



# Ten Years of Local Water Resource Management: Integrating Satellite Remote Sensing and Geographical Information Systems

Xavier Pons<sup>1\*</sup>, Jordi Cristóbal<sup>1,2</sup>, Oscar González<sup>1</sup>, Anna Riverola<sup>1</sup>, Pere Serra<sup>1</sup>, Cristina Cea<sup>1</sup>, Cristina Domingo<sup>1</sup>, Paula Díaz<sup>1</sup>, Manel Monterde<sup>3</sup> and Enrique Velasco<sup>3</sup>

<sup>1</sup>Department of Geography, Universitat Autònoma de Barcelona, 08193, Catalonia, Spain

<sup>2</sup>Department of Animal Biology, Plant Biology and Ecology,  
Universitat Autònoma de Barcelona, 08193, Catalonia, Spain

<sup>3</sup>Catalan Water Agency. Departament de Territori i Sostenibilitat,  
Provença, 204-208, 08036, Catalonia, Spain

\*Corresponding author, e-mail address: Xavier.Pons@uab.cat

## Abstract

On 2002, a novel initiative was undertaken by the local water administration of Catalonia (the *Agència Catalana de l'Aigua*) and the *Universitat Autònoma de Barcelona*, leading to a ten-year project where a high number of medium resolution satellite images (MODIS and Landsat) were integrated to the daily water management to improve decision making effectiveness. This paper describes the methodology followed in the successful application of remote sensing, as well as the main problems that had to be overcome during its execution. It also presents the products that have been calculated. These are integrated into the Agency's corporate GIS and immediately available via the intranet for the staff, and a selection is available on the Internet.

**Keywords:** Operational Remote Sensing, GIS, Water Resource Management, Data Harmonization, Crop Mapping, Snow Cover.

## Introduction

Water management has traditionally been done through data acquired in the field by technical personnel or by automatic networks. The costs of collecting statistically significant data over the whole territory becomes a major disadvantage of these methods, therefore other approaches must be found. In recent years, the use of remote sensing data for management and planning tasks has experienced a major increase; an example of this are the 11 applications described in the publication of the GMES working group [GMES, 2010], where it has been proved that remote sensing can be a helpful approach to calculate variables related to water management, such as land cover change, snow cover or water consumption.

When monitoring environmental resources, different remote sensing approaches have been attempted. In the particular case of water management, where several parameters have to be accounted for, a thorough knowledge of each one of them has to be achieved. Among these parameters, there are some directly related to water availability (e. g. snow cover and evapotranspiration) and some related to water consumption (e. g. crop type, crop and dynamics). Also, the size of the area to monitor will determine the image characteristics to be used. Finally, the intrinsic characteristics of the satellite images applied will determine the resulting products calculated and thus, the final monitoring detail. Some remote sensing applications for agricultural water management are presented by Choudhury et al. [1994], Vidal and Sagardoy [1995], Rango and Shalaby [1998], Bastiaanssen [1998] and Stewart et al. [1999].

In 2002, the Agència Catalana de l'Aigua (Catalan Water Agency, herein referred as ACA), a public agency within the Ministry of Environment of the Government of Catalonia, formalized an agreement with the Department of Geography of the Universitat Autònoma de Barcelona (herein referred as UAB). This agreement aims to contribute to the water resources management through a unique initiative that successfully applies remote sensing to a large regional area and demonstrates that an appropriate processing chain provides operational products (snow cover, evapotranspiration, crop mapping, etc) from available satellite images in real time, for a long-time series and with a detailed scale.

In this paper we explain the methods and the methodology used, and how it has been evolving to solve problems and to improve data quality during the ten-year project. There is also an in-depth explanation of the products calculated, such as crop field monitoring (both from a categorical and quantitative-modelled point of view), snow cover and evapotranspiration, as well as the advances on quality and efficiency made during the project execution. We also present the protocol followed to integrate all information gathered from remote sensing (RS) instruments (combining data from different sensors and different sources) into the ACA's data pool, and how it is made available to the public over the Internet.

## Study Area

The study area includes Catalonia, northeast of the Iberian Peninsula (Fig. 1), centered in  $1^{\circ} 40'$  of E longitude and  $41^{\circ} 44'$  of N latitude and an approximate area of 32106 km<sup>2</sup>. This region is characterized by a heterogeneous orography, with elevations ranging from sea level to about 3000 m and variable water availability, especially due to the recursive drought periods, both intra-annually (Mediterranean climate) and inter-annually. In 2002, Catalonia had a population density of 202.6 inhabitants per km<sup>2</sup>, and it rose to 234.7 inhabitants per km<sup>2</sup> in 2011.

## Material and Methods

### *Image Acquisition and Database*

In 1972, the United States Geological Survey (USGS) launched the first platform of the successful Landsat series. Thousands of images around the world have been captured by the different missions of this spatial program to date. The image archive of this project started in 2002 and, due to the revisiting period (16 days at the nadir), the spectral characteristics (7-8 spectral bands) and the spatial resolution (from 30 to 120 m, depending on the selected band), Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and Landsat-5 Thematic Mapper

(TM) imagery were chosen to address the work. This archive contains ETM+ imagery from January 2002 to May 2003, when a malfunction in the Scan Line Corrector (SLC) was detected [USGS, 2003]. Since June 2003 to present, TM imagery was the default imagery acquired. All images from these two platforms over paths 197 and 198 and rows 31 and 32 were processed. The archive also contains SPOT-5 HRG images bought to cover some punctual data gaps, due to cloud cover or to the need of greater spatial resolution images (10-20 m). Furthermore, TERRA/AQUA MODIS images, with a pixel size from 250 to 1000 m but a daily revisit period and a wider spectral resolution, have been included to the data pool.

Landsat data acquisition has been done through annual subscriptions. Additionally, in recent years, USGS opened their archive allowing free data downloading.

From 2002 to date, more than 500 images from Landsat and SPOT platforms and thousands of TERRA/AQUA MODIS have been processed by the UAB and their products delivered to the ACA.

