APPLICATION OF REMOTE SENSING TECHNIQUES FOR THE GROUNDWATER EXTRACTIONS MANAGEMENT IN MANCHA OCCIDENTAL AQUIFER.

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Abstract

The Mancha Occidental aquifer resources are regulated by the Spanish Water act (L 29/1985, L.A) which entered into force on 1 January, 1986, which establishes that renewable groundwater belongs to the public dominion. Nevertheless, in order to preserve the rights of wells' (and consequently groundwater) owners, the Catchment Authority (Guadiana River Basin Authority) granted groundwater consumption rights to former owners who presented a required standard documentation describing their exploitation before 1986. Irrigation authorisation has a "legal volume" and a perimeter within which the water owner can use the assigned volume. Due to the water extractions importance, Guadiana river basin authorities have declared the aquifer over-exploited involving the issue of an annual Exploitation Plan, that establishes which percentage of the registered volume for each exploitation can be extracted each year for irrigation aiming at protecting the aquifer and guarantying the rational use of hydraulic resources. Remote Sensing techniques are being used for water consumption estimation of irrigated crops since 1997, integrating gathered data in the framework of a Geographical Information System with aiming at controlling the Exploitation Plan fulfilling. Since 2002, the same methodology is being applied in the implementation of a "Quick Alert System", focused to undeclared irrigated crops detection in almost real time, with aim of getting a better knowledge of the ground water extractions and being able to make appropriate decisions during the irrigation campaigns in order to protect the water resources. Exploitations estimated to fail to fulfil the Exploitation Plan based in their spectral response and the crop standard water consumption have also been controlled with this system. Use of Remote Sensing in the monitoring of the Exploitation Plan fulfilment allows: i) controlling the water extractions in the exploitations which own water use rights, ii).controlling the irrigated surfaces position inside the exploitations and iii) detecting the existence of irrigated crops not declared to the Catchment Authority.

Keywords: Remote Sensing, Groundwater extractions, Water use rights, Exploitation Plan.

1 INTRODUCTION AND OBJECTIVES

The groundwater resources management in the Cuenca Alta del Guadiana (upper Guadiana River catchment) region can be considered as a paradigmatic case, both at Spanish and European level, regarding conflicts between economic development and environmental protection.

The '*Mancha Occidental'* aquifer, also called *Hydrogeologic Unit 04.04*, is located in the centre of Spain, within the Cuenca Alta del Guadiana region (figure 1). This aquifer extents across 5,260 Km^2 and stretches between three provinces: Ciudad Real, Cuenca and Albacete.

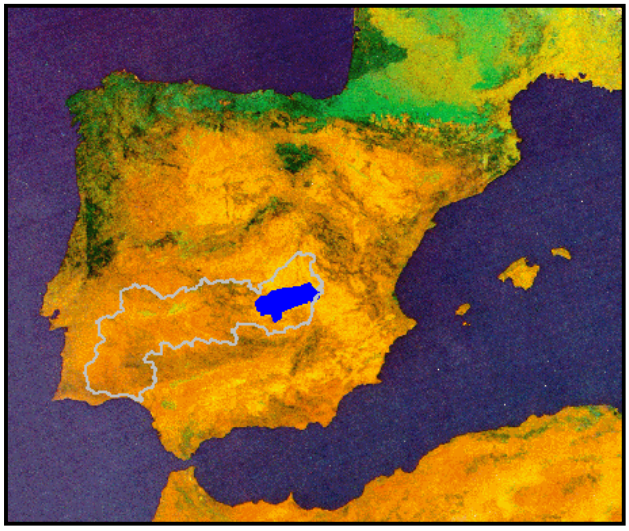


Figure 1*. Location of the Mancha Occidental aquifer (blue) in the Guadiana river basin and the Iberian peninsula.*

The area of the Mancha Occidental aquifer has about 280,000 inhabitants (SERNA *et al.*, 1995), whose major source of income is agriculture. Since the fifties, the area has experienced an important economic development due to the transformation from dry agriculture to irrigated agriculture. This development was possible thanks to groundwater exploitation from Mancha Occidental aquifer, which represents 92% of the water used in the area (SGOP, 1988). In table 2, the water balance of the aquifer is shown: the average (1974-1995) water volume extracted for irrigation is 372 Hm^3 out of a total input of 402 Hm^3.

