European Commission
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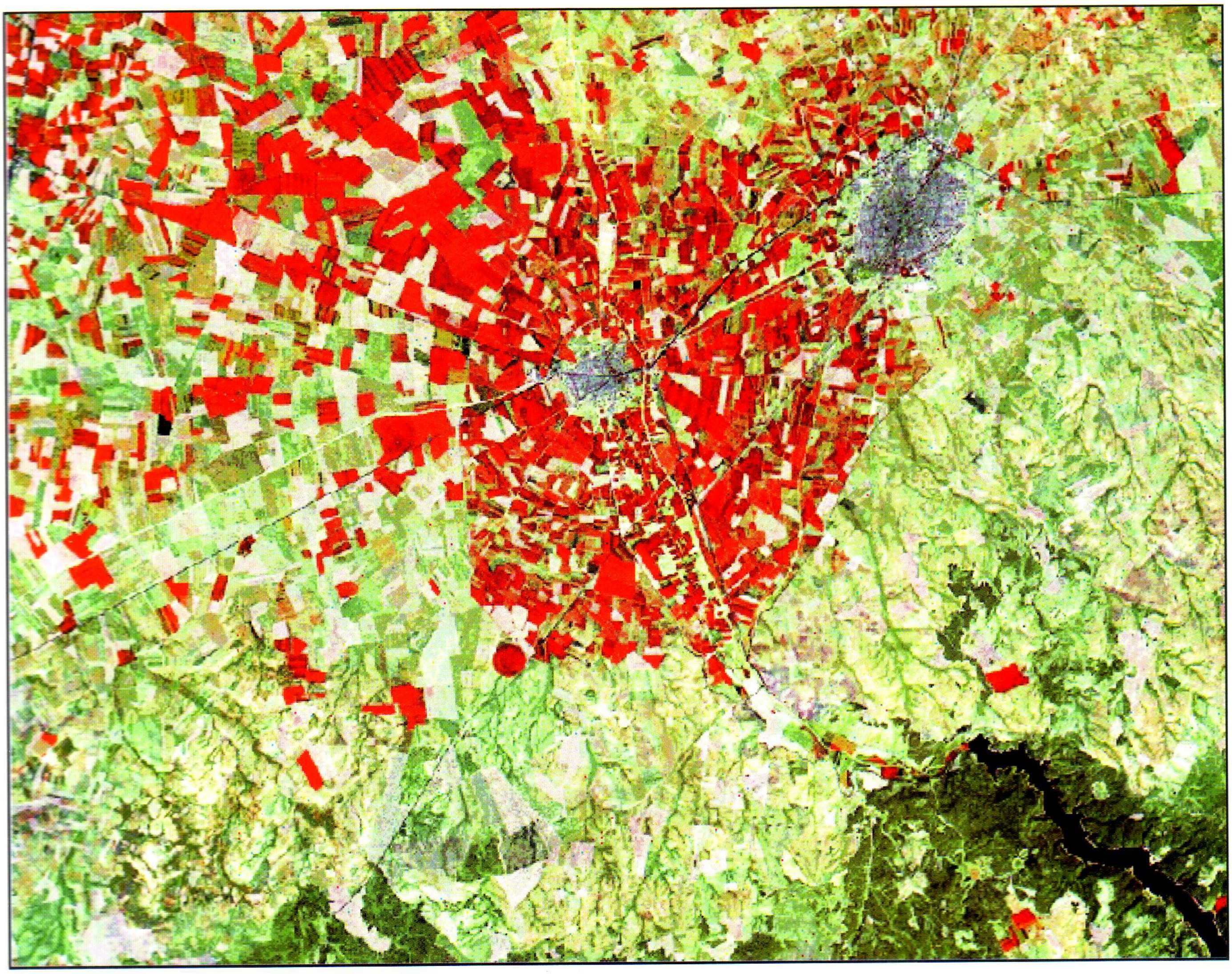
IV Framework Programme
Centre for Earth Observation

ASTIMwR

Application of Space Techniques to the Integrated Management of river basin Water Resources



GEOSYS S.L.
SISTEMAS DE INFORMACION DE LA TIERRA

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CONSORZIO DI
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SINSELE

GVADIANA
CONFEDERACION
HIDROGRAFICA

INSTITUTO
DA AGUA

IHERA
Instituto de Hidràulica,
Eng. Rural e Ambiente

MONTESINOS & CASTAÑO (Eds.)

FINAL REPORT

ASTIMwR PROJECT

January 1999

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SUMMARY

ASTIMwR ('*Application of Space Techniques to the Integrated Management of a river basin Water Resource*', Contract nº ENV4-CT96-0366) is a shared-cost project funded by the Directorate General XII of the European Commission within the Environment and Climate Programme, Area 3.3 (Centre for Earth Observation, CEO) of the Fourth Framework.

ASTIMwR (February 1997- January 1999) is the result of the joint effort of eight European Organisations and Companies, with the objective of providing water managers with truly operational applications based on Earth Observation (EO) data.

The customers of the ASTIMwR project are managers of areas of very different size: 55,412 Km^2 in Spain (Spanish part of the Guadiana river basin); 11,600 Km^2 in Portugal (Portuguese part of the Guadiana river basin) and 307 Km^2 (left side of the Sele river basin) in Italy. At all these management levels ASTIMwR identified that water managers need to know where, when, how, how much and by whom water is used. Indeed, only a reliable and manageable knowledge of the distribution of demand and consumption in time and space makes it possible to define and implement a satisfactory water allocation policy and plan future actions.

Currently available EO data and techniques offer opportunities for the routine use of Remote Sensing (RS) in the water industry sector, but the complexity of the software tools needed to handle such data discourage water managers. They request software products with few basic functionalities, tailored to the routine water problems and easy to use by their technicians. Water managers ask for easy-to-use work tools that help to generate useful information from satellite data and ancillary data (tables and maps).

Thus, the ASTIMwR Project has worked implementing a vertical computer application having a simple user-oriented interface (*user menus*) and addressing with EO data significant water management issues. The ASTIMwR system is composed of four independent modules that handle the following subjects: groundwater exploitation control, irrigation performance monitoring, analysis of wetlands evolution and evapotranspiration mapping.

The techniques applied in ASTIMwR have shown to be apt for application in different geographic and administrative contexts, which makes them extrapolable to other areas.

The ASTIMwR application is a pilot system. This means that it is expected to open the way to further developments and upgrades, for an operational use of Remote Sensing in water management. Its modular structure and its technical specifications will facilitate its up-grade and tailoring on the specific requirements and characteristics of each Water Management Authority.

DOCUMENT OVERVIEW

This document is the final report of ASTIMwR (‘*Application of Space Techniques to the Integrated Management of a river basin Water Resource*’) a shared - cost project funded by the Directorate General XII of the European Commission within the Environment and Climate Programme - CEO area - of the Fourth Framework (contract nº ENV4-CT96-0366).

The main purpose of the report is to document the activities carried out during the two-year life of the project and present its main results and conclusions.

The structure of the document is organised according to below:

Chapter 1 introduces the reader into the ASTIMwR project, by summarising the objectives, the development and the main results of the project. Work milestones and deliverables are pointed out to highlight the project progress.

Chapter 2 describes the objectives, the methodology and the main findings of each of the four modules that constitute the ASTIMwR software system. Each module was described by the Organisation involved in the methodological development and was reviewed by the authors of this document. This chapter is addressed to Remote Sensing experts and aims at documenting in detail the steps needed to achieve the scientific results of the project.

Chapter 3 includes the evaluation of the success criteria, with particular emphasis on the system evaluation against users’ requirements and the dissemination activities carried out during the project.

Chapter 4 draws the conclusions of the project, pointing out its main achievements and future developments.

1 INTRODUCTION TO THE ASTIMWR PROJECT

1.1 An overview

The main aim of ASTIMwR was to develop a pre-operational software application for management of water resources using EO data. The application had to be user-friendly, to enable its use by non-expert staff, it had to be based on methodologies of proven scientific value and had to provide information useful for water resources management.

The objective was achieved by developing a modular User Interface (UI) that integrates EO data and ancillary data in a friendly environment. The software modules implement in an operational context scientific methodologies that deal with groundwater exploitation control, irrigation performance monitoring, analysis of wetlands evolution and evapotranspiration mapping. Through the ASTIMwR UI, water managers without specific knowledge of GIS and RS techniques can easily handle EO data. The user-menu structure guides the operator in extraction information from the data to support water managers' routine work and decision-making processes. The efficiency of the modules was successfully tested in the Guadiana river basin (Spain and Portugal) and in the Sele river basin (Italy). A synoptic view of the ASTIMwR pilot areas is given in figure 1.1.

The ASTIMwR project is the result of a collaborative effort of nine European public and private Organisations.

Both technical partners and final users (costumers) compose the ASTIMwR Consortium:

- GEOSYS, S.L., Madrid, Spain, as coordinator and technical partner
- Confederación Hidrográfica del Guadiana, Ciudad Real, Spain, as final user
- Consorzio di Bonifica ed Irrigazione di Paestum, Capaccio Scalo, Italy, as final user
- Instituto da Agua, Lisbon, Portugal, as final user
- Instituto de Hidráulica, Engenharia Rural e Ambiente, Lisbon, Portugal, as final user
- Instituto de Desarrollo Regional, Albacete, Spain, as technical partner
- Istituto d'Idraulica Agraria, Universitá di Napoli, Naples, Italy, as technical partner
- International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands, as technical partner
- Winand Staring Centre, Wageningen, The Netherlands, as technical partner

The contact details of each member of the partnership are reported in Annex 1.

1.2 Staff Resources

The staff involved in the project is reported hereafter in alphabetical order:

Name	Organisation	E-mail address
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Table 1.1: Staff involved in the ASTIMwR project.

1.3 Milestones and deliverables

The activities of the ASTIMwR project were structured in three main phases:

a) **Definition phase**, where the users' requirements were identified and the ASTIMwR system was designed to satisfy such needs. The results of this phase are reported in the ***Users Requirements Document*** and the ***System Design Document,*** which are summarised in chapter 1.3.1 and 1.3.2 of this document. The complete version of these documents can be found in annex II and III of the 'ASTIMwR Interim Report (February 1998)'.

b) **Data gathering and processing phase**, where the technical partners defined in detail the methodologies to be implemented in the system, acquired and processed the relevant data to satisfy the users' technical needs. The results of this phase are gathered in Chapter 2 of this document.

c) **System Implementation phase**, where the programmers built up the ASTIMwR interface, which was tested and evaluated by the Consortium members. The activities and the results of this phase are summarised in chapter 1.3.3 of this document.

The milestones listed hereafter marked the progress of the work:

Milestone	Month	Key Activity	Deliverables
Project Kick-Off	1	Kick-off Meeting	Meeting Minutes
User Requirements Definition	6	First Progress Meeting	Users Requirements Document (first draft)
System Design Definition	6	First Progress Meeting	System Design Document (first draft)
Methodologies Definition and Data Processing (start)	6	First Progress Meeting	-
Methodologies Definition and Data Processing (end)	12	Second Progress Meeting	Users Requirements Document (final draft) & 2nd Interim Report
System implementation (start)	12	Second Progress Meeting	System Design Document (final draft)
System testing (start)	18	First Software Release	-
System testing (end)	23	Final Meeting	-
System implementation (end)	24	Final Meeting	Final Report
System evaluation	24	Final Meeting	Final Report

Table 1.2: Milestones of the ASTIMwR project.

During the project the progress of the work and the results were reported in the following deliverables:

Deliverable	Month	Author(s)	Editor	Distribution
Minutes of the Kick-off Meeting	1	GEOSYS	-	Internal
First Quarterly Report	3	Technical Partners (TP)	GEOSYS	Internal
Minutes of the First Progress Meeting	6	GEOSYS	-	Internal
First Interim Report (semestral)	6	TP	GEOSYS	To the European Commission (EC)
Users Requirements Document (first draft)	6	ITC	ITC	Internal
System Design Document (first draft)	6	ITC	ITC	Internal
Second Quarterly Report	9	TP	GEOSYS	Internal
User Requirements Document (final draft)	12	ITC/GEOSYS	GEOSYS	To the EC
System Design Document (final draft)	12	ITC/GEOSYS	GEOSYS	To the EC
Second Interim Report (annual)	12	TP	GEOSYS	To the EC
Minutes of the Second Progress Meeting	12	GEOSYS	-	Internal
Third Quarterly Report	15	TP	GEOSYS	Internal
Third Interim Report	19	TP	GEOSYS	To the EC
Minutes of the Third Progress Meeting	20	GEOSYS	-	Internal
Fourth Quarterly Report	21	TP	GEOSYS	Internal
Minutes of the Final Meeting	24	GEOSYS	-	Internal
User Interface Manual	24	TP	ITC	Internal
Technology Implementation Plan	24	TP	GEOSYS	To the EC
Final Report	24	TP	GEOSYS	To the EC

Table 1.3: Deliverables of the ASTIMwR project

All the above-mentioned documents were elaborated with the valuable and indispensable contribution of the members of the consortium. The authors would like to thank each of the partners for their solicitous collaboration in the elaboration and review of the project deliverables. Moreover, the authors would like to thank the CEO Technical Manager, Mr. Henrik Österlund and the Scientific Officer for DGXII, Mr. Martin Sharman, for the careful review of the deliverables.

During the project, the Consortium met every six months at a plenary meeting, to assess the work progress and organise the activities of the following semester. Except for the final meeting, all the meetings took place at the users' premises, which gave all partners the opportunity to better know the users' characteristics and needs.

Meeting	**Date**	**Venue**
Project Kick-Off	6-7/03/1997	Confederación Hidrográfica del Guadiana, Ciudad Real, Spain
First Progress Meeting	4-5/07/1997	Confederación Hidrográfica del Guadiana, Badajoz, Spain
Second Progress Meeting	12-13/02/1998	Consorzio di Irrigazione e Bonifica di Paestum - Sinistra Sele, Capaccio Scalo (SA), Italy and Universitá di Napoli “Federico II”, Naples, Italy
Third Progress Meeting	14-15/09/1998	Instituto da Água, Lisbon, Portugal
Final Project Meeting	21-23/01/1999	Instituto de Desarrollo Regional, Albacete, Spain

Table 1.4: Date and venue of the ASTIMwR plenary meetings.

1.3.1 User Requirements Definition

The User Requirements Document (URD) reports the results of the user requirements study, which analysed the operational needs of the customer organisations, detected the main structural constraints, delineated and prioritised the general functionalities of the system to be built within the ASTIMwR project.

The users of the ASTIMwR project - Confederación Hidrográfica del Guadiana, Istituto da Água, Consorzio di Bonifica di Paestum - are water managing Organisations working at different scale and in different legal context:

1. Confederación Hidrográfica del Guadiana (CHG), Spain, administrates the Spanish part of the Guadiana river basin (55,412 km^2) that shares with Portugal and that stretches through the Spanish Autonomous Communities of Castilla-La Mancha, Extremadura and Andalucia.

2. Instituto da Água (INAG), Portugal, administrates the Portuguese international catchments, among which the Guadiana river basin (11,600 Km^2 in Portuguese territory). In the ASTIMwR project, it had the technical support of IHERA (Instituto de Hidraulica, Engenheria Rural e Ambiente of the Portuguese Ministry of Agriculture).

3. Consorzio di Bonifica di Paestum Sinistra Sele (SINSELE), Italy, manages an area 307 Km^2, of which 110 are irrigated, which extends through seven Communities of the Salerno Province.

The geographical, legal and scalar factors strongly influence the user needs, and even if there is an overlapping in their requirements, an interesting and enriching variety in their priorities and capability to solve water problems arose from the user requirements study.

There was an outstanding agreement between the different users on the need for instruments and information to support the definition and the implementation of a satisfactory water allocation policy at all management levels and water sources (surface and ground water).

Water managing institutions need, independently of the size of the area they administrate, a sound support for planning water resources use; improving water use efficiency; ensuring the economical and environmental sustainability of water depletion, in relation with different users, urban areas, industry and agriculture.

The requirements expressed by the ASTIMwR users clearly showed that the most urgent needs are focused on:

a) Organisation and handling of the existing data

The users institutions own or have access to a huge amount of data, both in digital and analogical format. Nevertheless, data are often of few or no usefulness because they can not be easily handled and crossed with other relevant information. Indeed, in most cases water managers are civil engineers, agricultural engineers, hydrogeologists, specialised in hydraulic and irrigation infrastructures and not remote sensing experts. Water managers can find on the software market a very wide choice of *'horizontal'* products that allow expert customer to perform a huge amount of GIS operations. Nevertheless, water managers request '*vertical'* products, with few functionalities, tailored to the routine water problems and easy to use by their technicians.

Users need computer tools that enable them to:

- store data proceeding from different sources, and provided in different ways, formats and scales.
- facilitate the search of relevant information within the user's archives.
- convert into digital format and set up the database for all the existing data stored in analogical format.
- display and easily update the available digital data.
- process and interpolate tabular data to obtain understandable information.
- integrate several georeferenced information layers.

b) Gathering of reliable and updated information

At all the scales of work (basin, sub-basin, aquifer, irrigation district), water managers highlighted the urge to base their decision-making processes on objective and reliable information concerning:

- Landuse inventory, especially to distinguish and locate irrigated areas, non-irrigated areas and type of cultivated crops.
- Origin and destination of water, i.e. from where water is obtained (wells, surface reservoirs, river intakes, etc.) and where is it used.
- Estimation of water availability, to plan the allocation policy and implement systems for better management, based on the balance of water storage and water consumption.

- Effects and consequences of water depletion on the environment (water pollution, aquifer over-exploitation, and sensible area degradation).

The main themes identified to be of highest importance for water managers are:

- Water Balance
- Irrigation Monitoring
- Irrigation Performance
- Surface Reservoirs Management
- Environmental Management
- Water Quality Monitoring
- Thematic Information Management

The needs for information of the users were analysed to establish which of them could fit with the quality of EO data.

ASTIMwR limits its action to some of these issues, which can be considered as crucial for the users and where remote-sensing techniques can be used:

- Evapotranspiration mapping
- Irrigation performance monitoring
- Monitoring groundwater extraction
- Monitoring of wetlands of environmental interest.

1.3.2 System Design Definition

From the analysis of the user requirements it was possible to identify which users' work conditions determine the system design:

- Water managers need efficient tools for data storage and retrieval and for data exchange with other systems. Therefore, the system must have advance capabilities for visualisation, printing, documentation, data import, export and storage.
- The operators do not have skills to perform complex Geographical Information System (decision-making procedures. For this reason, the programming must allow automatic procedures that trigger a pre-programmed sequence of operations to carry out pre-defined tasks. Once the operator has selected the desired information, the system should automatically retrieve and process data to produce the requested output products.
- Most of the user' operations and queries are defined in space and time. Thus, time and space should be the access key elements for the queries of the interface.
- The ASTIMwR system should be installed in the users' computers and be compatible with their routine work. Personal Computers (PCs) are increasingly the most common hardware tool in official Organisations and, for this reason, the system must be PC-based, running in Windows '95/'98 or NT.

To meet these requirements it was decided to build a **User Interface (UI)**. The UI guides the operator in communicating with the system in order to let the system perform pre-defined tasks according to the wishes of the operator. In order to do this, the system components need to have available the input data required for the process and a clearly defined operations sequence. The UI calls a GIS tool hidden in the background, which performs the triggered operations without the intervention of the operator.

Visual Basic was selected as programming language for creating the customised interface and ‘Integrated Land and Water Information System’ (ILWIS), version 2.2, for performing the GIS calculations. The link between them was Dynamic Data Exchange (DDE).

The next step in the System Design was to identify the algorithms required to process the input data and transform them into useful information according to the customer requirements.

Three main elements were defined in detail in collaboration with the technical partners and the end users:

- The information (output) that the ASTIMwR Interface should generate.
- The computer procedures that must be triggered to produce the information.
- The input data required for carrying out these procedures.

Then, the logical structure to access the information was defined and the UI menu designed according to a sequence that considers the daily routinely work combined with a hydrologic logical order.

1.3.3 System Implementation, Testing and Validation

Once defined in detail the data combinations that could be carried out with the available data to satisfy the information requirements of the users, the technical partners sent the data set corresponding to each module to the programmers. Each data set was delivered together with a Microsoft Access database where the characteristics of each data and the GIS procedures that had to be applied to generate information were described in detail.

At the beginning of the implementation phase, each member of the Consortium selected a reference person (tester), in charge of interacting with the programmers and testing the ASTIMwR system.

Four versions of the User Interface were delivered to the Consortium for testing:

Version	Release date
Pre-alpha	July 1998
Alpha	September 1998
Beta	December 1998
Version 1.0	January 1999

Table 1.5: Released versions of the ASTIMwR User Interface.

The testers reported the bugs and suggestions of enhancement in pre-designed forms to facilitate the trailing of the bug and received periodical reports on the status of system enhancement.

Once version 1.0 of the system was ready for release, both the users and the technical partners carried out a comprehensive evaluation of the system. The evaluation included the following aspects:

a) Evaluation of the capabilities and functionalities of the ASTIMwR User Interface
   All the partners were asked to evaluate the basic functionalities (import/export/display/print) and the specific functionalities (menus of the module) available in the version 1.0 system.

b) Evaluation of the information generated
   The users evaluated the usefulness and efficiency of the information provided by each module for their work as water managers and the transparency from their point of view of the methodology applied.

   The technical partners identified whether the implementation of the project had brought about the new scientific findings.

c) Evaluation of the future development of ASTIMwR
   The users were requested to evaluate the cost-effectiveness of the ASTIMwR EO-based applications against traditional techniques to carry out the work performed by the ASTIMwR system. Furthermore, they were asked to express their willingness to invert their own funds in the update the EO applications with new data and in a future system enhancement.

   The technical partners evaluated the cost-effectiveness of ASTIMwR and it capability of satisfying the users' needs. Also, the technical partners were requested to consider their interest in working on the system enhancement and development after the end of the project.

The results of this evaluation are gathered in chapter 3 of this document.

1.4 Highlights of the project (press release)

The European project ASTIMwR - '*Application of Space Techniques to the Integrated Management of a river basin Water Resources'* - has concluded on 31st January 1999. The project has generated a easy-to-use software that takes advantage of the information provided by Earth Observation satellites to improve the management of water resources.

ASTIMwR had a budget of more than 1,800 Euro and selected as pilot area the Guadiana river basin (Spain and Portugal) and the Sele river basin (Italy).

Water managers can find in an important source of information in satellite images. Now water managers are able to use easily these data, which seemed to be reserved to specialists, for carrying out their work, thanks to the new software tool developed by ASTIMwR. Earth Observation techniques are taken from the world of scientific research to be implemented in an operational context.

The end of this two-year project is just the beginning of several lines of work, since the achievements of ASTIMwR have stimulated new investments related to Earth Observation by the water managers participating in the project as final users.

ASTIMwR is the result of the successful cooperation of five technical partners having very different scientific competencies - GEOSYS, S.L. (Spain), coordinator of the project, Instituto de Desarrollo Regional (Spain), International Institute for Aerospace Survey and Earth Sciences (Holanda), Winand Staring Centre (The Netherlands), Universitá di Napoli “Federico II” (Italy) - and four final users - Confederación Hidrográfica del Guadiana (Spain), Instituto da Agua (Portugal), Instituto de Hidráulica, Engenharia Rural e Ambiente (Portugal) and Consorzio di Bonifica ed Irrigazione di Paestum (Italy) - which have contributed to the success of the project with their knowledge of the real problems of water management.

ASTIMwR is the first project that is concluded within the Area 3.3 (Centre for Earth Observation) of the Fourth Framework Programme of the European Commission.

2 ASTIMWR SCIENTIFIC REPORT

This chapter presents the methodology and the main findings of the four modules that constitute the ASTIMwR software system (version 1.0) and it was written by the person(s) in charge of their scientific development.

2.1 Evapotranspiration Mapping

Author: *C.J. de ZEEUW, DLO-Staring Centre, Wageningen, The Netherlands*

The total water supply for irrigation purposes overpasses the real requirements of the crops in almost every irrigated region (MENENTI, 1993). Given the increasing limitations in water resources availability, irrigation efficiencies should therefore be improved by formulating a water management for an “optimal” distribution of available water volumes.

In combination with water volume measurements, the use of satellite remotely sensed data has proven to be a feasible alternative for this purpose, compared to conventional ground survey. Remote Sensing (RS) offers a means for regular and timely updating of information on the hydrological situation of irrigated land and the actual evapotranspiration rates of both irrigated and non-irrigated crops (MENENTI *et al.*, 1990 and D’URSO *et al.*, 1992).

Emphasis was given to the investigation of possible use of different satellite sources. Therefor Landsat-TM images, NOAA-AVHRR data and NOAA-AVHRR 10-days maximum NDVI composites were acquired. With these data sources the possibilities of processing and the usefulness at a user level were investigated. An interactive role of local water authorities contributed to this process and influenced data acquisition, data presentation and querying options in the system application. Also it was investigated if any part of the processing could be automated in such a way that calculation procedures and image processing could be performed at a user level. The complexity of energy balance calculations and its iterative processes were considered limiting factors in this matter.

It is not the scope of this document to explain in full extent the theory on energy balances and *ETa* mapping, wherefore is referred to BASTIAANSSEN (1995). Only the chosen methodology is documented.

Using the Surface Energy Balance Algorithm for Land (SEBAL), all components of the surface energy balance can be derived from satellite images containing thermal information. However, certain amount of ground data should be added, especially for atmospheric correction purposes (BASTIAANSSEN, 1995). Using the derived evaporative fraction and estimated values on the daily incoming net radiation, the *ETa* can be estimated in mm/day. The resulting *ETa* maps form an input to the water management application that is developed during the ASTIMwR project and can be input to hydrological studies.

To provide the users with useful information on actual evapotranspiration, different forms of information provision have been defined as required output of the module:

- Both high resolution and low resolution maps
- Detailed information in different years (summer / irrigation situation)
- Detailed information at different moments within one growing season
- General information at different moments within one growing season for the whole river basin
- Low resolution time series at a yearly basis for the whole river basin

With respect to the low resolution time series the suitability of NOAA-AVHRR 10-days maximum NDVI composites as SEBAL input was investigated and the usefulness to the water management system was established.

2.1.1 Objectives of the module

The main objective of this module is to provide the users with data on the crop water uptake, obtained with the aid of Remote Sensing techniques. Advantage of such information is that better spatial insight can be obtained, based on measured values instead of interpolated point data. In this scope, the possibilities to estimate the actual evapotranspiration (*ETa*) from agricultural areas and natural vegetation are investigated, using high and low resolution satellite images and low resolution satellite time series.

2.1.2 Test area and material

2.1.2.1 Selected study areas

The Guadiana river basin is chosen as study area at the low-resolution scale (figure 2.1) This river basin covers an area of 66,800 km^2 and is located on the sub-central part of the Iberian Peninsula. Within this river basin the Bullaque irrigated area is selected as study area for the *ETa* mapping on a high-resolution scale. This on-demand irrigation scheme consists of 5551 hectares and obtains its irrigation water from the Torre de Abraham water reservoir. A more detailed description of the irrigation scheme is given in paragraph 2.2.3.

