and January 2002 to May 2002, within 0-100 cm depth in different land uses are shown in Figure 1. The cumulated rainfall is 626 mm and 402 mm, for respectively 2000-01 and 2001-02 year, clearly above the annual average for the 2000/2001 cropping season and slightly smaller for the 2001/2002 season.

The mean SWC changes with year and season in relation to rainfall variability. As shown on Figure 1, the mean SWC responds positively to rainfall for the different sites during the study period, with a fast increase after a heavy rain event (i.e., 03/04/2001 and 09/04/2002) and a slow decrease thereafter. The driest profiles are observed in May, in spite of earlier rainfall this month. This process continues through the dry season until the next wet season. The profile refills in January 2002 after a significant accumulation within the soil of rain water during the August-December period in 2001.

The mean SWC depends on the development stage of crop and exhibited differences in temporal dynamics. In the dry season and in winter period, where vegetation consumption for annual crops is low, the land use does not appear to influence soil moisture dynamics; and the differentiation is driven by soil texture. During the post rainy season that corresponds to crop water consumption, the temporal dynamics of the mean SWC significantly changes according to vegetation cover. The vineyard maintains the SWC at a value of 40% during the dormant period and clearly decreases by the end of May with the development of the vegetation during the growing period. Mean SWC under pasture is significantly lower during the study period. The mean SWC varies between 31.1% on annual crops and 23.0% on pasture. The site on pasture-shrubs has the lowest mean SWC. It ranges from 9 to 32%, with an average value of 18.5%, in the first growing season. It ranges from 11.5 to 25.5%, with an average value of 18.5%, in the second growing season. Pea and chickpea crops keep a good water supply for the two years, with soil moisture content ranging from 28.5% to 44.8%, and an average of 35.7%. This may be ascribed to the short growing season for these two crops, but especially to the shallow root systems for pea and chickpea, which induces a restricted access to deep profile water. The bare land cover after pea appears to be more sensitive to the influence of rainfall, having the largest magnitude of soil moisture dynamics (from 22.3% to 51.4%).

We observe large differences in soil water dynamics among the fababean, wheat, oat, and triticale. The reason for the lowest mean SWC in oat is the sandy soil texture with a lower water retention capacity. Cereals show larger vegetation cover than fababean and the soil of this land use is drier.

