Methodology to assess the maximum irrigation rates at regional scale using geostatistics and GIS

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Abstract

Soil water holding capacity is an important parameter for irrigation scheduling and water balance modelling in fields. In the framework of "precision irrigation" the knowledge of the spatial distribution of this parameter is useful to advice the maximum irrigation rate specifically for each field in an irrigation district, region, etc. The soil water holding capacity (SWHC) can be assessed as the soil water content between the field capacity (FC) and the permanent wilting point (PWP). In this work, we present a methodology to assess the spatial distribution of the maximum irrigation rate depending on the soil water holding capacity. This methodology combines geostatistic techniques with geographical information system-GIS tool. A pilot zone of 12 400 ha located in the Palancia river lowland (between Valencia and Castellón province, Spain) in which the main irrigated crops are citrus (53.8 %), and vegetables (13.3 %), was selected to develop this methodology. For spatial modelling of SWHC, experimental semivariograms were assessed for the FC and PWP at three soil depth intervals (0-10, 10-30, 30-60 cm). Spherical models fitted well to the experimental semivariograms, with a very high spatial dependency index (ID = 0.05-0.41) which support reliable predictions on basis the fitted models. The cokriging spatial interpolation method, considering the percentage of sand as secondary variable, was the best option to minimize the root mean square error in the cross-validation test.

This spatial distribution of the SWHC modelled was implemented in a geographical Information System-GIS in combination with other spatial layers such as land use map that integrate information of crop type (mainly citrus or vegetables), irrigation system (drip or surface irrigation), etc. The combination of the SWHC layer with land-use layers in the GIS was used to estimate the maximum net irrigation rates for each field in the irrigated area. With this estimation of the spatial distribution of the maximum irrigation rates, the irrigation managers can optimize the irrigation rates in each field, therefore making use of the precision irrigation concept to minimize water losses by leaching.

Particularly in the study area, a range of maximum irrigation rates from 75 to 150 L m^{-2} were recommended for crops irrigated by surface system, and 11 to 25 L m^{-2} for citrus under drip irrigation depending on the SWHC. Irrigation rates higher than 132 L m^{-2} for surface irrigation systems were found in those fields located in areas with soils of alluvial origin and clayey textures, and lower than 60 L m^{-2} in those areas with soils developed on colluvial materials, indicating the importance of the soil water parameters in the assessment of irrigation rates.

Key words: precision irrigation, geostatistic, GIS, Irrigation rate, soil water holding capacity.

1. Introduction

The European Water Framework directive places legal constraints on the use of irrigation water with focus in the use of water-saving irrigation techniques (European Commission, 2000). This make necessary to promote efficient and sustainable water use for agricultural production. Therefore, the irrigation management must be oriented to fulfil the water requirements of crops altogether considering the physical and hydraulic properties of soils. Soil water holding capacity (SWHC) is an important hydraulic parameter for irrigation scheduling and water balance modelling in fields. In the frame of "precision irrigation" the knowledge of this parameter distributed spatially is useful to advice the maximum irrigation rate specifically for each field within an irrigation district, region, etc. The irrigation scheduling that considers these thresholds in the irrigation rate, would allow adapting the irrigation rates to particular soil conditions of each field, increasing the water efficiency, and reducing the water and the nutrient losses by leaching.

The soil water holding capacity usually is assessed as the soil water content measured between the field capacity (FC) and the permanent wilting point (PWP). As indicated by Sven (2012), soil variability is a major challenge and requires consideration of a system for precision irrigation. To optimize the irrigation practice in a region it is essential to know the specific SWHC for each field. The availability of this information spatially distributed would improve the irrigation water management in large areas. Providing this soil information is also valuable to choose representative places where to install the minimum number of soil water sensors for monitoring irrigation management in large districts. Additionally, several authors have linked soil water properties to crop yield indicating the importance of soil properties in the agricultural production. Several authors have used geostatistics approaches to estimate the spatial variability of these soil hydraulic parameters but generally at field scale (Santra et al. 2008). With this approach we can estimate the spatial distribution of the variable, and at the same time its variance giving an idea of the error spatial distribution.

In this work we present a methodology to assess the spatial distribution of the maximum net irrigation rate depending on SWHC in a large irrigation area. This methodology is based on geostatistic techniques in combination with a geographical information system-GIS tool.