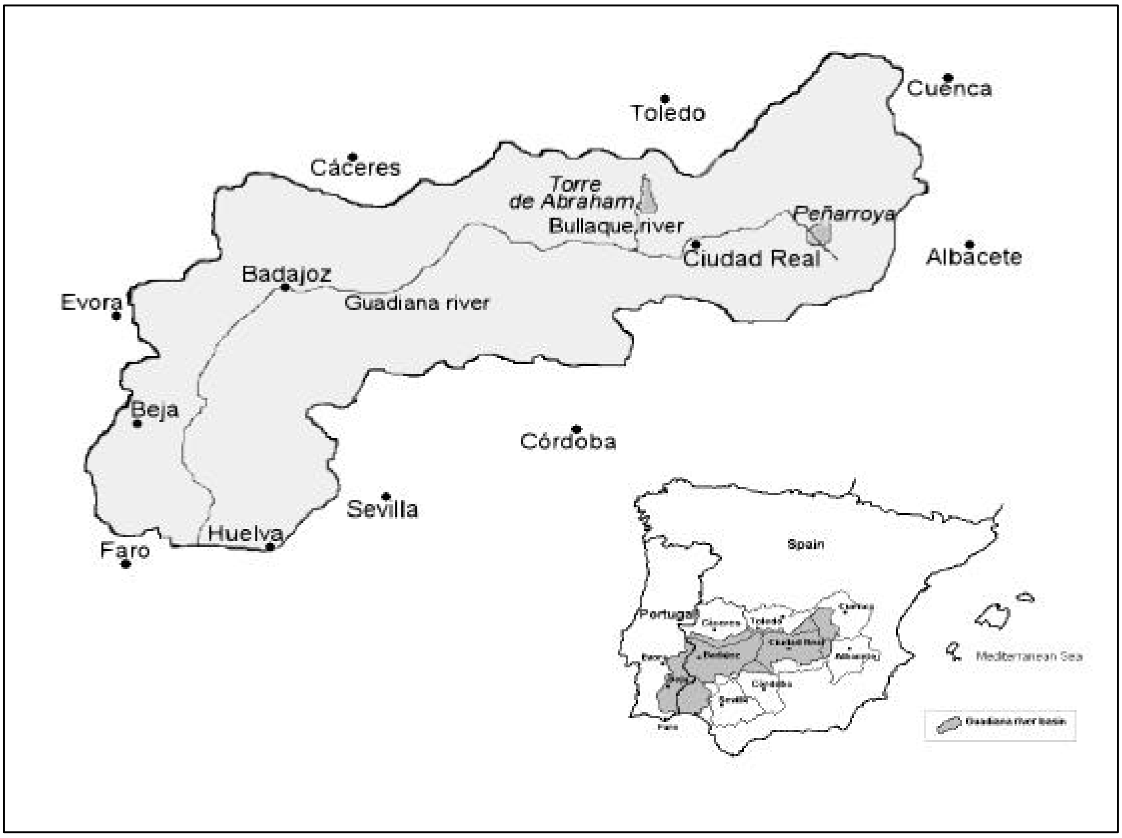


Figure 2.1. Location of the Guadiana river basin in Spain and Portugal (a) and the position of the Bullaque irrigated area within the river basin (b).

2.1.2.2 Available Landsat5-TM images

As input for the SEBAL program, Landsat5-TM images of the Bullaque irrigated area were selected in the period 1989 - 1997. For the years 1989, 1991, 1996 and 1997 mostly cloud free images were selected in the month of July. For 1997 also images of May, June and August were selected to obtain multi-temporal insight within one growing season. The characteristics of the available Landsat-TM images are shown in table 2.1. Available IRS data for the same area could not be used for SEBAL purposes, because this satellite does not possess a sensor for the recording of thermal reflectances. Subsets of equal size and geometry were created for all data. The upper left corner of the area of interest was set to (387015, 4360000) and the lower right corner to (402015, 4330000), using the UTM projection (zone 30) with the Hayford ellipsoid and European map datum. The geometric correction for 1989, 1991 and 1996 was done with a nearest neighbour re-sampling technique. The images of 1997 were corrected with a cubic convolution technique. General characteristics for the images as mentioned in table 2.1, were calculated for the approximated centre of the irrigation district, positioned at a latitude/longitude of 39.25, -4.25 (in digital degrees) or 0.6850, -0.0742 (in radians).

	15 July 1989	**21 July 1991**	**18 July 1996**	**18 May 1997**	**19 June 1997**	**5 July 1997**	**6 Aug. 1997**
Time of Day (GMT)	10:23:21	10:19:21	10:01:00	10:24:20	10:25:20	10:26:06	10:27:05
Nº of bands	7	7	7	7	7	7	7
Path/Row	201/33	201/33	201/33	201/33	201/33	201/33	201/33
Julian day number (-)	196	202	200	138	170	186	218
Local time, t(x) (dec. hours)	10.106	10.04	9.733	10.122	10.139	10.152	10.168
Longitude (dd)	-4.25	-4.25	-4.25	-4.25	-4.25	-4.25	-4.25
Latitude (dd)	39.25	39.25	39.25	39.25	39.25	39.25	39.25
Solar declination	0.375	0.356	0.363	0.340	0.409	0.397	0.288
Solar angle hour, $_a$ (rad)	-0.496	-0.513	-0.593	-0.492	-0.487	-0.484	-0.480
Solar Zenith angle, $_{su}$ (rad)	0.525	0.549	0.601	0.546	0.496	0.501	0.576
Earth-sun distance, d_s (AU)*	1.016	1.016	1.016	1.012	1.016	1.017	1.014

* 1 Astronomical Unit (AU) = 1.596 * 10 ^{8} km

Table 2.1. Available Landsat5-TM images (1001 rows, 501 columns) and generalised date specific surface characteristics for the Bullaque irrigated area, Spain.

2.1.2.3 NOAA-AVHRR data

At the NOAA scale the full Guadiana river basin is taken as the study area. For this area a set of twenty NOAA-AVHRR images of 1995 was selected, covering West Europe (Source: JRC-ISPRA). After formatting and geometric correction six of these images were considered to be of sufficient quality with regards to geometry and cloudiness for use as input to the SEBAL model in the Guadiana river basin. In annex 2 an overview of the available images is given. The images selected for processing are:

- 23 March, 1995
- 2 April, 1995
- 28 June, 1995
- 21 July, 1995
- 18 August, 1995
- 9 October, 1995

The NOAA-AVHRR images have a resolution of 1.1 km and contain five spectral bands (from visible to thermal infrared). Additional climatological information as required for atmospheric correction was obtained through RACMO. The RACMO model is a Regional Atmospheric Climate Model of the Royal Dutch Institute of Meteorology (KNMI), based on data obtained from the SYNOPS database. The resolution of the RACMO results is a 50km grid. The required topographic information (altitude and exposure) was derived from a Digital Elevation Model (DEM). For this reason the GTOPO30 DEM from the USGS EROS Data Centre is used (see also the web site http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.htlml). The data for the European continent originates almost completely from the Digital Chart of the World with elevations regularly spaced at 30-arc seconds (approximately 1 kilometre). The DEM provides information on altitude, exposition and slope.

2.1.2.4 NOAA-AVHRR maximum NDVI 10-days composites

At the Free University of Berlin a method is developed for the calibration and composition of so called NOAA-AVHRR maximum NDVI 10-days composites (KOSLOWSKY, 1996). Each image represents a decade within one year; 36 images in row represent a low-resolution time series for a specific year. In this way, extreme large data sets can be reduced to manageable data sets containing the most relevant data. For the Guadiana river basin images were prepared in this way for 1995 and 1996, including a geographical correction to a geographic longitude / latitude projection.

The image of one decade is structured in such a way that each pixel contains original values of the NOAA-AVHRR image (5 bands, not atmospherically corrected) corresponding to the day and time within that decade where the observed NDVI is the maximum. Additional information is added on for example zenith angle, day and time of pass. As a consequence adjacent pixels can represent the situation at different days and different times during that specific decade. This complicates the possible use of these data for energy balance studies (see paragraph 2.1.4).

Although this maximum NDVI 10-days composites often result in cloud free images, permanently clouded decades can remain in the data set as clouded pixel values in all bands and are not usable as input data to the SEBAL model.

Therefor the possible use of temporal interpolation techniques has been explored to estimate missing NDVI data that are required for energy balance calculations and the related ETa mapping. Furthermore it was investigated if these techniques are also applicable to the spectral (albedo) and thermal (temperature) information available in the data sets, in combination with the required atmospheric correction. Without this information the surface energy balance per decade can not be calculated.

2.1.2.5 The SEBAL program

BASTIAANSSEN (1995) developed a methodology for the calculation of surface energy balances, resulting in the SEBAL (Surface Energy Balance Algorithm for Land) program. During the last 5 years various versions of the SEBAL software have been developed and adapted at DLO–Staring Centre. Although efforts have been made to develop user-friendly software applications, too many features of the algorithm have proven the necessity of highly specialised user knowledge, a solid understanding of energy balance processes and an interactive use. Therefor within this project a research version of the model has been used, and no final user module has been incorporated in the ASTIMwR application.

This study is not focused on validation and testing of the SEBAL algorithm. This has been done in various research programmes, including the EFEDA-EC project in La Mancha, Spain. See for example ROERINK (1995), PELGRUM *et al.* (1994 and 1995) and AMBAST (1997).

The used program is written in C^{++} - code and requires raster data in ERDAS-Imagine format. VAN DER WAL (1995) did the basic programming, but PELGRUM (1996) and SU (1998) made adaptations of importance to the code and the applied methodology.

2.1.3 Applied methodology

2.1.3.1 Surface energy balance

The exchange processes occurring at the land surface control the redistribution of moisture and heat in soil and atmosphere. The land surface connects the moisture and the heat balances of the soil and the atmosphere. Assuming no horizontal advection, the energy fluxes are one-dimensional away or towards the surface. Therefore the thermodynamic equilibrium between dominantly turbulent transport processes in the atmosphere and dominantly laminar processes in the soil manifests itself in the energy balance which for the land surfaces reads as:

$$Q^* = G_0 + H + \lambda E \quad [W.\ m^{-2}]$$

Where:
Q^* = Net radiation flux density ($W.m^{-2}$)
G_0 = Soil heat flux density ($W.m^{-2}$)
H = Sensible heat flux density ($W.m^{-2}$)
λE = Latent heat flux density ($W.m^{-2}$)

As the energy required for photosynthesis and heat storage of the plant is very small, it is ignored in this equation. The sign convention is that Q^* is considered positive when radiation is directed towards the land surface, while G_0, H and λE are considered positive when directed away from land surface.

SEBAL solves the surface energy balance from remote sensing measurements in an iterative and interactive way (BASTIAANSSEN, 1995). The main input data are remote sensing images, but the model makes also use of analytical relationships combined with empirical relationships. If available, experimental ground data should be used for calibration. In figure 2.2 a schematisation is given of the surface energy balance calculation by the SEBAL model.

For the present study areas only few supplementary field data were available. Therefore most of the regression constants in the empirical relationships were used as derived during the EFEDA-EC project in Spain, where SEBAL was validated under very similar circumstances (PELGRUM *et al.*, 1995).

Net radiation flux density, Q^*

The energy source that drives the land surface flux densities G_o, H and $l E$ is the net radiation flux density Q^*, defined as the resultant of all incoming and outgoing radiation. It can be expressed as:

$$Q^* = K^{\downarrow} - K^{\uparrow} + L^{\downarrow} - L^{\uparrow} \qquad [W.m^{-2}]$$

Where:

K = Incoming (¯) and outgoing (-) short wave radiation (0.3-3.0 μm)

L = Incoming (¯) and outgoing (-) long wave radiation (0.3-3.0 μm)

The amount of incoming short wave radiation, $K^{¯}$, is a function of time and the particular place on the earth. K^{-} is the radiation reflected by the earth surface. The ratio between $K^{¯}$ and K^{-} is called surface albedo, r_0, and therefore, the net short wave radiation can be written as (1 - r_0) · $K^{¯}$. The incoming long wave radiation, $L^{¯}$ is the radiation emitted by the atmosphere and the outgoing long wave radiation L^{-} is the emitted long wave radiation by the earth surface. The law of Stefan-Boltzmann is used to describe both components.

Soil heat flux density, G_0

The soil heat flux is the energy used for warming or cooling the subsurface soil volume. The thermal conductivity of the soil and the temperature gradient of the topsoil determine this flux. It can be expressed as:

$$G_0 = l_s \cdot (¶T_s / ¶z) \qquad [W.\ m^{-2}]$$

Where:

l_s = Thermal conductivity of the soil (W K^{-1} m^{-1});

$¶T_s/¶z$ = Temperature gradient of the topsoil (K m^{-1}).

l_s and $¶T_s/¶z$, and therefore G_0, cannot be determined directly through remote sensing techniques. However, many investigations have shown that the mid-day G_0/Q^* fraction is reasonable predictable from reflectance and vegetation characteristics (DAUGHTRY *et al.*, 1990).

This ratio between the soil heat flux and the net radiation density, *G*, is estimated according to:

$$\Gamma(t) = \frac{T_0(t)}{r_0(t)}(0.0032 r_0^{avg} + 0.0062 r_0^{avg2})[1 - 0.978(NDVI)^4] \quad [-]$$

In which T_0 is the surface temperature expressed in degrees Celsius and r_0^{avg} is the mean daily albedo value. Finally, the expression used to define the soil heat flux density is:

$$G_0 = \Gamma \cdot Q^* \qquad [W.\ m^{-2}]$$

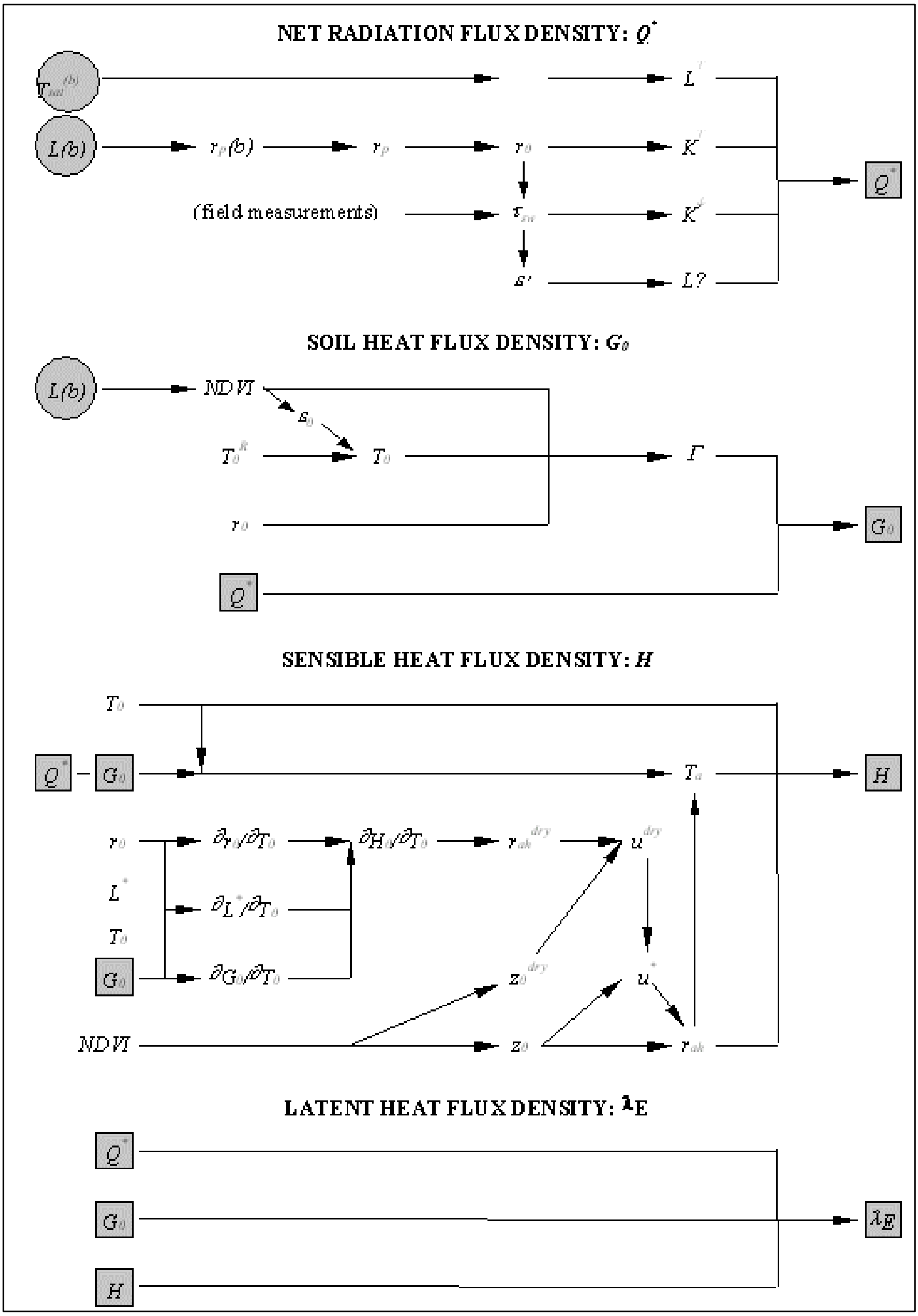


Figure 2.2: Schematisation of the SEBAL model, after BASTIAANSSEN (1995).

Sensible heat flux density, H

The sensible heat flux is the heat transfer between the ground and the atmosphere, enhanced by forced or free convection:

$$H = \frac{r_a C_p}{r_{ah}} \cdot dT_{a-sur} \quad [W.\ m^{-2}]$$

Where:

$r_a\ C_p$ = Air heat capacity [J m^{-3} K^{-1}]

r_{ah} = Aerodynamic resistance to heat transfer at a height *h* [s m^{-1}]

dT_{a-sur} = Air to surface temperature difference [K]

The aerodynamic resistance of the heat transport can be determined by:

$$r_{ah} = \frac{1}{k \cdot u^*} \cdot \left[ln\left(\frac{z}{z_{oh}} \right) - \Psi_h \right] [s.\ m^{-1}]$$

Where:

k = Von Karman constant (-);

u^* = Friction velocity (m s^{-1});

z = Reference height (m);

z_{oh} = Roughness length for heat transport (-);

Y_h = Stability correction for heat transport (-).

The slope between surface albedo and surface temperature provides essential information on the aerodynamic condition of a mixture of land surface elements (MENENTI *et al.*, 1989). Taking the first derivative of r_0 with respect to T_0 gives an expression as:

$$\frac{¶r_0}{¶T_0} = \frac{1}{K^{\downarrow}} \cdot \left(\frac{¶L^*}{¶T_0} - \frac{¶H}{¶T_0} - \frac{¶G_0}{¶T_0} - \frac{¶lE}{¶T_0} \right) \quad [K^{-1}]$$

The SEBAL program solves this equation by means of an iteration process.

Latent heat flux density, lE

The latent heat flux describes the energy used for evaporation of moisture from land surface elements. Since all the components of the surface energy balance are solved, the latent heat flux density can be determined as residual of the surface energy balance equation. Thus, it can be written as:

$$lE = Q^* - G_0 - H \quad [W.\ m^{-2}]$$

In order to determine the sensible heat flux, we need information on both the vertical temperature difference and the resistance for heat, which can be derived by examining the extreme conditions present in the images. Two conditions are distinguished, namely dry areas and wet areas.

In order to determine which pixel belongs to dry areas, a linearised theory proposed by MENENTI *et al.* (1989) is used. It has been observed that surface temperature and reflectance of inhomogeneous areas are correlated and that the relationships can be applied to determine the effective land surface properties (MENENTI *et al.*, 1989; FEDDES *et al.*, 1989). Using a simple parameterization of the relationship between soil heat flux and net radiation, and by assuming constant net radiation, air temperature and latent heat flux, a formal explanation can be given to the observed surface reflectance and temperature. At low reflectance, surface temperature increases with increasing reflectance. In this case, surface temperature may be termed as 'evaporation controlled' because the increase of the temperature is a result of the decrease of the evaporation as result of less soil moisture availability. Here the increase in excess sensible heat flux exceeds the decrease in net radiation due to increase of reflectance. Beyond a certain threshold value of reflectance, surface temperature decreases with increasing reflectance. This is due to the fact that the soil moisture has decreased to such an extent that no evaporation can take place in this case. Hence the available energy is purely used to heat up the surface. However, due to the increase of reflectance, the available energy decreases as a result of the decrease of net radiation (more is reflected away). This process leads to the decrease of temperature with increasing reflectance. Here the temperature is said to be 'radiation-controlled' (SU *et al*., 1998). A schematic representation is given in Figure 2.3. The threshold (r_t) value can then be used to determine the pixels belonging to dry areas.

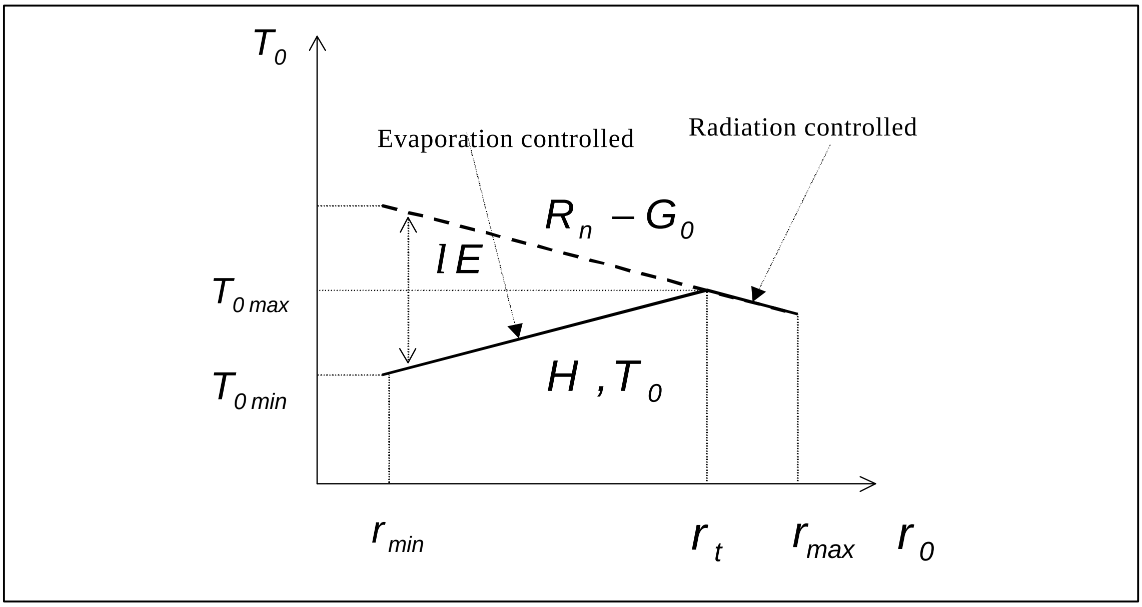


Figure 2.3: Schematic representation of the relationship between surface reflectance and temperature. The solid line denotes the relationship between temperature (and also sensible heat) and reflectance, the dashed line represents the relationship between available energy and reflectance and the difference between the dashed and the solid line gives the latent heat flux according to the energy balance.

2.1.3.2 Actual evapotranspiration calculation

The energy fluxes that are calculated by SEBAL are instantaneous fluxes with a unit of W.m $^{-2}$. For the ASTIMwR GIS oriented database application the user groups indicated that daily evapotranspiration rates in mm.day^{-1} are required as input. Therefore the instantaneous fluxes have to be converted to daily evapotranspiration values.

Extrapolation of the latent heat flux over the day is not possible because of the strong fluctuations that can occur during the day. However, the evaporative fraction remains more or less constant over the day [Bastiaanssen, 1995] and is thus much more suited to describe the partitioning of energy between the latent and sensible heat flux on a daily basis. The evaporative fraction is defined by:

$$\Lambda_{(x,y)} = \frac{lE_{(x,y)}}{lE_{(x,y)} + H_{(x,y)}} = \frac{lE_{(x,y)}}{Q^*_{(x,y)} - G0_{(x,y)}} \qquad [-]$$

Where:

L = Evaporative fraction (-)

lE = Latent heat flux density;

Q^* = Net radiation flux density;

G_0 = Soil heat flux;

H = Sensible heat flux.

The relevant daily amount of energy over a 24-hours period (Q^*_{24h}) is estimated by:

$$Q^*_{24h} = (1 - r0)K\downarrow_{24h} + L^*_{24h} - G_{24h} \qquad [J.m^{-2}]$$

Where:

Q^*_{24h} = Net radiation over 24-hour period (J.m^{-2})

K^{-}_{24h} = Incoming short wave radiation over a 24-hour period (J.m^{-2})

r_0 = Surface albedo (-)

G_{24h} = Soil heat flux over a 24 hour period (J.m^{-2})

L^*_{24h} = Net outgoing long wave radiation over a 24 hour period (J.m^{-2})

The daily soil heat flux G_{24h} is eliminated because the net soil heat flux is approximately 0 over a 24-hour period. The 24 hours incoming short wave radiation has been estimated from generally accepted data without considering cloud cover (this is realistic, as the used satellite images are cloud free). The net outgoing long wave radiation depends on the incoming and outgoing long wave radiation.

Applying the law of Stefan-Boltzmann these two components have been solved for both the surface and the air. This results in the following equation for the net outgoing long wave radiation:

$$L^*_{24h} = 8.64 \cdot 10^4 * (e_a\ s\ (T_a^{mean})^4 - e_0\ s\ (T_0^{mean})^4 - (1 - e_0)\, e_a\ s\ (T_a^{mean})^4\ )$$

Where:

L^*_{24h} = Net outgoing long wave radiation over a 24 hour period ($J.m^{-2}$)
e_0 = Surface emissivity (-), calculated as 1.009 + 0.047 ln(NDVI)
T_0^{mean} = Mean daily surface temperature (K)
e_a = Apparent atmospheric emissivity (-) calculated by $1.08\ (-\ln\ t'_{sw})^{0.265}$
T_a^{mean} = Mean daily air temperature

The daily average air temperature is obtained from meteorological data collected at nearby weather stations. The mean daily surface temperature was extrapolated from the instantaneous values that were established by the atmospherically corrected satellite data. Empirical relations between instantaneous data and daily data were applied as derived in the EFEDA-EC experiment. As in this experiment was shown that this relation is also dependent on the actual ground cover, which should not be neglected, a site specific NDVI dependent empirical relation was derived from the EFEDA-EC project (internal document, DE WIT, 1996), which reads as:

$$T_0^{mean} = \frac{T_0^{TOP}}{-0.5682\ NDVI + 1.4965} \quad [K]$$

Where:

T_0^{mean} = The mean daily surface temperature (K)
T_0^{TOP} = The surface temperature at time of pass (K)
NDVI = Normalized Difference Vegetation Index (-)

As the time of pass in the different years was almost similar and the empirical character of the equation is obvious, for all years the same equation is applied. Due to unavailable field data, validation of this relation was not possible.

The daily evapotranspiration for every pixel was calculated using:

$$ETa = \Lambda \frac{Q^*_{24h}}{l} \quad [mm.day^{-1}]$$

Where:

Q^*_{24h} = Net radiation over a 24 hour period ($MJ.m^{-2}$)
Λ = Evaporative fraction (-)
l = Latent heat of vaporization for water (2.454 $MJ.kg^{-1}$)

2.1.3.3 Time series and hydrological indicators

To investigate the possible use of NOOA-AVHRR maximum NDVI 10-days composites the following activities have been carried out:

- Data formatting and preparation of 1995 and 1996;
- Development and application of an enhanced methodology for cloud correction of NDVI values;
- Investigate possibilities to derive T_0 and r_0 values from the data that can serve as SEBAL input;
- Investigate if alternative data combinations (r_p, T_{sat}) can serve as hydrological indicators at the low resolution scale;
- Show the usefulness of cloud corrected NDVI time series for information on the hydrological situation.

2.1.4 Processing of remotely sensed data

2.1.4.1 Landsat5-TM images

General land surface characteristics for the Bullaque irrigated area

As the area covered by the Bullaque test site is relatively small, some image dependent variables can be averaged over the area. For this purpose the rounded centre co-ordinates of the Bullaque irrigated area (thus not of the satellite image) are taken as reference (latitude 39°15', longitude 4°15'). For the applied equations is referred to BASTIAANSSEN (1995). Table 2.2 shows the values calculated for the solar declination, solar angle hour, solar zenith angle and earth-sun distance for all images.

Spatial land surface characteristics derived from Landsat-TM image

In contrast to the land surface characteristics as mentioned several other characteristics are influenced by their spatial distribution and geographical position. The reflectances as recorded by the satellite sensors represent the characteristics observed at the top of atmosphere. Thus, for insight in the characteristics at land surface atmospheric corrections to recorded reflectance values are required.