INPUT		**OUTPUT**	
Source	**Water Volume (Hm^3)**	**Demand**	**Water Volume* (Hm^3)**
Rainfall Infiltration	180	Irrigation	372
Rivers Infiltration	80	Urban use	30
Recharge from neighbouring aquifers	60	-	-
Irrigation	20	-	-
TOTAL INPUT	**340**	**TOTAL OUTPUT**	**402**

Table 1. *Water balance of Aquifer of Mancha Occidental (CHG, 1995);*
** average value for the period 1975-1994*

Water resources of the Mancha Occidental aquifer are subject to the Spanish Water Act ('*Ley de Aguas*'), which entered into force on 1st January, 1986. It rules the competencies of the national and regional water organisations and the legal framework for the use and protection of water resources.

An important change established by the Water Act concerns the property of water: starting from 1st January, 1986 both surface and ground water belong to the public dominion. Nevertheless, in order to preserve property rights of people owning wells (and water) before that date, it was established that former owners could keep their property rights if they presented to the respective Catchment Authority a standard documentation describing their exploitation in 1985 (L.A., 1985). This documentation, gathered together in an irrigation dossier (*'Expediente Administrativo')*, includes personal details of the water owner, well characteristics, water volume extracted and the area under irrigation before 1986. On this basis, the Catchment Authority decides whether to grant or not the water rights. In the former case, the registered irrigation dossier has a 'legal water volume' and a perimeter within which the water owner can use the assigned volume. The Catchment Authority respects these water rights provided that the water owner does not change the exploitation characteristics (extracted volume, well depth, irrigated area extent and location). Exceptions to this rule are crisis situations that require the intervention of the Catchment Authorities. For instance, if the water volumes extracted from an aquifer are far higher than its recharge capacity, the aquifer is declared overexploited and the local Catchment Authority is empowered to set severe limits aiming at protecting the aquifer and allowing the recovery of groundwater levels. This leads to the issue of the Exploitation Plan ('*Regimen de Explotación*') establishing which percentage of the registered volume can be extracted each year for irrigation.

From 1974 to 1987, the Mancha Occidental aquifer registered an important increase in water extraction (figure 2), which turned in few years from 152 Hm^3/year to 553 Hm^3/year, exceeding by more than 60% the renewable resource of the aquifer. This evolution significantly affected the aquifer hydrologic equilibrium and led to the declaration of over-exploitation on 4 February, 1987.