2. Material and methods

2.1 Study area description

A pilot zone of 12 400 ha located in the Palancia river lowland (between Valencia and Castellon province, Spain) in which the main crops are citrus (53.8 %), and vegetables (13.3 %) was selected to develop this methodology (Fig. 1). The climate of the area is classified as Mediterranean with moderate annual temperatures (Tmean = 16.5 ºC) and annual rainfall of 500 mm, with intensive rainfall events during autumn, and a mean rainfall of 200 mm in this season. The distribution of soil types within the study area is very heterogeneous. In general, the hillsides are dominated by Calcisols and Chromic Cambisols with loam textures. The alluvial area located at the river lowland, and close to the sea is dominated by Gleyic Cambisols or Gleysols with silt-clay textures. At the south part of the area the dominant soil are Luvisols with clayey textures. Parallel to the shore coast line are located the Arenosols, which are not usually cultivated. The main irrigation system is localised, generally associated to citrus orchards, but surface irrigation is also frequent in some parts of the study area mainly associated to vegetable crops.

2.2. Soil sampling design

In this study area, a systematic-random sampling was carried out to select 100 different fields (Fig. 1). In each field two sites were selected, and in each site soil samples from three depths (0-10, 10-30, 30-60 cm) were taken with an auger. This sampling procedure ensures the independence in the selection of sampling fields, while simultaneously avoiding gaps and clusters in the region.

2.3. Soil Water Holding Capacity assessment

The soil water holding capacity is assessed as the soil water content between the field capacity (FC) and the permanent wilting point (PWP). These points were assessed following the Richards method (1947) using disturbed soil samples which had been previously air dried and subsequently sieved to pass a 2 mm-mesh sieve. The soil water content at was assessed at 20 kPa, and the permanent wilting point at 1500 kPa. Other parameters related to the SWHC were the soil texture that was determined following the Bouyoucos densimeter method (1927).

2.4. Geostatistics method

Geostatistic techniques were used to know the spatial distribution of the field capacity and the permanent wilting point at the three different depths. With this approach both the spatial distribution of the variable and its variance can be estimated, providing not only an estimation of the spatial distribution of the FC and PWP but also the spatial estimation of their errors.

We followed five steps to develop this geostatistic methodology. First exploratory data analyses were carried out to know the frequency distribution of the variables, and to test for normality using the Kolmogorov-Smirnov test at a significance level of 95%. Second, a spatial continuity analysis was performed. The experimental semivariogram was elaborated in this step. Third, the Spatial modelling. The theoretical semivariogram was fit to the experimental data using the GS+ geostatistic package. Four, spatial interpolation: the variables were spatially interpolated using the ordinary Kriging (OK) and ordinary Cokriging (COK). Five, uncertainty analysis. The uncertainty generated in the interpolation procedure was evaluated using the cross-validation test, and analysing the Root Mean Square Error (RMSE) as indicator for the error magnitude, and the Root Mean Standardized Square Error (RMSSE) as indicator for the variance precision.

3. Results

3.1 Geostatistics modelling

The Kolmogorov-Smirnov test results for the frequency distribution of field capacity (FC) and the permanent wilting point (PWP) show a normal distribution at the 95% confidence level. Accordingly these variables can be used in a statistical procedure without any normal transformation, ensuring reliable interpolations based on the corresponding semivariograms. Following a general geostatistics procedure, the experimental semivariograms were developed to explore the spatial continuity in the three soil depth intervals (0-10, 10-30 and 30-60 cm). In Figures 2 and 3, where the experimental semivariograms are shown, we observe spatial continuity at all the three soil depth intervals for both the FC and the PWP. The theoretical model that best fitted to the experimental data was the spherical type. Additionally cross-semivariograms of the main variable (either FC or PWP) in combination with a secondary variable, which was the sand percentage, were elaborated to be used in the cokriging interpolation. These cross-semivariograms represent the spatial correlation between the main and the secondary variable.

Several geostatistic parameters characterising the spatial structure of the FC and PWP in the three depth intervals were obtained from the fitted model, and shown in table 1 and 2. The nugget (Co) characterises the micro-scale variability that is unknown, whereas the partial sill (C) indicates the variation which can be addressed by the spatial correlation structure that is considered by the model. The range (a) is the distance at which the sill is reached, and indicates the distance at which the spatial correlation is observed.