Spectral radiances

For the calculation of the planetary albedo, r_p, the in-band spectral radiance ($L_{(b)}$) has to be derived from the DN-values stored in the Landsat-TM bands. The r_p calculations require $L_{(b)}$ values of 6 bands (band 6, infrared region 10.4 – 12.5 m is not considered for this purpose). In paragraph 2.3.4 the applied methodology is given.

Albedo (planetary and surface)

The planetary albedo for each band is calculated as:

$$r_{p(b)} = \frac{pL(l)_{(b)}\, d_s^2}{K\downarrow^{TOA}{}_{(b)}\, \cos q}$$

Values for d_s are given in table 2.1 and the calculation procedure for $L(\,)_{(b)}$ is explained paragraph 2.3.4. For the at the top of atmosphere in-band incoming short-wave radiation ($K^{TOA}_{(b)}$) and weight factors for the six Landsat-TM bands standard values have been used (see also DE ZEEUW, 1998). The weight factors are used to calculate the broad band planetary albedo, r_p.

The most correct procedure is to fit the planetary albedo to in-site measured surface albedo values. Hence, the fitting equation is applied to the full image. In this case however, no measured field data on surface albedo were available. Therefor, the surface albedo is derived from an atmospheric correction procedure, developed at the National Aerospace Laboratory (NLR) of The Netherlands (VERHOEF, 1997). For this procedure the in-band DN values are calibrated for a large and deep water body present in the image. Lake Torre de Abraham is used for this purpose. As the Landsat-image of 1996 shows shallowness in this lake in that specific year (high reflection values in band 2 and 3), this image is calibrated with the aid of lake Gasset which shows darker pixel values in band 2 and 3. For the darkest in-band pixel value in these lakes the background reflectance is assumed to be equal to the direct reflectance. In paragraph 2.3.4 the basic concepts of the applied atmospheric correction are given.

The in band two way transmissivity (t''_{sw}) as calculated by the NLR software could not be extrapolated to atmospheric transmissivity by simply applying weight factors to the in band t''_{sw} values. Therefor this factor is derived from the following relation:

$$t''_{sw} = \frac{r_p - r_a}{r_0}$$

Where:

r_0 = Broadband surface albedo [-]

r_p = Broadband planetary albedo [-]

r_a = Atmospheric albedo [-]

r_p and r_0 are calculated as described and r_a is assumed to be the global minimum value of r_p in the image.

NDVI

Using atmospherically corrected reflectance data of bands 3 (red) and 4 (infrared) of the Landsat5-TM images the standard *NDVI* at land surface is obtained as follows:

$$NDVI^{sur} = \frac{r_0(4) - r_0(3)}{r_0(4) + r_0(3)} \text{ [-]}$$

Where:

$NDVI^{sur}$ = NDVI at land surface [-]

$r_0(3)$ = Surface reflectance in band 3 (red) [-]

$r_0(4)$ = Surface reflectance in band 4 (infrared) [-]

For the calculation of in-band surface reflectance the mentioned NLR method is used. Negative *NDVI* values are set to zero and open water surfaces are assigned a value of 100%. Water surfaces are classified in the image as the pixels for which $r_0 < 0.09$ and NDVI < 0.09.

Surface emissivity, $_0$

In order to derive the surface temperature (T_0) from the black body temperature (T_0^R), the broad band thermal infrared surface emissivity ($_0$) has to be calculated. $_0$ is an empirical function of the NDVI (VAN DE GRIEND and OWE, 1992), restricted to the range NDVI = 0,16 – 0,74:

$$e_0 = 1.009 + 0.047\, ln(NDVI)$$

For water bodies $_0$ is set to one, pixels with NDVI values less than 0,16 are set to 0.92 and pixels with NDVI values larger than 0,74 are set to 1.

Surface temperature, T_0

Band 6 (10.4 - 12.5 m) of Landsat-TM measures emitted long-wave radiation from the earth surface and atmosphere. DN-values of band 6 are converted to spectral radiance at top of atmosphere ($L_6^{TOA}(\ )$) by:

$$L_6^{TOA}(\,l\,) = 0.1238 + \frac{(1.560 - 0.1238)}{255} DN \qquad [mW.cm^{-2}.sr^{-1}.\mu m^{-1}]$$

Satellite temperature (T_{sat}) is derived from the spectral radiance by:

$$T_{sat} = \frac{1260.56}{ln(\frac{60.776}{L_6^{TOA}(\,l\,)} + 1)} \qquad [K]$$

Applying the law of Stephan Boltzmann, the outgoing long-wave radiation at the top of atmosphere $L^{\ TOA}$ is:

$$L^{\uparrow TOA} = s\, T_{sat}^{\ 4} \qquad [W.m^{-2}]$$

where:

= Stephan Bolzmann constant ($5.67 * 10^{-8}$)

Due to unavailable ground measurements the outgoing long-wave radiation at land surface ($L8_0$) is related empirically to $L8_{TOA}$ by (SWINBANK, 1963):

$$L^8_0 = 1.20\, L8_{TOA} - 171 \ [W.m^{-2}]$$

The empirical relation as derived in the EFEDA-EC project (PELGRUM *et al.*, 1995) performed moderately and was therefore not applied. Using the Stephan Boltzmann law reversely, the black body temperature of the earth (T_0^R) is calculated by:

$$T_0^R = (L8_0 / \quad)^{0.25} \qquad [K]$$

Now the surface temperature (T_0) can be calculated as:

$$T_0 = (T_0^{R\ 4} / \quad _0)^{0.25} \qquad [K]$$

Surface roughness length, $z_{0,m}$
The surface roughness can be related directly to the calculated *NDVI* (BASTIAANSSEN, 1995). As field measurements are unavailable, the relation between $Z_{0,m}$ and NDVI as established in the EFEDA-EC project is used (PELGRUM *et al.*, 1995):

$$Z_{0,m} \quad Z_{0,h} \quad e^{(-6.65 + 6.38\, NDVI)} \qquad [m]$$

Where:
$Z_{0,h}$ = Surface roughness for heat

Incoming short wave radiation, $K^{\downarrow}$
The incoming short-wave radiation ($K^{\downarrow}$) at the surface is an area average value and is calculated as the product of the incoming short wave radiation at the top of atmosphere ($K^{\downarrow TOA}$) and the one-way transmissivity (t'_{sw}).

$$K^{\downarrow} = t'_{sw} . K^{\downarrow TOA} \qquad [W.m^{-2}]$$

Where:

$$K \downarrow_{TOA} = \frac{K \downarrow_{EXO} \cos(f_{su})}{d_s^2} \qquad [W.m^{-2}]$$

The solar constant, $K^{\downarrow}_{EXO}$ is put to 1375 W.m^{-2} (DE BRUIN, 1996). This value is taken as a constant for all the images. Values for d_s en $_{su}$ are given in table 2.2.1 and t'_{sw} is derived from the two-way transmissivity (t''_{sw}). The transmissivity is calculated on a pixel basis, but for the calculation of the area averaged incoming short wave radiation the mean value in the image subset is used. In table 2.2 the calculation results are given.

	7 July 1989	21 July 1991	18 July 1996	18 May 1997	19 June 1997	7 July 1997	6 August 1997
K TOA	1143	1130	1095	1143	1164	1158	1114
τ'_{sw}	0,726	0,787	0,694	0,770	0,825	0,872	0,862
K	830	890	760	880	960	1010	960

Table 2.2: Results of K¯ calculation for the Bullaque irrigated area ($W.m^{-2}$).

Further input variables required by SEBAL

As de ratio of $z_{0,m}$ / $z_{0,h}$ is assumed to be 1, the KB^{-1} factor (ln ($z_{0,m}$ / $z_{0,h}$)) is fixed to 2.3. The two way transmissivity is calculated for every pixel with $t''_{sw} = r_p - r_a / r_0$ resulting in an average t''_{sw} for the satellite images.

The one-way transmissivity is calculated as the square root of the two-way transmissivity.

$$t'_{sw} = \sqrt{t''_{sw}} = \sqrt{\frac{r_p - r_a}{r_0}}$$

Climatic data on air temperature at time of pass (T_a*) are very limited available. For 1989 and 1991 only daily minimum and maximum air temperatures are available for corresponding time of pass. In 1996 and 1997 an automatic weather station in Cabañeros administrated at an approximately 12 minutes interval T_a* values. An interpretation of the available data is shown in table 2.3.

	7 July 1989	21 July 1991	18 July 1996	18 May 1997	19 June 1997	7 July 1997	6 August 1997
T_{min}	14.0	18.0	15.0	5.5	10.3	13.2	11.5
T_{max}	30.0	37.0	36.0	25.4	28.1	28.9	28.9
T_{mean}	22.0	27.5	25.5	15.5	19.2	21.0	20.2
T_a*	25.0 *	30.0 *	28.3	18.6	24.0	25.2	24.0
τ''_{sw}	0.527	0.619	0.481	0.593	0.680	0.761	0.743
τ'_{sw}	0.726	0.787	0.694	0.770	0.825	0.872	0.862
$\varepsilon_2{}'^{avg}$	0.8130	0.8305	0.8558	0.7568	0.6982	0.6372	0.6516
L↓ ($W.m^{-2}$)	364	398	401	311	309	286	288

Table 2.3: Air temperature values Ta at Cabañeros weather station (1996 and 1997) and Ciudad Real (1989 and 1991) and the calculated values for L¯ with its used input. *: Estimated*

Now L can be estimated from T_a^* by:

$$L \downarrow = e_2'^{avg} \; sT_a^{*4}$$

In Which $_2'^{avg}$ is the area effective apparent emissivity of the atmosphere, empirically approached by:

$$e_2'^{avg} = 1.08(-\ln t_{sw}')^{0.265}$$

Results for the Bullaque irrigated area on these variables are given in table 2.3.

2.1.4.2 NOAA-AVHRR data

Although the principles are similar, most SEBAL input parameters are derived in a different way from NOAA-AVHRR images than from Landsat5-TM images. This is due to the different spectral information and spatial resolution of the data. Without repeating the theory from paragraph 2.1.4, the different approaches for the NOAA scale are given.

For the atmospheric correction of the images (i.e. the conversion of at satellite measurements to surface measurements) the NLR approach as applied to the Landsat5-TM data is unsuitable (the spectral satellite information is different). Therefore the NOAA data are coupled to the RACMO model (SU et al., 1998) and a Digital Elevation Model (DEM). See also paragraph 2.1.2.

Another complicating factor at the NOAA scale is the heterogeneity of land surface characteristics across the river basin; no area-averaged values can be used. Topography (including hill exposition in relation to received solar energy), vegetation cover and land use are to be considered at this scale and also the spatial distribution of the available surface radiation is of importance. Therefor a parameterization using the NOAA data, RACMO and a DEM is developed.

Finally, an improved SEBAL algorithm and RACMO's regional potential air temperature at blending height are required to establish the partition of the available surface energy. See figure 2.4 for a schematic representation of the approach and annex 3 for further details on applied mathematical functions.

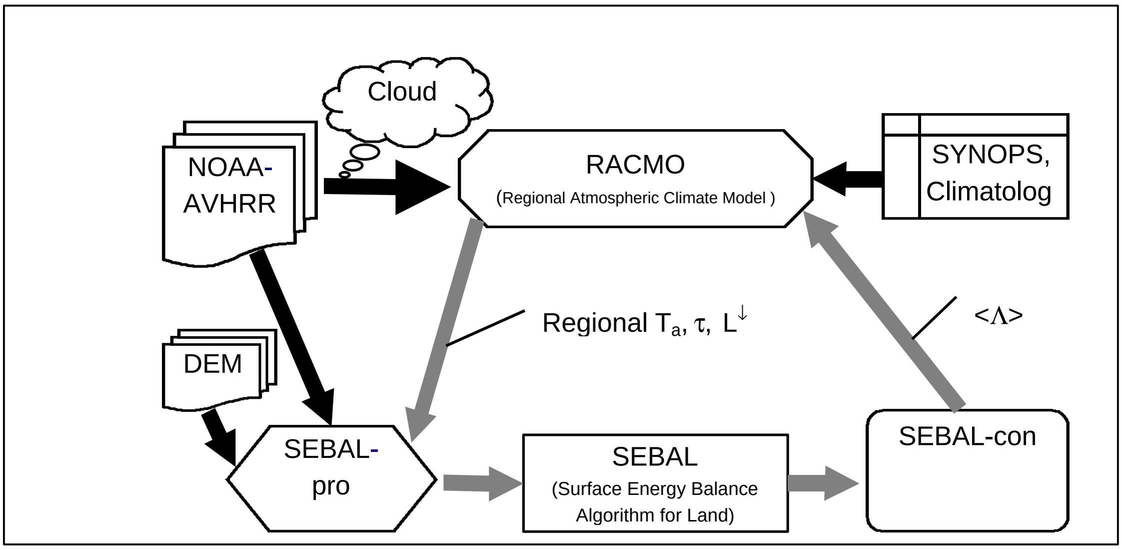


Figure 2.4: Schematic representation of the use of additional data for data pre-processing at the NOAA scale.

2.1.4.3 NOAA-AVHRR 10-days maximum NDVI composites

In annual low resolution time series cloud cover is complicating analysis of available data sets. To correct for this cloudiness different methods have been applied in the last few years. In previous papers (e.g. MENENTI et al., 1993b; VERHOEF et al., 1996) a Fast Fourier Transform (FFT) algorithm was used to perform the Fourier analysis (FOURIER, 1818; MAIN, 1990). For this FFT approach observations must be equally spaced in time and relatively error (cloud) free and equidistant in time. Therefor the algorithm Harmonic Analysis of Time Series (HANTS) was developed which can deal with time series of irregularly spaced observations and identifies and removes cloud-contaminated observations (VERHOEF, 1997). The algorithm was applied to the available NOAA-AVHRR 10-days maximum NDVI composites for the Guadiana river basin.

The algorithm considers only the most significant frequencies expected to be present in the time profiles (determined, for instance, from a preceding FFT analysis) and applies a least squares curve fitting procedure based on harmonic components (sines and cosines) (VERHOEF, 1997). For each frequency the amplitude and phase of the cosine function is determined during an iterative procedure. Input data points that have a large positive or negative deviation from the current curve are removed by the assignment of a weight equal to zero. After recalculation of the coefficients on the basis of the remaining points, the procedure is repeated until the maximum error is acceptable or the number of remaining points has become too small.

The curve fitting process is controlled by 5 parameters, which have to be set at the beginning of each HANTS run. These 5 control parameters are:

- Number Of Frequencies (NOF). A curve is described by means of (2 x NOF - 1) parameters (amplitude and phase), where NOF includes the zero frequency (mean), which has no phase. NOF has been set to 3; the selected frequencies are the zero frequency (mean NDVI) and the frequencies with time periods of 1 year and six months. So the output consisted out of 5 Fourier components (3 amplitudes and 2 phases).
- Hi/Low Suppression Flag (SF). This flag indicates whether high or low values (outliers) should be rejected during curve fitting. SF has been set to low as cloudy observations lead to low NDVI values.
- Invalid Data Rejection Threshold (IDRT). Digital numbers below or above a certain threshold value should be considered invalid. IDRT has been set to +0.7(i.e. NDVI values higher than 0.7 are rejected). In the input data a few high outliers existed.
- Fit Error Tolerance (FET). During curve fitting the absolute difference in the Hi/Lo direction of the remaining (i.e. not rejected) data points with respect to the current curve is determined. Iteration stops when the difference of all remaining points becomes smaller than the FET. The FET value should not be set too low, as otherwise the fit might be based on too few points, which gives unreliable results. FET has been set to 0.05 NDVI units.
- Degree of Over-Determinedness (DOD). The number of valid observations must always be greater than or equal to the number of parameters that describe the curve (2 x NOF - 1). DOD has been set to 13; together with the minimum of 5 time steps this gives that each fitted curve is based on a minimum of 18 observations in time, which is half of all data points.

The HANTS algorithm offers greater flexibility in the choice of frequencies and the length of the time series than the FFT algorithm. Also it is quite easy to exclude certain images from the time series since the samples are not required to be equidistant in time. The price paid is a processing time of roughly ten times that of the FFT, but this is still acceptable (approx. 20 minutes for a series of 36 images of the Guadiana river basin on a work station, if two frequencies are selected). However, due to the removal of obvious errors, the computed amplitudes and phases at the selected frequencies are much more reliable than with the direct FFT algorithm [Roerink *et al*., in prep.].

One of the disadvantages of this algorithm is that there are no objective rules to determine the HANTS control parameters. This is done on the basis of experience and after running several combinations of control parameters. Due to this fact harmonic analyses with HANTS are not considered appropriate as a system module at the user level.

In contrast to NDVI values, the data on albedo and temperature in the composites are not representative for the full decade (ten days). As a consequence within one image adjacent pixels can represent totally different environmental, climatological and atmospherical circumstances. It was investigated if T_{sat} and r_p values can be made usable as SEBAL input and if the T_{sat} / r_p relation can be used as hydrological indicator.

2.1.5 Results

2.1.5.1 High resolution maps Bullaque irrigated area

With the SEBAL program the surface energy balance has been calculated. An important step in the iterative calculation process is the manual interpretation of the threshold values of r_0 (see paragraph 2.1.3). The slope of the linear regression line is calculated as a function of the calculated resistance (r_{ah}). In table 2.4 the threshold values of r_0 are given for the different Landsat-TM images.

	7 July 1989	**21 July 1991**	**18 July 1996**	**18 May 1997**	**19 June 1997**	**7 July 1997**	**6 August 1997**
Threshold value of r_0	0.31	0.38	0.35	0.18	0.21	0.30	0.26

Table 2.4: The threshold values of surface reflectance at which pixels are considered to represent a dry situation.

In annex 4 an example is given of the surface energy balance results for the Landsat-TM image of 1991 (map 1). The net radiation (*Q**) for each pixel is equal to the sum of the soil heat (G_0), the latent heat (*E*) and the sensible heat (*H*). In map 2 of annex 4 the spatial distribution of the net radiation in relation to calculated evaporative fraction and actual evapotranspiration is shown for this specific date. For a statistical overview of the surface energy balance results of all Landsat-TM images is referred to DE ZEEUW (1998).

From these results it can be found that the influence of irrigation on the surface energy balance is evident. For the irrigated area the differences between the months of July in 1989, 1991, 1996 and 1997 are limited. Similar irrigation practices took place during these years, although climatic conditions were different. This can be clearly observed outside the irrigated area (in 1989 Q* is low, in 1991 and 1996 moderate and in 1997 high). The distribution of this total energy over its different components is varying, resulting in deviating evaporative fraction and actual evapotranspiration values in the non-irrigated areas.

The surface energy balance results have been used to establish the evaporative fraction ( ). The ratio between the latent heat and sensible heat expresses the relative quantity of energy used for evapotranspiration of the land surface. In map 2 (annex 4) an example of the spatial distribution of is given. The evaporative fraction of the irrigated crop is in general close to 1, indicating good water availability for these crops. Outside the area the evaporative fraction decreases, but values remain in general above 40% in bare soil regions, where *ETa* is mainly dictated by evaporation of bare soil, and thus with much lower potential rates than inside the irrigation area. The forest section in the northern part of the image show high values of , which could only be explained by possible water availability through deeper ground water resources. However, the SEBAL program has never undergone a good validation for forest areas. Therefor not much attention should be given to these values.

In annex 4 (map 2) also the *ETa* map of the Landsat-TM image of 1991 is presented. It is shown that in the irrigated area and the forest part in the North, *ETa* rates are high and very close to the potential evapotranspiration rates (also expressed by evaporative fractions equal to 1). Outside these areas *ETa* rates decrease rapidly to values close to zero.

Especially the four maps of the growing season of 1997 give a clear impression on how water use during the growing season develops, and that the water availability within the irrigation scheme is very good (see ASTIMwR application). This is explained by the on demand system where water scarcity is solved rather by area reduction than by irrigation practices.

The SEBAL balance results have not been validated due to a lack of required field measurements. However, compared to the EFEDA-EC project, the results are within the expected range of outcome. Furthermore *ETa* results (derived from the energy balance) have been compared to one-dimensional model calculations (SOMMA *et al.*, 1998) and showed a good correlation. For a complete overview of the high resolution results one is referred to the ASTIMwR application and DE ZEEUW (1998).

2.1.5.2 Low resolution maps

A more general overview of the hydrological situation in the whole Guadiana river basin is obtained through NOAA-AVHRR imagery. Results on the surface energy balance, evaporative fraction and calculated ETa are inserted into the ASTIMwR application for six different dates (see paragraph 2.1.2). Figure 2.5 shows for a representative pixel in an irrigated area and a pixel in a non-irrigated area the ETa as mapped on the different dates analysed during 1995. The precipitation (mm/day) is also shown in this graph.

As an example, in annex 4 (map 3), the results at NOAA scale of 2 April 1995 are given. In annex 4 (map 4) the six ETa maps of the 1995 Guadiana river basin are shown. In table 2.5 general statistical information as derived from the NOAA-AVHRR data through the SEBAL procedure are shown.

From figure 2.5 and table 2.5 it can be concluded that the NOAA-AVHRR results are more 'flattented' than the Landsat-TM results. This is explained by the higher degree of mixed spectral information obtained at this coarser resolution. The variation of the hydrological situation during the growing season is indicating mainly dry circumstances in 1995. This corresponds with the observed situation; very limited irrigation practices took place in 1995 due to the shortage of water (both rainfall and reservoirs).

The obtained results give a good spatial and temporal insight in the hydrological situation of the river basin (see also annex 4). However, with instantaneous NOAA-AVHRR data one is fully dependent on available imagery obtained under clear sky conditions. Thus NOAA-AVHRR data are an insecure source of information and in practice it will be impossible to construct equidistant time series based on these data. Therefor also the possible use of low resolution maximum NDVI 10-days composites has been investigated in this project.

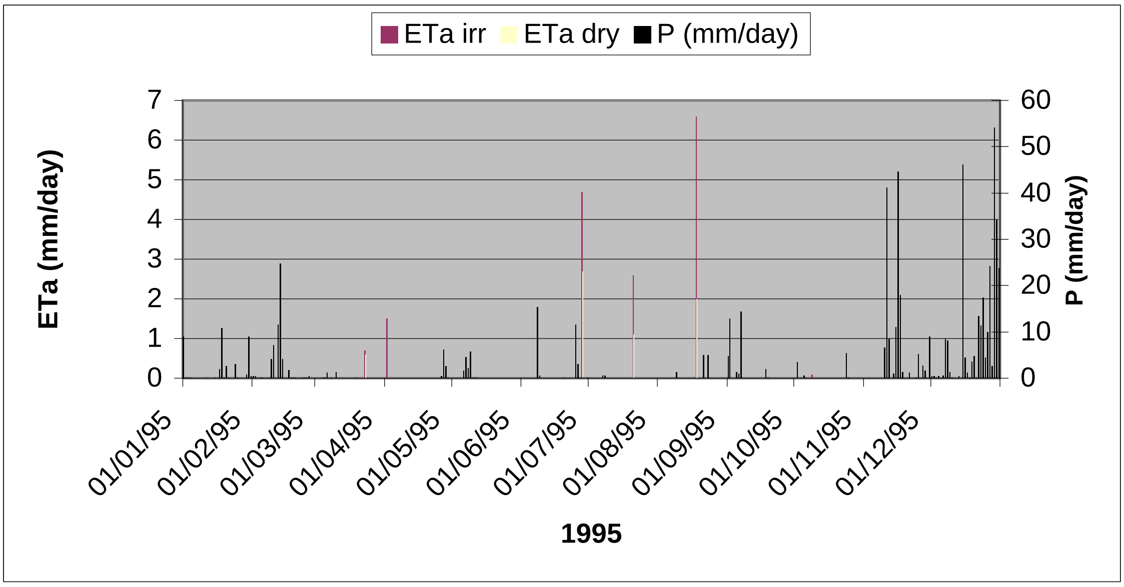


Figure 2.5: ETa values at different dates as analysed for 1995 for two different pixels within the Guadiana river basin. The 'ETa dry' represents the situation in the surroundings of Alcazár de San Juan, the 'ETa irr' represents the Bullaque irrigated area. On the second y-axis the precipitation during 1995 is shown.

Date	Q*	G0	H	LE		ETa (avg)	ETa (min)	ETa (max)
23-03-95	583	58	341	183	0.39	0.8	0	6.1
02-04-95	500	46	391	62	0.22	0.5	0	6.9
28-06-95	425	80	179	165	0.47	1.1	0	8.1
21-07-95	430	90	163	175	0.49	2.4	0	11.4
18-08-95	453	82	106	263	0.69	2.4	0	9.3
09-10-95	260	44	168	47	0.32	0.4	0	4.6

Table 2.5: Generalized overview of energy balance results (in $W.m^{-2}$), evaporative fraction (-) and actual evapotranspiration ETa (mm/day) of six analysed dates in 1995, averaged for the Guadiana river basin. For ETa also the range (minimum and maximum) of values is given.

At present, the calculation procedure is still too much research oriented to be considered an applicable tool at the user level. Too many procedures require specialized input and are too labour intensive to be automated into water management applications as the ASTIMwR system.

2.1.5.3 Low resolution times series (10-days periods)

The HANTS algorithm as applied to the available data sets of 1995 and 1996 has shown to be a useful tool for the optimization of cloud contaminated series. In figure 2.6.a. for one pixel in the irrigated area of Bullaque (1995) the original measurements per decade are given, together with the trend as calculated with HANTS. Figure 2.6.b illustrates how the trend curve is constructed as the sum of amplitudes at three different frequencies.

In figure 2.7 the same situation for 1996 is given. In figure 2.7.a the original measured values are shown during the year, the HANTS results are shown and the rejected measurements are indicated (assumed to be clouds). If one compares figure 2.6.a and 2.7.a, it is very clear by means of the NDVI that in 1996 irrigation took place, and in 1995 not (NDVI values around 0.3 during summer time in 1996 and around 0.1 in 1995).

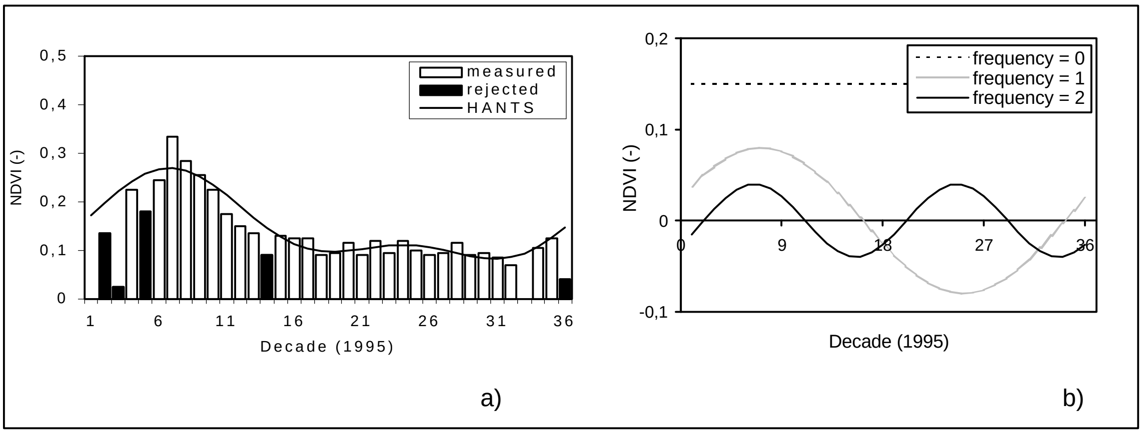


Figure 2.6: Measured NDVI values at top of atmosphere and interpolated by HANTS (a) and visualization of the three different components used to built-up the curve (b). The graphs represent the center pixel of Bullaque irrigated area in 1995.

