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ESTIMATING WATER CONSUMPTION AND IRRIGATION REQUIREMENTS IN A LONG-ESTABLISHED MEDITERRANEAN RURAL COMMUNITY BY REMOTE SENSING AND FIELD DATA†

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ABSTRACT

The present study illustrates an original methodology for estimating irrigation requirements and quantifying real water consumption in a long-established Mediterranean rural community (Delta Llobregat, Barcelona, Spain), combining data from remote sensing, field mapping and *in situ* measurements. Because of land fragmentation and crop diversification, SPOT-5 imagery was used, given its spatial and temporal resolution and spectral attributes. Simultaneously, four flow meters were installed in two representative locations to measure water inputs and outputs every 5 min. Conveyance and irrigation efficiency were estimated for the entire irrigation community. The average conveyance efficiency was 46.8% and the classical and net irrigation efficiency reached 26.4 and 59.8%, respectively, with half of the water volume (55% or 3.2 hm^3) returned to the river or diverted to wetlands, the maximum percentage of estimated error being about 3.4%. These results indicate an exceptionally high water loss rate due to the irrigation system (flooding), the ageing conveyance network and urban infrastructure breakdown. The applied protocol proved useful for monitoring low-efficiency irrigation systems in small communities experiencing intense urban and industrial pressures. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: satellite imagery; hybrid classifier; flow meter; conveyance efficiency; irrigation efficiency; water balance

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RÉSUMÉ

La présente étude illustre une méthodologie originale pour estimer les besoins d'irrigation et de quantification de la consommation réelle d'eau dans une communauté rurale établie de longue date en Méditerranée (delta du Llobregat, Barcelone, Espagne), combinant des données de télédétection, de la cartographie sur le terrain et des mesures in situ. En raison de la fragmentation des terres et de la diversification des cultures, l'imagerie SPOT-5 a été utilisée en raison de ses résolutions spatiales, temporelles et spectrales. Simultanément, quatre débitmètres ont été installés dans deux endroits représentatifs pour mesurer toutes les 5 minutes les débits entrants et sortants. Le transport et l'efficacité de l'irrigation ont été estimés pour toute la communauté d'irrigation. L'efficacité de transport moyen était de 46.8% et l'efficacité de l'irrigation classique et nette ont atteint 26.4 et 59.8%, la moitié du volume d'eau (55%, soit 3.2 hm^3) est retournée à la rivière ou détournée vers les zones humides, l'erreur maximale étant de l'ordre de 3.4%. Ces résultats indiquent un taux de perte d'eau exceptionnellement élevé en raison du système d'irrigation (par submersion), du vieillissement du réseau de transport et de la dégradation des infrastructures urbaines. Le protocole appliqué est avéré utile pour surveiller des systèmes d'irrigation à faible efficacité dans les petites communautés connaissant des pressions urbaines et industrielles intenses. Copyright © 2016 John Wiley & Sons, Ltd.

MOTS CLÉS: l'imagerie satellite; classificateur hybride; débitmètre; l'efficacité de transport; efficacité de l'irrigation; bilan d'eau

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INTRODUCTION

The primary sector is the largest consumer of water in the Mediterranean countries, and this is especially true in long-established irrigation systems such as the Spanish irrigation infrastructure, where nearly 70% is over 90 years old (Berbel and Gómez-Limón, 2000). Moreover, the Mediterranean climate is characterized by marked spatial and seasonal variability (e.g. Venezian Scarascia *et al.,* 2006). Changes in rainfall distribution may have negative effects on water availability for crops, producing water scarcity and potential conflicts over the use of water (Salvati *et al.,* 2009).

For planning purposes, river basin management authorities need accurate knowledge of agricultural land use and consistent estimates of the spatial and temporal distribution of crop water requirements (Casa *et al.,* 2009). In turn, reliable estimation of irrigation water requirements should include a calculation of the water balance (Salvati *et al.,* 2008), defined as the ratio between the volume of water used for a specific purpose and the volume extracted or derived from a supply source for that purpose (Jasrotia *et al.,* 2009). In an agricultural area irrigated with canals five variables (including two input and three output variables) should be considered in water balance analysis (Hamdy, 2007a): (i) the volume extracted from the supply source (water supplied), usually provided by the river basin authority; (ii) effective precipitation, usually derived from meteorological data, also considering soil characteristics; (iii) the volume of water required to support crop growth including water evaporated from the soil and crop evapotranspiration; (iv) water losses produced during water conveyance, and (v) water returned to the river or to the sea by the canal system.

Remote sensing (RS) has some advantages over traditional methods for mapping and monitoring vegetation status and the water balance with cost-effectiveness, temporal resolution and geographical extent being the most important attributes (Ambast *et al.,* 2002; Incerti *et al.,* 2007; Serra and Pons, 2008; Peña-Barragán *et al.,* 2011). Crop water requirements have been obtained with RS data using different methods. Some of them are based on crop evapotranspiration ($ET_{c.}$) extracted from reference evapotranspiration (ET_0) and crop coefficients (K_c), related to a defined crop type and its vegetative stage. In general, large regions have been analysed and low and medium RS spatial resolutions have been applied (Gontia and Tiwari, 2010). For example, in the case of Karatas *et al.* (2009), the objective was to assess irrigation performance in Turkey (140 000 ha), using images from the advanced very high resolution radiometer of the NOAA satellite, according to the Surface Energy Balance Algorithm for Land (SEBAL) method (Bastiaanssen *et al.,* 1998). The SEBAL method is an image-processing method comprising several submodels that calculates evapotranspiration and other energy exchanges using thermal infrared radiation as well as visible and near infrared (NIR) data. In addition to satellite data, the model requires weather data parameters such as air temperature or wind speed. Another option is the METRIC model (Mapping Evapotranspiration at high Resolution and with Internalized Calibration, an extended modification of SEBAL) (Allen *et al.,* 2007) applied, for instance, by Folhes *et al.* (2009), to estimate the total water supply for irrigation in Brazil in fields characterized by their large size (more than 6 ha) using Landsat images.