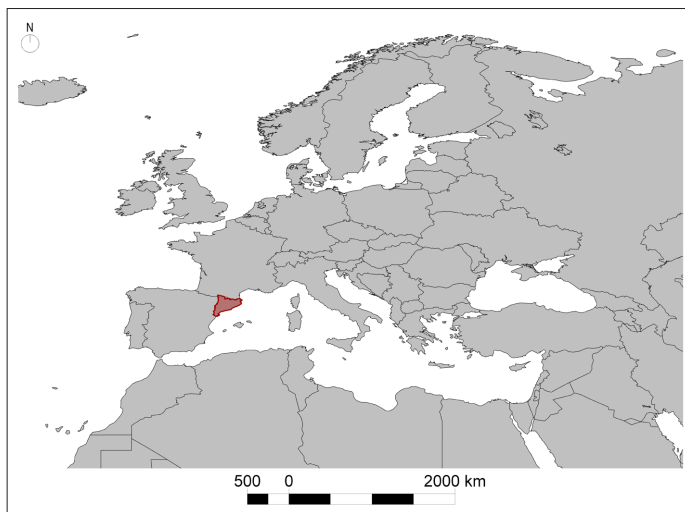


Figure 1 - In red, location of the study area.

### ***Converting Files and managing Metadata***

Since 2002, different file formats have been used to distribute Landsat imagery (CEOS, GeoTIFF, NDF, etc). These distribution formats depend on the source of acquisition and on the pre-processing level of the data. The same situation occurs with the associated metadata files (XML, TXT, etc). We also have to consider other platform images, distributed in their own formats, like MODIS imagery (HDF).

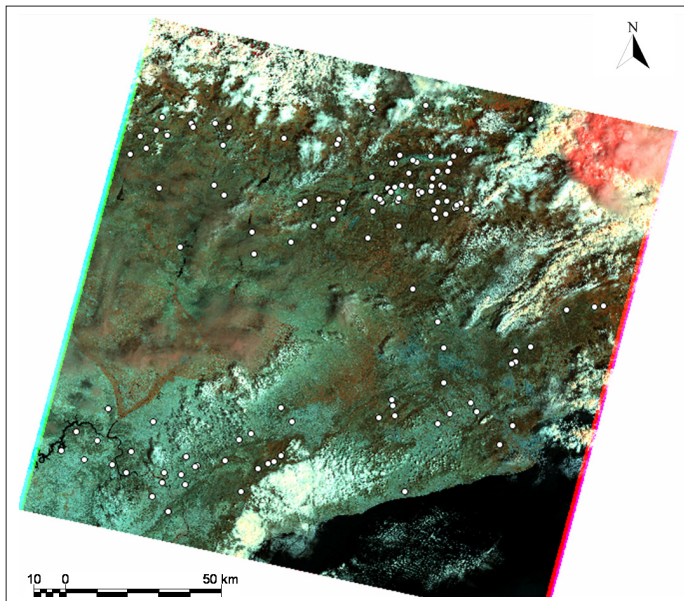
All data used have been processed with MiraMon [Pons, 2004], a GIS and remote sensing software developed, distributed and maintained by the Centre de Recerca Ecològica i Aplicacions Forestals (Centre for Ecological Research and Forestry Applications, herein referred as CREAM). All related metadata is valuable information, such as radiometric calibration values, processing steps (lineage) and dates, etc., and needs to be saved for a later image processing [Cristóbal et al., 2003]. Metadata is stored in a common multiband

file, and can be completed or maintained through the MiraMon Metadata Manager (GeMM), following ISO standards conveniently extended through profiles to support important remote sensing information.

### ***Image georeferencing***

Once images have been imported, the next step is to correct them geometrically. This is a required step in order to correct deformations caused by the Earth curvature, the relief, etc; and the Palà and Pons [1995] algorithm is used for this purpose.

The process of searching these GCP was firstly done digitizing manually GCP on screen, using a 2.5 m resolution ortho-rectified image of the study area from the Cartographic Institute of Catalonia (ICC) as the reference image to locate them. On 2009, a full automated correction procedure was developed and implemented; this new procedure allocates hundreds of GCP per image at a range of elevations throughout the entire image [Pons et al., 2010] as shown in Figure 2, providing RMS of 1/3 pixel (independent test points set, median value of 11.2 m for the whole series).



**Figure 2 - RGB (4+5+7) composite of Landsat 5 TM image. GCP are represented as white points.**

Once GCP are set, images are corrected applying a first-degree polynomial that accounts for the relief using a Digital Elevation Model (DEM) of 30 m resolution from the ICC. For each image, about 60% of the GCP fit the model and the remaining 40% provide the estimation of the planimetric accuracy.

To save disk space and to improve spatial coherence, consecutive frames of the same orbit (e.g., 198-31+198-32) have been perfectly mosaicked due to the very low RMS. In the case of MODIS imagery, the 250 m and 500-1000 m georeferenced product have been

downloaded from the Warehouse Inventory Search Tool [WIST, 2010]. The products are the TERRA/AQUA MODIS Daily Surface Reflectance at 250 m (MYD/MOD09GQK) and 500-1000m (MYD/MOD09GHK), was used for our purposes.

### ***Radiometric Correction***

Atmospheric conditions (water vapour, aerosols, etc.) and different illumination of scenes caused by the solar position according to the acquisition date, month, location on Earth and relief (presence of cast shadows, zones being more illuminated than others, etc), can cause undesired artefacts on remote sensing images. These artefacts should be corrected by applying a process known as radiometric correction. Among the several methods available, we have used the simplified model proposed by Pons and Solé-Sugrañes [1994]. This model only needs the input of two parameters: the radiance received by the sensor from an area where only atmospheric contribution exists, and the atmospheric optical depth (the other parameters that are used in the model, are directly read from the image metadata or are easily available from external sources). These parameters were firstly obtained interactively by an operator, but in 2009 we developed a method based on pseudo-invariant areas to automatically obtain these values [Pons et al., 2010].

The simplified model of Pons and Solé-Sugrañes [1994] takes into account several factors like relief and solar position (incidence angles and projected shadows), Earth-Sun distance, decrease in radiation on its way down and up because of the atmosphere, atmospheric optical depth, exoatmospheric solar irradiance, sensor calibration parameters, etc.