The low nugget effect (Co) in relation to the Sill (C) indicates the spherical semivariogram model adequately simulates the spatial structure of the FC and PWP. The micro-scale variability defined by the nugget (Co) is less important than the spatial variability represented by the model. This spatial structure is addressed by the spatially dependency index (DI), calculated as the relation between the nugget effect (Co) and the total sill (Co + C). In our area this index is between 0.05 and 0.41. Following the classification proposed by Cambardella et al. (1994) for this index, all the semivariograms modelled for the FC and PWP present strong to moderate spatial dependencies (tables 1 and 2).

Other useful information about the spatial distribution can be extracted observing the semivariograms (Fig. 3 and 4). The higher sill observed for the FC and PWP at 0-10 cm depth indicates that the spatial variability is higher in surface horizons. This is likely due to the tillage effect, and the texture in deeper horizons, which tends to be more uniform. Additionally, at deep soil horizons the range is higher, indicating a lower spatial randomness for FC and PWP. The distance of the range in the semivariograms is between 2715 and 4985 meters (table 1 and 2). This range indicates the maximum distance at which spatial correlation is found. These ranges indicate the distance at which the soil hydraulic properties can be predicted on basis the semivariogram, so we could consider this information as a guide to optimise the installation of soil water sensors that is to obtain maximum soil water content information with the minimum number of sensors.

The sand percentage was included as secondary variable in the spatial modelling, because it is negatively correlated with the FC and PWP (Pearson correlation coefficient of -0.612 with PWP and -0.631 with FC). This improved significantly the spatial dependency and reduced the interpolation errors (Table 3). Just in the case of the PWP at the 30-60 cm soil depth interval the error was not reduced and the inclusion of the sand percentage as secondary variable was discarded. The root mean square error (RMSE) for the COK was always 4.4% lower than for the OK (table 3), and the standardized root means square error (SRMSE) closer to one. Therefore, the cokriging, considering the percentage of sand as secondary variable, provided the best interpolation method: it minimized the root mean square error in the cross validation test. The cokriging interpolation technique was then used to elaborate the FC and PWP maps. The SWHC map was assessed as the difference between the FC and the PWP maps averaged for a 60 cm soil depth.

TABLE 1

Descriptive parameters of the theoretical semivariograms and spatial dependency for the Permanent Wilting Point-PWP spatial modeling.

Depth (cm)	Variable	C_0 (%)2	Sill (%)2	Range (m)	Model	DI = $C_0/(C+C_0)$	Spatial dependency
0-10	PWP	9	23.6	2825	Spherical	0.28	Moderate
	% sand	59	124	2825	Spherical	0.32	Moderate
	PWP x % sand	-6	-45.5	2825	Spherical	0.12	Strong
10-30	PWP	10	21	2955	Spherical	0.32	Moderate
	% sand	55	177	2955	Spherical	0.24	Strong
	PWP x % sand	-2	-49	2955	Spherical	0.04	Strong
30-60	PWP	5.74	20.5	4700	Spherical	0.22	Strong

* Co: Nugget effect, DI: dependency Index

TABLE 2

Descriptive parameters of the theoretical semivariograms and spatial dependency for the Field Capacity-FC spatial modeling.

Depth (cm)	Variable	C_0 (%)2	C (%)2	Range (m)	Model	DI $C_0/(C+C_0)$	=Spatial dependency
0-10	FC	9.7	32.03	2715	Spherical	0.23	Strong
	% sand	59	122	2715	Spherical	0.33	Moderate
	FC x % sand	-3	-62.36	2715	Spherical	0.05	Strong
10-30	FC	10	26	3060	Spherical	0.28	Moderate
	% sand	56	176	3060	Spherical	0.24	Strong
	FC x % sand	-7	-49.5	3060	Spherical	0.12	Strong
30-60	FC	19	27	4985	Spherical	0.41	Moderate
	% sand	76	153	4985	Spherical	0.33	Moderate
	FC x % sand	-3.5	-54.5	4985	Spherical	0.06	Strong

TABLE 3.

Cross-validation errors of the krigring and cokriging spatial interpolation for field capacity and wilting point at different soil depths.