Although energy balance approaches (as SEBAL and METRIC) are completely useful for estimating evapotranspiration, as explained above, these methods depend upon data acquired from thermal sensors, usually with low–medium RS spatial resolutions (e.g. Landsat-5 thermal band is 120 m, 100 m in Landsat-8 and 90 m in ASTER). For this reason, they are suitable to apply to homogeneous cover, mainly fields of large extension in the case of crops (Folhes *et al.,* 2009). In the case of heterogeneous areas, as in our work, small parcel size and land-use variability can mean that low–medium spatial resolution is not accurate enough for them to be used (Cristóbal *et al.,* 2011). In addition, for some authors they may occasionally be time-consuming, the selection of dry and wet pixels being initially difficult to automate (Rafn *et al.,* 2008; Ahmad *et al.,* 2009). Finally, as Allen *et al.* (2011) assert, the effects of evaporation from precipitation events that occur between satellite overpasses may be missed.

Based on these premises, the present study illustrates an alternative method for calculating agricultural water consumption in a Mediterranean irrigation community, located very close to the city of Barcelona (north-east Iberian peninsula) and characterized by a crop mosaic and land fragmentation. This rural community, established in 1860, is based on a very old conveyance network. The initial hypothesis was that conveyance losses would be higher and irrigation efficiency lower than the average value observed on a regional scale, due to the irrigation system (mainly by flooding), and the age of the conveyance network. To better explore conveyance losses in time and space, our work incorporates RS images to provide detailed information about spatial distribution of crops and *in situ* data extracted from some flow meters installed in the irrigation canals.

MATERIALS AND METHODS

Study area

Catalonia, the Spanish region where the study area is located (Figure 1), has endured different periods of severe droughts (as in 1944 or 1973) with significant restrictions on water