In the Landsat thermal bands case the original values are converted to Land Surface Temperature (LST) values using the methodology proposed by Cristóbal et al. [2009]. This method is supported by the radiative transfer equation and its main advantage is the non-dependence of specific radiosondes. The methodology is designed to obtain the LST in global conditions using the TIGR-TOVS radiosonde database [Aires et al., 2002; Chevallier et al., 1998], representative of most weather conditions at a global scale. The algorithm is designed for water vapour ranging from 0 to 8 g·cm<sup>-2</sup>, covering the all water vapour conditions in Spain. In the case of MODIS imagery, the radiometrically corrected products provided by the WIST were used as they were considered good enough for our purposes.

### **Results**

Images geometrically and radiometrically corrected are used to calculate different products needed for improving water management. The main products generated include quasi continuous snow cover maps, crop maps, and products on evapotranspiration and crop water demand. All these products are then integrated into the ACA's corporate GIS designed to easily distribute the images within ACA's managers and workers. Moreover, some selected products are distributed through the Internet. An explanation of these processes is provided below.

#### ***Snow cover map***

Snow cover map is an essential variable to understand the water cycle that can be accurately mapped from those adequate satellite image series [Cea et al., 2007]. In 2002, ACA undertook the snow campaign in Catalonia through satellite images from Landsat-7 ETM+. In subsequent campaigns, Landsat-5 TM, MODIS and occasionally SPOT-HRG were used.

Due to the variability of the Pyrenees seasonal dynamics, the snow campaign is performed during the months from October to June, depending on the first snow fall detected. Occasionally, when snow was detected during months like July or September, the data from these months were also included. Snow cover map is a very important variable that can be accurately mapped from those adequate satellite image series [Cea et al., 2007; Spisni et al., 2010].

For the period from 2002 to 2007, images used for the estimation of snow cover were Landsat-5 TM and Landsat-7 ETM+. These images, with a nominal spatial resolution of 30 m, and a reviewing period of 16 days, are ideal for the snow cover map. The preparation of maps and indexes of the snow cover is mainly based on two processes: one applied to areas of direct solar radiation, and a second applied to topographic cast shadow areas, detected through the radiometric correction performed on the images. To retrieve the snow surface in direct solar radiation areas, we used the method proposed by Dozier [1991] and also used by other authors [Derksen and LeDrew, 2000; Fily et al., 1999; Swamy and Brivio, 1996]. Dozier's method creates a standard rate of snow cover index (*Normalized Difference Snow Index, NDSI*) based on the radiometrically corrected images. This index is calculated using the information from the visible and middle infrared bands, as shown in the following equation:

$$NDSI = (Green - Middle IR) / (Green + Middle IR) \quad [1]$$

It is then necessary to apply a water masses mask to the resulting snow cover index, and then select as snow pixels all *NDSI* values over 0.4 according to the author. This mask prevents selecting much of water bodies (dams, reservoirs, rivers and sea water) instead of snow covered areas, but it hardly omits any snow cover. A semi-manual procedure [Cea et al., 2005] based on the ISODATA algorithm and on filters [Irish, 2000], is applied to remove all clouds and cloud shadows. If a zone affected by clouds or their shadow does not allow selecting snow areas, a second snow discrimination is applied comparing and working, simultaneously, with the present image and an image from a previous date (In Fig. 3 and in Fig. 4).

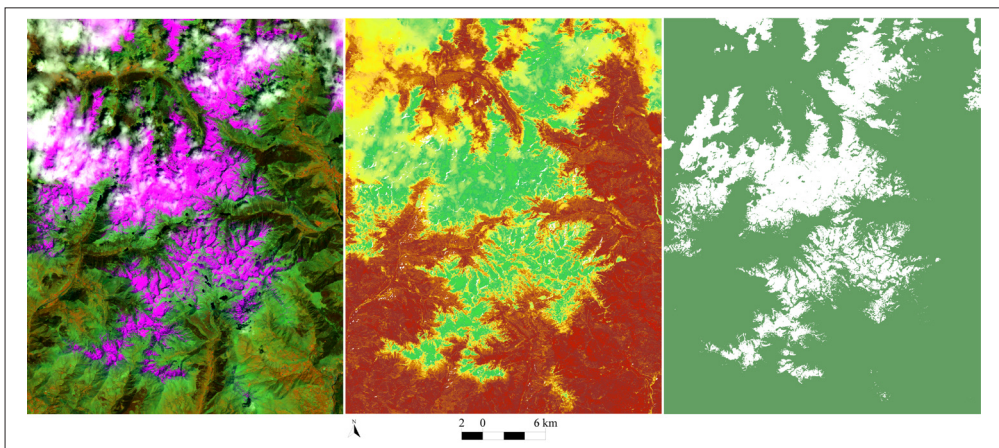
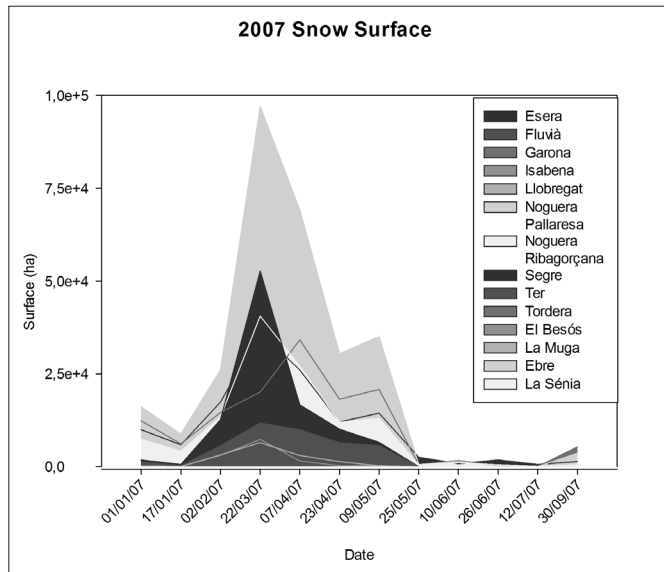


Figure 3 - From left to right, example of a geometric and radiometric corrected image, its *NDSI* and the final snow cover map obtained.