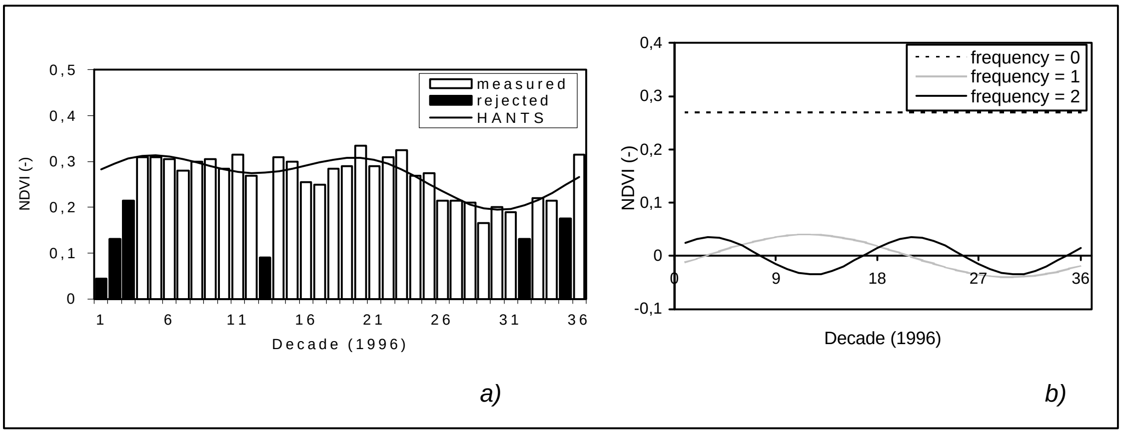


Figure 2.7: Measured NDVI values at top of atmosphere and interpolated by HANTS (a) and visualization of the three different components used to built-up the curve (b). The graphs represent the center pixel of Bullaque irrigated area in 1996.

At the scale of the whole Guadiana river basin this tight link between NDVI and water availability is clearly shown in map 5. In 1996 NDVI values are considerably higher than in the much dryer year 1995, especially in the areas with irrigation facilities.

The disadvantage of the applied HANTS algorithm is that there are no objective rules to determine the control parameters. This is done on the basis of experience and research trials. As a result, the application in its current form can not be integrated as an automated module into the ASTIMwR application.

Applying the HANTS algorithm on albedo and temperature values

To create input data for SEBAL not only NDVI values but also the related original NOAA-AVHRR spectral information should be corrected; not only for cloud cover, but also in order to get representative values for each 10-days period.

Figures 2.8.a and b show how T_{sat} (band 4 NOAA-AVHRR) values and r_p values develop through time (1995). Where albedo values are still simple to simulate, temperature values are not. Not only extreme values caused by cloudiness are filtered out, but also the variation within the seasons, which is not desirable.

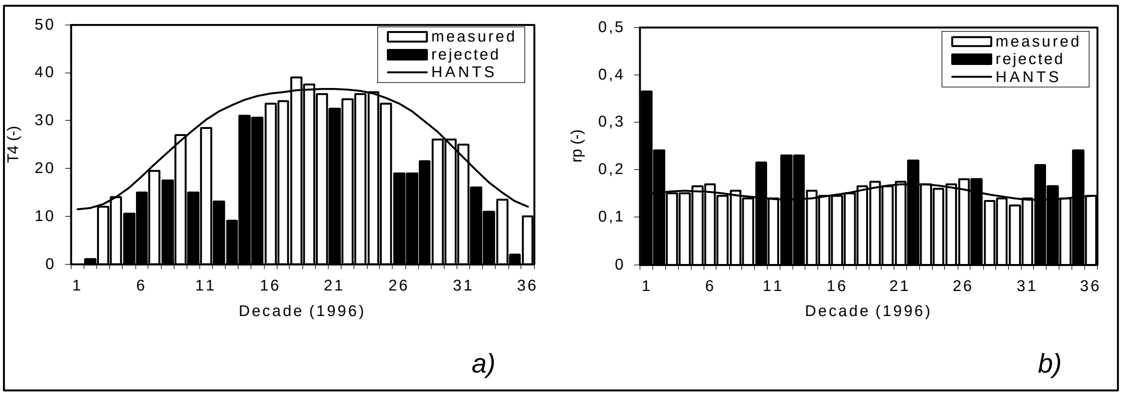


Figure 2.8: Measured T_{sat} values (band 4 NOAA-AVHRR) with the HANTS derived curve (a) and rp values with a fitted HANTS curve (b). The graphs represent the centre pixel of Bullaque irrigated area in 1996.

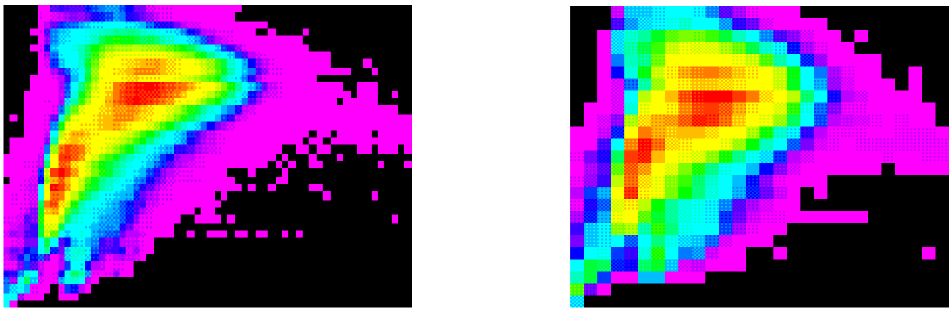
However, the meaning of these regenerated values is doubtful. The r_p values are within an acceptable range of deviation and can be assumed representative for a decade, but the temperature values only reflect very general seasonal trends, instead of decade specific climatological variation for the chosen year. Above that, a random selected T_{sat} value within one decade is far from representative for that specific decade, especially in irrigated areas where the influence of water availability on surface temperature is large and can vary within one decade from a saturated to a dried-out situation.

Also practical limitations were encountered in the process of atmospheric correction. Once a decade-representative value is generated, no decade representative atmospheric circumstances could be defined, as for example RACMO output is on a daily basis. This would result in a pixel based atmospheric correction, for which no raster model exists. As the quality of the input values and the resolution of the RACMO input was already shown to be insufficient, no further development of such a model has been initiated.

Based on the mentioned limitations of the maximum NDVI 10-days composites, no reliable input for SEBAL could be generated out of these data. Only regenerated NDVI values can be used as hydrological indicator. Therefor NDVI results for 1995 and 1996 (per decade) are incorporated in the ASTIMwR application. Especially the annual insight based on the relation between biomass and water availability is considered as valuable information.

The T_{sat} / r_p relation as possible hydrological indicator

To use the T_{sat} /r_p relation as hydrological indicator is only possible if the relative difference between 'warm' and 'cold' pixels is of a same shape as the T_0 / r_0 relation (i.e. atmospheric correction for a decade can be described with a linear function). This was tested with the aid of an available Landsat-TM image. Figure 2.9 shows that for a selected quarter-scene in the Guadiana river basin similar feature space plots can be generated.



a) b)

Figure 2.9: T_0 / r_0 diagram (a) and T_{sat} / r_p diagram (b) for a Landsat-TM quarter-scene in the Guadiana river basin.

It was found that at the Landsat-scale similar functions can be derived. However, after a resampling to NOAA scale, these relations do not sustain. In the near future algorithms will be investigated with more simplistic characteristics than SEBAL; for example SEBI (Surface Energy Balance Index), which is based on a linear relation between the extreme values derived from the T_0 / r_0 relation. If satisfactory results can be obtained with such an approach on instantaneous NOAA-AVHRR data, a next step could be to investigate the use of the T_{sat} / r_p relation as alternative input relation.

In theory the combination of NOAA-AVHRR maximum NDVI 10-days composites and SEBAL would be a good hydrological indicator to the users, but is in practice not applicable. No representative input data can be generated out of the time series. New opportunities might occur if simpler algorithms are developed and temperature and albedo values as measured at the top of atmosphere can be used as model input parameters.

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2.2 Irrigation Performance Monitoring

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2.2.1 Introduction

Irrigated agriculture is a large consumer of available water resources and is often characterised by low efficiency. A possible reason for disappointing low efficiency is the negative ratio between available water resources, irrigation water supply and the required amount of water to satisfy crop transpiration at a reasonable level (ASTIMwR, 1995).

Given the increasing limitations in water resources availability, irrigation efficiencies should be improved by formulating water management for an "optimal" distribution of available water volumes. The use of satellite remotely sensed in combination with ground data has proven to be a feasible alternative compared to conventional ground survey for detecting inefficient use of water. Remote sensing offers a means for regular and timely updating of the database on e.g. irrigated land. Multispectral satellite images with the support of a Geographical Information System (GIS) for manipulating large data sets can therefore contribute to the appraisal of irrigation management at a relatively low cost (MENENTI *et al.*, 1990 and D'URSO *et al.*, 1992).

2.2.2 Objectives of the module

The principal objective of the module is to implement and test a methodology to assess irrigation performance with the use of satellite data in order to improve irrigation water management and thereby enhancing water use efficiency. This objective is achieved through the following steps:

- Determination of the irrigation performance related to uniformity of irrigation water distribution;
- Determination of the irrigation performance related to optimum crop conditions;
- Determination of the irrigation performance related to actual crop conditions;
- Relating these performance indicators to on-site problems.

2.2.3 Test area

For implementing and testing the methodology four irrigation districts are chosen: Bullaque and Peñarroya in the Spanish part of the Guadiana river basin, Lucefecit in the Portuguese part of the Guadiana river basin and Paestum in the Sele river basin in Italy. The methodology and the results for the districts of Bullaque, Peñarroya and Paestum are dealt with hereafter. For more details on the study one is referred to BOSS and JACOBS (1997) and JACOBS and AZZALI (1998). The results of the study in the Lucefecit district, Portugal, can be found in SERRÃO and VOS (1999).

To fulfil the principle objective of assessing irrigation performance, a comparison will be made including both *spatial* and *temporal* aspects:

1. The spatial aspect comprises the physical differences between three irrigation districts. To fulfil this purpose three irrigation districts are selected that physically differ from each other in the way water is supplied to the fields. The irrigation districts of Bullaque and Paestum are so called *on-demand systems*, in which water within the system is conveyed by pressurised pipelines. The irrigation district of Peñarroya is a *gravity system*; i.e. water is carried to the fields by open canals. The selection of these different systems is done because irrigation performance depends largely on the *logic* of the system, i.e. the way water is distributed (BOS and NUGTEREN, 1974 and PLUSQUELLEC *et al*., 1994).

2. The temporal aspect implies a comparison of the irrigation performance of these systems *over different years* to detect systematic trends possibly present in irrigation performance.

2.2.3.1 Bullaque irrigation district

The on-demand irrigation system of Bullaque is located in the upstream part of the Guadiana river basin on the left bank of the Bullaque river, a tributary to the Guadiana river (figure 2.1).

The irrigable area of Bullaque consists of 5551 hectares, which is divided into four irrigation sectors. At the end of 1997 the dam of the reservoir of Bullaque on the Bullaque river is enlarged, increasing the current reservoir capacity to 190 $10^6 m^3$ (CONFEDERACIÓN HIDROGRÁFICA DEL GUADIANA, 1996). Water is conveyed from the dam to three water towers by means of an open, lined canal of 18.2 km length. The water towers include a set of pumps and a small elevated water reservoir for regulating the pressure in the pipe system. Storage of water for direct use is mainly done in the canal where a constant water level is maintained. The layout of the irrigation district is shown in figure 2.10.

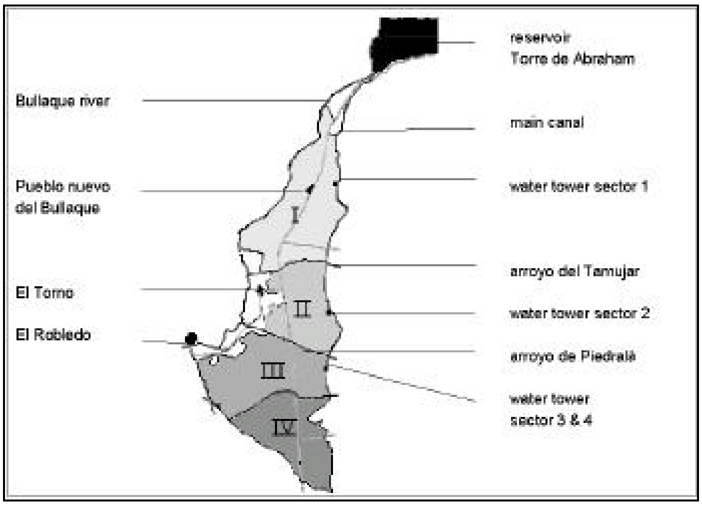


Figure 2.10: Bullaque irrigation district

Irrigation in the district takes mainly place by using water from the reservoir; the usage of e.g. private tubewells for irrigation is not common in the area. The system of water distribution of Bullaque is an “on-demand system”, in which farmers control both timing and quantity of irrigation. The flexibility of the system is high; whenever a farmer wishes to irrigate his fields, he can just turn the sprinklers on to match his water needs.

The *Comunidad de Regantes de Torre de Abraham* (Irrigation consortium of Bullaque district), founded in 1986, is the responsible body for the operation and maintenance of the distribution system and for the payment of the water charges.

The prevailing crop in the area is maize, cultivated on about 95% of the area (IRRIGATION CONSORTIUM, 1997, personal communication). Before each irrigation season (starting in April, ending in September) farmers indicate the crop they want to irrigate, which will be noted down in contracts, established by the Irrigation consortium. In years with low water availability, the organisation will only allow for a winter- spring crop (usually wheat) to be cultivated. However no control system exists on the amount of water to be distributed to the fields, which is characteristic for many on demand systems.

The *Confederación Hidrográfica del Guadiana* is responsible for the management at higher level, i.e. the operation and maintenance of the reservoir, the dam and the head of the main canal. The *Confederación* also decides on how much water is to be allocated for drinking water and for irrigation purposes.

Till 1992 water charges were calculated on basis of the number of sprinklers a farmer used in a plot. The assumption behind this is that a sprinkler has approximately the same discharge throughout the irrigation system. However, discharges actually depend on the pressure at the nozzle of the sprinkler (which will be lower in remote areas of the irrigation system). Therefore, about two hundred *contadore*s (water volume measuring devices) have been installed in 1995. Currently, water is measured per group of plots and, on this basis, water charges are calculated. Payments for water are made to the irrigation consortium after each irrigation season.

2.2.3.2 Paestum irrigation district

The irrigation district of Paestum is located on the left bank in the downstream part of the Sele river basin in the municipalities of Paestum and Capaccio, Province of Salerno, Campania, Italy (figure 2.11). The irrigated area has an extension of 11,000 ha are irrigated.

Part of the district is selected as test site and covers an area of 3,000 hectares, divided into eleven irrigation sectors served by a network of pressurised pipelines delivering water ”on-demand”. Water is conveyed from a barrage on the Sele river through a lined canal of 12 km reaching the main pumping station of the Paestum district. The water from the canal is pumped to a compensation reservoir of 45,000 m^3 placed at 120 m height approximately, from which the pressurised pipeline system starts. The layout of the irrigation district is shown in figure 2.11.

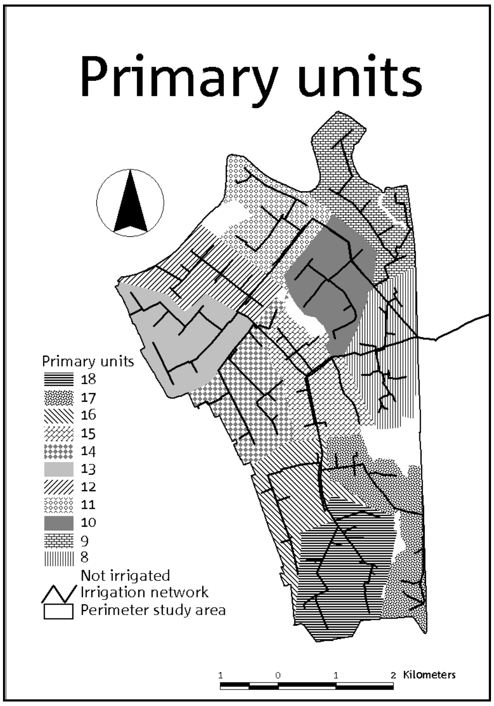


Figure 2.11: Paestum irrigation district

The system of water distribution of Paestum is an "on-demand system". As in Bullaque, the farmer opens his outlet, the piezometric level in the reservoir will drop and if the piezometric level in the reservoir reaches a certain level, the pumps will start pumping automatically from the main canal.

The *Consorzio di Bonifica di Paestum* (Irrigation consortium) is the responsible body for the operation and maintenance of the distribution system and for the payment of the water charges.
The prevailing crops in the area are artichokes, maize, fruit-trees and tomatoes. Double cropping is extensively practised in the area. Before the start of the irrigation season (lasting from March to October) farmers indicate which crop they want to irrigate. This information is formally reported in the contracts, established by the irrigation consortium. As in Bullaque no control system exists on the amount of water to be distributed to the fields.

Until now, irrigation fees have been fixed only in relation to the extension of the irrigated area. However, a first attempt is nowadays being made by the Consortium toward a taxation that includes also the effective water consumption. Payments for water are made to the Irrigation consortium after each irrigation season.

2.2.3.3 Peñarroya irrigation district

The gravity irrigation district of Peñarroya is located in the upstream part of the Guadiana river basin on both banks of the *Guadiana Alto*, after which the river disappears into the aquifer (figure 2.1).

The irrigable area of Peñarroya amounts to 7,842 hectares, spread out over 10 sectors. The dam of Peñarroya was finished in 1959 and its reservoir capacity is 47.5 x $10^6 m^3$. Irrigation of all sectors started in 1980. The canal has a discharge of 10 m^3/s and a total length of 7.1 km. At *Partidor Santa María,* water is split into two main canals: The *Canal Principal de la Margen Derecha* (right bank main canal, discharge at head equals 7.5 m^3/s) and the *Canal Principal de la Margen Izquierda* (left bank main canal, discharge at the head equals 2.5 m^3/s). From these main canals the water is diverted into secondary and tertiary canals with a total length of 46.6 km. The irrigation district is shown in figure 2.12.

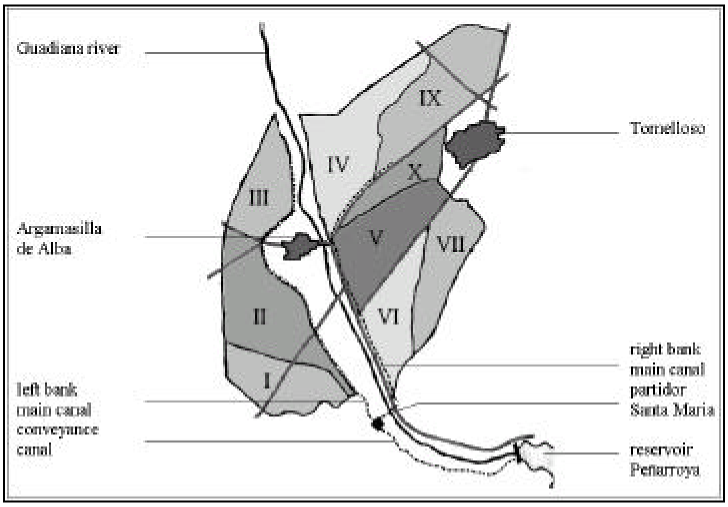


Figure 2.12: Peñarroya irrigation district.

In the main and secondary canals the water is distributed to the tertiaries by means of a duckbill weir (broadcrested overflow structure) to maintain a constant upstream water level and a modified neyrpic type undershot structure as an inlet for the distributaries. The outlets from the tertiaries to the field channels consist of simple blocks in the tertiary canal with an outlet to the field channel, which are either open or closed. All main, secondary and tertiary canals are lined and operate at continuous flow in the main canals.

Apart from using canal water for irrigation, the usage of private tubewells is quite common in the area. The prevailing crop types in the irrigation season are grapes and melons.

The Irrigation consortium of Peñarroya is responsible for the operation and maintenance of the irrigation system from the *Partidor Santa Maria* to the field channels. For operation of the system, ten *vigilantes* (water guards) are employed, one for each sector. The water guards are responsible for the setting of the outlets. In the Peñarroya district, arranged demand schedules (CLEMMENS, 1987) are adopted for irrigation water distribution. At the beginning of the irrigation season (April - May), a calculation is made of the available water for irrigation divided by the area of the irrigation district. Thus, a total amount (volume) is calculated and assigned per hectare for the whole season, independent of the crop type. The total amount is translated in hours, calculated on the assumed discharge of 30 l/s[1].

Farmers have to submit a petition to the Irrigation consortium of the irrigation district requesting the needed irrigation hours (AZZALI and D'URSO, 1997). The water guard will assign him a time when and for how long he can take the water (depending on the water available and the plot size). Before requesting water, a payment has to be made to the account of the Irrigation consortium and this will be registered in a contract. After the daily allocation of water the total amount of water to be distributed to the different sectors will be calculated and communicated to the operators of the dam.

The distribution system of Peñarroya differs substantially from that of Bullaque and Paestum. Basically it is the type of *distribution* system (water is conveyed through canals instead of pressurised pipelines) that causes the following differences. Firstly the way water is *allocated:* farmers in the Peñarroya district get fixed quantities of water per hectare, depending on the water available in the district, whereas in Bullaque and Paestum, farmers fully control quantities of water supplied to their fields. Secondly, the *timing* of irrigation: farmers in the Peñarroya district have limited control over the timing of irrigation while in Bullaque and Paestum, farmers fully control when they are going to irrigate. Finally, apart from differences in infrastructure, the occurrence of private tubewells for irrigation is more frequent in Peñarroya than in Bullaque and Paestum. Generally put, water distribution in the irrigation district of Peñarroya is less flexible.

2.2.4 Methodology applied

2.2.4.1 Irrigation Performance Indicators

To quantify irrigation performance, three Irrigation Performance indicators relating to different water allocation policies are considered (MENENTI *et al.*, 1989)[2]. The functioning of the irrigation systems is hereby evaluated at three levels, where the quantity and quality of the required information increases from the first to the third indicator:

---

[1] Assumed here is that the discharge reaching the fields is always the same (30 l/s). This is a rough and rather incorrect assumption, for in a gravity system like Peñarroya, seepage losses in the canals can be substantial (even with lined canals), which without corrective measures results in quite uneven discharges reaching the fields (MEIJER, 1993).

[2] The use of the irrigation performance indicators to evaluate irrigation performance has been developed and tested with good results in two research projects, in the Po river plain, Italy and in Mendoza, Argentina. The results are described in detail in e.g. VISSER *et al*., 1989; MEUWISSEN, 1989 and MENENTI, 1990.

1. Allocation of irrigation water proportional to the irrigated area (IP1). *Irrigation efficiency* is defined as the ratio of the amount of water applied to one hectare of irrigated land within a specific reference unit and the amount of water applied to one hectare in the larger unit of which the reference unit is a part. The indicator measures deviations from uniform water allocation. The allocation is not usually related to the actual water requirements but to the potential water requirements. In case of an on-demand system, IP1 may show *random variations*, not necessarily structural over the years, while in the case of a gravity system where canal seepage and resulting head- tail differences might occur, *structural variations* in IP1 are expected[3].
2. Allocation of irrigation water to match crop water requirements (IP2). *Irrigation efficiency* at this level is defined as the ratio of water requirements of the crops and the quantity supplied to each crop. Crop water requirements are likely to be more uniformly met in an on-demand system than in a gravity system because of the higher flexibility of the system. Farmers in on-demand systems are able to anticipate quickly to weather conditions and e.g. a peak in water demand (PLUSQUELLEC *et al.*, 1994), whereas farmers in gravity systems first have to apply for water.

Allocation of irrigation water in relation to the actual evapotranspiration i.e. which portion of the water applied has actually been used on crop evapotranspiration (IP3). Irrigation efficiency at this level is defined as the ratio of actual evapotranspiration resulting from irrigation (= total actual evapotranspiration – actual evapotranspiration resulting from rainfall) and the quantity of irrigation water applied. This actual evapotranspiration is calculated with a model that simulates the soil water balance throughout the irrigation season.

The definitions of the performance indicators used in the study are shown in table 2.6 below.

$\mathrm{IP1}_{ij} = \dfrac{V_{ij} / A_{ij}}{V_i / A_i}$	$\mathrm{IP2}_{ij} = \dfrac{\sum_{k=1}^{k=n} Ep_k * A_{ijk} * 10}{V_{ij}}$	$IP3_{ij} = \dfrac{\sum_{k=1}^{k=n} \left(\left(Ea_{k,w} - Ea_k \right) * A_{ijk} * 10 \right)}{V_{sim}}$
In which:		
V_i	= Volume supplied to unit i (m^3);	
V_{ij}	= Volume received at reference unit j, within higher order unit i (m^3);	
A_i	= Irrigated area in unit i (ha);	
A_{ij}	= Irrigated area in reference unit j, within higher order unit i (ha);	
A_{ijk}	= Area of crop k in unit j (ha);	
n	= Total number of crops k.	
E_{pk}	= Potential evapotranspiration of crop k (mm);	
$Ea_{k,w}$	= Actual evapotranspiration of crop k following the application of an irrigation volume V_{ij} (mm);	
Ea_k	= Actual evapotranspiration that would occur without any irrigation (mm);	
V_{sim}	= Volume of water supplied to unit j according to simulation model (m^3).	

Table 2.6: Performance indicators.

[3] *Random variations* are defined as variations caused by coincidences which are not yearly repeated. *Structural variations* are considered a trend which is yearly repeated.

To calculate the Performance indicators the following data are needed:

- Volumes of water supplied to each reference unit;
- Location and distribution of cultivated / irrigated area, derived from satellite data;
- Location of the boundaries of the command areas for the canal network.
- Meteorological data to calculate the reference evapotranspiration (E_0);
- A crop map and a crop coefficient (Kc) map, information derived from satellite data;
- The data collected to calculate IP2;
- Leaf area index and soil cover maps, derived from satellite data;
- Hydraulic characteristics of the soil (van Genuchten Parameters, VAN GENUCHTEN, 1980);
- Hydrological model (SWAP / SIMODIN).

The performance indicators are calculated for the total irrigation seasons and, if multi-temporal imagery was used for that particular year, at the decades covering the acquisition dates of the satellite images.

2.2.4.2 Data acquisition

Satellite data
The acquired images are listed in table 2.7 below.

District	Date	Satellite	Sensor
Bullaque	15-07-1989	Landsat 5	TM
	21-07-1991	Landsat 5	TM
	18-07-1996	Landsat 5	TM
	18-05-1997	Landsat 5	TM
	19-06-1997	Landsat 5	TM
	05-07-1997	Landsat 5	TM
	06-08-1997	Landsat 5	TM
Peñarroya	24-07-1989	Landsat 5	TM
	28-07-1991	Landsat 5	TM
	11-07-1996	Landsat 5	TM
	13-04-1997	IRS-1C	LISS-III
	24-06-1997	IRS-1C	LISS-III
	18-07-1997	IRS-1C	LISS-III
	15-08-1997	Landsat 5	TM
Paestum	30-05-1997	Landsat 5	TM
	17-07-1997	Landsat 5	TM
	18-08-1997	Landsat 5	TM

Table 2.7: Remote sensing data.

Meteorological data
For Bullaque and Peñarroya, the meteorological input data required for the calculation of potential evapotranspiration (see below, section “data processing”), except the sunshine hours, origin from the meteorological station Cabañeros. The sunshine hours origin from a meteorological station in Ciudad Real and have been collected at the *Instituto Nacional de Meteorología*, Madrid. Meteorological data for Paestum is collected from a field station in the area.

Field data
Volume data used for irrigation for Bullaque and Peñarroya are gathered at the Irrigation Consortia. For Bullaque, measuring devices are installed at secondary unit level (since 1996) and volumes consumed are noted down at the end of the irrigation season. For Peñarroya, total volumes consumed are derived from the written water petition forms.

For Paestum, volume-measuring devices are installed at both primary and secondary unit levels. At primary level, volumes are read and noted down every 3 days during the irrigation season. At secondary level, volumes are noted down only at the end of the irrigation season (see 2.2.3).

Groundtruth information is gathered during the irrigation season of 1997. This includes crop types, crop stages, height of the crops, soil cover values (% of crop coverage) and Leaf Area Index (LAI) values.