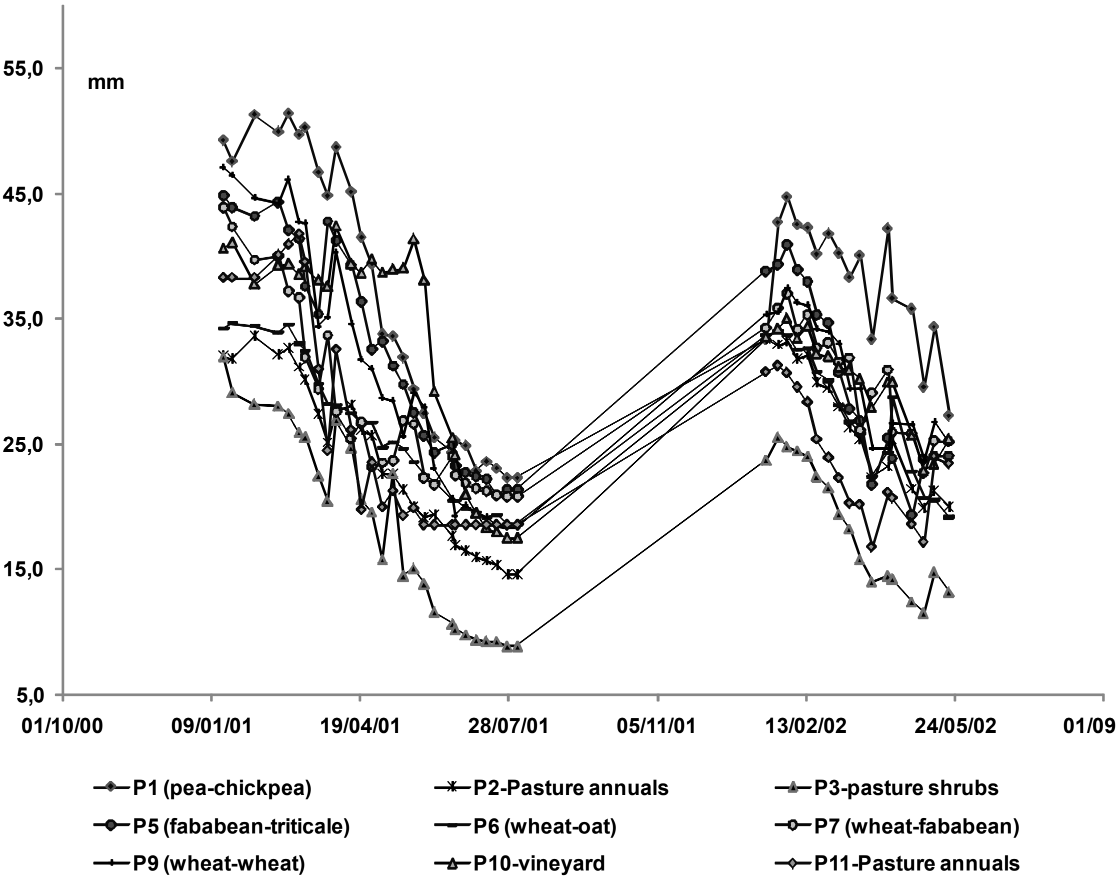

Figure 1. Temporal variations of mean SWC under different land uses for two seasons.

3.2. Variation of mean soil water content profile

The variation of mean SWC profile within 0-100 cm is shown in Figure 2, for the period [January 2001 - August 2001], the period [January 2002 - May 2002], the period [April 2006 - July 2006], and the period [January 2013 - June 2013] and for different land uses. Mean SWC profiles for different land uses vary in relation with average precipitation and soil type. The 2013 growing season benefits from a sufficient rainfall supply. The mean SWC profile significantly changes with field location within the hill slope, and changes with soil thickness, as previously observed by Qui et al. (2001).

Inspection of the 2001-2002 data shows that the pasture sites have the lowest mean SWC profiles and that the largest mean SWC profiles are found on chickpea and pea. We observe increasing and waving trends of soil moisture changes with depth, which is consistent with previous results from Fu et al. (2003). This is ascribed to the high evapotranspiration as compared to the rainfall amount, to the differences in soil physical properties and in root vertical distributions. The increasing type corresponds to the annual crops. The waving type is observed for pastures (mainly shrubs) and vineyard. For pasture on vertisols (field P11), soil moisture varies greatly and is strongly affected by flows of rainfall water within shrinkage cracks in the root zone, where such shrinkage cracks are observed on swelling soils during drying periods.

For the [2005-2006] season, we observe that the wheat crop on plot H located on the rim bottom near the watercourse bed, with deep soils depicts larger mean SWC profiles than those observed on the plot M that is located on the rim top with medium soil thickness. The fababean is located on plot L, a plot that depicted the same characteristics than plot M. However, the fababean shows relatively large mean SWC profile. This difference is ascribed to a larger wheat fraction cover and consequently to a larger evapotranspiration rate. The mean SWC observed on pasture is low.

For the [2012-2013] during the wheat growing season on three plots, we observe increasing and waving trends of soil moisture changes with depth. The plot B located in middle slope had a waiving profile. The plot A and C located on the rim top at the two sides of the catchment have similar increasing trend of the profile with difference at the lower parts which might be related to the heterogeneity of soil properties and the spatial variation of precipitation not taken into account for this experimental period.