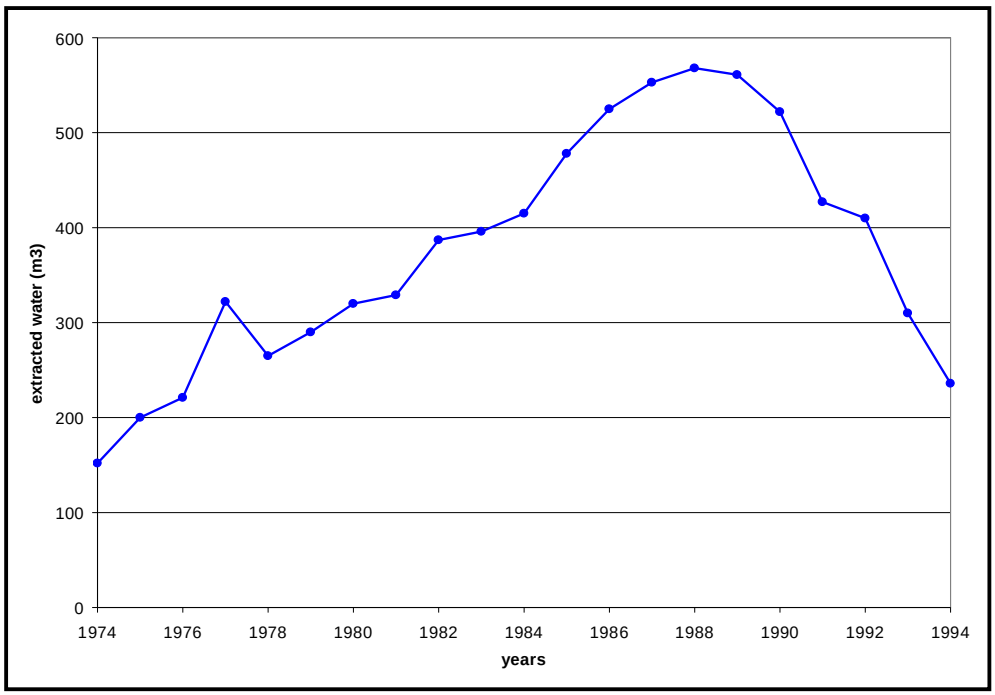


Figure 2*. Evolution of water extraction in Mancha Occidental aquifer 23 from 1974 to 1994 (CHG, 1995).*

Since 1991, the local Catchment Authority *(Confederación Hidrográfica del Guadiana*, CHG) yearly issues the Exploitation Plan for Mancha Occidental aquifer, which establishes the limitations to water extraction depending on the availability of water resources in the aquifer. These limitations are established for every parcel, depending on the amount of surface holding irrigation rights.

It must be highlighted that Mancha Occidental aquifer is directly linked to the conservation of a broad number of wetlands existing in the area, that is partially included in the UNESCO´s Programme Man and Biosphere (MaB) and contains some wetlands inscribed in the RAMSAR list. Regarding this point, the effects of the decrease in the aquifer levels has been specially dramatic over 'Las Tablas de Daimiel' National Park, the most important natural site in the area which still is actually seriously damaged.

In this context, the CHG is utilising Earth Observation techniques for monitoring groundwater extraction for irrigation purposes. This has implied, first of all, organising the administrative data related to groundwater irrigation in a rational structure. Then, Remote Sensing techniques are used to get updated information about land use and irrigation activities. Through GIS techniques, all the data are integrated and irrigation activity is monitored at aquifer, municipality and parcel level.

2 MATERIALS AND METHODS

In order to know how water consumption is distributed in space and time, it is necessary to give objective, reliable and timely answers to questions such as: 'Who irrigates?', 'Where?', 'When?', 'What?', and 'How much?'.

Geographical Information Systems (GIS) offer valuable help in handling data and providing water managers with thematic information, defined in time (when), in space (where) and linked to administrative information (who).

The detection of irrigated crops may be done through field survey, questionnaires and aerial photography. However, at a regional scale these conventional techniques are very time-consuming and expensive, which limits the quality and quantity of updated and reliable data available for water management. The CHG is using Earth Observation (EO) techniques since 1997 as a valuable alternative to traditional survey, using high resolution satellite images, acquired during the performance of the irrigation practices.

Monitoring of water exploitation can be performed using Earth Observation data because of the characteristics of the information provided by satellite images:

- Temporal information: the periodicity of the observation enables a comprehensive study of crops throughout the whole irrigation season.
- Spatial information: the extent of the area covered by satellite images allows wide areas to be monitored at the same time.
- Spectral information: satellite images provide information on the irrigated areas and the type of crops. Knowing the extent of irrigated crops and applying standard water rates, it is possible to estimate water extraction for irrigation.

Information obtained from the image processing is integrated with the alphanumeric and cartographic databases into a GIS system in order to monitor the fulfilment of the Exploitation Plan.