Soil depth (cm)	***Field capacity***		***Wilting point***	
	Kriging RMSE/RMSSE	***Cokriging RMSE/RMSSE***	***Kriging RMSE/RMSSE***	***Cokriging RMSE/RMSSE***
0-10	5.66 / 1.18	4.42 / 1.05	4.99 / 1.30	4.10 / 1.00
10-30	4.62 / 1.21	4.15 / 0.96	5.28 / 1.36	4.39 / 1.06
30-60	5.65 / 1.19	5.23 / 1.02	3.84 / 1.12	3.72 / 1.29

3.2. Development of the maximum net irrigation rates map.

The maximum net irrigation rates (L m^{-2}) map (fig. 5) was elaborated based on the field capacity and wilting point spatial distribution. This modelled spatial distribution of water holding capacity was integrated in a GIS with other spatial layers such as the citrus spatial distribution, land use map, and irrigation system (drip and surface irrigation). All these layers were used to estimate the maximum irrigation net rates for each field in the irrigated area. Using a GIS tool that allows combining the SWHC layer with the other spatial layers we could elaborate the maximum net irrigation rate (I_{max}) in L m^{-2} map using the following equation (Eq. 1):

$$I_{max} = 10 * BD * d * SWHC * MAD * P / IE \quad (1)$$

Where:

BD: soil bulk density (g cm^{-3}). We estimate that in the area and at 0-60 cm depth the average bulk density is 1.3 g cm^{-3}.

d: the irrigated rooting depth (cm), that for vegetables crops and citrus younger than 5 years we assume 65 cm, and 85 cm for older citrus.

SWHC: Is the soil water holding capacity (cm^3 cm^{-3}) defined as the difference between the soil water content at Field Capacity (FC) and the Permanent Wilting Point (PWP).

MAD: Is the maximum allowable depletion limits. This parameter represents the soil water content in relation to the SWHC that the farmer permits to dry before the next irrigation application. And it is similar to the average fraction of the SWHC that can be depleted from the root zone before the water plant stress arises. This parameter can be estimated as a function of the irrigation system and the crop. We assume equal to 0.3 for drip irrigation in citrus (is more frequent), and 0.5 for surface irrigation for vegetables and citrus (Santa Olalla & de Juan, 1993, Allen et al.,1998).

IE: Irrigation efficiency. This value was estimated as 0.90 for the drip irrigation system, and 0.70 for surface irrigation.

P: Is the percentage of the wetted soil. We assume that is 50% of the shaded area by the crop for drip irrigation, 75% for furrow irrigation and 100% for flood irrigation.

In base on this map (fig. 4), the irrigation manager could optimize the irrigation rates field by field depending on the SWHC, the irrigation system, and the crop, minimizing the water losses by leaching. As shown in the map, those areas with a SWHC higher than 20%, and the irrigation system by surface, the net maximum irrigation rates recommended can reach to 125 L m^{-2} per irrigation event. Additionally, the citrus orchards older than 15 years irrigated by surface, the net irrigation rates is in a range from 71 to 151 L m^{-2} depending on the SWHC which vary in a range from 11 to 19%, indicating the importance of the soil water parameters in the determination of the irrigation rate. Comparing this scenario (same SWHC range, and citrus crop), but under drip irrigation, the maximum net irrigation rates are in a range from 11 to 25 L m^{-2}, similar percentage of increment in irrigation rate than for surface system.

Conclusions

We developed a methodology integrating geostatistics techniques in a GIS framework to estimate the net irrigation maximum rate for precision irrigation, which is based on the estimation of the spatial distribution of the soil water holding capacity.

The geostatistical interpolation technique which provided best interpolation results for field capacity and wilting point, was the ordinary cokriging using the sand content as auxiliary variable. Using this technique the root mean square errors decreased 4.4% regarding the ordinary kriging.

With this methodology we were able to estimate the spatial distribution of the irrigation rates that avoids water losses by leaching. This spatially distributed information in the study area allows the irrigation manager to advice specific irrigation rates for each field. In our study area the citrus orchards older than 15 years irrigated by surface, were recommended irrigation rates in a range from 71 to 151 L m^{-2}, and for drip irrigation from 11 to 25 L m^{-2}.