In order to retrieve the snow cover in areas affected by topographic cast shadows, a new methodology was developed. In this novel approach, an unsupervised classification based on ISODATA algorithm [Duda and Hart, 1973] is used applying two sets of input variables, topographic variables like DEM and instantaneous solar radiation, and Landsat solar bands as well as other products like *NDSI*. This algorithm results in several thematic classes, among which is the snow. In recent years, another approach based on MODIS images have been developed: Since 2008, MODIS images have been used due to the daily availability of satellite images, also because of the sensor technical characteristics which allow a whole coverage of Catalonia and part of the Aragon and French Pyrenees, all with a spatial resolution of 500 m; MODIS image processing involves downloading data of MOD09. Images with high cloud cover and bow-tie effect, as well as with other important distortions are excluded. This determines that just about 2-3 images per week are finally used to generate snow cartography twice per week during the snow campaign.



**Figure 4 – Example of snow cover surface dynamics (in this case during the 2007) campaign in the different river basins analyzed.**

Once primary process has concluded over MODIS images, a secondary process starts consisting on obtaining snow cover maps with a non-supervised classification method also based on the ISODATA algorithm, which takes advantage of the fact that the spectral characteristics of the snow cover are different from all the other covers. Finally, an expert supervision is done to detect errors of commission and omission of the obtained layer, and results are compared with supporting data (such as precipitation, thickness and temperatures obtained through the meteorological stations net from the Catalan Meteorological Service, etc). This methodology provides the snow surface of direct solar radiation and the topographic self and cast shadow areas. The maps obtained combined with other data related to snow cover that ACA has, allows an

exhaustive monitoring of the temporal and spatial variability of the snow cover, becoming a very important tool for the management of the water resources in Catalonia.

The accuracy of the snow cover product has been assessed by checking that in 100% of the cases, field campaigns and automatic stations allowed to verify that neither commissions nor omission errors occurred. This was not possible in zones near the snow line where there is no data to perform a validation.

To monitor water resources, the snow area estimated has to be transformed into water volume. In order to determine the volume of water in the form of snow (SWE Snow Water Equivalent) it is essential to know as precisely as possible the distribution of the snowpack, as well as its thickness and density parameters. Nevertheless, optical remote sensing is able to estimate the snow cover surface. By using snow metrical automatic stations placed in the Pyrenees, which record data on the thickness data, combined with field campaigns to obtain snow density data, information on the thickness distribution and density of the snow is gathered.

### ***Crop Map Product***

Rural areas, especially crop zones, should be monitored to improve the water management of a country. The type of crop in an area often determines the irrigation method and the water consumption, so the knowledge of the different crops is crucial to manage the water needs.

There is a large tradition of methods and applications to discriminate crops using remote sensing data [e.g., Barbosa et al., 1996; Campbell, 2003; Genovese et al., 1999]. In the particular case of crop map products, Landsat imagery characteristics offer the possibility to closely monitor the phenological development of different crops in Catalonia, especially fast-growing crops, such as herbaceous crops.

For the purpose of elaborating the crop map as well as the actual evapotranspiration product and crop water demands (see section below) two pilot areas located at the end of the Ter and Muga rivers were delimited including all irrigation communities inside those limits. A hybrid classifier to map crop was then applied according to the methodology proposed by Serra et al. [2003]. The input variables for this classifier were all the available Landsat solar bands from the agricultural period (usually from May to September) and, in addition, all vegetation and moisture (tasselled cap) indexes. Previous to the classification, clouds were removed as well as non-agricultural areas masks allowing reducing possible confusions in the classifying method. About 50 information bands per year are selected as input data. To reduce this large number of bands, the principal components analysis statistical technique is applied, from which only the new obtained bands explaining approximately 90% of the total variance are finally used.

To associate statistical classes with informational ones on the basis of fidelity and representativity parameters, the unsupervised classification result is combined with training areas obtained by field work [Serra et al., 2009]. Finally, to reduce the salt and pepper effect, a selective non classical modal filter is applied, removing those areas formed by just one or two pixels.

To calculate the crop map accuracy, the global accuracy has been used, which is calculated by dividing the number of well classified pixels by the total number of pixels including unclassified pixels. Accuracy is tested through independent test areas. All maps show high level of success, about 85%, even when being composed by many agricultural classes. An example of the results obtained is illustrated in Figure 5.