In the districts of Bullaque and Paestum, soil samples to determine the soil hydraulic characteristics, have been taken.

2.2.4.3 Data pre-processing

The pre-processing of satellite data included a geometric and atmospheric correction.

Geometric correction
All images have been geometrically corrected to the UTM system. The transformation errors were within 1, indicating that the average deviation from the source did not exceed 1 pixel (30 metres for Landsat and 25 metres for IRS images).

Atmospheric correction
In case Landsat images are used (districts of Paestum and Bullaque), Kc maps based on ground reflectance values have been created. The Digital Numbers of each band (DN_b) therefore have to be converted to ground reflectance values and later converted into the surface albedo. Furthermore, for Bullaque, a *multi-temporal classification* has been performed. An atmospheric correction is required to obtain comparable measurements of reflectance values between the sensor bands at the different dates. The reason is that the RS images are acquired on different dates and thus show different atmospheric conditions. For Peñarroya, significant errors were made to perform atmospheric corrections but some crucial parameters were missing (i.e. response functions for IRS sensors) which led to unsatisfactory results. These images have therefore been classified separately.

Calibration

First, a calibration of the Landsat images was done to convert Digital Numbers (DN_b) to radiance $L_{s,b}$. For Landsat TM, the radiance in each band can be described as:

$$L_{s,b} = A_0 + A_1 * DN_b$$

In which:

A_0 = Offset; $(W/(m^2 \cdot mm \cdot sr))$

A_1 = Gain; $(W/(m^2 \cdot mm \cdot sr))$

$L_{s,b}$ = Spectral radiance in band b, as measured in the satellite. $(W/(m^2 \cdot mm \cdot sr))$

With only calibration, no useful information is achieved. The planetary reflectance r_p is introduced here to compare different images:

$$pL_{s,b} = r_{p,b} E^0_{s,b} \cos q_s / d^2$$

In which:

$r_{p,b}$ = Planetary reflectance (reflectance on the top of the atmosphere) in band b;(-)

$E^0_{s,b}$ = Solar constant, i.e. the irradiance of the sun outside the atmosphere, perpendicular to the direction of the sun. $(W/(m^2 \cdot mm))$ in band b;

q_s = Zenith angle (rad, °);

d = Relative earth-sun distance in astronomical units (-).

Combination of these formulas results in:

$$r_{p,b} = \frac{p\,(A_0 + A_1 * DN_b) d^2}{E^0_{s,b} \cos q_s}$$

The calibration data used are listed in table 2.8.

Band	A0	A1	$E^0_{s,b}$ (W/m^{2}μm)
TM 1	-0.06662	0.04979	129.2
TM 2	-0.15732	0.11958	150.0
TM 3	-0.11269	0.07827	104.3
TM 4	-0.23286	0.12564	134.0
TM 5	-0.08640	0.02750	47.59
TM 7	-0.05114	0.01734	18.78

Table 2.8: Calibration data (EPEMA, 1990).

Applying the formula for the planetary reflectance, corrections are made for:

- Influence due to difference in seasons (through d);
- Sensitivity of the sensor (through A_0 and A_1);
- Position of the sun (θ_s).

Calculation of ground reflectance r_g

This procedure of $r_{p,b}$ calculation increased the internal comparability between the different images. To transform the calculated $r_{p,b}$ values into ground reflectance values r_g, use was made of the darkest pixel method, developed by Verhoef (VERHOEF, 1992 and VERHOEF, 1997). The darkest pixel concept is used here to estimate the aerosol optical thickness τ_A with the use of ρ_{so} (bi-directional reflection of the atmosphere itself) by inversion of an atmosphere model. The results are gain and offset values for each band for background reflectance values of 0% and 100%. The procedure to estimate the actual background reflectance is explained in Annex 5. With the known planetary reflectance r_p and the estimated background reflectance, the ground reflectance values r_g could be calculated.

Evaluation atmospheric correction

Since no field measurements of ground reflectance values were available to evaluate the results of the atmospheric corrections, mean ground reflectance values for different “stable objects” are determined and compared at different acquisition dates. “Stable objects” are objects that have similar ground reflections during the year, e.g. coniferous forest or urban areas. As an example, in the Paestum district calculated reflectance values of the urban area Battipaglia[4] (adjacent to Paestum) were compared. The before and after atmospheric correction situations are shown in figure 2.13 and 2.14.

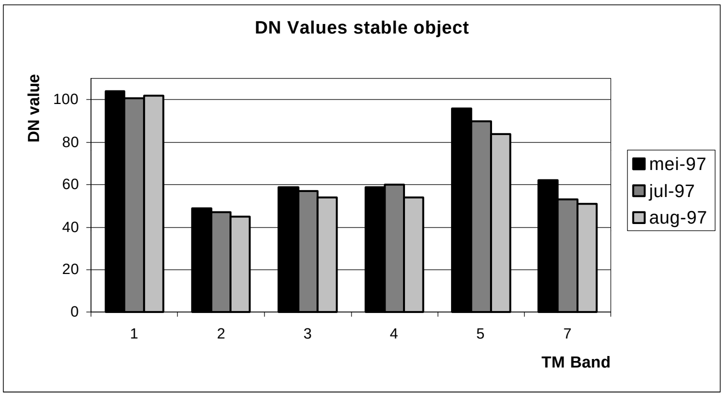


Figure 2.13: DN values Battipaglia before atmospheric correction.

[4] A representative stable area, within the town of Battipaglia, of 5*5 pixels (2.25 ha) was chosen to determine average DN and reflectance values on all three images.

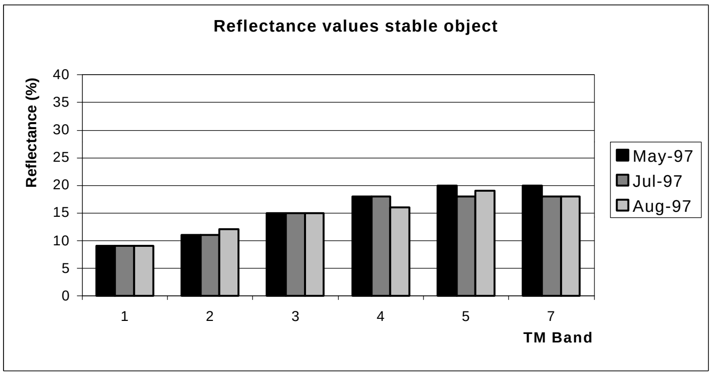


Figure 2.14: Spectral reflectance Battipaglia after atmospheric correction.

It can be seen from the figures that the reflectance values of the stable objects do not deviate much per band in the different months (standard deviation between 0 and 1.2), whereas the DN values do differ very much (standard deviation between 1.5 and 6). The results were satisfactory and similar to the results of Bullaque. The resulting reflectance maps were used for all further image processing.

2.2.4.4 Data processing

Irrigation Performance Indicator 1 (IP1)

The calculation of performance indicator 1 is the least complex of all indicators:

$$\mathrm{IP1}_{ij} = \frac{V_{ij} / A_{ij}}{V_i / A_i}$$

A crop map has to be made from which the area irrigated A_{ij} has to be extracted. An example of Paestum 1997 is used here[5].

In June and July 1997 ground truth data for about 60 parcels are collected: the crop type and the Leaf area index is measured. Volume data on primary and secondary unit level was also available.

Since the irrigation district of Paestum is multi-cropped throughout the year a multi-temporal crop classification is necessary. Several multi-temporal classifications have been tested and the results are presented in table 2.9.

[5] For information on IP1 Bullaque and Peñarroya, the reader is referred to JACOBS and AZZALI, 1998.

Several agglomeration techniques were applied and compared for the definition of spectral features of each class. Separability and reliability indexes (D'URSO & MENENTI, 1995) were used to evaluate which technique gave the best results. Fifteen different sets of signatures, corresponding to different statistical clustering criteria, were derived from the approximately 70 polygons extracted in the Landsat TM images of Paestum. The plots set, corresponding to a multivariate set (the variates being the spectral characteristics of each plot), were agglomerated by means of clustering techniques.

Class separability was estimated accordingly to the Jeffries-Matusita distance; the resulting separability index JM^* are given in table 2.9. In the second stage of the procedure, the above mentioned training sets were used to carry out maximum likelihood supervised classifications.

For each classified image, rejection classes were created by thresholding and the reliability indexes A^* was calculated. Table 2.9 shows the resulting values together with those corresponding to the global performance indicator CP=JM•A*.

Classifications	Remarks	JM*	A*	CP
A: 60 cl, ML, PC	Overestimation of bare soil	0.901	0.528	0.475
B: 58 cl, ML, PC	Overestimation of bare soil	0.902	0.496	0.447
C: 60 cl, MD, PC	Overestimation of bare soil	0.901	0.647	0.583
D: 61 cl, ML, NDVI	Worthless A*	0.973	0.338	0.329
E: 61 cl, MD, NDVI	Worthless A*	0.973	0.375	0.365
F: 60 cl, ML, MJA	Worthless A*	0.997	<0.2	<0.2
G: 60 cl, MD, MJA	Worthless A*	0.997	<0.2	<0.2
H: 58 cl, MD, PC	Lot of bare soil	0.901	0.599	0.539
I: 57 cl, MD, PC	Very little bit bare soil	0.903	0.543	0.491
J: 64 cl, ML, NDVI	Very good classification	0,903	0,566	0,512
K: 18 cl, ML, NDVI	Good classification	0.876	0.587	0.514
L: 64 cl, MD, NDVI	No Fruit trees, River misclassified	0.903	0.726	0.656
M: 18 cl, MD, NDVI	No Fruit trees, River misclassified	0.876	0.663	0.581
N: 60 cl, ML, PC	Very good classification	0.909	0.513	0.467
O: 59 cl, MD, PC	Good classification	0.910	0.577	0.525
P: 66 cl, ML, NDVI	Best classification	0.932	0.555	0.517
In which:				
JM* = normalised seperability index (JM / JM_{max})				
JM = Jeffries-Matusita index, $JM_{max} = \sqrt{2}$				
A* = normalised thresholding index				
CP = Global performance indicator (CP = JM* • A*)				
Cl = Classes				
ML = Maximum likelihood				
PC = Principle component				
NDVI = Normalised difference vegetation index				
MJA = May July August				

Table 2.9: Results of crop classification.

The first column of table 2.9 describes the method of classification: the number of classes, the classification method and the type of multi-temporal image on which the classification is performed. Three different multi-temporal images have been created: An image of the three principle components of the three dates (3 bands), an image of the three NDVI values of the three dates (3 bands) and an image of the ground reflectance values in band 2,3,4 and 5 of the three images (12 bands).

The second column describes the visual evaluation of the classified image. The third column describes the separability of the spectral signatures of the ground truth fields. The fourth column describes the result of thresholding the classified image. The final column describes the global performance of the classification.

In general, the higher the global performance the better the classification[6]. However, a visual, thus subjective, evaluation of the classification is also needed. A general remark is that higher salt and pepper effects occur when classified with the Maximum Likelihood while the Mahanalobis Distance method misclassifies the archaeological site in the study area and underestimates the area cultivated with fruit trees. Comparing the results presented in the table it is clear that there are no significant differences in global performance in the four bold printed classifications. Based on a visual interpretation of the maps the best of the four (classification "**P**") is chosen. This results in a raster map of the different crops from which the area irrigated A_{ij} is extracted for each reference unit.

Volume data V_{ij} were gathered as described at the beginning of this section. To be able to calculate IP1 values at the decade covering the acquisition dates of the satellite images, volume data that apply to these dates are needed. These are available for the primary units (where measurements took place every three days) but not yet for the secondary units. Therefore, the fraction of water given in the decade of interest at primary unit level compared to the total (yearly) volume given to that unit is determined. This fraction is multiplied by the seasonal volumes of each secondary unit to determine Vij values at the decade.

With the calculated Aij and known Vij values, IP1 can now be calculated.

Irrigation Performance Indicator 2 (IP2)

The second performance indicator is more complex than the first one due to the requirement of the calculation of the potential evapotranspiration for each crop, Ep_k:

$$\mathrm{IP2}_{ij} = \frac{\sum_{k=1}^{k=n} Ep_k * A_{ijk} * 10}{V_{ij}}$$

6 This global performance indicator and its' two components are extensively described in D'URSO and MENENTI (1996).

The potential evapotranspiration Ep_k can be determined in several ways. Here, two different methods for IP2 calculation are applied. The first method, applied in the case of the irrigation districts of Bullaque and Peñarroya, is a hybrid classification approach to determine crop water requirements. The second method, used for Paestum, is an analytical approach. The two approaches will be explained using the examples of Bullaque and Paestum.

A. Bullaque 1997

In the last week of May, 1997, groundtruth data (crop information) was collected in the field for several parcels in the district. A total number of 106 polygons indicating descriptions of cereals, maize (summer crops are for 95% maize crops), bare soil and uncultivated land have been digitised on the screen. Apart from crop type descriptions, LAI values have been measured. These LAI measurements were repeated for 8 selected fields on 28-6-1997. The crop description and the LAI values were stored as attributes for the groundtruth vector file. These attributes will be used to form Kc groups of crops at different growth stages. The volume data for 1997 has been collected at the Irrigation Consortium of Bullaque. This data has been aggregated to secondary and primary unit level.

After the atmospheric corrections, NDVI maps (for Landsat 5 TM: [(4-3)/(4+3)*200])[7] were calculated from the four images of the irrigation season of 1997. The irrigated area was first discriminated from the non- irrigated area by applying a threshold on the August image (NDVI threshold set at 75). After this, masks of the NDVI images were made from the calculated irrigated area in order to focus the classification only to the irrigated area. Since only maize is grown in the Bullaque district, no real crop classification has been made. The aim of the classification was to create classes of similar maize growth stages and measured LAI values to determine Kc values, since it has been demonstrated that crop coefficients can analytically be related to vegetation cover percentage, LAI values and growth stage (AZZALI *et al*., 1991; JENSEN *et al.,* 1990).

A *multi- temporal classification* was performed. The four NDVI maps of the irrigated area of the different months were classified simultaneously. The four layers are stacked together, after which a clustering analysis is performed. Different numbers of clusters were tried after which the groundtruth polygons (with measured LAI values and known crop heights, h) in each cluster were located and checked whether the crop characteristics of those polygons were similar. A number of 5 clusters appeared to be the most suitable.

The average values of the groundtruth information for each cluster (class) are summarised in table 2.10. The 5 crop classes are assumed to be groups of similar crop coefficients, i.e. a homogenous canopy development.

[7] Stretching (*200) is made for better visual interpretation purposes.

Date	29/05/1997	28/06/1997	29/051997	28/06/1997
	h (cm)	h (cm)	LAI	LAI
Class 1	17	72	0.2	2.00
Class 2	24	100	0.36	3.20
Class 3	35	100	0.49	3.80
Class 4	40	118	0.60	4.05
Class 5	76	243	1.14	5.60

Table 2.10: Average values groundtruth information per class.

It can be seen that class 1 is less developed (and thus later sown) than class 5 at 29 May and 28 June. Comparing relatively the values of table 2.10 for the classes, Kc values have been assigned to these 5 classes. Assigning these Kc values is based on literature (DOORENBOS and PRUITT, 1977), experimental values from Mendoza (AZZALI *et al.*, 1990) and the stage of the crop. For each stage a separate Kc value is assigned as given in table 2.11.

Class	Sowing	Harvest	Initial	Crop dev.	Mid season	Late season
1	30/04	30/09	0.25	0.65	0.90	0.70
2	30/04	30/09	0.30	0.70	0.95	0.70
3	15/04	12/09	0.35	0.75	1.05	0.75
4	15/04	12/09	0.35	0.75	1.10	0.75
5	01/04	01/09	0.40	0.75	1.10	0.75

Table 2.11: Crop classes: sowing date, harvesting date and Kc values, Bullaque 1997.

The determined Kc values for each class have been used in the Criwar program, version 2.0 (BOS *et al.*, 1996). Criwar was used to calculate the Potential Evapotranspiration (Etpot) with the Penman-Monteith method (VERHOEF and FEDDES, 1991) for 10-day periods. The resulting potential evapotranspiration values (Annex 6) are used to calculate IP2.

The IP2 values can be calculated with the total volumes applied, listed in Annex 7 and 8. To calculate *seasonal* IP2 values (during the irrigation season) at the times of the images, the average irrigation calendar as applied by farmers in the Bullaque district is elaborated in co-operation with the Irrigation Consortium of Bullaque (personal communication, 1998)[8].

B. Paestum 1997

For Paestum, IP2 is calculated using an analytical approach, in which the potential evapotranspiration is determined using the Penman-Monteith equation (MONTEITH, 1965). This equation establishes a relationship between evapotranspiration and crop factors (LAI, albedo and crop height) for a given set of meteorological variables.

[8] The irrigation calendar is determined at: Frequency: 4 days; Gifts: Start 2 weeks after sowing and end two weeks before harvesting. Total crop duration is 150 days, thus 120 irrigation days, 120/4=30 gifts on average. Sprinkler nozzles supply the same amount of water each gift (IRRIGATION CONSORTIUM, personal communication, 1998); Amount: see annex 7 and 8.

Using the equation, the albedo and LAI values need to be calculated on a pixel by pixel basis (i.e. albedo and LAI maps). An average crop height of 0.4 m can be used[9].

To calculate the albedo from reflectance values, the reflectance of the pixel in each band has to be multiplied by the weight of the solar constant in that band compared to the sum of all solar constants in all bands, after which all fractions have to be summed up:

$$r = \sum_0^b r_{g,b} * \frac{E_{s,b}^0}{\sum_0^i E_{s,b}^0}$$

In which:

r	= surface albedo;
$r_{g,b}$	= reflectance of pixel in band b;
$E_{s,b}^0$	= Solar constant in band b (EPEMA, 1990).

In order to create a LAI map, the spectral signatures of fields where LAI has been measured are extracted. In an Excel worksheet the relation has been made between the signatures of band 3 and band 4, the WDVI and a LAI is calculated (CLEVERS and VERHOEF, 1993). The relationship is based on the following equations.

$$WDVI = (R_4 - R_3 \cdot s_b)/100$$
$$LAI_{Clevers} = (-1/a_{av}) \cdot \ln(1 - WDVI \cdot 100 / WDVI_{\inf})$$

In which:

WDVI	= Weighted Difference Vegetation Index
R_3	= Reflectance in Band 3
R_4	= Reflectance in Band 4
sb	= Average slope of R3 and R4 of bare soil
LAIClevers	= Calculated LAI
αav	= Average extinction coefficient of irrigated area (0.42)
WDVIinf	= WDVI in which R3 and R4 are minimum values for irrigated area

To validate the calculated LAI values, they are compared to the LAI measured in the field. The calculated and field values appeared to deviate insignificantly (Table 2.12). Thus, the above described relationship between the reflectance in band 3 and band 4, could be used to calculate the LAI of each pixel.

9 D'URSO (n.d) shows that under conditions of high incoming radiation compared to the wind speed, the crop height is not a very important factor in the Penman-Monteith formula. This applies to both the Paestum and the Bullaque irrigation district.

Crop	**RMS**	**SD**	**# Obs.**
Artichokes	1.00	0.32	2
Maize	0.72	0.47	10
Grass	0.73	0.43	9
Tomatoes	0.74	0.45	14
Fruittrees	0.71	0.33	9
Average	0.78	0.25	44

Table 2.12: Correlation between measured and calculated LAI.

The LAI and Albedo maps are used as input for the Penman-Monteith formula to calculate the potential evapotranspiration Ep. From the potential evapotranspiration maps the Ep is extracted for each reference unit and IP2 is calculated.

Irrigation Performance Indicator 3 (IP3)

The third performance indicator is the most complex of the three since it involves actual evapotranspiration, Ea_k:

$$IP3_{i\,j} = \frac{\sum_{k=1}^{k=n}\left(\left(Ea_{k,w} - Ea_k\right) * A_{ijk} * 10\right)}{V_{sim}}$$

The actual evapotranspiration Ea_k is calculated using a computer model (SIMODIN) that simulates the soil water balance. It is based upon the SWAP model (FEDDES *et al.* 1988) which is a one dimensional soil water model and uses the van Genuchten equation (van Genuchten 1980). SWAP simulates the components of the soil water balance over time. SIMODIN runs the SWAP model for multiple soil columns at the same time. Each soil column represents a unit. The input structure of SIMODIN is shown in figure 2.15.

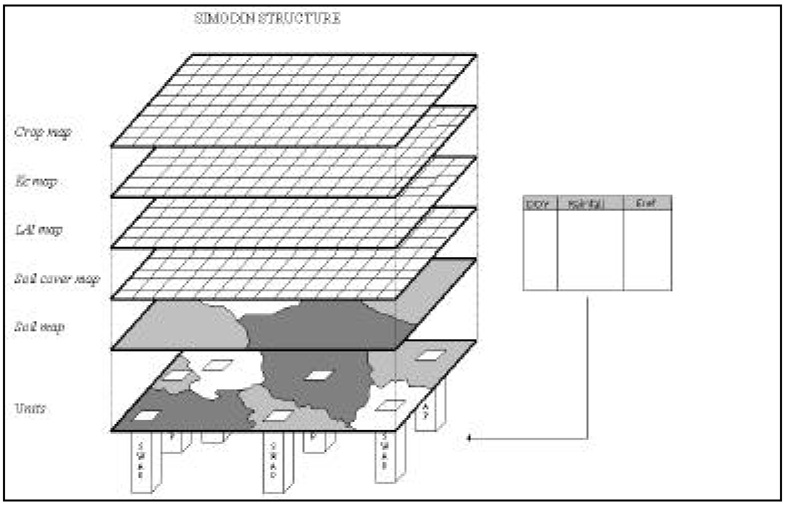


Figure 2.15: SIMODIN input structure.

The input for SIMODIN consists of three types of data that need to be calculated for each unit:

- Soil hydraulic characteristics;
- Determination of top layer boundary conditions;
- Meteorological data set.

As an example for the calculation of IP3, the irrigation district of Paestum is used. First, the hydraulic characteristics of the different map units should be determined. This is done by using the collected disturbed as well as undisturbed soil samples from the field. The soil hydraulic characteristics of the undisturbed samples are extrapolated to complete mapping units by calibration with disturbed samples. This procedure for the irrigation district of Paestum is extensively described in D'URSO and BASILE (1997) and in BASILE and D'URSO (1997). The soil characterisation process results in a soil map with known soil hydraulic characteristics, see figure 2.16.

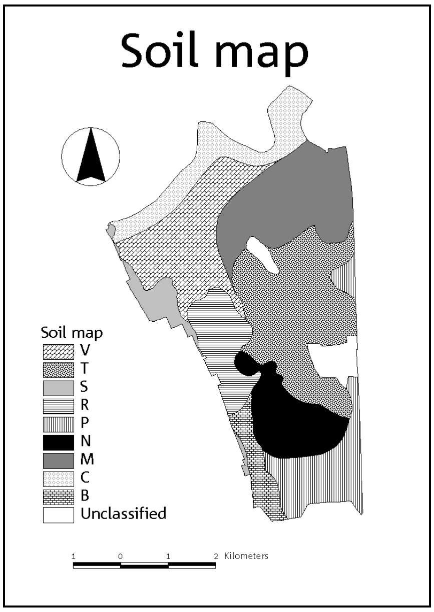


Figure 2.16: Paestum soil map

Regarding the calculation of the top layer boundary conditions, a crop map, LAI map (created for IP2), Kc and soil cover map for a number of days throughout the season are needed.

To calculate the Kc map, first the reference evapotranspiration E0 needs to be calculated. For determining the reference evapotranspiration (E0), the standard crop parameters: LAI = 2.88 and albedo = 0.23 (SMITH, 1990) are taken as input for the Penman-Monteith equation (see under IP2). Now Kc can be determined by applying the following equation:

$$Kc = \frac{Ep}{E0}$$

The measured LAI are plotted against the soil cover values (collected in the field), see figure 2.17, and the correlation is determined. The resulting correlation equation is applied in the LAI map created under IP2, to derive soil cover values per pixel.

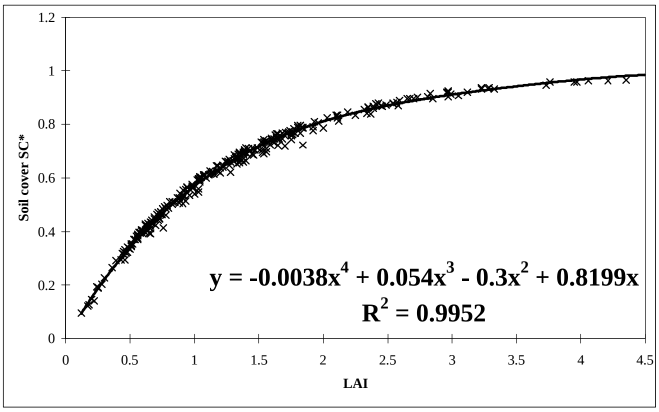


Figure 2.17: Correlation between LAI and soil cover.

With the known crop types, LAI, Kc and soil cover maps, the top layer boundary conditions as needed for SIMODIN are hereby determined.

The meteorological data are the final input data to run the SIMODIN model. The model is run for two situations. First a run without irrigation is made, to determine the actual evapotranspiration if no irrigation water would have been applied. The second run comprises a simulation of actual irrigation practice in the Paestum district.

The output from the model comprises for each unit the actual evapotranspiration values without irrigation $Ea_{k,w}$ as well as with irrigation, Ea_k, for each day of the season. Now IP3 can be calculated.

2.2.5 Results

2.2.5.1 Irrigation Performance Indicator 1 (IP1)

Practical applicability of IP1

- IP1 < 1 indicates that less water is applied to this unit than the average amount applied to the complete irrigation district.
- IP1 = 1 indicates that water applied to this unit is equal to the average amount applied to the irrigation district. On demand irrigation systems with a uniform crop distribution normally have an IP1 close to 1 over all its units.
- IP1>1 indicates that more water is applied to this unit than the average amount applied to the district.
- Acceptable IP1 values lie between 0.9 and 1.1. If these values are not met one or more of the following reasons can apply to the situation.

<u>IP1 < 0.9:</u>

- Farmers in this unit are cultivating crops that need less water then farmers in other units. This can usually be found in parts of the irrigation district where water availability is low (e.g. tail end of canal systems) or where the soils are not suitable for crops with high water requirements (e.g. very sandy soils);
- Farmers irrigate their crops much more efficiently and therefore need less water than farmers in other parts of the irrigation district;
- Use of other sources of water in this area more than in other parts of the district e.g.:
    - Private tubewells;
    - Superficial groundwater level;
    - Soils with high capacity for capillary rise.

<u>IP1 > 1.1</u>

- Farmers in this unit are cultivating crops that need more water than farmers in other units. This can usually be found in parts of the irrigation district where water availability is high (e.g. head of canal systems) or where the soils are very suitable for crops with high water requirements.
- Water supplied to farmers does not reach their fields. This can be due to losses of water from the canals and the pipelines before reaching the fields. It points to problems with the irrigation infrastructure (leaking) or to misuse (stealing) of water by upstream farmers. Another reason for this can be that farmers use the water for other than irrigation purposes;
- Water does not reach the root zone of the crops. This can happen in areas where there are high evaporation losses with sprinkler systems or high superficial water flows, due to a large gradient of the field or to a crust on the topsoil causing a very low infiltration rate;
- Water percolates rapidly into the subsoil. This can be due to a high density of macropores in the root zone or to a very high infiltration rate.

Note that this list is not complete. In every unique situation low or high IP1 values can have unique reasons. This list is merely meant as a guideline for the irrigation manager.

IP1 results Bullaque

The calculated IP1 values for 1989-1997 are listed in Annex 7 and 8. The IP1 values at secondary unit level are shown in figure 2.18 and at primary unit level in figure 2.19.