3 MONITORING OF THE FULFILMENT OF THE EXPLOITATION PLAN

The control of the groundwater use for agriculture in the Mancha Occidental aquifer has to take into account different possibilities:

- Water consumption in plots with Irrigation Rights assigned.
- Location of the irrigated areas in plots with Irrigation Rights assigned.
- Existence of irrigated crops not declared to the CHG (illegal irrigation).

3.1 Monitoring of Water Use in plots with Irrigation Rights assigned.

With this aim, satellite images are acquired and processed, combining the obtained information with the administrative data included in the Irrigation Dossiers and the limitations expressed in the annual Exploitation Plan.

During the last two years, six images belonging to the ETM sensor of Landsat 7, have been acquired each year, covering the whole extent of the aquifer in the different stages of the crops phenological development. The most appropriate dates for this purpose, are late spring (for crops seeded in winter and harvested at the end of the spring) and summer (for crops seeded during the spring and harvested at the end of the summer).

According to these criteria, crop ground truth was collected during three field surveys, in May, June and August . The crop surveys were performed along a south-west north-east line across the aquifer, selecting large fields and crops representative of the area. The survey was carried out with the support of topographic maps, satellite colour composites and aerial photography, stored in a GIS system connected to a GPS, that provided over the laptop screen and in “real time”, the location of the field staff.

Once acquired, the satellite images were geometrically corrected and georeferenced to the *Universal Transverse Mercator* (UTM) projection, to give EO data the same geographical co-ordinates as the rest of the data in the GIS are measured

A Principal Componet Analysis (PCA) was applied to all the images in order to maximise variance of the data, enhancing the information content, segregating noise, and reducing dimensionallity of the dataset. Next, a crop classification was carried out on all the available PCA images and used training areas within the sampling segments of the field surveys. 60% of the ground truth data was entered into the training sample set, while the remaining data were used later to assess the classification accuracy. A Maximum Likelihood classifier was applied, with a threshold obtained empirically in significant subareas. Various classification procedures were performed in areas with different agronomic and environmental conditions in order to minimise the effect of external variables in the crops spectral response. The results were integrated into a final classification.

Once a satisfactory classification was obtained, a majority filter was applied. The majority filter selects the predominant (most frequently occurring) value or class name of a pixel and its 8 neighbours. (3x3 matrix). Then, the classification for each date was merged into one global classification using Boolean algebra that excluded all those pixels that might have been misclassified. Some post classification procedures were also applied towards achieving an improvement in the results.

The classes represented in the global classification are alfalfa, cereal, corn, sugar beet, onions, melon and other crops.

The degree of accuracy of the classification was calculated through a *k x k* confusion matrix, for which the ground truth excluded from the training sampling was used. The obtained classification has overall accuracy of 92.3%, an average accuracy of 88,86%, an average reliability of 85,86 and a kappa coefficient of 0,95.

The extraction of the information concerning the irrigation monitoring and the fulfilment of the Exploitation Plan is based on the combination of the alphanumeric and cartographic data with the crops distribution map. The alphanumeric data of each irrigation dossier are linked to the vector data (parcel boundaries, limits of the municipality, limit of the aquifer) through the code/name of the vector files, while vector data are correlated with raster data (crop classification, false colour composites) through their geographical co-ordinates. In this way, the thematic maps derived from remotely sensed data are related to the administrative information concerning the registered wells through the vector files.