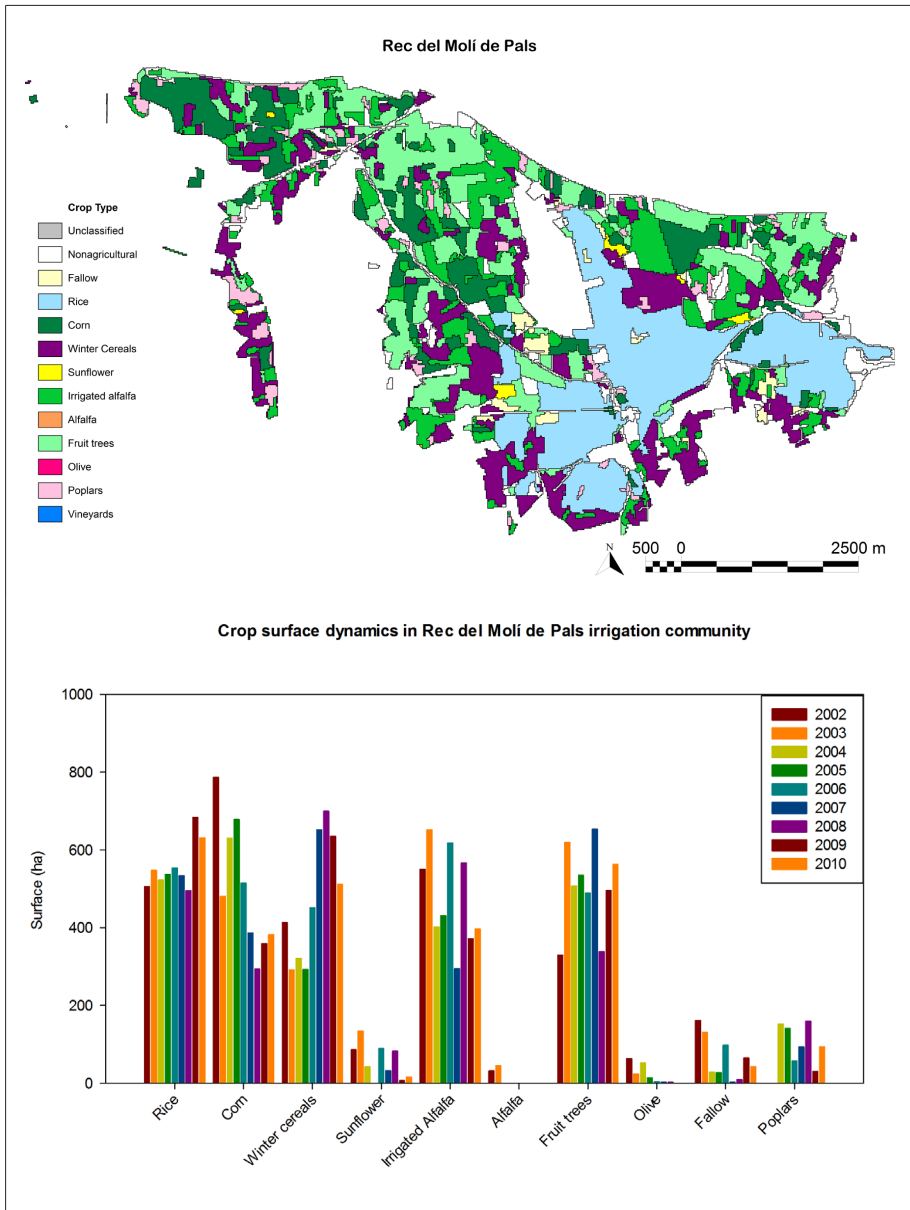


Figure 5 - Crop map of the “Rec del Moli de Pals” irrigation community in 2010 (up), and crop surface dynamics between 2002 and 2010 (down).

**Actual Evapotranspiration Product and Crop Water Demand**

GIS modelling and remote sensing data are essential tools for computing and monitoring evapotranspiration along the year. This is, indeed, an indispensable variable in the calculation of water balance. Bastiaanssen et al. [1998] developed the Surface Energy Balance Algorithm for Land (SEBAL), which was implemented in 2002 to calculate the daily evapotranspiration (AET<sub>d</sub>) to manage crop water needs in the irrigation communities of the end of Ter and Muga

ivers. However, from 2007 to present, the Mapping Evapotranspiration with High Resolution and internalized Calibration (METRIC) method, developed by Allen et al. [2007], which include some improvements in the SEBAL method was used. This method is based on satellite image processing and includes 25 submodels to calculate  $AET_d$  as well as other energy flows of the Earth's surface [Allen et al., 2001; Bastiaanssen et al., 1998; Bastiaanssen, 2000; Morse et al., 2000]. METRIC, has been improved by the inclusion in the model of new algorithms to obtain the surface temperature [Cristóbal et al., 2009], air temperature [Cristóbal et al., 2008] and net radiation [Cristóbal et al., 2009], variables needed to obtain the  $AET_d$ .

Using METRIC, every 16 days the AET is calculated using Landsat imagery. AET within Landsat overpasses,  $AET_{16}$  is calculated between images over the same path and row by using the ratio between AET calculated by METRIC and a reference evapotranspiration (ET<sub>0</sub>). This reference value is obtained from the meteorological stations data from Catalan Meteorological Service ([www.meteocat.com](http://www.meteocat.com)). The ratios are treated as crop coefficients (K<sub>c</sub>) determined specifically for each pixel in the image. From these constants, we can calculate the AET for the days in which images are not available through the following relationship [Allen, 1998]:

$$AET_{16} = ETO * Kc \quad [2]$$

Crop water demand can be determined for the different irrigation communities every 16 days, thanks to  $AET_{16}$  and the rainfall during this time period.

Once  $AET_{16}$  is obtained, we subtract the effective precipitation for the same period than  $AET_{16}$  to estimate the water volume for irrigation, as crop water use efficiency information is not available in our study area. Then, we use the crop map product to estimate what is the water volume for irrigation for each one of the crops. This demand (Tab. 1) can be used to optimize the water supply in a particular agricultural zone.

**Table 1- Total water need for the different crop types in the irrigation community of the “Rec del Molí de Pals”, for the period from May to September 2010.**

Crop type	Surface (ha)	Water needs (hm <sup>3</sup> )	m <sup>3</sup> /ha
Rice	631.2	5.0	7921
Corn	381.6	2.3	6027
Irrigated Alfalfa	396.2	1.9	4796
Fruit trees	562.9	3.2	5685
Poplars	92.9	0.6	6459

According to Bastiaanssen et al. [1998] and Allen et al. [2007] the accuracy of the AET product is  $\pm 1$  mm/day<sup>-1</sup>. Although we do not have an eddy covariance or lysimeter data to validate it, for each AET Landsat image we check the variability of a short well-irrigated grass area (golf course) near a meteorological station that computes the

reference evapotranspiration,  $ET_0$ , according to Allen et al. [1998] methodology. The AET of this short well-irrigated grass should be similar to the  $ET_0$ , so this allows us to verify if the model is within an  $ET_0$  range of about  $\pm 1$  mm/day<sup>-1</sup>. During the analyzed series, all Landsat AET products were within this range.

This is compliant with the requirements for water resource management because of the wide variability of the crop types in our study area. Indeed, our study area presents from low AET crops, such as sunflower (2-3 mm/day), to high AET crops, such as corn (more than 6 mm/day). Taking into account that in our study area corn and alfalfa are two of the main crops in terms of surface, the error of the model makes METRIC methodology useful to compute AET and, therefore, is useful for the water resource management.

### **Daily water management**

In order to integrate all these products into the daily water management of the ACA, two new tools were introduced: A corporate GIS and a Corporate Server.

### **Corporate GIS**

The Catalan Water Agency has a corporate GIS, where all products and images generated are integrated together and immediately available via the intranet for any user. The public that uses this information range from ministry workers (mainly planners) in charge of the water management, to technicians and field inspectors. From the information available in the corporate GIS, quantification and estimates of surface water storage can be calculated; with the GIS, a layer can be incorporated on land plots, which facilitate the management of water consumption, essential information during drought periods.