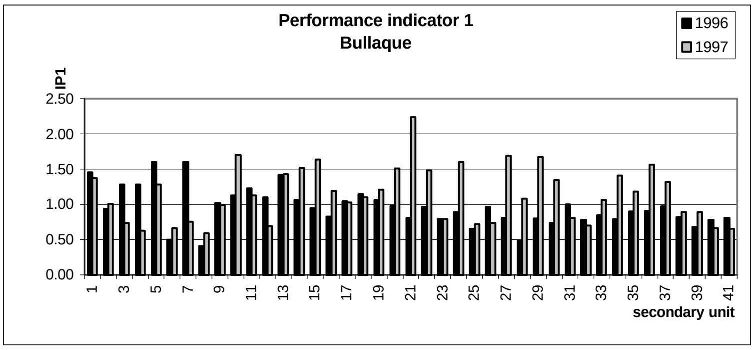


Figure 2.18: IP1 secondary unit level Bullaque 1997.

As can be seen in figure 2.18, a random variation seems to occur (as expected in an on-demand system). Because these performance indicators are based on the actual volumes supplied to the secondary units in 1996 and 1997, no head tail end differences within or between the sectors are to be expected. Since this figure is difficult to interpret due to the high number of units, a higher level, the sector level must be analysed (figure 2.19).

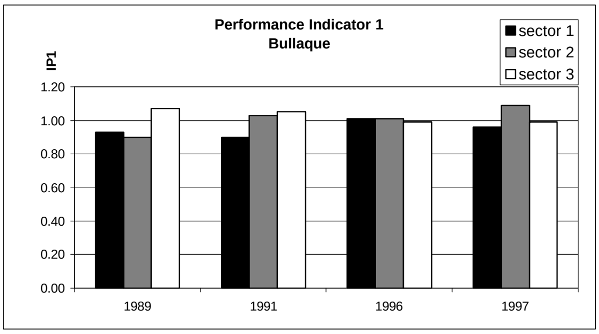


Figure 2.19: IP1 primary unit level Bullaque.

In figure 2.19 the results of IP1 at sector level are given for each year. With regard to the temporal aspect, IP1 values of the sectors are close to 1 over the years, indicating a uniform water distribution. No trend can be detected, as no similar sequence of IP1 values is repeated each year. To enhance the interpretability of the spatial aspects of the system, the weighted average over the three years per sector are calculated (BOSS and JACOBS, 1997):

$$IP1_{av} = \frac{\sum V_{ij} / \sum A_{ij}}{\sum V_i / \sum A_i}$$

In which:

IP_{1av} = Weighted average IP_1 over the years;

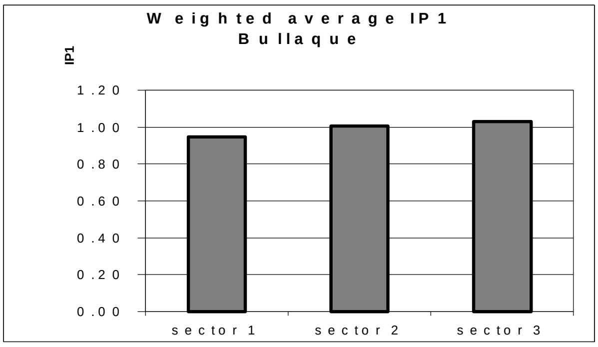
$\sum V_{ij}$ = Sum of volumes supplied to reference j in the mentioned years;

$\sum A_{ij}$ = Sum of irrigated areas of reference j in the mentioned years;

$\sum V_i$ = Sum of volumes supplied at higher order unit i in the years;

A_i = Sum of irrigated areas at higher order unit i in the years.

weighted averages are presented in figure 2.20.



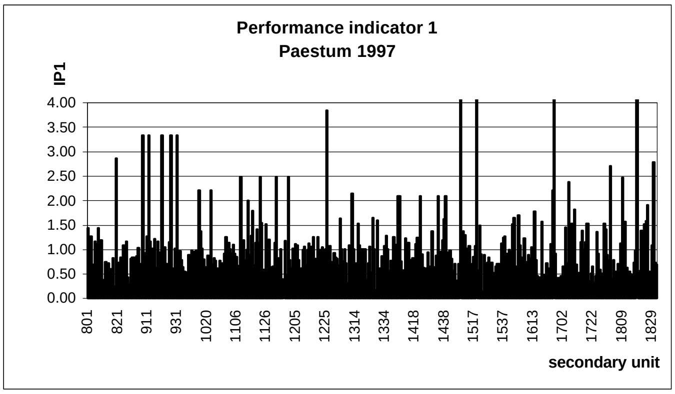


Figure 2.21: IP1 Paestum 1997 secondary unit level.

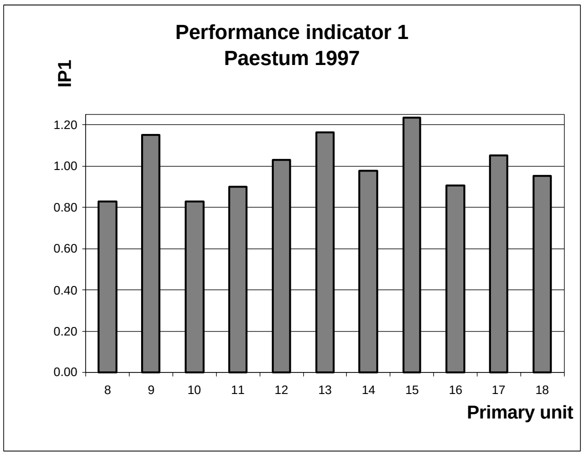


Figure 2.22: IP1 Paestum 1997, primary unit level.

IP1 results Peñarroya

The Aij and Vij values as well as the resulting IP1 values for 1997 are listed in Annex 10 and 11. The IP1 values at secondary unit level are shown figures 2.23. The left part of the figure, sector 3,2,1 represents the left bank main canal of the system, from the tail end (secondary unit T3-2) to the head end (T1-1). The right part covers the Right Bank main canal from the head end (T6-1) to the tail end (T4-1).

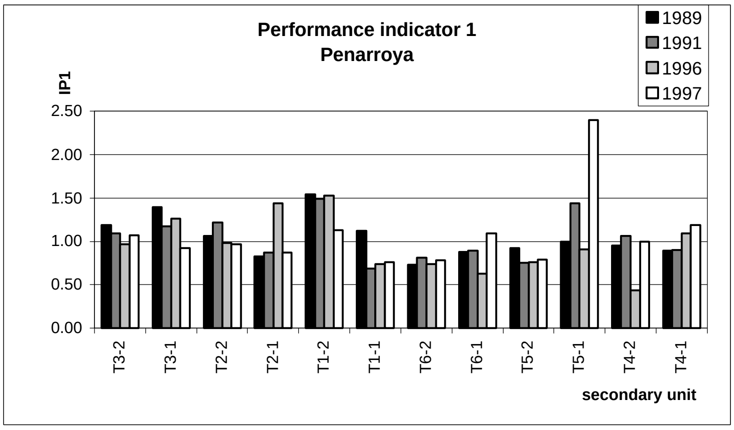


Figure 2.23: IP1 secondary unit level Peñarroya 1997.

In the figure large variations between IP1 values of the tertiary units can be seen, however it is clear that this is not a random variation. Regarding the temporal aspect, a trend can be seen in which IP1 values of a tertiary unit are more or less the same for each year. However, comparing between the tertiary units (spatial aspect) is difficult. Therefore, the weighted average is calculated for the tertiary units and is presented in figure 2.24.

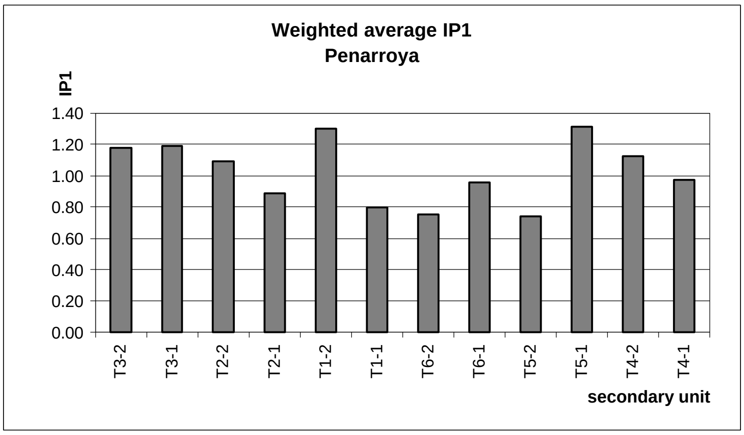


Figure 2.24: Weigthed average IP1 Peñarroya secondary unit level.

Comparing between the tertiary units, a trend can not be detected from figure 2.24. Therefore it is necessary to zoom out to a higher level of aggregation: the sector level, see figure 2.25.

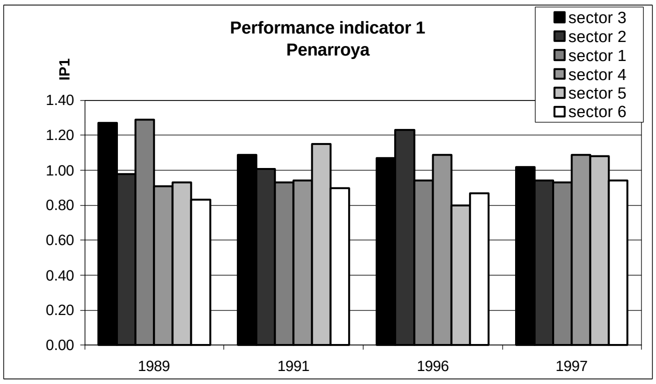


Figure 2.25: IP1 primary unit level Peñarroya 1997.

The results of IP1 at sector level as shown in figure 2.26 in which sector 3 and 4 appear to have higher values than the other sectors over the years. In order to obtain a more clear picture of the water allocation uniformity between the sectors, over the years, the weighted average of IP1 in head (inside sectors: 1 and 6) tail (outside sectors: 3 and 4) order is shown in figure 2.26 below. The location of the sectors is shown in figure 2.12.

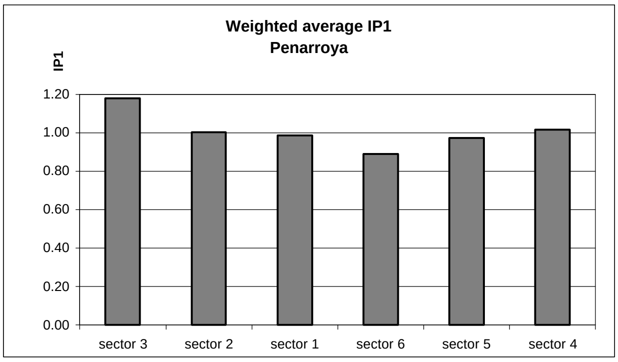


Figure 2.26: Weighted average primary unit level Peñarroya.

IP1 values deviate substantially (maximally 24%) from IP1= 1 (uniform water allocation). This means that water distribution is not uniform.

A trend is also seen, involving an increasing IP1 from the head ends to the tail ends. The value of sector 3 is 22% higher than sector 1 and the value of sector 4 is 11% higher than sector 6. Higher values at the tail sectors can be explained as follows. As mentioned, the input data for volumes used are those recorded at the Irrigation consortium. The organisation records the volume data by means of hours, assuming that a flow of 30 litres per second reaching the fields is maintained in the entire system. However, conveyance losses are likely in a gravity system; such losses can amount to values between 20-40% (BOS and NUGTEREN, 1974). If such losses are indeed present, farmers located at the tail ends will compensate for this by requesting more hours of water and the numerator in the formula of IP1 consequently increases. Such pattern results in higher values for IP1 at tail end locations as is shown in the sectors' weighted average over the years.

IP1 values on the left bank are higher than those on the right bank, probably due to the worse condition of the left bank canal compared to the right bank canal. However, since no information is available on the condition of the left and right bank main canal, no valid explanations can be offered at this point.

2.2.5.2 Irrigation Performance Indicator 2 (IP2)

Practical applicability of IP2

Acceptable IP2 values lie between 0.8 and 1.2, assuming that farmers also have to take into account factors like the irrigation calendar, soil properties, and water availability. All these factors may cause deviations from the optimum water supply. If such IP2 values are not met, one or more of the following reasons can apply to the situation.

<u>IP2 < 0.8:</u>

- Leaching requirements of the soil: Farmers apply more water to leach damaging salts to the subsoil or to the groundwater (intended percolation of water);

Water supplied to farmers does not reach the fields. This can be due to losses of water from the canals and the pipelines before reaching the fields. It points to problems with the irrigation infrastructure (leaking) or to stealing of water by upstream farmers. Another reason for this can be that farmers use the water for other than irrigation purposes;

Water does not reach the root zone of the crops. This can be due to high evaporation losses with sprinkler systems or to high surface flows, due to a large gradient of the field or to a crust on the topsoil causing a very low infiltration rate;

Water percolates rapidly to the subsoil. This can be due to a high density of macropores in the root zone or to a very high infiltration rate.

<u>IP2 > 1.2</u>

- Low water availability due to low levels of reservoir resulting in crop water stress;
- Use of other sources of water e.g.:
- Private tubewells;
- High rainfall;
- Superficial groundwater level;
- Soils with high capacity for capillary rise.
- High water prices;

Note that this list is not complete. In every unique situation low or high IP2 values have unique reasons. The list is merely meant as a guideline for the irrigation manager.

IP2 results Bullaque

IP2 values have been calculated for 20 May, 20 June, 10 July, 10 August and as a seasonal (total) value and are shown in Annex 7 and 8. The seasonal IP2 results at primary unit level are shown in figure 2.26. IP2 values are always less than 1, indicating that farmers are overirrigating their fields. This is not so strange in a system where water can be used without limitations, at any time and without quantitative restrictions.

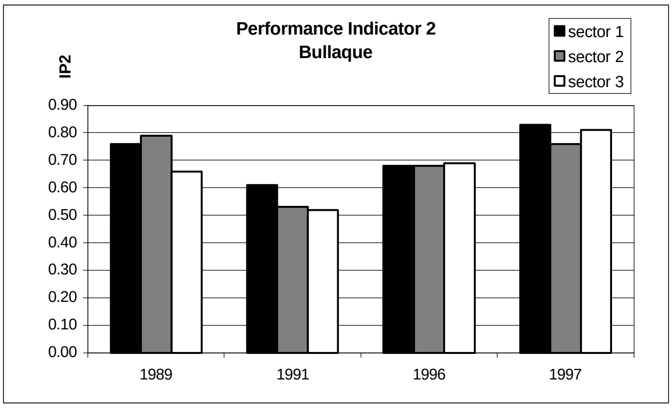


Figure 2.26: IP2 Bullaque, primary units level.

IP2 results Paestum

IP2 values are calculated for 30 of May, 17 of July and 18 of August and are shown in Annex 12 and 13. The IP2 results at primary units level are shown in figure 2.27. As can be seen in this figure, IP2 values are always higher than 1, indicating that farmers are underirrigating their crops. This results from a high degree of water scarcity in the main system. The authorities had to close some primary units in summer because of this.

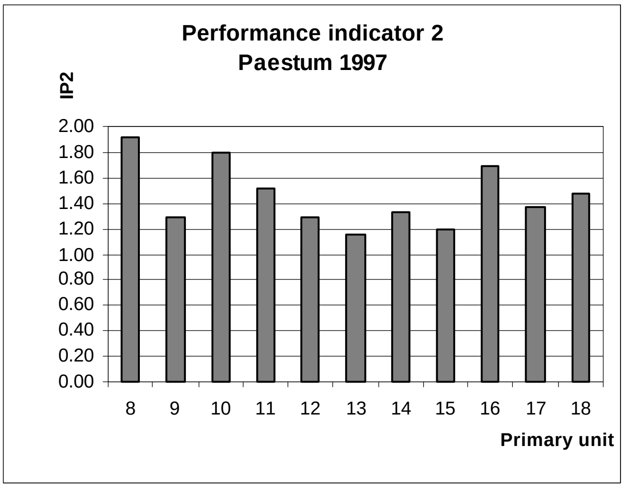


Figure 2.27: IP2 Paestum, primary unit level.

IP2 results Peñarroya

IP2 values are shown in Annex 10 and 11. The IP2 results at primary units level are also shown in figure 2.28. It is clear that after the dry period (1992 – 1995) the reservoir was not filled yet in 1996 resulting in extremely high water stress. Overall harvest levels were very low (IRRIGATION CONSORTIUM, 1997, personal communication). In 1997 the situation was restored to more or less usual IP2 values. Generally spoken the values are somewhat higher than in Bullaque district. This is to be expected: water use in Peñarroya is restricted; water has to be applied for officially and water prices are three times higher than in Bullaque.

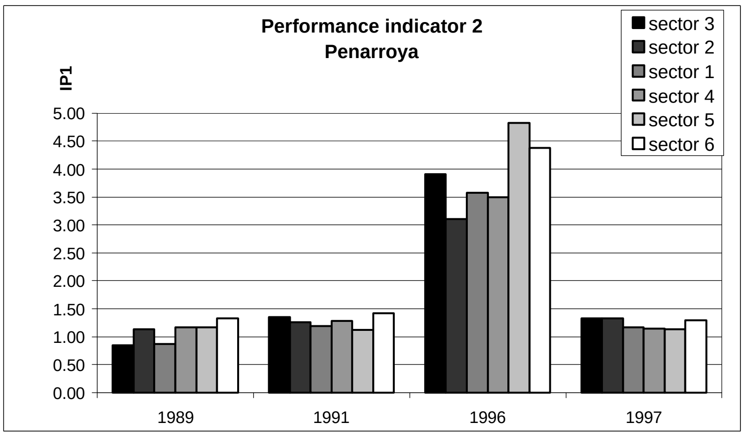


Figure 2.28: IP2 Peñarroya , primary unit level.

2.2.5.3 Irrigation Performance Indicator 3 (IP3)

IP3 is in the framework of the ASTIMwR project only calculated for the irrigation districts of Bullaque and Paestum.

Practical applicability of IP3
0.8 < IP3 < 1.0: Irrigation water is applied in an effective way taking into account the local soil and hydrological conditions.

IP3 < 0.8:
- Leaching requirements of the soil: Farmers apply more water to leach damaging salts to the subsoil or to the groundwater (intended percolation of water);
- Water supplied to farmers does not reach their fields. This can be due to losses of water from the canals and the pipelines before reaching the fields. It points to problems with the irrigation infrastructure (leaking) or to stealing of water by upstream farmers. Another reason for this can be that farmers use the water for other than irrigation purposes;
- Water does not reach the root zone of the crops. This can be due to high evaporation losses with sprinkler systems or to high surface flows caused by a large gradient of the field.

IP3 > 1:
An IP3 value higher than 1 may occur under very particular combination of crop and soil data. Because of the rarity of these values the input data of the soil water model should be checked.
Note that this list is not complete. In every unique situation low or high IP3 values can have unique reasons. The list is merely meant as a guideline for the irrigation manager.

IP3 results Bullaque
In Annex 7 and in figure 2.29 the values of IP3 for the secondary units of Bullaque in 1997 are shown.

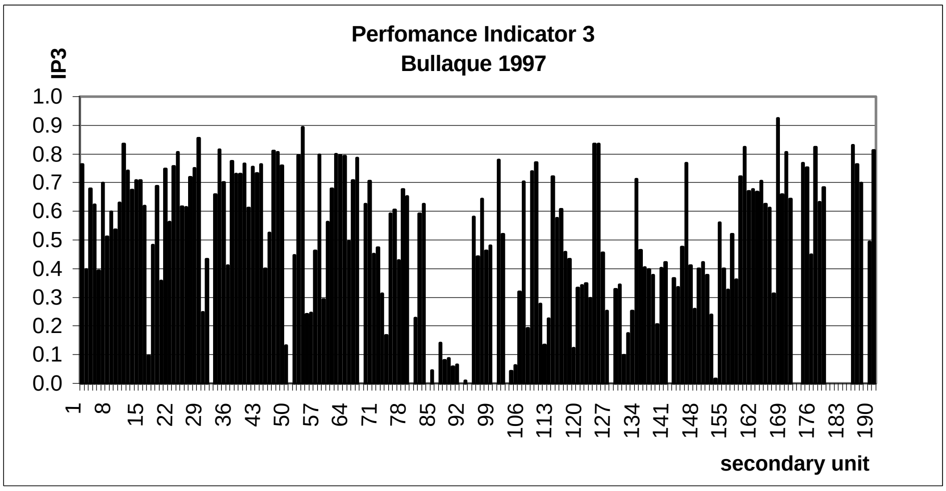


Figure 2.29: IP3 Bullaque 1997, secondary units.

As can be seen from figure 2.29, IP3 is distributed more or less randomly over the secondary units. It can be seen however that between unit 84 and 94 low values of IP3 are predominant. This means that irrigation effectiveness has been low in this area and it points at soils with a very high infiltration rate (most of the water applied has been lost for the crop).

In Annex 9 and in figure 2.30 the IP3 values at primary unit level for Bullaque in 1997 are shown.

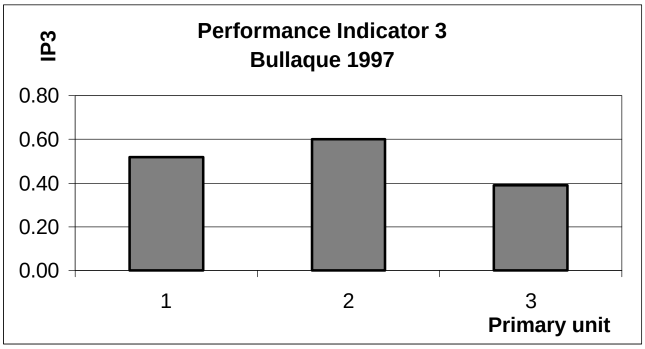


Figure 2.30: IP3 Bullaque 1997, primary unit level

As can be seen in the figure, the effectiveness of irrigation is not very high in the different units. A lot of water is not used for crop transpiration. Water can be used in this case for other purposes (e.g. leaching) or the current irrigation scheduling must be more optimally adapted to the soil type.

IP3 results Paestum

IP3 values for Paestum 1997 are shown in figure 2.31 and 2.32 as well as in Annex 12 and 13[10]. It is very clear that there is relatively little difference between secondary units within the same primary unit, compared to the difference between primary units. This is due to the big influence of the soil hydraulic characteristics on IP3. When the soil map (figure 2.16) is compared with the IP3 maps in the application, this can be seen even more clearly. Furthermore it can be seen that IP3 values are generally very low.

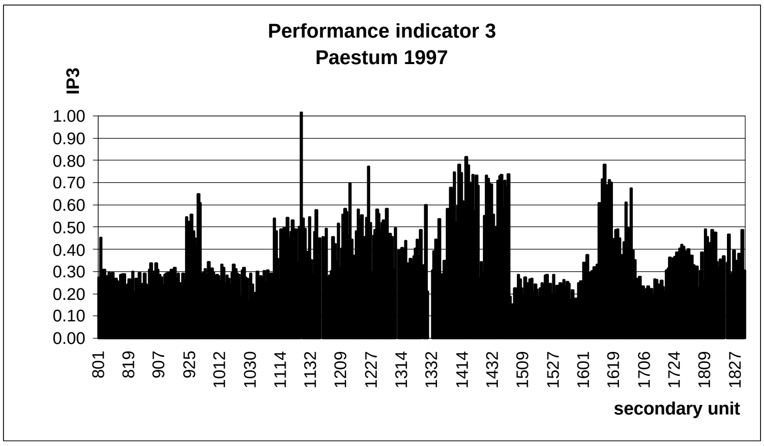


Figure 2.31: IP3 Paestum, secondary unit level.

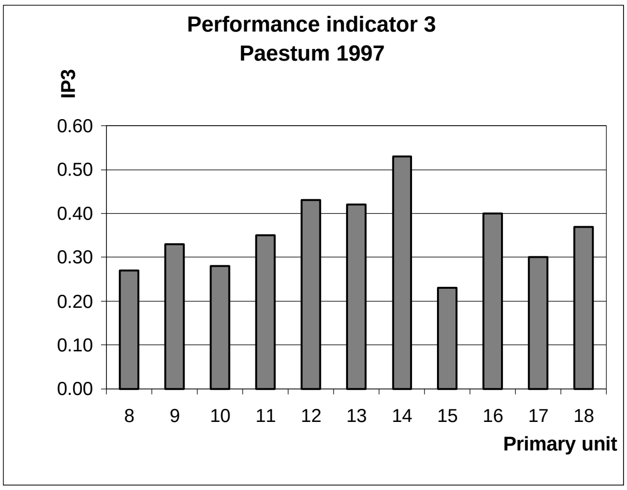


Figure 2.32: IP3 Paestum, primary unit level.

If the figures of Bullaque (2.29 and 2.30) are compared with those of Paestum (2.31 and 2.32) it can be seen that irrigation in Bullaque is more effective than in Paestum.

[10] The first number of the secondary unit code is the primary unit code.

2.2.5.4 General evaluation of irrigation performance

To evaluate the overall performance of an irrigation district one should take into account all the possible combinations of performance indicator values. This is done in the table 2.13.

IP1	IP2	IP3	Rank*	Explanation
< 0.9	< 0.8	< 0.7	––	Waste** of ample amount of water. Crops with very low PET are expected.
	≈ 1	< 0.7	–	Amount of water is more than sufficient but it is not used effectively. Crops with low PET are expected.
		≈ 1	++	Correct use of sufficient amount of water. Crops with low PET are expected.
	> 1.2	< 0.7	–	Amount of water applied can be correct but it is not used effectively.
		≈ 1	+++	Amount of water applied can be correct and it is effectively used.
≈ 1	< 0.8	< 0.7	––	Waste of ample amount of water.
	≈ 1	< 0.7	––	Waste of high amount of water.
		≈ 1	++	Correct use of sufficient amount of water.
	> 1.2	< 0.7	–	Amount of water applied can be correct but it is not used effectively.
		≈1	+++	Amount of water applied can be correct and it is effectively used.
>1.1	< 0.8	< 0.7	–––	High waste of ample amount of water.
	≈ 1	< 0.7	––	Amount of water is more than sufficient but it is not used effectively. Crops with high PET are expected.
		≈ 1	+	Correct use of sufficient amount of water. Crops with high PET are expected.
	> 1.2	< 0.7	––	Amount of water applied can be correct but it is not used effectively. Crops with very high PET are expected.
		≈1	++	Amount of water applied can be correct and it is effectively used. Crops with very high PET are expected.
IP3 > IP2			XXX	May occur under very particular combination of crop and soil data: check input data of soil water model.
IP3 > 1				

Table 2.13: Evaluation of irrigation performance.

* The ranking of different possibilities is related to the total amount of water used and wasted in the system: the least amount of water used in the most efficient way while achieving maximal crop growth gets the best rank (+++), the most water wasted gets the least rank (–––). For example: IP1 > 1.1, IP2 < 0.8 and IP < 0.7 would mean wasting a lot of water: more water is applied to this unit than on average in the system (IP1 > 1.1), more water is applied than needed for maximum crop growth (IP2 < 0.8) and a lot of this water is not used for crop evapotranspiration (IP3 < 0.7). IP1 < 0.9, IP2 < 0.8 and IP3 < 0.7 would also mean wasting a lot of water but less than the former example for less water than on average in the system is applied (IP1 < 0.9).

** Waste of water is meant here in the sense of water not used for crop evapotranspiration purposes. It is of course always possible that water is used for other purposes like leaching salts out of the soil or animal husbandry purposes.

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2.3 Monitoring of Groundwater Extraction

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2.3.1 Introduction

Efficient planning and management of resources should be based on a comprehensive knowledge of the distribution of demand and consumption in time and space, and on the realistic estimation of the resources available to satisfy this demand.

In semi-arid and arid regions, irrigation consumes up to 80% of water resources (MOPU, 1990), so irrigation monitoring at both river basin and parcel scales is key for water resources management. 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 (what is irrigated, how much), defined in time (when), in space (where) and linked to administrative information (who).

Much thematic information has a "dynamic" character and is only valuable if it is up-to-date. Because irrigation distribution varies from year to year in relation to the climatic conditions, water availability, agricultural practices and market demand, water managers need to monitor water annually. On the other hand, administrative information such as databases of water users, parcel boundaries and municipal boundaries has a "static" character and changes only exceptionally.