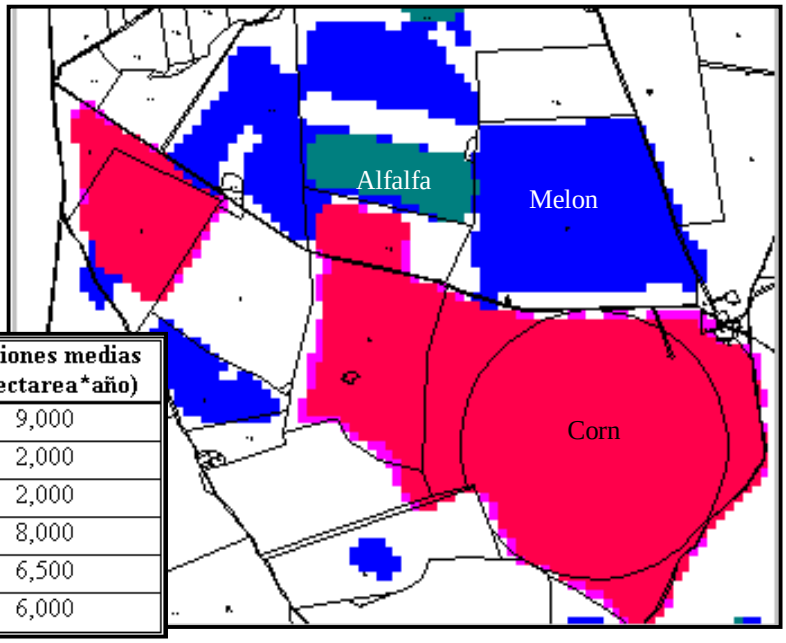
The Exploitation Plan requires, for each irrigation dossier, a comparison of both the irrigated area and the water consumption in the current year with the values assigned for the same year by the Exploitation Plan approved by the local Catchment Authority. In this way it is possible to detect the farmers that might be exceeding the assigned amounts and, consequently, might be infringing the Exploitation Plan.

For this reason, the final map of the distribution of irrigated crops was crossed with every exploitation parcel to calculate the number of pixels of each vegetation class falling within its boundaries. The multiplication of these values by the area of the pixel results in the estimation of the extent of each vegetation class within each exploitation parcel. This value is compared with the assigned area according to the Exploitation Plan and, if the first exceeds the latter, the exploitation plan established by the Catchment Authority may have been infringed.

The monitoring of the fulfilment of water consumption limits requires the multiplication of the class areas by average water rates (table 2). The resulting water volumes are compared with those established by the Exploitation Plan and any consumption anomaly is detected.

Crop type	**Average Water Rates (m^3/hectare *year)**
Alfalfa	9,000
Corn	8,000
Irrigated Cereal	2,000
Melon	6,000
Onion	6,000
Other crops	4,278
Sugar Beet	8,000

***Table 2**. Average water rates for the most representative irrigated crops in the aquifer*



Cultivo	Dotaciones medias (m^3/hectarea*año)
Alfalfa	9,000
Cereal regado	2,000
Colza	2,000
Remolacha	8,000
Maíz	6,500
Melón	6,000

***Figure 2**. Estimation of the water consumption by exploitation by the crossing of the irrigated crops map, the exploitation perimeters and the standard average water rates*

The estimation of the extent of the irrigated area and the water consumption, as well as the comparison with the corresponding authorised values, was performed also at municipality and aquifer level, to supply the Catchment Authority with a global view of the exploitation trend in the monitored irrigation season.

3.2 Detection of irrigated crops not declared to the CHG.

During the summers of 2002 and 2003, the CHG has performed an early warning system designed in order to detect and control the presence of non authorised irrigations. This system is called “Quick Alert”, as its main aim is detecting the illegal irrigation in almost real time.

Field campaigns were planned in order to the foreseen Landsat images acquisition schedule. Images were purchased and processed in a short time period, and false colour composites and irrigated areas maps were elaborated.

Irrigated areas maps were calculated using two Spectral Indexes, the Normalised Difference Vegetation Index (NDVI) and the Leaf Moisture Index (LMI), that are sensitive indicators to the presence and condition of green vegetation.

Moreover, some non irrigated vegetation (forest, riverbank vegetation) can reach values very similar and even higher than irrigated crops in the considered indexes, making it necessary to delineate such areas manually by on-screen digitation. A Spatial Analysis operation, is then performed in order to eliminate these areas from the final map.

Vineyard maps were produced by a masked multi-temporal supervised classification method applied on images belonging to 2002.

On the other hand, all the vector files containing the limits of the exploitation with rights assigned, were merged into a global file, that was crossed with irrigated areas and vineyard maps, so as to detect the presence of possible non authorised irrigated plots.