The amount of work that has been done to integrate all the products described on this paper involves, in average, the process of daily MODIS images, as well as one or two Landsat scenes per week, generating about 2 GBytes of weekly products. All these information is integrated in the corporate GIS system for the immediate use. All space-derived products are delivered to the ACA, who then integrate it into the corporate GIS to combine it with other products from different companies, therefore the server allows to merge information from different sources. As an example, the snow maps are included into a snow area prediction model done by the Meteorological Server of Catalonia, as well as with data on precipitation, temperature, etc. All this information was used to elaborate a water management document, which were used on internal weekly meeting. In this GIS, a special section for satellite imagery (both corrected geometrically and radiometrically) and products is provided. That way, any technician in the Agency can check for appropriate images or derived products (crop maps, snow maps, etc), permanently updated.

Furthermore, previous effort has been made to design a careful step-by-step protocol, where all processes are defined. The protocol describes the field data acquisition used as ground truth data for image testing, a thorough description of all processes involved on the product generation, as well as the processes involved in the final integration of all data products to the Agency's corporate GIS.

### **Corporate Server**

All images acquired from 2002 onwards, processed by the Department of Geography of the UAB in collaboration with the ACA, and complemented with images brought by CREAM have

been also included into an image catalogue. Additionally CREAM has been involved in the final design and implementation of the MiraMon server called SatCat [UAB & CREAM, 2012], through an agreement with the Ministry of Environment of the Government of Catalonia (DMA). This map browser and catalogue, OGC compliant, is conformed by Landsat images that cover all the region of Catalonia. These include the path 198 rows 30, 31 and 32, and the path 197 row 31. Depending on the area (because of orbit overlapping), meteorological conditions and sensor performance, the revisiting time can vary between 8 to 16 days. On June 2004, the SatCat Server was made publicly available through Internet by the Documentation Centre of the DMA for consultation and downloading of images. The browser allows searching and downloading images visualized in false colour and true colour, while facilitating the process of selecting specific images for a certain study area. Currently images in the MMZ and GeoTIFF formats can also be downloaded. Finally, the server has been a great asset to consultants and researchers (among others), as it improves the search and visualization of Remote Sensing data and, thus, the access to a large amount of imagery in a quickly and efficient manner.

### ***Further work***

One of the main challenges of the project is its continuity, considering the current global economical context, the very recent Landsat-5 TM failure and the fact that Landsat-7 contains some nodata areas due to the SLC-offs failure. In this sense, the current policy of the USGS regarding the free usage of the Landsat archive and new data, represents substantial economic savings, which represents a major improvement to data policy access. This also gives the opportunity to revise historical data to provide more robust models for water management decision making. Fortunately, plans for launching Landsat-8 seem to go forward and latest news schedule it for Dec-2012 or Jan-2013, so it will be launched in less than a year. The improved radiometric resolution (12 bit) the two new solar bands (New Deep Blue and cirrus), together with one more thermal band will provide an excellent data bank. Moreover, the two Sentinel 2 satellites (to be launched in 2013 and 2014) will provide, through the MSI sensors, a precious and synergic material to improve surface monitoring since they have a higher number of spectral bands (13), a better spatial resolution (10 m in 4 bands, 20 m in 6 bands and 60 in the remaining 3), with narrow widths, which limits the influence of water vapour and other atmospheric constituents, a radiometric resolution of 12 bits, a larger swath of 290 km and a better revisit time than SPOT or Landsat, while providing a solar time-pass very similar to the latest Landsats. This will allow improving land classification, atmospheric correction, and cloud/snow separation (one of the problems encountered in the current project), among others. In addition we expect that the SWIR bands of MSI will improve the assessment of vegetation conditions [GMES, 2010]. Also in the GMES context, Sentinel-3 (to be launched in 2013 and 2014) will provide the opportunity of having a 16 band (OLCI) and 9 bands (SLSTR) high quality pair of instruments with very high revisiting time.

### **Conclusions**

Due to the regular episodes of drought, fires and other environmental disturbances, a better water management is needed in Catalonia. Under this scenario, remote sensing data plays a key role through the availability of constantly updated and near real time

data, which can be used in management and planning tasks. The UAB and the ACA have been working together to integrate the knowledge of traditional methods of planning and the data obtained through satellite images for the past 10 years. During this period the main work has evolved to solve problems encountered in different steps of the process, from the image acquisition to the final resulting products: snow maps, crops maps and evapotranspiration and water demand.

The need to work with near-real time remote sensing data without cloud presence or possible sensor errors, forced the team to work with different data sources and not only with Landsat imagery. The heterogeneity from the different platform-sensor combination of the optic and thermal used (regarding spatial resolution, temporal resolution, number of spectral bands, etc), required adjustments and improvements of the process management and developed methodologies to the different image typologies. To this end, two different research lines have been followed during these years, and thus automating and standardizing all satellite images regarding the geometric and radiometric correction, while improving the work done on temporal series of both single sensor images, as well as combining images from different sources. On 2008, two events drove us into more research to improve efficiency and quality of the data values and processes; one event was that by the end of 2008, the USGS opened the historical catalogue of Landsat, and simultaneously, the Spanish Plan Nacional de Teledetección began, fostered by the Instituto Geográfico Nacional, which also distributed Landsat imagery over the Iberian Peninsula.

Enhances on image processing directly affect to the derived products quality, improving snow and crop maps and water crop demand. In summary, an improved processing system, delivers a more reliable data to be used in water management. Furthermore, it is important to remark the CREAM effort to publish and distribute the generated knowledge, through the development of technologies compliant with the WMS and WCS OGC standards. These WCS and WMS servers contain ten years of information on water resources, and can be accessed by any ACA worker from anywhere and at anytime.

To sum up, during the ten-year project where satellite images have been used to improve managing and planning water resources, a successful processing chain, which merges different data sources, has been developed to obtain products that can be directly applicable by the local government, performing an outstanding monitoring of water related phenomena like snow cover, crop phenology and irrigation.