The "dynamic" data can be obtained through field survey, questionnaires and aerial photography. However, at a regional scale these conventional techniques are time-consuming and expensive, which limits the quality and quantity of updated and reliable data available for water management. Earth Observation (EO) techniques are a valuable alternative to traditional survey, because remotely sensed data, integrated in a Geographical Information System, can provide water managers with accurate information at a reasonable cost (MONTESINOS & LOPEZ-CAMACHO, 1991).

2.3.2 Objective of the module

The objective of this module is to set Earth Observation techniques in an operational context for monitoring groundwater extraction for irrigation purposes. This means first of all organising the administrative data related to groundwater irrigation in a rational structure. Then, Remote Sensing techniques that have been widely developed and tested in the research world are used to get updated input data about land use and irrigation detection. Through GIS techniques, all data are integrated and irrigation activity is monitored at aquifer, municipality and parcel levels.

2.3.3 Test area

In order to ensure the operational character of the module, a problematic area of the Guadiana river basin (Spain) has been selected, where groundwater over-exploitation made irrigation monitoring a primary issue. Nevertheless, the module is easily adaptable and extrapolable to any other area where irrigation must be monitored for administrative purposes.

The selected test area is Aquifer 23, also called *Acuífero de La Mancha Occidental* or *Unidad Hidrogeológica 04.04,* which is located in the Cuenca Alta del Guadiana (figure 2.33). This aquifer has an extent of 5,260 Km^2 and stretches between three provinces: Ciudad Real, Cuenca and Albacete.

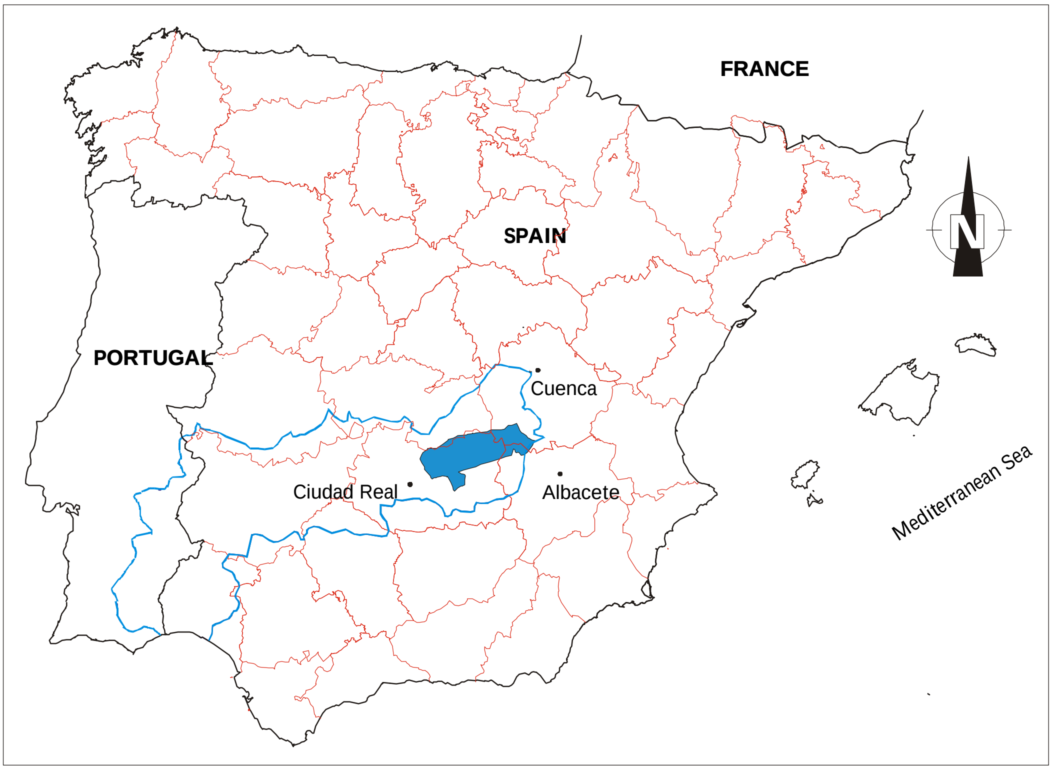

Figure 2.33: Location of the test area in light blue Aquifer 23; in blue the Guadiana watershed basin. In red, the boundaries of the provinces.

The area of Aquifer 23 has about 280,000 inhabitants (SERNA *et al*., 1995), whose predominant 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 made possible by the exploitation of groundwater extracted from Aquifer 23, which represents 92% of the water used in the area (SGOP, 1988). In table 2.14, 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 2.14: Water balance of Aquifer 04.04. (CHG, 1995) average value for 75-94*

Water resources of Aquifer 23 are subject to the Water Law (‘*Ley de Aguas*’), which entered into force on 1st January 1986. This regulates the competences 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 Law of 1985 concerns the property of water: starting from 1st January 1986 both surface and ground water belong to the public domain. In order to preserve property rights of persons owning wells (and water) before that date and to smooth the social effects of the property change, it was established that former owners could keep their property rights but only if they presented to the competent Catchment Authority the documentation describing their exploitation in 1985 (L. A., 1985). This documentation, gathered together in an irrigation dossier (‘*Expediente Administrativo’)*, includes the personal data of the water owner, the well characteristics, the water volume extracted and the area under irrigation in 1985. On this basis, the Catchment Authority decided whether to concede or not the water rights. In the former case, the registered irrigation dossier has a ‘legal water volume’ and an area 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 volumes, 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 capability, the aquifer is declared over-exploited and the local Catchment Authority is empowered to set severe limits aimed at protecting the aquifer and allowing the recovery of the groundwater levels. One such limit is the Exploitation Plan (‘*Regimen de Explotación*’) that establishes what percentage of the registered volume can be used for irrigation each year.

Effective implementation of Water Law requires monitoring of water use and checking that the water use restrictions are respected both in situations of normality and in conditions of over-exploitation.

From 1974 to 1987 Aquifer 23 registered an important increase in water extraction (see figure 2.34), which passed 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 its hydrologic equilibrium and led to the declaration of over-exploitation on 4 February 1987.

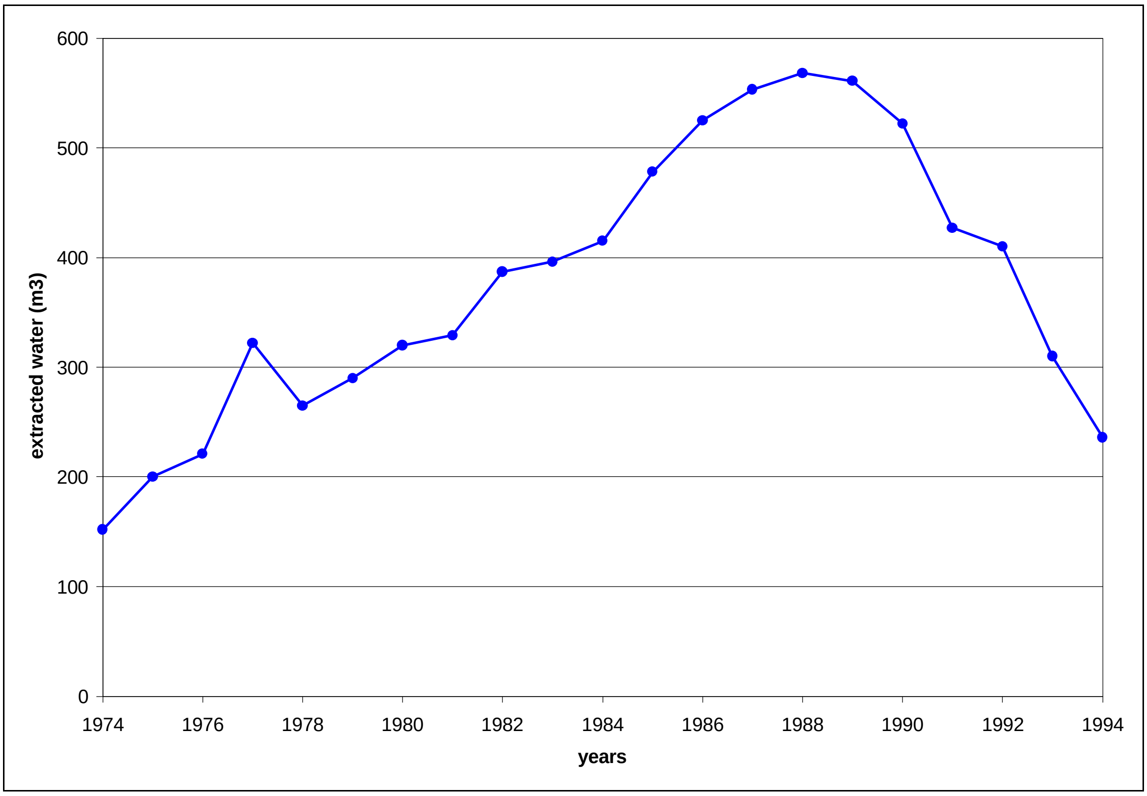

Figure 2.34: Evolution of water extraction in Aquifer 23 from 1974 to 1994 (CHG, 1995).

Since 1991 the local Catchment Authority *(Confederación Hidrográfica del Guadiana,* CHG) has issued the Exploitation Plan for Aquifer 23, which establishes the limitations to water extraction depending on the availability of water resources in the aquifer.

The present module answers the need for a cost-effective methodology for monitoring water extraction and the fulfilment of the Exploitation Plan. The year selected for the implementation of the methodology is 1997, but the system works for any year, provided that the corresponding parameters and images are available for input.

The Exploitation Plan for 1997 authorises water extraction from underground according to table 2.15 and providing that the total water consumption for agriculture does not exceed 170 Hm^3/year (B.O.C.R., 1997).

Exploitation rule	Water Volume (m^3/year)	Crop extent (hectares)	Authorised volume (% of the legal volume)
I	< 21,390	≤ 5	100
II	< 42,780	> 5 and ≤ 10	50, exploitation rule I for the first 5 hectares
III	< 128,340	> 10 and ≤ 30	35, exploitation rule II for the first 10 hectares
IV	> 128,340	> 30	25, exploitation rule III for the first 30 hectares

Table 2.15: Ranges and rates established in the Exploitation Plan of 1997 for Aquifer 23 (B.O.C.R., 1997).

2.3.4 Methodology applied

The remote sensing techniques applied for monitoring water exploitation are founded on basic concepts of image processing and GIS spatial analysis. Within ASTIMwR these methods were defined in an operational context, using the methodology developed and tested for the Upper Guadiana River Basin (Spain) by MONTESINOS (1990).

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

- 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 monitoring wide areas 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 the water extraction.

For monitoring water extraction and the fulfilment of Exploitation Plan alphanumeric, vector and raster data are need. For simplicity, the acquisition, pre-processing and processing of each of these data sets are described separately hereafter.

2.3.4.1 Alphanumeric Data

The administrative data of the wells inventory and water users have to be organised in an alphanumeric database to be linked with spatial data. In Aquifer 23, this information was extracted by a database provided by *Comisaría de Aguas* of CHG.

The database was structured to include, for each irrigation dossier (see paragraph 2.3.3), all the data necessary to identify the water owner and the registered volume and to create a linkage with the geographical data (vector and raster data).

For each record, the database reports:

- Name of the PROVINCE where the well is located.
- Name of the MUNICIPALITY where the well is located
- Code of the AQUIFER that the well belongs to.
- Name of the ESTATE where the well is located.
- Identification Number of the cadastral POLYGON where the well is located.
- Identification Number of the cadastral PARCEL where the well is located.
- X co-ordinate of the well in UTM
- Y co-ordinate of the well in UTM
- Fiscal Identification Number of the well owner.
- FORENAME of the well owner.
- FIRST SURNAME of the well owner.
- SECOND SURNAME of the well owner (in Spain, person are identified with two surnames).
- Number of REQUESTED HECTARES, i.e. number of hectares that the well owner declared as irrigated with the well in 1985.
- Number of REGISTERED HECTARES, i.e. number of hectares that finally were recognised by the Catchment Authority as irrigated in 1985 according to the documentation presented by the well owner. Multiplying this area by a standard rate (4,278 m^3/hectare*year), the amount of water assigned to the well owner is calculated. The farmer is entitled to use this amount only within the boundaries of the parcels that were irrigated in 1985.

In the ASTIMwR test area there are 11,456 irrigation dossiers registered between 1986 and 1994 and stored in the CHG's archives in analogue format.

2.3.4.2 Vector Database

Each irrigation dossier includes a sketch map showing the limits of the parcels irrigated in 1985, which are called "exploitation parcels". To perform a spatial analysis, administrative data, water volume and area extent must be related to geographical objects such as parcels, municipalities, and provinces, all stored in digital format.

The available digital cadastre was completed by scanning, vectorising and georeferencing rural maps or by using aerial ortophotographs to digitise exploitation parcels on the screen.

The sketch map guides the operator in associating each record of the alphanumeric database with the corresponding registered parcels by means of an easy-to-use application. The software application links each alphanumeric record with the digital data of the associated cadastral parcel by storing the co-ordinates of the parcel boundaries in a binary field of the alphanumeric database. This improves the data management efficiency, because vector data are integrated within the alphanumeric database and, thus, can be handled within a simple and compact structure. The use of the application implied an important increase in work efficiency. An operator analysed about 100 irrigation records per day, while, with traditional methods, the rate was down to 5 per day.

The parcel assignation work was supported by Landsat TM geocorrected colour composites acquired in spring and summer between 1984 and 1998. These images, displayed on the background of the cadaster, gave the operator an overview on the irrigation evolution in the registered parcel and the criteria followed by the Water Authority awarding the water rights.

The boundaries of Aquifer 23 and its municipalities were retrieved from CHG and stored in vector format.

The linkage between the vector data and the alphanumeric database is given by the name of the spatial element represented in the vector file (exploitation parcel, aquifer, municipality).

2.3.4.3 Raster Database

The raster database is the “dynamic” element of the irrigation monitoring process, and it needs to be up-dated year on year to facilitate the estimation of the amount and spatial distribution of water consumption in the managed area. The UTM co-ordinates constitute the linkage between this database, the registered wells and exploitation parcels.

The study of the characteristics and the development of crops in Aquifer 23 showed that the most suitable dates for identifying crops grown within the monitored area are: late spring for the crops seeded in winter and harvested at the end of spring; and summer for crops seeded in spring and harvest at the end of summer (GALAN, 1998). According to these criteria, crop ground truth was collected during three field surveys, in May, June and July 1997, within 18 segments of 25 Km^2 each. The crop survey was performed along a south-west north-east line across the aquifer, selecting larger fields and crops representative of the area. The survey was carried out with the support of topographic maps and aerial photography. The results of the fieldwork were stored in digital format using the cadastre to locate the samples on the satellite image (figure 2.35).

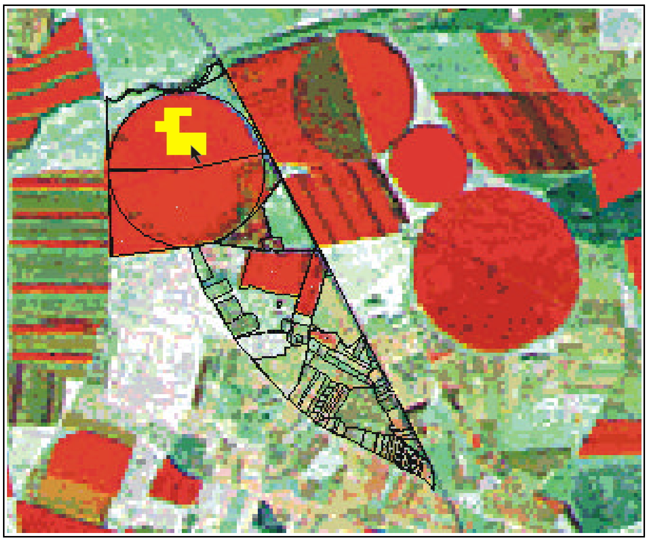

Figure 2.35: Digital catastre overlaid on a colour composite image, to facilitate the location of the training fields.

The selection of the images was influenced by the high cloud coverage that characterised 1997. By combining dates of acquisition of Landsat 5 TM and IRS-1C LISS III, it was possible to obtain cloud free coverage of the area for the following dates:

Satellite	Sensor	Date	Scene Frame (path-row)
IRS-1C	LISS - III	17, April 1997	017 - 042
IRS-1C	LISS - III	24, June 1997	017 - 042
IRS-1C	LISS - III	18, July 1997	017 - 042
Landsat 5	TM	7, July 1997	200 - 33
Landsat 5	TM	15, August 1997	201 - 33

Table 2.16: Satellite images used for the exploitation monitoring in 997.

Once acquired, the satellite images were geometrically corrected and georeferenced to UTM, the same geographical co-ordinates in terms of which the rest of the data in the GIS are measured (MATHER, 1987). The intensity interpolation was done by the Nearest Neighbour method because this does not alter the pixel brightness value during resampling (JENSEN, 1986).

A crop classification was carried out on all the available images and used training pixels 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 used with a threshold obtained empirically in significant subareas. 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 be misclassified.

The classes represented in the final classification are:

- Alfalfa
- Cereals
- Colza
- Corn
- Sugar beet
- Melon

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 95.9%, defined as the ratio between the sum of the pixels belonging to the diagonal (sampled pixels correctly classified) and the total number of sampled pixels. The average accuracy is 74.9 %, and the average reliability is 79.7 %. Because the literal interpretation of percentage accuracies derived from a confusion matrix can be misleading (MATHER, 1987), also a visual check was performed comparing the classification with the false colour composites of the different dates (band 4,5,3 for Landsat 5 TM, band 4,3,2 for IRS-1C LISS III). This analysis revealed that there were areas that were unclassified in the final classification, although they presented hints of active vegetation in the colour composites.

Vegetation Indices are sensitive indicators of the presence and condition of green vegetation (LILLESAND & KIEFER, 1987) and for this reason, they were used to detect these unclassified areas.

The Normalised Difference Vegetation Index (NDVI) was calculated according to the formula:

$$NDVI = \frac{NearIR - Visible\,\mathrm{Re}\,d}{NearIR + Visible\,\mathrm{Re}\,d} \times 100$$

where *Near IR* is the satellite band corresponding to the near infrared range (Band 4 in Landsat 5 TM, band 4 in IRS-1C LISS III);
Visible is the satellite band covering the Red Visible range of the spectrum (Band 3 in Landsat 5 TM, band 3 in IRS- 1C LISS III);
100 is a scaling factor.

This equation is applied to each of the acquired images in order to obtain NDVI maps for every date. The Visible Red channel of the multispectral sensor enables estimates of the plants' chlorophyll activity (low values for high vegetation activity), while the Near-infrared channel gives information about the biomass content in vegetation (high values for high biomass contents). The characteristic response of active and healthy vegetation in these two channels is amplified by the NDVI ratio, calculated for each pixel of the image: the higher the NDVI value the healthier the vegetation, whereas, the low NDVI corresponds to the more senescent, dead or non existent the vegetation cover (DRURY, 1987).

The comparison by superposition of the NDVI map of each date with the corresponding false colour composite leads to identify the NDVI threshold value that separates healthy vegetation from the other surface elements (bare soil, urban areas, non active vegetation, etc.).

The definition of the threshold NDVI is a delicate task, based on the knowledge of the local vegetation cover and the ground truth data acquired coinciding with the image acquisition by the satellite. Also, the season of the year must be taken into account for establishing the limit value, as the soil moisture is higher during the wet seasons (autumn, winter and the beginning of spring) than during the warm ones (end of spring and summer). Because of this, non irrigated vegetation (forest, riverbank vegetation) can reach NDVI values very similar and even higher than irrigated crops, making it necessary to delineate such areas manually by digitising on the screen (see below).

Based on the threshold NDVI value of the map, for every date a new bit map (NDVI mask) is produced in which "1" values means active vegetation and "0" values means non-active vegetation.

Once obtained, the four NDVI masks are merged into one global NDVI mask for the whole irrigation year (April to September) having the following classes:

- Spring crops (i.e. crops/active vegetation detected by the NDVI only in spring). This class includes wheat, oats, rye, colza, etc.
- Summer crops (i.e. crops/active vegetation detected by the NDVI only in summer), like corn, melon, sunflower, potato, flax, lupine, etc.
- Spring and summer crops (i.e. crops/active vegetation detected by the NDVI only in spring and summer), which include alfalfa and long-cycle potato.

The obtained global Normalised Difference Vegetation Index mask is merged with the crop classification to include into the final thematic map all the areas having active vegetation. This merging was performed with logical operators in raster format so that if a pixel is classified through the crop classification, its value is kept, while if a pixel is unclassified, it takes the value of the NDVI map.

Finally, forest and riverbanks vegetation, which are photosynthetically active, are identified on the false colour composites and digitised on the screen to create a mask. This mask is crossed with the thematic map to exclude riverbanks and forests and to keep only those areas that can be considered as irrigated.

2.3.4.4 Information Extraction

The extraction of the information concerning the irrigation monitoring and the fulfilment of the Exploitation Plan is based on the linkage structure created during the data preparation (figure 2.36).

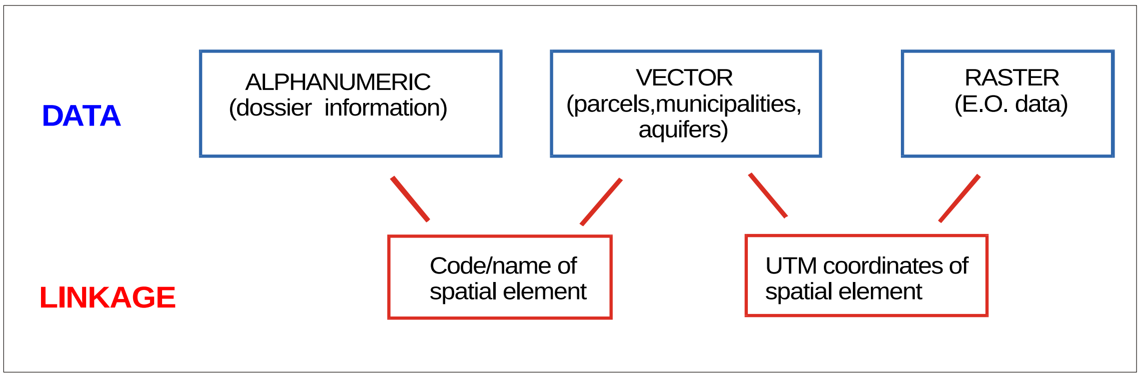

Figure 2.36: Linkage between the databases integrated into the system.

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 names 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 (masks).

The Exploitation Plan requires, for each irrigation dossier, a comparison of both the irrigated area and the water consumption in 1997 with the values assigned for the year by the local Catchment Authority. In this way it is possible to detect the farmers that are exceeding the assigned amounts and, consequently, infringing the Exploitation Plan.

For this reason, the final thematic map for 1997 is crossed with each irrigation dossier vector mask (exploitation parcels) 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 (in this case 25 m x 25 m, i.e. 0.0625 hectares) results in the estimation of the extent of each vegetation class in 1997 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 irrigation dossier is infringing the exploitation plan established by the Catchment Authority.

The monitoring of the fulfilment of the water consumption limits requires the multiplication of the class areas by average water rates (table 2.17 and 2.18). The obtained 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
Irrigated Cereal	2,000
Colza	2,000
Sugar Beet	8,000
Corn	6,500
Melon	6,000

Table 2.17: Average water rates for the crops identified by the crop classification for 1997. Source D.O.C.M (1998)

Crop type	**Average Water Req. (m^3/hectare *year)**
Spring Crop	2,500
Summer Crop	7,000
Spring – Summer Crop	9,000

Table 2.18: Average water rates for the active vegetation classes identified through the NDVI maps for 1997.

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 levels, to provide the Catchment Authority with a global view of the exploitation trend in the monitored irrigation season.

2.3.5 Results

The crop classification performed on the images acquired for 1997 (see table 2.16) and referring to the area corresponding to Aquifer 23 are reported in the table below.

Crop type	Crop area (hectares)	Water consumed (Hm^3)
Alfalfa	1,073	9.6
Irrigated Cereal	19,363	38.7
Colza	6,257	12.5
Sugar Beet	1,777	14.2
Corn	182	1.4
Melon	5,521	33.1
Total	**34,173**	**109.5**

Table 2.19: Results of the merging of the crop classifications performed on the images acquired in April, June July and August 1997, calculated within the boundaries of Aquifer 23.

If crops are grouped into spring, summer and spring-summer crops and added to the data obtained from the NDVI maps, the irrigation activity in the studied area can be summarised by table 2.20.

Crop Group	Crop area (hectares)	Water consumed (Hm^3)
Classified crops	34,173	109.5
Spring	3,741	7.5
Summer	3,002	18.0
Spring-Summer	92	0.8
Total	**41,008**	**135.8**

Table 2.20: Results of the merging of the crop classification with the NDVI mask for 1997 calculated within the boundaries of Aquifer 23.

The implementation of this module required the organisation of the data concerning the irrigation dossiers for the test area. This allowed an effective exploitation database for Aquifer 23 to be built and constitutes the basis for monitoring groundwater exploitation in this aquifer. Moreover, the data retrieval in the archives led to the identification of biases in the information submitted by the farmers for the registration of their water rights. Indeed, the data retrieval and analysis showed that only 36% of 11,456 irrigation dossiers contained satisfactory information. An automatic procedure assigned the exploitation parcels to another 5,686 irrigation dossiers that lacked some data. The remaining 1,621, corresponding to about 20,000 hectares, could not be resolved and, thus, could not be taken into account when drawing the conclusions on the Exploitation Plan fulfilment.

An analysis through a decision tree has identified the biases of the associated information, in order to facilitate the enhancement of the information. The details about the results of the data retrieval and the automatic filling-in of the database (fig. 2.37) are described in CHG (1996).

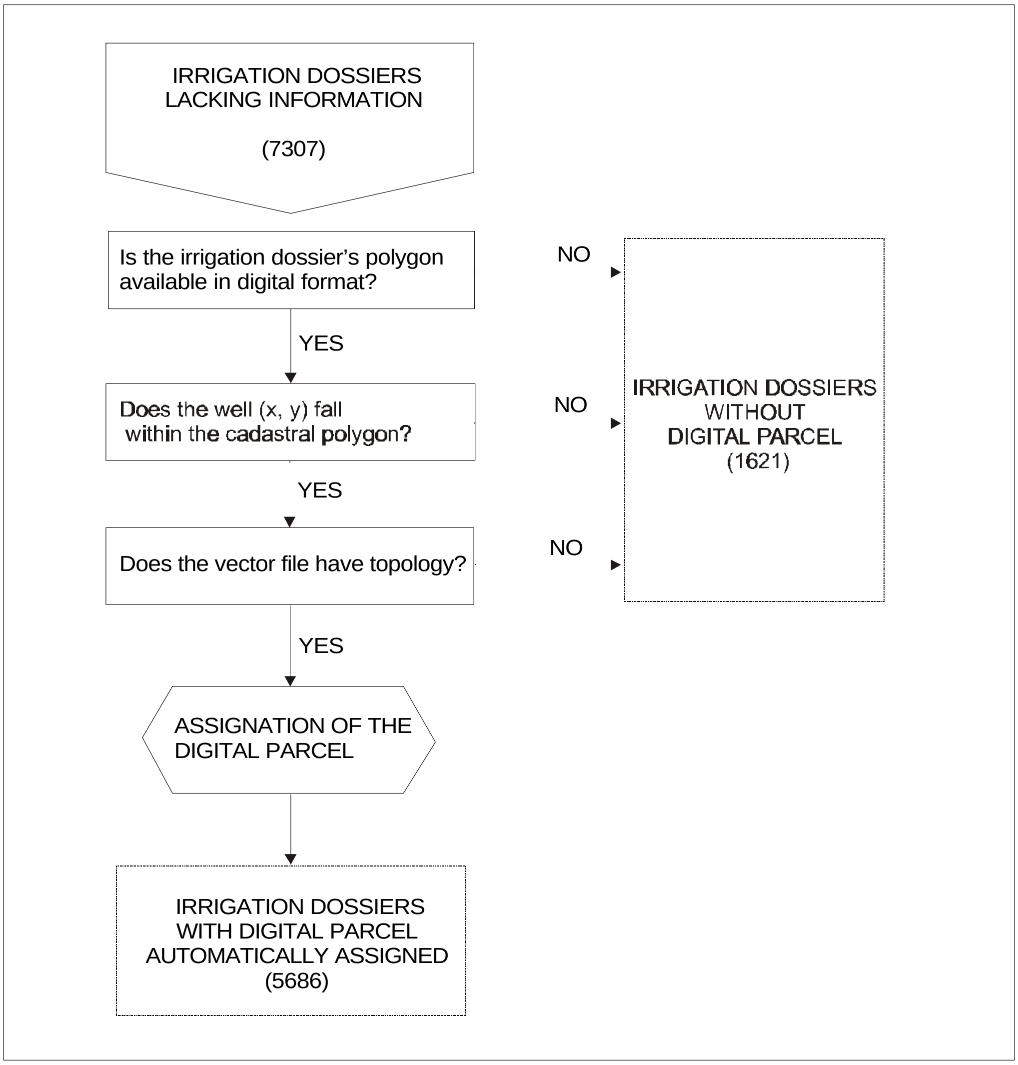

Figure 2.37: Flow chart for the automatic assignation of digital parcels to the irrigation records.