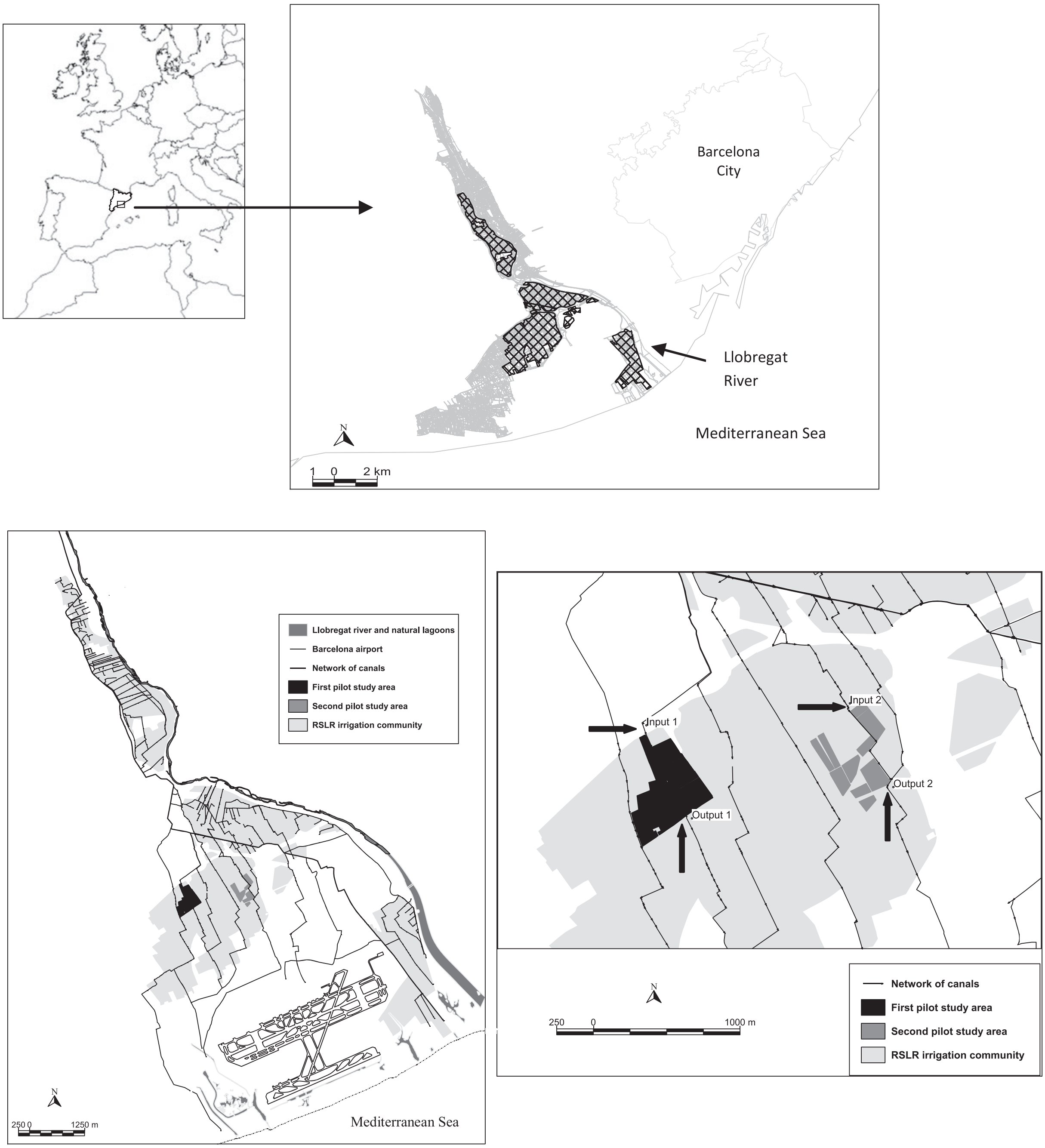

Figure 1. Map of the study area, located near the city of Barcelona in Catalonia, north-east Spain (upper left). The Agrarian Park is shown in grey and the irrigation community of the Right Side of the Llobregat River (RSLR) in hatched pattern (upper right). The network of canals from the irrigation community of the RSLR near Barcelona airport is shown in the lower left map. The location of the two pilot study areas representative of irrigated crops and placement of the four flow meters are shown in the lower right map (input label indicates where the water from the canal enters the first and the second pilot study area (input 1 and input 2, respectively): output label indicates where the water from the canal leaves both pilot study areas (output 1 and output 2). Flow direction: north–south)

supply. The most recent period of water scarcity occurred in 2007, as a consequence of the lack of sufficient rainfall in the headwaters of Catalan rivers during the autumn of 2006 (Serra and Pons, 2013). It was regarded by the Catalan Water Agency (CWA), the public water authority in Catalonia, as the worst drought since 1944. Therefore, to minimize water-scarcity issues exhaustive information about agricultural water consumption is needed.

The Llobregat River's lower valley and delta, located in Barcelona's province, consist of about 30 km^2 of alluvial valley, up to 1 km wide, and a delta of 80 km^2. The study area includes the irrigation community 'Right Side of the Llobregat River' (RSLR), which groups all owners of the irrigable area, united by law for the independent and common administration of public water (Pujol *et al.,* 2006). The RSLR manages by turns the water that arrives at its boundaries from the basin authority and all the farmers pay a share according to their irrigation surface. The entire surface is within the Agrarian Park of Baix Llobregat, a rural protected area of 2938 ha close to Barcelona that has been the main supplier of fresh fruit and vegetables to the city for many centuries. Because of this location and the flat land, the Agrarian Park is under great pressure from urban and industrial uses, aggravated by the international airport serving Barcelona. The RSLR, created around 1860, was composed of 2773 parcels at the time of the present study, with an area of 1109 ha, and currently it extracts and distributes water from the river using a 12.7 km long canal network. In general, the canals are made of traditional materials (mainly masonry with bricks and stonework) and are superficial, but in some locations they have been covered. One of the most important characteristics of the Agrarian Park, in general, and of the RSLR in particular, is the small size of fields: only 12.2% of parcels were larger than 1 ha. As in ancient times, the most common crop irrigation system is by flood, which consumes a very large volume of water, with the exception of fruit trees that are mainly irrigated by drip.

Long-term average precipitation in the area ranges between 550 and 600 mm yr^{-1}. Average annual temperature is around 15.5–16 °C. Average texture composition of soils in the delta Llobregat area is 18% clay, 34% sand and 48% silt, with predominant soil types being xerorthent combined with xerofluvent. Average root soil depth in the area is 130 cm, with maximum potential available water capacity encompassing 55 mm (Hiederer, 2013).

Remote sensing images

Given that the median field size is quite small and typology of crops diverse, determining crop phenology required high-quality spatial, spectral and temporal resolution of RS images. For this reason some satellites/sensors were initially discarded as not useful because of their low spatial resolution, such as the Moderate Resolution Imaging Spectrometer (MODIS from TERRA/AQUA), or because of low spectral resolution, such as IKONOS or QuickBird. Therefore, RS imagery used in this work mainly corresponds to the SPOT-5 satellite and HRG sensor, achieving good spatial resolution (10 m) combined with a useful spectral resolution (from visible to SWIR) and an acceptable temporal resolution. For each image the four multispectral bands were used (covering 0.50–0.59 µm (green), 0.61–0.68 µm (red), 0.78–0.89 µm (near infrared, NIR) and 1.58–1.75 µm (short-wave infrared, SWIR)), recorded at a spatial resolution of 10 m including the SWIR band. Six 2011 images free of clouds were selected, corresponding to the path 045 and scene 267: 16 February, 6 May, 7 June, 17 June, 19 July and 13 August. Figure 2 summarizes the methodology applied. The first step was the geometric correction of images using the procedure developed by Pons *et al.* (2010a) based on a mean of 314 fitting and 308 test ground control points automatically located, giving RMS errors below 10 m. The second step was the radiometric correction (atmospheric and topographic), through which digital numbers were converted into reflectance values using