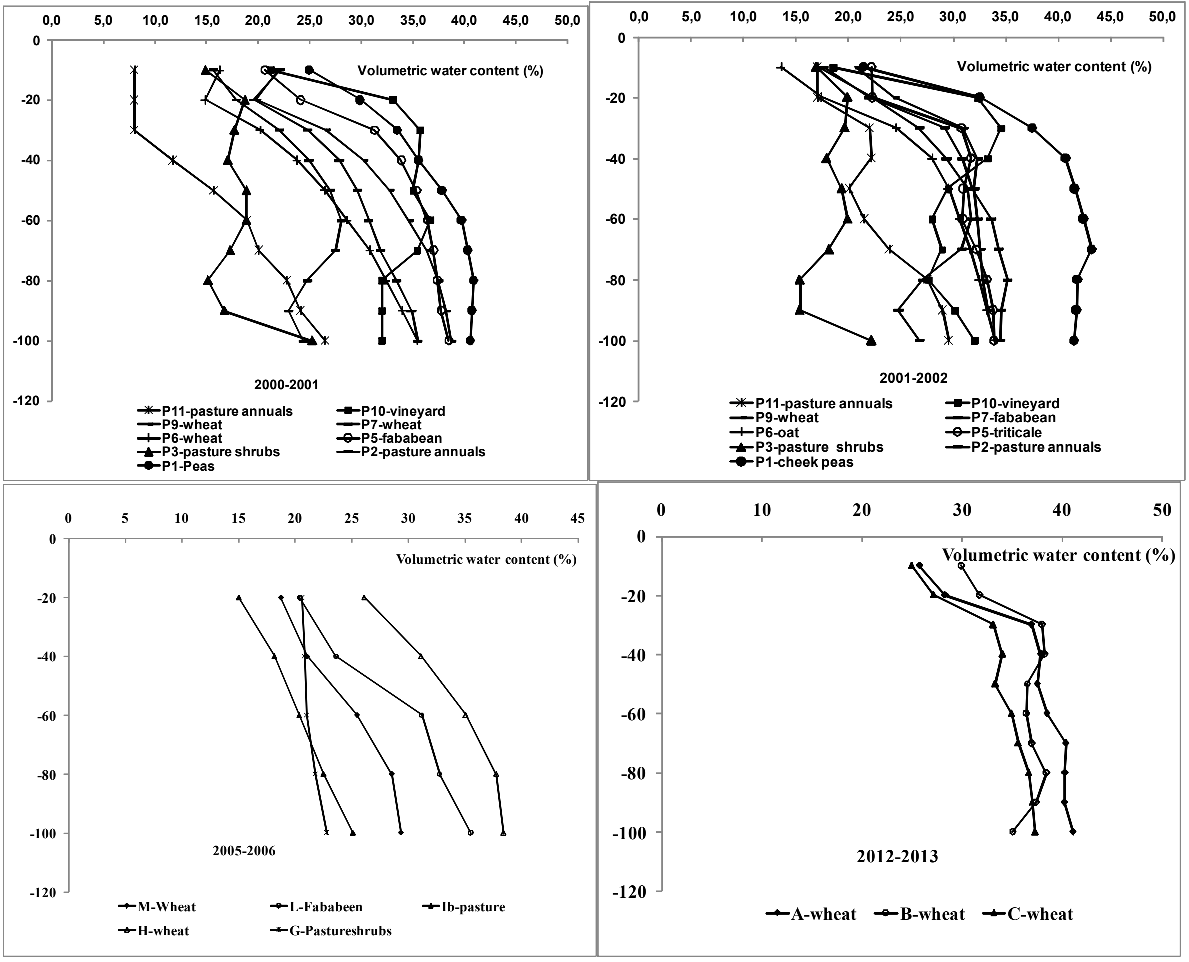

Figure 2. Variations of mean soil moisture profile in different seasons and land uses.

3.3. Variation of the water balance

The point scale water balance over the 1 m depth layer is obtained by integrating the soil moisture profiles derived from neutron probe and gravimetric measurements. Table 1 reports the comparison of water balance parameters between seasons and under different land uses. Lateral inflow and outflow and capillary rise from groundwater and drainage are neglected.

We observe a large interannual variability of the seasonal precipitation. The precipitation occurs during the winter months; soils are wet, and evaporative demand is low. There was no runoff for most of the sites; the observed amounts corresponded to less than 10% of the annual rainfall. The pasture sites had the highest runoff amounts. The observed amount of available water at a given date is variable; which is explained by the soil retention capacity. The amount of available water we observe ranges from 160 mm to 290 mm. The amount of available soil water observed at the end of summer ranges from 0 mm to 55 mm. A larger variability is found in the soil water storage changes ΔS calculated from the observed SWC; it varies from 160 mm to 280 mm for 2001, from 46 mm to 104 mm for 2002, from -3 mm to 76 mm for 2006, and from 62 mm to 88 mm for 2013 experimental periods. The available soil water content varies in relation to crop succession. This is ascribed to spatial heterogeneity of rainfall distribution in the soil, as well as to drainage and extraction regime by rooting system (McGowan and Williams, 1980). The observed average potential evapotranspiration for the whole experimental period is equal to 4.4 mm day-1 in 2001, to 2.2 mm day-1 in 2002, to 1.6 mm day-1 in 2006, and to 2.5 mm day-1 in 2013. This is consistent with previous findings that during summer months, evaporative demand is high and tends to be relatively small in winter season.