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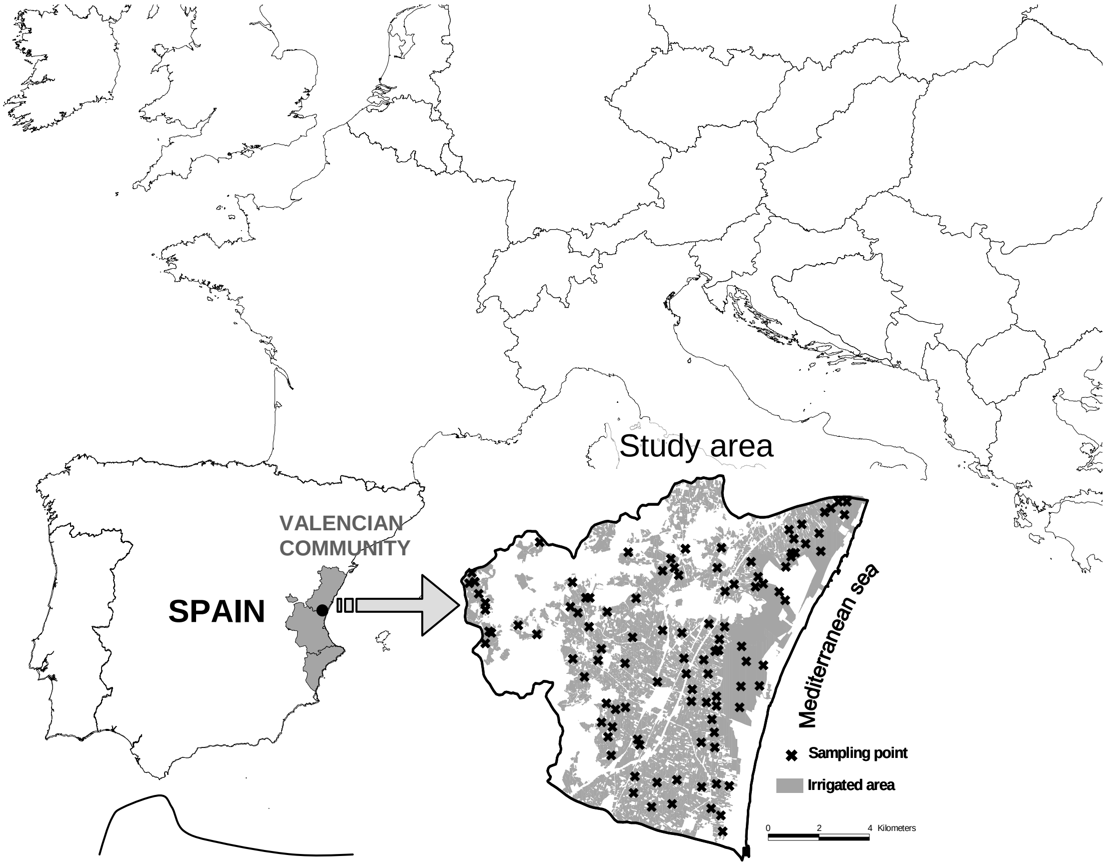


Figure 1. Study area location and soil sampling spatial distribution.