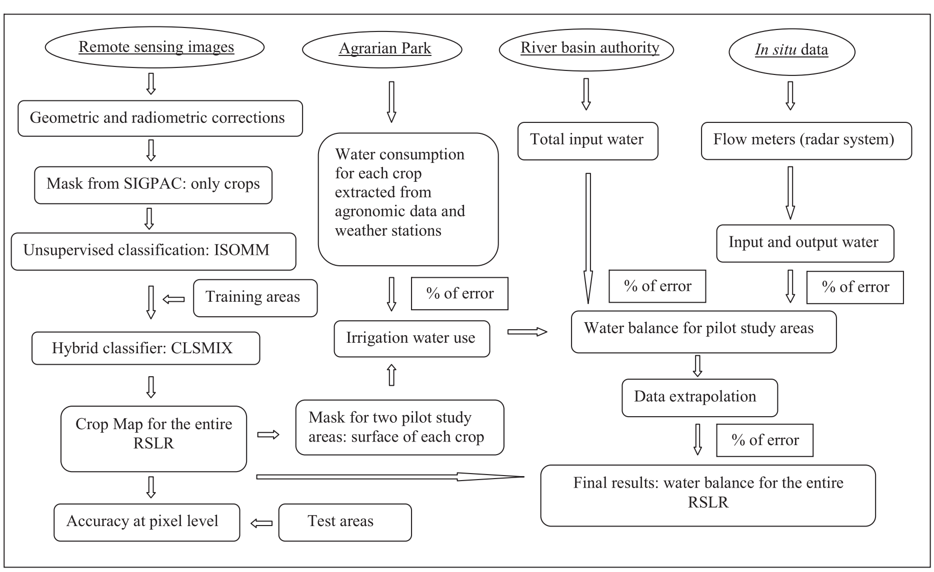

Figure 2. Protocol applied in the RSLR water requirements

sensorcalibration parameters and other factors such as atmospheric effects, the solar incident angle taking into account the relief extracted from a digital elevation model (see Pons *et al.,* 2010b).

Crop classification and water requirements

Using the six SPOT images, a crop map for the entire RSLR was developed using a hybrid classifier implemented in the GIS MiraMon software (Pons, 2006). It combines two modules: an unsupervised classification (IsoMM module) and a supervised stage (ClsMix module) consisting of a spatial between statistical categories, obtained from an unsupervised classification, and thematic classes, defined by training areas. This hybrid classifier has been successfully used to classify Mediterranean crops and forest lands characterized by high spatial fragmentation due to their parcel size and crop diversity (Serra *et al.,* 2009; Moré *et al.,* 2006). To identify the study area a mask was applied using the Geographical Information System of Agricultural Fields (in Spanish Sistema de Información Geográfica de Parcelas Agrícolas: SIGPAC). SIGPAC is a public register for agricultural parcel identification, at a scale of 1 : 10 000, and is currently a mandatory reference for identifying an agricultural holding (Ministerio de Agricultura, Pesca y Alimentación (MAPA), 2007).

The 6 SPOT images included in the classification process were equivalent to introducing 24 bands, and in order to improve the hybrid classifier results, the Normalized Difference Vegetation Index (NDVI), the most commonly used index to supply information about vegetation, was calculated for each image to determine the chlorophyll activity of crops according to their phenology. This index is the result of subtracting the red band from the NIR band, divided by their sum. The final crop map discriminated between the following crop types: artichokes (*Cynara scolymus*), horticulture (tomatoes, potatoes, etc.), fruit trees (mainly peach (*Prunus persica*) and apple (*Pyrus malus*) trees), winter cereals (mainly wheat (*Triticum aestivum*)), maize (*Zea mays*), alfalfa (*Medicago sativa*), greenhouses and flooded land. To quantify water consumption, a theoretical budget was applied for each crop, taking into account that the expenditure on winter cereals and artichokes was equivalent to zero because they are not irrigated in the summer (although the latter may be irrigated in dry years but 2011 was not the case). Two other important considerations were that greenhouses are irrigated with groundwater and were excluded from the analysis, and that flooded land corresponds to an aged agricultural practice (*estanyar* in the local nomenclature), in which fields are flooded for several weeks to wash away soil salt and to minimize the occurrence of animal plagues. After that flooding, when the soil is drier, it is very common to cultivate horticulture, but in order to avoid classification confusions (different crop types in the same fields and year) it was considered that in all the analysed time periods the fields remained flooded although this option was equivalent to overestimating the final water spend. In consequence, the water consumption of flooded land was considered equal to a rice field when it is flooded at the beginning of the cultivation period. The next step was the $ET_{c.}$ evaluation method as suggested by the FAO: reference evapotranspiration (ET_0) was multiplied by crop coefficient (K_c) related to the crop type and its vegetative stage (Allen *et al.,* 1998). ET_0 was obtained from the same meteorological station from where precipitation was extracted, while K_c was obtained from FAO parameters.