Table 1. Variation of water balance components for the 2001, 2002, 2006, and 2013 monitoring periods for each land use. AW: available soil water, P: in season precipitation. R: in season runoff, ΔS: variation of the soil water storage in the 0-100 cm layer. ETa: estimated crop evapotranspiration (P+ΔS -R)/number of days between the two dates.

Land use	AW (mm)	AW (mm)	P (mm)	R (mm)	ΔS (mm)	ETa(mm day-1)
2001	**17/01/2001**	**10/08/2001**				
P2-pastures-annuals	219	48	166	14	172	1.6
P3-pastures-shrubs	185	0	137	4	198	1.6
P5-fababean	249	43	183	3	206	1.9
P6-wheat	167	7	197	1	160	1.7
P7-wheat	289	55	210	2	243	2.2
P9-wheat	271	0	213	1	280	2.4
P10-vineyard	161	0	172	5	191	1.8
P11-pastures-annuals	282	48	207	4	235	2.1
2002	**22/01/2002**	**20/05/2002**				
P2-pastures-annuals	229	108	96	1	125	1.9
P3-pastures-shrubs	149	25	84	4	124	1.7
P5-triticale	204	78	106	1	126	2.0
P6-oat	161	61	106	1	104	1.8
P7-fababean	208	102	107	1	106	1.8
P9-wheat	154	77	105	2	77	1.5
P10-vineyard	104	58	102	1	46	1.2
P11-pastures-annuals	212	139	104	1	73	1.5
2006	**19/04/2006**	**05/07/2006**				
Ib-pastures-annuals	113	88	50	0	25	1.0
G-pastures-shrubs	105	92	50	0	35	1.1
H-wheat	198	122	50	0	76	1.6
M-wheat	121	124	50	0	-3	0.6
L-fababean	157	117	50	0	40	1.2
2013	**02/01/2013**	**05/06/2013**				
A-wheat	189	101	289	5	88	2.4
B-wheat	197	135	289	5	62	2.2
C-wheat	171	88	289	5	82	2.3

Despite drought conditions during summer, bare soils following annual pasture and legumes provide larger amounts of soil water as compared to annual crops. During the wheat growing periods, the soil with medium or low soil thickness is maintained dry in 2001, 2002 and 2006 due to water use by wheat crop. The results show that annual rainfall is mainly converted into evapotranspiration during the growing cycle for different land uses. Therefore, evapotranspiration is the predominant factor that influencing the soil water content dynamics. The evapotranspiration ratios differ significantly in relation to land use, the soil properties and the rainfall conditions. The average evapotranspiration for the whole experimental period varies from 1.6 to 2.4 mm day^{-1} in 2001, from 1.2 to 2 mm day^{-1} in 2002, 0.6 to 1.6 mm day^{-1} in 2006, and from 2.2 to 2.4 mm day^{-1} in 2013. We observed differences up to 60% in 2001 and 2002 seasons and of 40% in 2006 season. Reduced rates of evapotranspiration depend on properties of the soil and the crop. However, when soil water becomes limiting, surface soils dry out, actual evapotranspiration may occur at less than the potential rate. The observed values in 2002 and 2013 seasons assume that there is sufficient water in the soil for evapotranspiration to occur at the potential rate.

4. CONCLUSION

Under hilly watersheds devoted to rainfed agriculture, soil water content depict significant seasonal variations, in relation to the precipitation chronicles, with dry soils in summer and saturated soils in winter, while spring season corresponds to high rates and large variabilities for crop water consumption. These variations are due to the difference in soil physical properties, the field position within the hillslope, and the vegetation type. The mean SWC under pasture was significantly different as compared to annual crops and vineyard. Our results also indicate that the spatial variation in mean SWC profile is controlled by both the distribution of the vegetation roots and soil characteristics. We observed large differences in soil water dynamics among the fababean, wheat, oat, and triticale.Therefore, much research is needed for the understanding and the modeling of the spatiotemporal temporal dynamics of soil water balance in small watersheds with different land uses and sequences.

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