### **Acknowledgements**

The authors would like to thank our colleagues of the Research Group of Methods in Remote Sensing and GIS (GRUMETS) who have collaborated in several tasks in the image processing. This study would not have been possible without the financial support of the Ministry of Science and Innovation and the FEDER funds through the research project “SCAITOMI (TIN2009-14426-C02-02)”. The Government of Catalonia also provided funding to our Research Group “GRUMETS (2009SGR1511)”. We would also like to express our gratitude to the Catalan Water Agency and to the Ministry of Agriculture, Livestock, Fisheries, Food and Natural Environment of the Government of Catalonia for their investment policy on the availability of Remote Sensing data, which has made possible to conduct this study under optimal conditions. Parts of this study are going to be used as pilot cases in the FP7 European project “QUALity aware VISualisation for the Global Earth

Observation System of Systems (GeoViQua)” (Ref. 265178). Xavier Pons is recipient of an ICREA Academia Excellence in Research grant 2011-2015.

## References

- Aires F., Chédin A., Scott N. A., Rossow W.B. (2002) - *A regularized neural net approach for retrieval of atmospheric and surface temperatures with the IASI instrument*. Journal of Applied Meteorology, 41 (2): 144-159. doi: [http://dx.doi.org/10.1175/1520-0450\(2002\)041<0144:ARNNAF>2.0.CO;2](http://dx.doi.org/10.1175/1520-0450(2002)041<0144:ARNNAF>2.0.CO;2).
- Allen R.G., Pereira L.S., Raes D., Smith M. (1998) - *Crop evaporation for computing crop water requirements*. FAO Irrigation and Drainage Paper, 56.
- Allen R.G., Morse A., Tasumi M., Bastiaanssen W., Kramber, W. Anderson H. (2001) - *Evapotranspiration from Landsat (SEBAL) for water rights management and compliance with multi-state water compacts*. Geoscience and Remote Sensing Symposium, 2001. IGARSS apos; 01. IEEE 2001 International, 2: 830-833. doi: 10.1109/IGARSS.2001.976651.
- Allen R.G., Tasumi M., Morse A., Trezza R., Wright J.L., Bastiaanssen W., Kramber W.J., Lorite-Torres I., Robison C.W. (2007) - *Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) - applications*. American Society of Civil Engineers, Journal of Irrigation and Drainage Engineering, 133 (4): 395-406.
- Barbosa P.M., Casterad M.A., Herrero J. (1996) - *Performance of several Landsat 5 Thematic Mapper (TM) image classification methods for crop extent estimates in an irrigation district*. International Journal of Remote Sensing, 17: 3665-3674. doi: <http://dx.doi.org/10.1080/01431169608949176>.
- Bastiaanssen W.G.M., Menenti M., Feddes R.A., Holtslag A.A.M. (1998) - *The Surface Energy Balance Algorithm for Land (SEBAL): Part I formulation*. Journal of Hydrology, 212-213: 198-212. doi: [http://dx.doi.org/10.1016/S0022-1694\(98\)00253-4](http://dx.doi.org/10.1016/S0022-1694(98)00253-4).
- Bastiaanssen W.G.M. (1998) - *Remote Sensing in Water Resources Management: the State of the Art*. International Water Management Institute, Colombo, Sri Lanka, p. 118.
- Bastiaanssen W.G.M. (2000) - *Sensible and latent heat fluxes in the irrigated Gediz Basin, Western Turkey*. Journal of Hydrology, 229: 87-100.
- Campbell J.B. (2003) - *Introduction to remote sensing*. New York. The Guilford Press.
- Cea C., Cristóbal J., Serra P., Pons X. (2005) - *Mejoras en la detección Semiautomática de nubes y sombras en imágenes Landsat*. XI Congreso Nacional de Teledetección, Puerto de la Cruz. Tenerife, pp. 359-362.
- Cea C., Cristóbal J., Pons X. (2007) - *An improved methodology to map snow cover by means of Landsat and MODIS imagery*. IEEE International Geoscience and Remote Sensing Symposium. Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International. 23-28 July 2007, pp. 4217-4220. doi: 10.1109/IGARSS.2007.4423984.
- Chevallier F., Chérury F., Scott N. A., Chédin A. (1998) - *Neural network approach for a fast and accurate computation of the longwave radiation budget*. Journal of Applied Meteorology, 37: 1385-1397. doi: [http://dx.doi.org/10.1175/1520-0450\(1998\)037<1385:ANNAFA>2.0.CO;2](http://dx.doi.org/10.1175/1520-0450(1998)037<1385:ANNAFA>2.0.CO;2).
- Choudhury B.J., Ahmed N.U., Idso S.B., Reginato R.J., Daughtry C.S.T. (1994) - *Relations between evaporation coefficients and vegetation indices studied by model simulations*. Remote Sensing Environment, 50 (1): 1-17. doi: <http://dx.doi.org/10.1016/0034->