In situ data: measurement of canal flow and local precipitation

The CWA provided data on the total input of daily water extracted from the Llobregat River from 6 May to 12 July 2011, resulting from a long-established water concession of $1.5\,m^3\,s^{-1}$. This measurement corresponded to the unique input point located in the north-east of the RSLR and managed by the CWA. The total output of water could not be measured at just one exit point because the system has diverse output points. Therefore, two pilot study areas located in the centre of the RSLR were analysed first. These two areas were selected because they included some of the crop types cultivated in the irrigation community and because they integrated different numbers of fields and sizes (34 fields in the first area and 10 in the second). After obtaining a map with the crops cultivated in the RSLR and applying a mask for identifying the fields included in the two pilot study areas, the real water consumption was calculated with the help of four Vegapuls 61 flow meters installed inside the canal sections. Two of them were used for measuring the input of water and the other two for measuring the output, with the objective being to extrapolate the conveyance efficiency to all the RSLR in a cost-efficient manner. Vegapuls 61, a radar sensor, emits short microwave pulses in the irrigation canal direction; these pulses are reflected by the water surface and received back again by the antenna system, giving a measurement every 5 min. This information allowed us to identify with high precision (accuracy ±2 mm of flow level) the input and output flow before and after use in crop irrigation. Another input considered was local precipitation, a parameter to be included in the balance because the CWA provides more or less volume of water based on rainfall. Precipitation data were obtained from the closest meteorological station and a percentage reduction was applied to quantify effective rainfall. A water balance formula was thus adapted to consider the specific irrigation system from the RSLR community based on the assumption that input (I) water is equal to output (O) water. The total input water (I) is

$$I = Vd + Pe \quad (1)$$

where V_d is the total volume of water diverted by the river basin authority to the RSLR community and P_e the total effective precipitation.

V_d was provided by the river basin authority and P_e calculated using the closest meteorological station to the study area. As P_e is the portion of total precipitation that is useful for crops, this amount is estimated using the method developed by the USDA Soil Conservation Service. This empirical method assumes that a range between 60 and 80% of precipitation up to 250 mm month^{-1} can be used by the crops with decreasing efficiency with rainfall (Tsanis and Naoum, 2003). In the case of output water, the formula applied was

$$O = Vc + Vl + Vr \quad (2)$$

where V_c was the volume of water consumed by crops, V_l the volume of water conveyance losses from the canal system and V_r the volume of water returned to the river or sea. As mentioned above, V_r was obtained using flow meters. In consequence, V_l was measured as

$$Vl = O - (Vc + Vr) \quad (3)$$

Water conveyance efficiency was applied to evaluate some segments of canals, corresponding to the first and the second pilot study area, and to extrapolate the results to the entire RSLR. In this work it has been calculated as

$$Wce = 100 - \left(\frac{Vl}{Vl + Vc} * 100\right) \quad (4)$$

where V_l is the volume of water conveyance losses. Irrigation efficiency was also measured for each pilot study area and for all the RSLR. According to Keller and Keller (1995), irrigation efficiency (Ie, in %) was measured as

$$Ie = \frac{Vc}{Vd} * 100 \quad (5)$$

where V_d corresponds to the irrigation water delivered from the canals.

In order to consider the criticism from Perry (2007) about Israelsen's (1950) classical concept of efficiency, due to the lack of considering other beneficial water uses such as environmental purposes or recoverable flows (e.g.

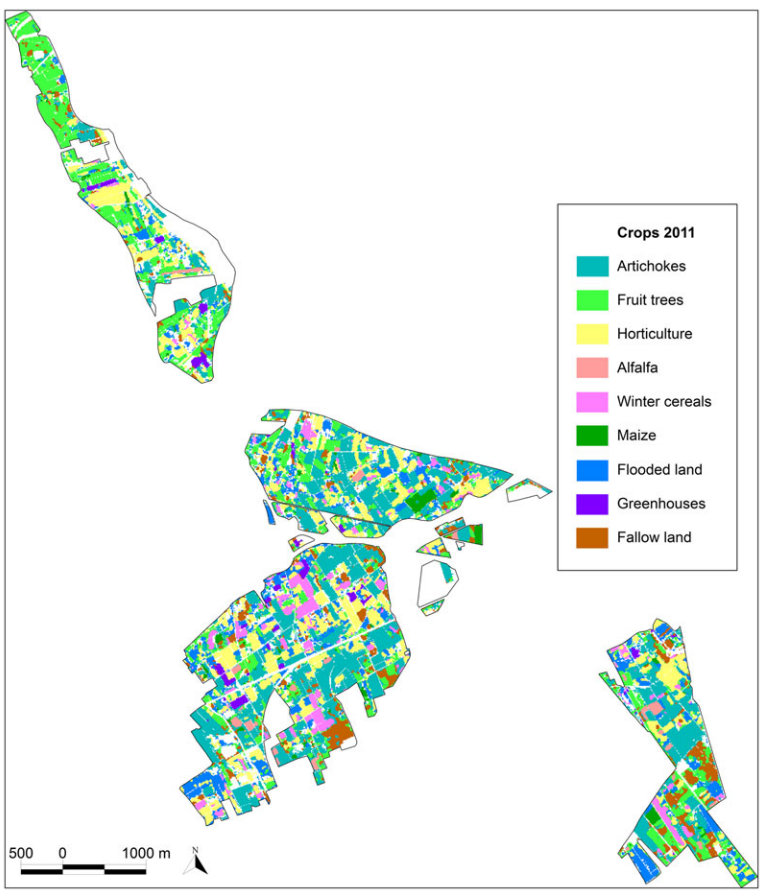

Figure 3. Final crop map of the study area. Source: own elaboration from a hybrid classification

percolation to freshwater aquifers or returned to the river), a net irrigation efficiency (*Nie*, in %) was measured according to Jensen (1984):

$$Nie = \frac{Vc}{Vd - Vr} * 100 \tag{6}$$

where V_r corresponds to the volume of water returned to the river.