Figure 3. Overlying of the limits of parcels with assigned rights over the irrigated areas map.

Two field crews, using laptops with GIS systems installed and a GPS connected, surveyed the whole aquifer during the irrigation campaigns gathering information related to the detected irrigated parcels. The administrative situation of every exploitation was revised in order to avoid and limit possible failures, and all the collected information was issued to the CHG appropriate service.

4 CONCLUSIONS

Almost 775 parcels were visited during July and August between both aquifers, travelling around 10.500 km. The administrative situation of the 110 parcels of bigger extent was reviewed, assuring that no valid administrative dossier was linked to them. Finally, 61 reports containing the main information referred to location, irrigated surface and other characteristics were elaborated and forwarded to the Field Rangers service.

Besides this, the 25 parcels exceeding their authorised water consumption in a bigger quantity were identified and also visited, certifying the existence of irregularities. Reports containing all the necessary information for the CHG in order to denounce these situations, were also elaborated.

The non-authorised water spent on one hand in the bigger 60 parcels not declared and on the other hand, in the 25 parcels not being more water consuming between those not keeping the Exploitation Plan, adds up an approximate volume of 11,270 Hm^3, which involves the 14,5% of the global groundwater consumption in the whole aquifer.

Earth Observation techniques have proved to be a very valid tool to provide water managers with valuable up-to-date data on the distribution and use of water resources, enabling the estimation of the water use for irrigation purposes at different administrative levels and the monitoring of the evolution of the managed area over a number of years to be analysed.

The methodology of exploitation monitoring implemented and tested in this module has proven to be cost- and time-effective when compared with traditional techniques. In fact, between 1992 to 1996, CHG spent about 2 million EUROS (400,000 EUROS per year) on monitoring water exploitation using aerial photography and field survey; the analysis of the

survey required several months so that the results became available long after the conclusion of the harvest. Using remote sensing techniques, the same study was valued at about 60,000 ECU per year and could be performed within a few weeks if the ancillary data are already organised and prepared.

References

CHG (1995). Informe: El Problema Hidráulico de la Cuenca Alta del Guadiana. Confederación Hidrográfica del Guadiana, Ministerio de Obras Públicas, Transportes y Medio Ambiente, Ciudad Real.

DRURY S.A. (1987). Image interpretation in geology. Allen & Unwin. London.

JENSEN J.R. (1986). Introductory digital image processing. Prentice-Hall, Englewood Cliffs, New Jersey.

L.A.(1986). Legislación de Aguas. Ediorial Tecnos, s.a., Madrid.

LILLESAND T.M. & KIEFER R.W. (1987). Remote sensing and image interpretation. John Wiley & Sons.

MATHER P.M. (1987). Computer processing of remotely-sensed images. An introduction. John Wiley & Sons.

MONTESINOS S. & LOPEZ-CAMACHO B. (1991). La teledetección en la evaluación de la extracción de aguas subterráneas. 9ª Conferencia Internacional sobre Hidrogeología General y Aplicada. SMAGUA '91. Pp 265-272. Zaragoza.

MONTESINOS S. (1990). Teledetección: su utilización en la cuantificación y seguimiento de recursos hidráulicos aplicados al regadío. Informaciones y Estudios nº 51. Servicio Geológico. Ministerio de Obras Públicas y Urbanismo, Madrid.

MOPU (1990). Plan Hidrológico. Síntesis de la documentación básica. Ministerio de Obras Públicas y Urbanismo, Dirección General de Obras Hidráulicas.

SERNA J. & MARIO GAVIRIA (1995). La quimera del agua, presente y futuro de Daimiel y La Mancha Occidental. Siglo Veintiuno Editores, Madrid.

SGOP(1988). Evolución de las extracciones y niveles piezométricos en el acuífero de la Llanura Manchega. Secretaría General de Obras Públicas. Estudio 06/88. Madrid.