- 4257(94)90090-6.
- Cristóbal J., Pons X., Serra P. (2003) - *Sobre el uso operativo de Landsat-7 ETM+ en Europa*. X Congreso Nacional de Teledetección, pp. 193-196.
- Cristóbal J., Ninyerola M., Pons X. (2008) - *Modeling air temperature through a combination of Remote Sensing and GIS data*. Journal of Geophysical Research, 113, D13106: 1-13. doi:10.1029/2007JD009318.
- Cristóbal J., Jiménez-Muñoz J.C., Sobrino J.A., Ninyerola M., Pons X. (2009) - *Improvements in land surface temperature retrieval from the Landsat series thermal band using water vapour and air temperature*. Journal of Geophysical Research, 114, D08103: 1-16. doi: <http://dx.doi.org/10.1029/2008JD010616>.
- Cristóbal J., Ninyerola M., Pons X., Llorens P., Poyatos R. (2009) - *Regional scale net radiation estimation by means of Landsat and TERRA/AQUA imagery and GIS modelling*. In: Geophysical Research Abstracts, European Geophysical Union, 11, EGU2009: 12835.
- Derksen C., LeDrew E., (2000) - *Variability and change in terrestrial snow cover: data acquisition and links to the atmosphere*. Progress in Physical Geography, 24 (4): 469-498.
- Dozier J. (1991) - *Remote sensing of alpine snow cover invisible and near-infrared wavelengths*. <http://www.avalanche.org/~moonstone/1991%20cssa%20symposium/REMOTE%20SENSING%20OF%20ALPINE%20SNOW%20COVER.htm>. (last accessed: 28/11/2002).
- Duda R.O., Hart P.E. (1973) - *Pattern Classification and Scene Analysis*. John Wiley and Sons, New York, 6: 226-227.
- ESA, Sentinel-2 Mission (2010) - *GMES Sentinel-2 Mission Requirements Document*. European Space Agency, Final. (last accessed: 08/03/2010).
- Fily M., Dedieu J.P., Durand Y. (1999) - *Comparison between the results of a snow metamorphism model and remote sensing derived snow parameters in the Alps*. Remote Sensing of Environment, 68: 254-263. doi: [http://dx.doi.org/10.1016/S0034-4257\(98\)00116-3](http://dx.doi.org/10.1016/S0034-4257(98)00116-3).
- GMES Working Group, June (2010) - *25 Uses of GMES in the NEREUS Regions*. NEREUS Earth Observation/GMES Working Group.
- Genovese G., Hiderer R., Attardo C. (1999) - *Rapid estimates of crop area changes derived from satellite observations*. Spatial statistics for production ecology seminar, Wageningen, pp.19-21.
- Irish R. (2000) - *Landsat 7 Science Data Users Handbook*. NASA. [http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7\\_Handbook.pdf](http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7_Handbook.pdf) (last accessed: 14/10/2011).
- Morse A., Tasumi M., Allen R.G., Kramber W.J. (2000) - *Application of SEBAL Methodology for Estimating Consumptive Use of Water and Streamflow Depletion*. In the Bear River Basin of Idaho through Remote Sensing; Final Report.
- Palà V., Pons X. (1995) - *Incorporation of relief into geometric corrections based on polynomials*. Photogrammetric Engineering and Remote Sensing, 61: 935-944.
- Pons X., Solé-Sugrañes L. (1994) - *A Simple Radiometric Correction Model to Improve Automatic Mapping of Vegetation from Multispectral Satellite Data*. Remote Sensing of Environment, 47: 1-14.
- Pons X. (2004) - *MiraMon*. Geographical Information System and Remote sensing software. Centre de Recerca Ecològica i Aplicacions Forestals, CREAM. Bellaterra. ISBN: 84-931323-4-9.
- Pons X., Cristóbal J., Pesquer L., Moré G., González O. (2010) - *Fully automated and coherent*

- radiometric (atm+top) correction of Landsat TM images through pseudoinvariant areas.* In Lacoste-Francis (ed.) Proc. 2010, in *ESA Living Planet Symposium*. ESA Communications, Noordwijk, Holanda, CD-ROM, ISBN 92-9221-250-6. p. 978.
- Pons X., Moré G., Pesquer L. (2010) - *Automatic matching of Landsat image series to high resolution orthorectified imagery.* In Lacoste-Francis (ed.) Proc. 2010. *ESA Living Planet Symposium*. ESA Communications, Noordwijk, Holanda, CD-ROM, ISBN 92-9221-250-6, p. 978.
- Rango A., Shalaby A. (1998) - *Operational applications of remote sensing in hydrology success prospects and problems.* *Journal des Sciences Hydrologiques, IASH*, 43 (6): 947-968.
- Spisni A., Tomei F., Pignone S., Muzzi E., Panzacchi A., Antolini G., Villani G., di Lorenzo M., Foraci R., Bittelli M., Brooks E.S. (2011) - *Snow cover analysis in Emilia-Romagna.* *Rivista Italiana di Telerilevamento/Italian Journal of Remote Sensing*, 43 (1): 59-73.
- Swamy A.N., Brivio P.A. (1996) - *Hydrological modelling of snowmelt in the Italian Alps using visible and near infrared remote sensing.* *International Journal of Remote Sensing*, 17: 3169-3188. doi: <http://dx.doi.org/10.1080/01431169608949137>.
- Serra P., Pons X., Saurí D. (2003) - *Post-classification change detection with data from different sensors: Some accuracy considerations.* *International Journal of Remote Sensing*, 24: 3311-3340. doi: <http://dx.doi.org/10.1080/0143116021000021189>.
- Serra P., Moré G., Pons X. (2009) - *Thematic accuracy consequences in cadaster land-cover enrichment from a pixel and from a polygon perspective.* *Photogrammetric Engineering and Remote Sensing*, 75: 1441-1449.
- Stewart J.B., Watts C.J., Rodriguez J.C., De Bruin H.A.R., van de Berg A.R., Garatuzapayan J. (1999) - *Use of satellite data to estimate radiation and evaporation for northwest Mexico.* *Agriculture Water Management*, 38: 181-193. doi: [http://dx.doi.org/10.1016/S0378-3774\(98\)00068-7](http://dx.doi.org/10.1016/S0378-3774(98)00068-7).
- UAB & CREAM (2012) - *Servidor d'Imatges de Satèl·litde Catalunya* - SatCat Online at <http://www.opengis.uab.cat/wms/satcat/index.htm> (last accessed: 24/02/2012).
- United States Geological Survey (2003) - *ETM+ SLC-off to SLC-off Gap-filled Product.* [http://landsat.usgs.gov/Landsat\\_7\\_ETM\\_SLC\\_off\\_data.php](http://landsat.usgs.gov/Landsat_7_ETM_SLC_off_data.php) (last accessed: 11/10/2011).
- Vidal A., Sagardoy J.A. (1995) - *Use of remote sensing techniques in irrigation and drainage.* *Water Reports 4*, FAO, Rome, Italy, p. 202.
- Warehouse Inventory Search Tool (2010) - National Aeronautics & Space Administration. Online at <https://wist.echo.nasa.gov/api/> (last accessed: 01/07/2010).

**Received 14/10/2011, accepted 05/05/2012**

© 2012 by the authors; licensee Italian Society of Remote Sensing (AIT). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).



© 2012 The Author(s). Published by Taylor and Francis. This work is licensed under the Creative Commons Attribution License [creativecommons.org/licenses/by/4.0/](http://creativecommons.org/licenses/by/4.0/) (the "License"). Notwithstanding the ProQuest Terms and Conditions, you may use this content in accordance with the terms of the License.