Finally, in order to consider experimental error, a general evaluation, in percentage terms, was performed by considering different sources of information. One was the declared accuracy of instruments, another was the personal communication provided by local experts in hydrological matters working with the Catalan regional agency of water management and the last was personal field experience in some farms of the area. According to the accuracy of the flow meters, the estimation was 5% in the case of data from the CWA (personal communication) and 1.2% from local measurements with Vegapuls. In our water balance it was assumed that the main error corresponded to the effective precipitation measure, considered as 10%, whereas 5% was the percentage considered in the case of crop water consumption.

RESULTS

RSLR crop map, water supplied and local precipitation

Figure 3 shows the final crop map. Out of 1109 ha of cultivated land, 32.1% was occupied by artichokes, 19.6% by horticulture, 19.0% by fruit trees, 10.8% by flooded land, 7.6% by fallow land and, finally, 10.9% by the remaining crops. The accuracy of the final crop map was quantified using a confusion matrix with the test pixels obtained from fieldwork. An overall accuracy of 88.1% was obtained, the main confusion being between alfalfa and maize, probably due to a similar wet state, and winter cereals and fallow land being confused with artichokes, probably due to a similar wetness condition.

According to the temporal NDVI profile (Figure 4(a)), artichokes and winter cereals showed the highest values in April and May and the lowest in August when the winter cereals had been harvested (Serra and Pons, 2008) and the artichokes, a perennial crop, remain dry as the downward trend indicates. In the case of maize, a summer cereal, the highest NDVI values occurred in June–July, when they are very green. An initial unexpected result was the high value in April (with a value of about 0.6, equivalent to active green vegetation) and the low value in May; a probably explanation of this situation may be that maize fields were first cultivated with another crop, perhaps winter cereals, rather than being uncultivated land. In the case of fruit trees, the distinctive green signature is a constant increase from February, with the highest NDVI values reaching 0.6. Akin to alfalfa, the NDVI dynamics showed an irregular behaviour due to the cuts produced during the harvesting process and subsequent growth: the highest value (about 0.8) was observed at the beginning of June with a subsequent, rapid decline. Finally, tomatoes, an example of horticulture, showed a continuous increase from the end of April until values of about 0.4 in mid-July.

According to the CWA, 5 hm^3 of water were extracted from the Llobregat River and supplied to the RSLR from 6 May to 12 July 2011. Figure 4(b) shows the water supplied in $m^3\ s^{-1}$ throughout the period studied, normally ranging between 0.8 and 1 $m^3\,s^{-1}$ but dipping below 0.6 $m^3\,s^{-1}$ four times, all of which correlated with the precipitation that occurred in June (Figure 4(c)). Assuming that in the entire study area the precipitation was homogeneous as reported by the closest meteorological station, during the same period of time, total precipitation was 148.2 mm or 1482 $m^3\,ha^{-1}$. To quantify the effective precipitation, the USDA method was applied, the total effective precipitation being equivalent to 85% or 1260 $m^3\,ha^{-1}$.

Water balance of pilot study areas

As described above, the water balance of the two pilot study areas was calculated to monitor crop water requirements and to extrapolate the results to the entire irrigation community. In the first pilot study area (16.7 ha in total), 5.4 ha corresponded to horticulture (10 fields), 3.2 ha to artichokes (5 fields), 2.7 ha to flooded land (5 fields), 2.2 ha to fruit trees (4 fields), 1.6 ha to winter cereals (5 fields) and 1.6 ha to fallow land and greenhouses (5 fields) (Table I). According to the FAO procedure, the water consumption of irrigated crops was rather variable. In the case of horticulture, considering the case of tomatoes, a requirement of 2170 $m^3\,ha^{-1}$, equivalent to 11 700 m^3 of water, was estimated. In the case of flooded land, the 2.7 ha consumed 9070 m^3, and the 2.2 ha of fruit trees a total of 5790 m^3.

The evolution of water input in the first pilot study area (Figure 4(d)), derived from the flow meter installed at the entrance of the canal that provided water to the area, showed that at the end of May and the beginning of June the water input was highest, ranging between 0.08 and 0.09 $m^3\,s^{-1}$, whereas the minimum corresponded to the periods of elevated precipitation. Figure 4(d) also shows the output of water, extracted from the flow meter installed at the canal exit. The most usual volume of water that left the corresponding canal was between 0.04 and 0.05 $m^3\,s^{-1}$. The water balance of the first pilot study area showed a total input of 370 000 m^3 (357 000 m^3 water supplied and 13 000 m^3 of effective precipitation, with an estimated error of ±4280 and ±1300 m^3, respectively) and the same output (Table II).