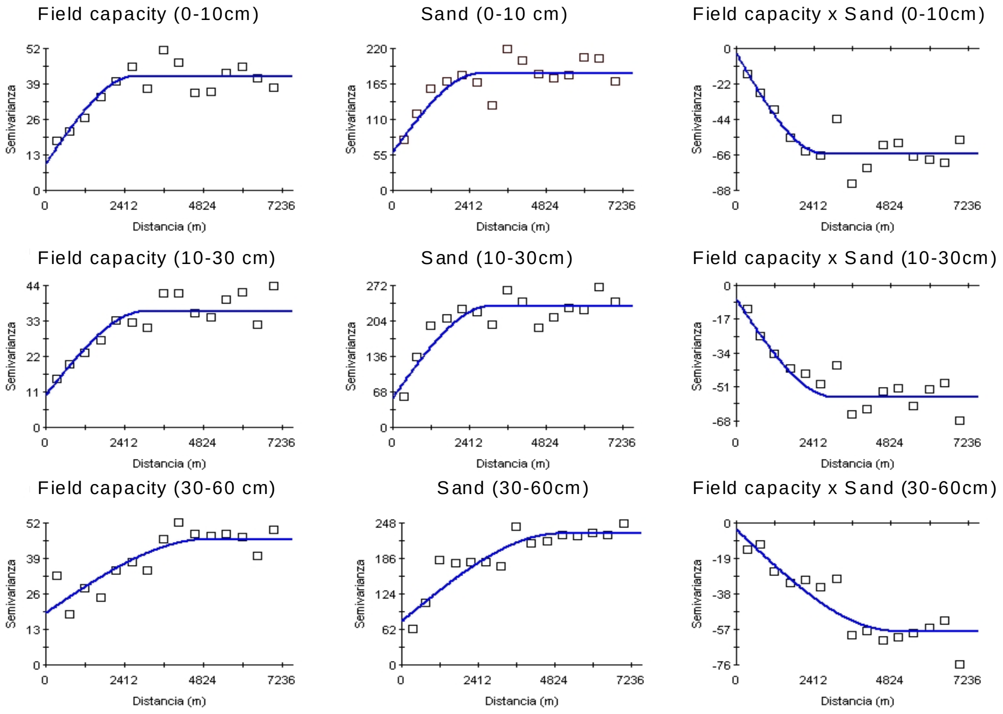
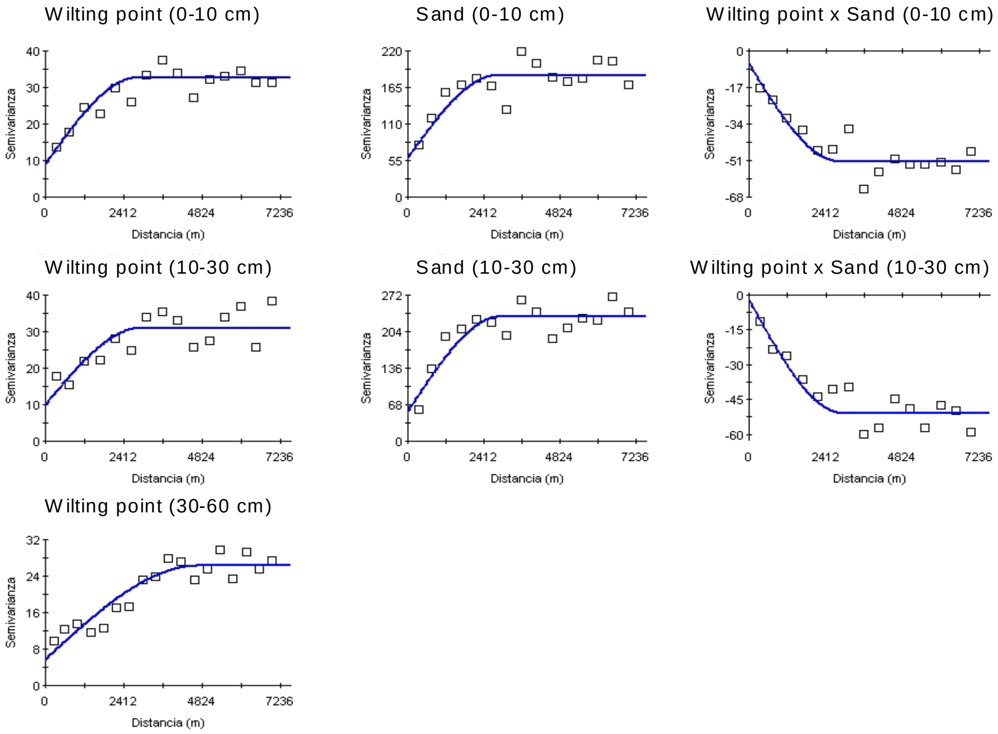


Figure 2. Experimental semivariograms and cross-semivariograms with the fitted theoretical spherical models, for the field capacity and sand percentage content within the three soil depth intervals (0-10, 10-30, 30-60 cm).



Wilting point (0-10 cm)

Sand (0-10 cm)

Wilting point x Sand (0-10 cm)

Wilting point (10-30 cm)

Sand (10-30 cm)

Wilting point x Sand (10-30 cm)

Wilting point (30-60 cm)

Figure 3. Experimental semivariograms and cross-semivariograms with the fitted theoretical spherical models, for the permanent wilting point and sand percentage content within the three soil depth intervals (0-10, 10-30, 30-60 cm).

Figure 4. Combination of Soil Water Holding Capacity (SWHC) map with other GIS layers associated to land-use layer to develop the maximum net irrigation map (L m^{-2}).