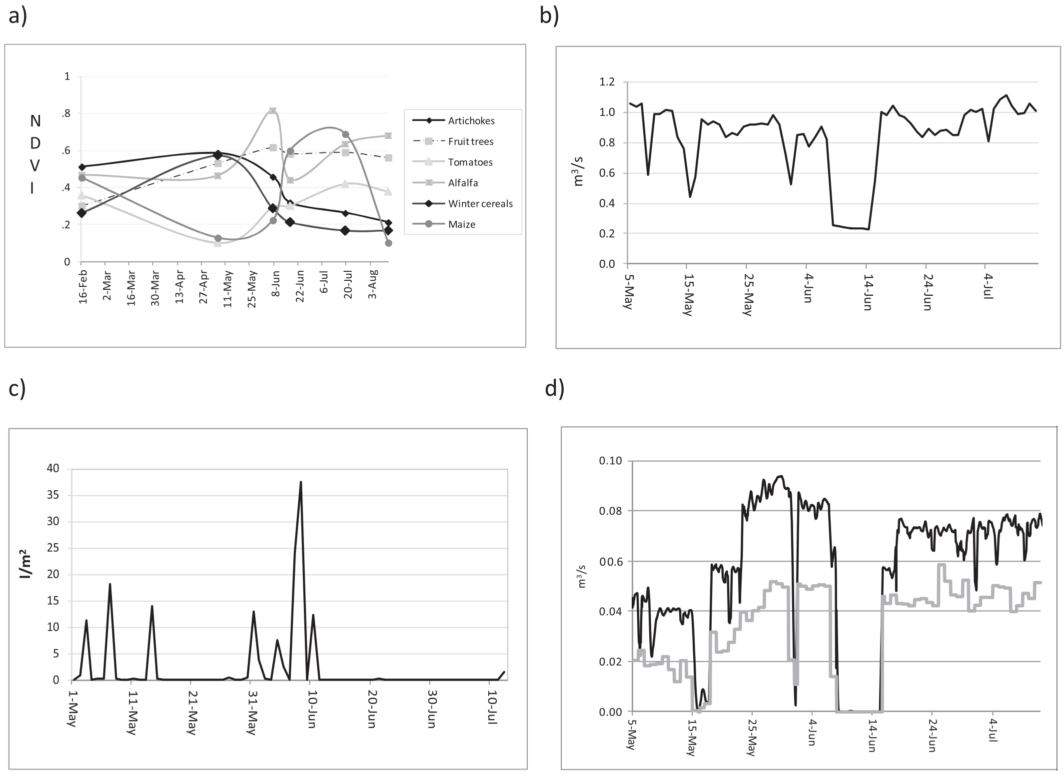

Figure 4. (a) Dynamics of mean NDVI values for main crops in 2011, (b) changes from May to July in water volume supplied by the Catalan Water Agency (CWA) to the Right Side of Llobregat River (RSLR), (c) changes from May to July of local precipitation in RSLR, (d) evolution of input and output water ($m^3 s^{-1}$) in the first pilot study area according to flow meter measurements

In the output analysis, total crop consumption was 26 560 m^3 (±1330 m^3), the canal output 247 030 m^3 (±2960 m^3) and the conveyance losses 96 410 m^3 (±1160 m^3). According to the conveyance efficiency considered in this work, this was equivalent to 21.6% (±0.6%) whereas according to the classical and the net efficiency irrigation, the results showed an efficiency of only 7.2% (±0.2%) and 21.6% (±0.6%), respectively.

The same protocol was applied in the second pilot study area, where 6.4 ha were cultivated with horticulture and 2.4 ha with artichokes, given the following water balance: 236 000 m^3 of total water input (228 000 hm^3 of water supplied and 8000 m^3 of effective precipitation, with an estimated error of ±3540 and 800 m^3, respectively) (Table II). According to the total outputs, water consumption of crops was 13 890 m^3 (±690 m^3), losses were 22 080 m^3 (±260 m^3) and the water

Table I. Estimated water consumption for the two pilot sites and for the entire study area

		Pilot site 1		Pilot site 2		Entire study area	
Crops	Water consumption (m^3/ha)	ha	Total water consumption (m^3)	ha	Total water consumption (m^3)	ha	Total water consumption (hm^3)
Artichokes	0.0	3.2	0.0	2.5	0.0	356.7	0.00
Fruit trees	2630.1	2.2	5786.2	0.0	0.0	210.5	0.55
Horticulture	2174.4	5.4	11741.8	6.4	13916.0	217.5	0.47
Alfalfa	2187.4	0.0	0.0	0.0	0.0	16.4	0.04
W. Cereals	0.0	1.6	0.0	0.0	0.0	62.4	0.00
Maize	2860.0	0.0	0.0	0.0	0.0	21.3	0.06
Flooded land	3355.9	2.7	9060.9	0.0	0.0	120.4	0.40
Fallow land	0.0	1.2	0.0	1.3	0.0	104.2	0.00
Total		16.3	26588.9	10.2	13916.0	1109.4	1.52

Table II. Water balance for the two pilot sites and for the entire study area. In parentheses, the estimated experimental errors according to different sources are shown

	Input (m^3)			output (m^3)			
	Delivered to the main canal from the river	Effective precipitation	Total	Water consumption of crops	Conveyance looses	Returned to the river	Total
Pilot study area 1	357 000 (±4 284)	13 000 (±1 300)	370 000 (±5 584)	26 590 (±1 330)	96 410 (±1 157)	247 000 (±2 964)	370 000 (±5 451)
Pilot study area 2	228 000 (±2 736)	8 000 (±800)	236 000 (±3 536)	13 916 (±696)	22 084 (±265)	200 000 (±2 400)	236 000 (±3 361)
Entire study area	5 000 000 (±250 000)	750 000 (±75 000)	5 750 000 (±325 000)	1 520 000 (±76 000)	1 020 625 (±12 247)	3 209 375 (±38 512)	5 750 000 (±126 760)

returned to the river was 200 030 m^3 (±2400 m^3). According to the conveyance efficiency, this was equivalent to 38.7% (±0.9%), whereas according to the classical and the net efficiency irrigation, the results showed an efficiency of only 5.9% (±0.2%) and 38.6% (±0.9%), respectively.

RSLR water balance and irrigation efficiency

The water balance for the entire RSLR was finally obtained (Table II). The inputs were the volume of water extracted from Llobregat River, 5 hm^3 in total, and the effective rainfall of 0.75 hm^3. To calculate the outputs in the water consumption by crops, two new crops (maize and alfalfa) were added: the water consumption calculated for maize was 2860 $m^3\,ha^{-1}$ and 2180 $m^3\,ha^{-1}$ for alfalfa. Therefore, water consumption of fruit trees, horticulture, alfalfa, maize and flooded land gave a total volume of 1.52 hm^3. Losses of water conveyance were calculated for all the study area according to the results obtained from the pilot study areas. An average value was calculated between the percentage of conveyance losses from the first (26.1%) and the second (9.4%) study area, yielding an average 17.7% or 1.02 hm^3, and giving the amount of water returned to the river of about 3.2 hm^3. According to the conveyance efficiency this was equivalent to 59.8% (±0.3%), and the volume of water returned to the river was equivalent to 55.8%, just 44.2% being used for irrigation. Finally, according to the classical and the net efficiency irrigation, the results showed an efficiency of 26.4% (±0.2%) and 59.8% (±3.4%), respectively.

DISCUSSION

According to Hamdy (2007b), conveyance efficiency in traditional Mediterranean open canal systems with surface or flood irrigation and manual control can reach about 60%. The results show that our pilot study areas had high conveyance losses, supporting our initial hypothesis. According to the results, the second pilot study area seems to be more efficient than the first, but a possible explanation may be the smaller total surface and fewer fields (10 compared to 34). In fact, the losses obtained should be considered rather high in both areas because they were 3.6 times the water consumption of crops in the first pilot study area and 1.6 times in the second, and because 26.1% of the total consumption was due to network losses in the former area and 9.4% in the latter. As shown in this work, the water returned to the river or discharged to wetlands was computed to be very high in both cases. Nevertheless, our measures included just a segment of the canals and part of the volume of this water was used to irrigate other fields located outside the pilot study areas measured with flow meters. Therefore, this volume of water should not be considered as a real loss.

In the case of the RSLR results, they showed that 40% of total consumption was due to conveyance losses and just 44% of water volume used to irrigation. Comparing these results with some Australian irrigation systems based on canals, similar percentages of losses were computed in South Burdekin or in Burdekin-Haughton in 1999–2000, irrigation areas established in the early 1950s, but being clearly below the corresponding to New South Wales, with an older origin but expanded in the 1970s (Marsden Jacob Associates, 2003). On the other hand, according to Hamdy (2007b), irrigation efficiencies in traditional Mediterranean open canal systems with surface or flood irrigation can reach 30%. Analysing the classical irrigation efficiency, our results showed very low values in all cases: 7.2% in the first pilot study area, 5.9% in the second and 26.4% for the entire RSLR. According to the net irrigation efficiency, the results were more similar to those reported by Hamdy: 21.6, 38.6 and 59.8%, respectively. Nevertheless, all these efficiency percentages remained quite similar to or below the percentages (from 50 to 80%) reported by Loukas *et al.* (2007) in the two major basins of the Thessaly region of Greece, the Pinios River and the Lake Karla basins, taking into account that the network transportation was newer than in our study area (from the 1960s and 1970s). In the case of the Grand Valley and the Imperial Irrigation District on the Colorado River in the USA, formed from the early 1910s, the percentages of effective irrigation efficiency at the end of 1970s were 64.9 and 61.0%, respectively (Keller and Keller, 1995), clearly above our results.

A possible explanation for the low efficiency in our study area could be the old conveyance network (initiated in the nineteenth century) and the gradual breakdown of irrigation canals by roads and urban settlements causing low functionality (deflected and disorganized) compared to its original capacity (Paül and Tonts, 2005). Although our initial hypothesis was of there being a large volume of water losses, due to the irrigation system used and the ageing conveyance network, the results were even worse than expected. As Hamdy (2007b) points out, average losses in irrigation systems suggest that only 45% of water diverted reaches the crops but in our study area this percentage was worse: just 26.4% of the volume of water was used for irrigating crops. In this sense, for some authors the best way to save water would be to apply water markets (Pujol *et al.,* 2006). This option would likely be very difficult to implement in the RSLR for two reasons: the traditional belief of farmers that water is a common property and low farm incomes. Moreover, the introduction of new technical irrigation systems, such as the automation of canal control gates, the use of pipe systems, etc., could be difficult because 60% of farm owners are over 55 years old and just 17% are younger than 45 (according to the Spanish Agrarian Census 2009), an issue that may produce more conservative attitudes and resistance to change.

CONCLUSIONS

This work is the initial estimation of agricultural water consumption applied to a long-established Mediterranean irrigation community characterized by land fragmentation and crop diversification. Our protocol that merges phenological information and real water consumption may be useful for similar study areas and scale of analysis. SPOT-5 images used and the flexible hybrid classifier have produced good results (82% of thematic accuracy) despite the spatial fragmentation of fields. The four flow meters installed in two representative canal locations have given highly precise water inputs and outputs. After extrapolating the results from the pilot study areas to the entire RSLR, the total balance shows large volumes of conveyance losses and low irrigation efficiencies, below 60%, percentages to be considered in future times of water scarcity. Although the irrigation system used and the aged conveyance network may explain a part of the low efficiency, intense urban and industrial pressures have intensified breakdown of the transport network. This situation may become worse as new urban projects are being promoted that may further deflect canal networks and fragment agricultural fields.

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