The spatial analysis at irrigation dossier level has shown that only 4.3% of the registered wells having associated an exploitation parcel are infringing the Exploitation Plan (table 2.20). This is positive for the recuperation of the ground water levels in Aquifer 23. In 1993 the European Commission issued a 5-year subsidy plan for releasing water resources from agriculture and helping the recovery of the area (D.J.C.C.M, 1993): this intervention might be the main reason for such low irrigation rates.

Irrigation dossiers category	**Number of irrigation dossiers**	**Percentage***	**Water consumption (Hm^3)**
Irrigation dossiers infringing the Exploitation Plan	428	4.3%	32

Table 2.20: Data concerning the irrigation dossier infringing the Exploitation Plan for 1997 in Aquifer 23.
** the percentage is calculated from the number of irrigation dossiers having a parcel associated (9,835).*

Although the Water Law only requires monitoring of the fulfilment of the Exploitation Plan at the level of individual irrigation dossiers, the local Catchment Authority can gain an overview of the irrigation activity in its territory by analysing the situation in each administrative unit.

In table 2.21 the municipalities located within Aquifer 23 are listed. Beside each name, it is possible to compare the allowed irrigation activity with the irrigation detected in 1997 using remote sensing techniques. At municipality level, no irregularities are highlighted, which suggests that the irrigation dossiers infringing the Exploitation Plan are distributed evenly over the territory.

Municipality	**Registered area (hectares)**	**Allowed water consumpt. (m^3)***	**Irrigated area (hectares) ****	**Water consumpt. (Hm^3)**
Alcázar de S. Juan	26,359	56670899	4,916	15.6
Alberca de Z.	41	148,023	11	0.02
Almagro	337	876,560	78	0.2
Arenas de S.Juan	1,422	3,832,055	251	0.8
Argamasilla de A.	4,687	10,868,120	276	1.1
Bolaños de C.	492	1,847,223	49	0.1
Campo de C.	7,465	20,756,773	429	1.8
Carrión de C.	435	1,601,991	4	0.007
Casas de Haro	114	232,402	0	0.0
Casas de los Pinos	120	244,488	0	0.0
Daimiel	18,389	52,996,020	4,209	12.7
Herencia	4,041	8,666,817	911	2.7
Las Labores	833	1,716,066	194	0.4
Manzanares	12,786	35,372,545	2,085	5.8
Membrilla	978	3,794,644	154	0.4
Las Mesas	1,205	2,928,002	50	0.2
Minaya	997	1,241,679	734	3.2
Mota del Cuervo	437	1,157,351	7	0.04
Osssa de Montiel	263	901,661	8	0.04
Pedro Muñoz	722	2,363,253	29	0.08
Pedroñeras	1,769	4,642,073	36	0.1
Provencio	1,783	5,086,555	33	0.2
Puerto Lápice	664	1,486,772	141	0.3
San Carlos del V.	47	125,003	6	0.1
San Clemente	1,098	2,836,586	79	0.2
Socuéllamos	8,077	22,797,103	327	1.4
Solana (La)	23	92,961	4	0.1
Tomelloso	4,956	15,145,942	111	0.5
Torralba de C.	2,487	8,205,003	510	1.4
Valdepeñas	1,952	6,686,411	242	0.7
Villarrobledo	7,214	17,554,031	1,289	3.6
Villarrubia d.l.O.	1,674	5,345,404	359	1.0
Villarta de S. Juan	2,484	5,075,811	850	2.5

*Table 2.21: Results of the monitoring of the fulfilment of the Exploitation Plan for 1997 at level of municipality. * According to the Exploitation Plan for 1997; ** Irrigated surface within the registered parcels.*

The calculation of water consumption at aquifer level (table 2.22) confirms the behaviour observed at the scale of irrigation dossiers and municipalities: the water consumption within the registered parcels conforms to the limits set by the Exploitation Plan.

Registered area (hectares)	**Allowed consumption for 1997(m^3)*** *(registered irrigation)*	**Irrigated area in 1997 (hectares)**** *(registered irrigation)*	**Consumption in 1997(Hm^3)***** *(registered irrigation)*
115,815	302,190,917	18,354	57.3

Table 2.22: Results of the monitoring of the fulfilment of the Exploitation Plan for 1997 at aquifer level.
*According to the Exploitation Plan for 1997; ** Irrigated surface within the registered parcels.*
**** water consumption within the registered parcels.*

Monitoring irrigation activities with EO data also enables the detection of deficiencies in the control of the water use in the managed area. Indeed, the comparison between the irrigated area within the registered parcels of Aquifer 23 and the irrigated area within the whole aquifer shows that there exists significant irrigation activity (22,654 hectares) that is not controlled by the local Catchment Authority (table 2.23).

Total irrigated area (hectares)*	**Total water consumption (Hm^3)***	**Not controlled irrigated area (hectares)***	**Not controlled water consumption (Hm^3)***
41,008	136	22,654	78.7

Table 2.23: Results of the monitoring of the fulfilment of the Exploitation Plan for 1997 at level of aquifer.
** These values include registered irrigation, registered irrigation not input into the vector database, and unregistered irrigation.*

In the case of Aquifer 23, this surface includes both the areas associated with the irrigation dossiers that could not be input into the vector database for technical reasons (see above) and the irrigation activity that is carried out without the relevant authorisation.

Moreover, the computing of irrigated area and water volumes on the whole aquifer provides the Catchment Authority with an estimate of the water consumption for the studied year (about 136 Hm^3). This estimate confirms the positive downward trend in groundwater extraction in the test area, where the Exploitation Plan had set 170 Hm^3 as an upper threshold for the water extraction in 1997.

The analysis carried out during the ASTIMwR project has shown the importance of organising and managing data in order to be able to extract information from them. Firstly, data need to be in a digital and georeferenced format to be more easily editable and usable. However, even when data are well catalogued and stored, the conversion to digital format reveals biases and deficiencies that must be amended to enhance the quality of the analysis results.

Earth Observation techniques provide water managers with valuable up-to-date data on the distribution and use of water resources. They enable estimates to be made of the water use for irrigation purposes at different administrative levels and the analysis of the evolution of the managed area over a number of years.

The methodology of exploitation monitoring implemented and tested in this module has been demonstrated to be cost- and time-effective when compared with traditional techniques. Indeed, 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.

2.3.6 References

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2.4 Monitoring of wetlands evolution

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2.4.1 Introduction

An important concern of water managers is the compatibility of socio-economic activities based on water resources with the protection of environment. Wetlands are very sensitive areas that often host niches of flora and fauna of ecological interest. Their subsistence is closely linked to the quantity and quality of water and monitoring their evolution is important to prevent their degradation.

Most of the wetlands are characterised by having the aquifer water table close to the topographical surface, thus, a general lowering of the water table leads to major changes in their hydrological functioning (LLAMAS, 1991). The area covered by wetlands has suffered an important reduction on a global scale mainly due to surface drainage of marshlands to transform them into arable land (DUGAN, 1990). However, in the developed countries this process has stopped in the Seventies because of the increasing public interest in the conservation of these ecosystems. Nowadays, the major cause of reduction of wetland surface in semiarid regions like Southern Spain and Portugal is the scarcity of subterranean water supply, due to poor aquifer management.

Wetlands are the result of the interaction of many elements. This makes each wetland unique, although there are basic factors that are common to all of them. According to USEPLA (1989), one of the requirements for the legal existence of a wetland is the presence of water in the form of permanent or periodic inundation, or saturation of the soil for a sufficiently long time (at least one week) during the period of vegetation growth. The answers to the questions: “where, when and which waters are present in wetlands?”, are the keys to explain the presence of certain types of vegetation and/or soils. Thus, the hydrologic dynamics are the basic elements defining wetlands. The emphasis on vegetation and soil done by USEPLA (1989) as the other two elements to define legally a wetland, can be explained (LLAMAS, 1991) by the fact that wetland administrators are better schooled in Biology or Soil Science than in hydrology (KUSLER, 1988).

2.4.2 Objective of the module

The aim of this module was to develop a tool for water managers to monitor the evolution of wetlands using EO data. The tool was designed on the characteristics of two wetlands used as test areas, but it can be extrapolated and adapted to other wetlands.

In the module, satellite data are combined with hydrological data to analyse the relation between the development of irrigated land and the trend of groundwater table; the evolution of wetland vegetation; and the evolution of hydrologic parameters like precipitation.

2.4.3 Test areas

Two pilot areas were selected in the Guadiana river basin: O Sapal de Castro Marim (Portugal), at the river mouth, and Las Tablas de Daimiel (Spain), in the upper part of the basin. These wetlands represent two very different situations with regard to hydrological behaviour and socio-economic aspects. Las Tablas de Daimiel is a continental wetland linked to an aquifer. Since it has been thoroughly studied, the basic need of water managers in this area is to handle several information layers simultaneously. O Sapal de Castro Marim is a coastal wetland whose dynamics are barely studied. For this, the main need is for a system useful to detect changes and evolution, in the past years and in the future, related with the dynamics of the system.

2.4.3.1 Las Tablas de Daimiel

Las Tablas de Daimiel is, like many wetlands in the Iberian Peninsula, directly linked to an aquifer. It is located at the confluence of the Guadiana and Gigüela rivers and used to be a discharge area of the "La Mancha Occidental" / 04.04 aquifer (SGOP, 1979), a calcareous aquifer of about 5000 Km^2 and good hydraulic conditions -high transmisivities- (ITGE, 1989). It is also fed by the Gigüela and the Guadiana rivers. Las Tablas de Daimiel is a National Park, which implies the maximum legal protection in Spain and have 1675 hectares susceptible of flooding (ÁLVAREZ-COBELAS, VERDUGO and CIRUJANO, 1996). During the last ten years, Las Tablas has turned from discharge area into a recharge area (SGOP, 1984; SGOP, 1988; LÓPEZ-CAMACHO *et al*., 1996), due to the general drawdown of water table levels (SGOP, 1991).

To follow up the evolution of wetlands, water managers need to understand the relationship between the water table and the flooded surface in wetlands. To achieve this goal, the module combines the information layers that are necessary to determine the availability of hydrologic resources in continental wetlands, namely: flooded surface, aquifer water table level, rainfall data, pumped volumes and superficial flows (figure 2.38). Evapotranspiration was not considered in this module because there is one devoted to it (section 2.1).

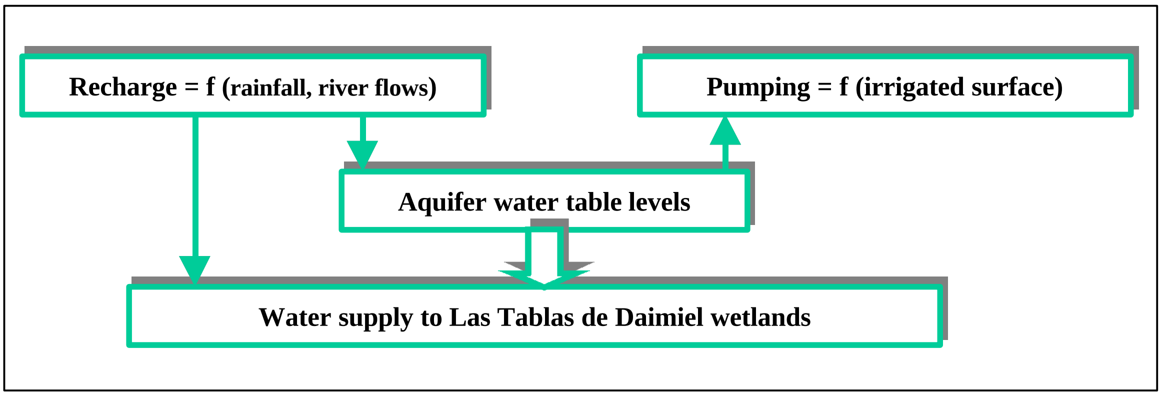

Figure 2.38: Simplified scheme of the hydrologic dynamic of Las Tablas de Daimiel.

The study area (75,775 hectares) has been selected according to its closeness to Las Tablas and to the flow lines of the aquifer, and is extensive enough to be representative of the aquifer (about 1/6 of the whole aquifer surface). Maps were produced for part of the Aquifer System 04-04 included in the maps (scale 1:50,000) of Daimiel and Villarrubia de los Ojos, the area close to Las Tablas de Daimiel. This frame has been also used in previous studies concerning the influence of the exploitation of subterranean waters in the proximity of Las Tablas de Daimiel (SGOP, 1984).

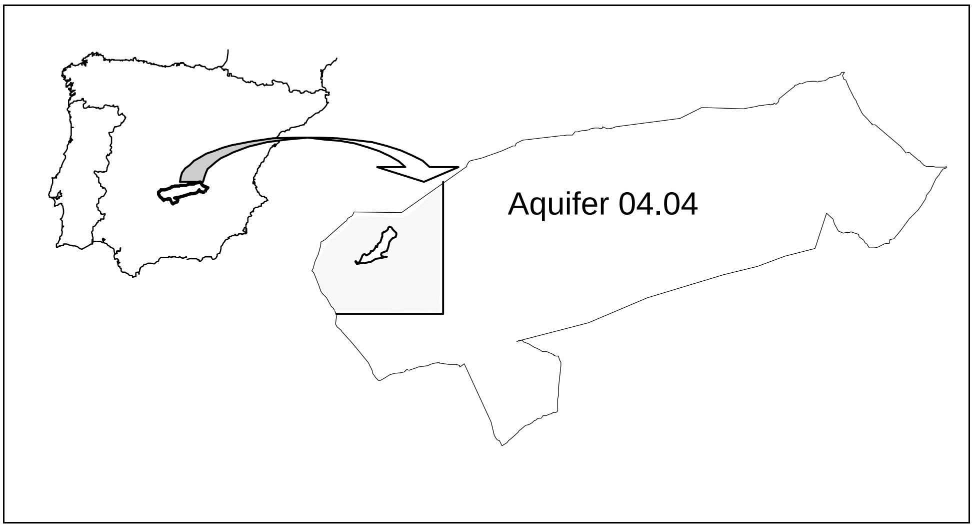

Figure 2.39: Study area (Las Tablas de Daimiel National Park and the Aquifer of the studied zone).

2.4.3.2 O Sapal de Castro Marim e Vila Real de Santo António.

O Sapal de Castro Marim is a coastal wetland located in the Portuguese margin of the Guadiana river mouth (fig. 2.40). It has a surface of 2,089 hectares (Dec.Lei nº 162/75) and is an example of saline wetland where human actions have changed the original landscape of the area. The main environmental values of this wetland are its dominant hypersaline mosaic vegetation (LOUSA, 1986) and aquatic bird fauna (FARINHA and TRINIDADE, 1984). It also has important populations of insects, birds and fish (XAVIER, 1995). The area was declared Natural Reserve in 1975, which means certain environmental protection even when within the area some human activities can be developed (salt mining, agriculture, etc.). For the area, there are only a few scientific studies but no cartography for different years.

The main causes of degradation of coastal environments are modifications of topography, irrigation water, fertilisers, land-use changes, changes in the natural cover and farming (CORRE, 1976). Elements related to land uses and irrigation can be monitored by using Remote Sensing techniques. Hence, the study in this area has been focused on the applicability of different Remote Sensing techniques to determine vegetation cover changes and their correlation with major changes of environmental parameters.

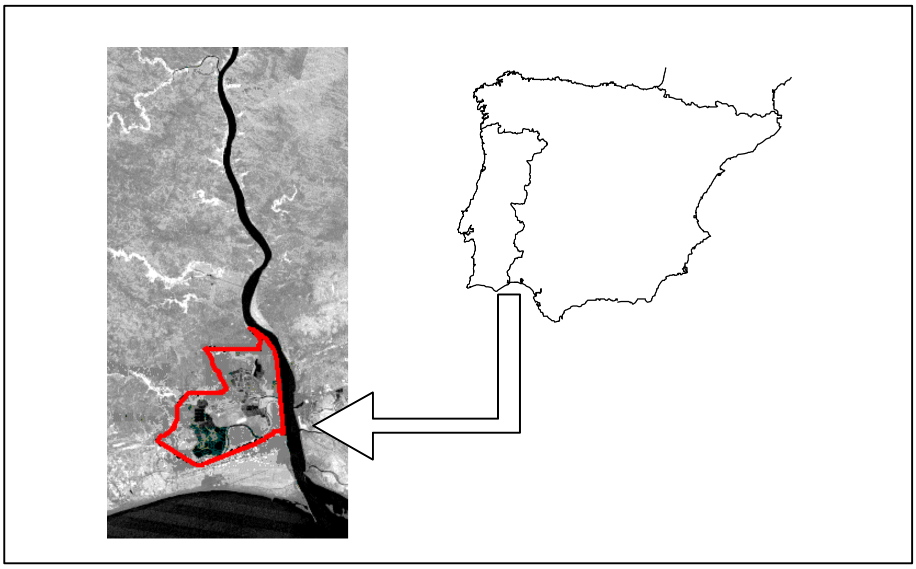

Figure 2.40: O Sapal de Castro Marim e Vila Real de Santo António Natural Reserve.

2.4.4 Methodology applied

Two criteria were followed for selecting the methodology: it had to produce reasonably good results for the ASTIMwR test sites and it had to be suitable for integration into a user-friendly software tool. Brief comments are made to explain the reason why other methodologies tested during the project were not included into the module.

Several information layers have been produced to assess the evolution of the wetland areas. Their combination with existing ones allowed obtaining new relevant information. Of course, the layers of information used for the two test sites were different, in accordance with their dynamics and needs. However, together they constitute a comprehensive database, so that different combinations of the layers used can be extrapolated to other areas.

2.4.4.1 Processing of rainfall data

The integration of rainfall data into the system is essential, since precipitation is the main aquifer recharge and an indicator of the meteorological conditions of a time period. Moreover, rainfall data have been very useful to interpret flooding levels in wetlands.

Several methods to estimate area rainfall were tested. Finally, the Thiessen method was selected and implemented in the system because it is widely used, is easy to automate and works reasonably well for flat areas like the ASTIMwR test sites. The increase of accuracy in rainfall calculations given by other methods would not justify their greater complexity for the kind of user-friendly application implemented.

Once the interpolation method was selected, the available rainfall data were pre-processed according to the following steps:

1. Selection of the rainfall period, based on the data at disposal for each rainfall station. Rainfall data were obtained from the Spanish Instituto Nacional de Meteorología. The period selected was 1956/57 - 1995/96.
2. Selection of the rainfall stations. Some rainfall stations were removed because they had a small number of data.
3. Grouping of rainfall stations in homogeneous groups (geographical proximity, topographic height and rainfall average) in order to perform the double mass analysis which allow to detect inconsistencies in data of some rainfall stations. Inconsistent data were removed from data series.
4. Fulfilment of data series. For Las Tablas de Daimiel region (a flat area with good quality rainfall data) a simple regression method was used.

The studied area is provided with 25 rainfall stations, but data from 9 of them were not finally used. Indeed, since the region has a homogeneous distribution of rainfall, it was preferable to use a smaller number of datasets of good quality than more datasets with low quality data.

2.4.4.2 Wetland (flooded surface) evolution

The protection of wetlands requires the knowledge of their evolution and dynamics. Since often little information on the flooded surface trends is available, a method was implemented in the module to detect of water surfaces from Landsat TM satellite images. This provides water managers with data on the past evolution of flooded surface and enables to monitor the present situation nearly in real time.

The implemented methodology generates water surface maps from Landsat TM images by calculating the following difference (ÁNGEL MARTÍNEZ, 1995), used by CEDEX (MOPTMA) for mapping continental waters in Spain:

$$\frac{Band4}{Band3} - \frac{Band4}{Band5}$$

If the result of this difference is greater or equal to 0.4, the system classifies automatically the pixel as water surface.

In the studied area, Las Tablas de Daimiel, field data exist with measurements of flooded surface (PNTD, 1998). This has been very useful to calibrate the method and to evaluate its limits and potentialities.

The comparison between maps obtained from the images and field data has shown the limitations of this methodology. Urban areas tend to be misclassified as water, and therefore they have to be masked prior the application of the formula. Also, when the water body is very shallow some pixels can result as misclassified. This is due to the fact that the Landsat TM sensor is not able to detect small water channels and water covered by phreatophytic vegetation. The misclassification is higher when water is abundant in the wetland, since in wet periods a shallow sheet of water spreads under vegetation, while during dry periods water is concentrated only in deep pounds with no vegetation.

Even when these limitations lead to an underestimate of the number of flooded hectares for each date, the methodology is useful to see evolutionary trends (fig. 2.41). The obtained values show efficiently the evolution of the flooded surface in Las Tablas de Daimiel, and are coherent with values measured in the field, rainfall data and transfers from other basins.

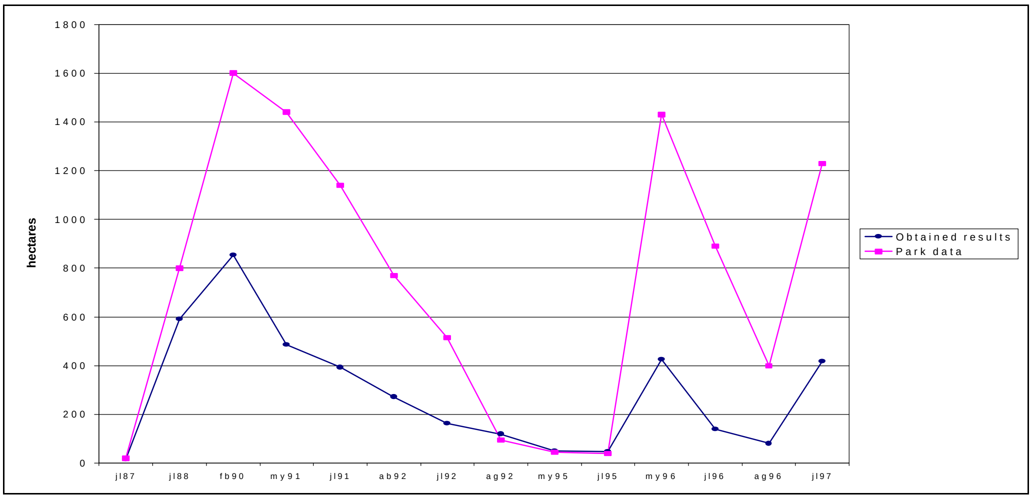

Figure 2.41: Comparison between values measured in the field and calculated with Remote sensing data.

2.4.4.3 Evolution of irrigated surface

When dealing with big aquifers intensely used for agriculture, direct methods for estimating water extraction are not affordable by water administrators. Therefore, a low-cost indirect method has to be used. Remote Sensing techniques have proved to be the most suitable for these purposes, since they provide the following advantages:

- Wide surface coverage at relatively low costs (comparing with direct methods).
- Availability of historical records: Landsat TM sensor has been operative since 1984 overflying the surveyed area every 16 days.
- Identification of irrigated areas: in semiarid climates crops irrigated in summer are easily identified since their spectral response is that of very healthy vegetation within a subdesertic area.

The images dates were selected taking into account not only the cloud coverage, but also the yearly phenologic evolution of the crops to be classified in the area.

Multitemporal supervised classification has been used to generate crop maps. The methodology applied combines maximum likelihood techniques of classification with decision tree criteria (FRIEDL & BRODLEY, 1997). These criteria have been adopted by using the Normalized Difference Vegetation Index (NDVI) which is an adequate indicator of crop biophysic parameters, allowing the follow-up of its phenologic evolution (GILABERT, GANDÍA & MELIÁ, 1996). In figure 2.42, the graphics show the evolution of the crop coefficients (Kc) used for the estimation of the water requirements for each crop (which are related to the phenologic state). Kc are generally empirical ratios of crop evapotranspiration (Et) to some reference Eto, and are calculated for a particular crop at a given grow stage and soil moisture condition (JENSEN, BURMAN & ALLEN, 1990). This coefficient and the NDVI evolution through the year are closely related, and respond to the same type of graphic (VELA et al., 1998).

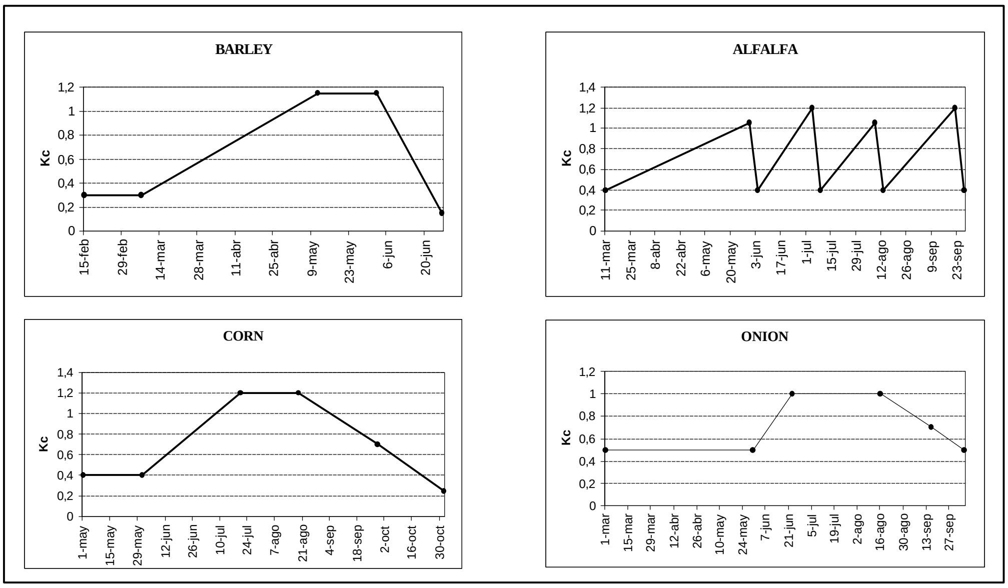

Figure 2.42: Mean crop coefficients (Kc) for some representative crops in the area. These coefficients are indicative of the phenologic status (photosyntethic activity and Leaf Area Index) within the annual crop evolution. (Data supplied by ITAP – Instituto Técnico Agronómico Provincial). (VELA et al., 1998).

In La Mancha region the optimal dates to be used in the classification in this area are the following:

- Late spring: In the middle days of May, the spring irrigated crops reach their ripeness, thus their photosynthetic activity and Leaf Area Index (LAI), which are the parameters that condition the spectral response of vegetation in the Normalized Vegetation Index (NDVI), are in their maximum.
- Spring-summer (middle of June): The spring crops have already dried and are ready for harvesting or have been already harvested, while the summer crops have just been sowed, giving both of them a low spectral response.

- Summer (end of July or first days of August): The summer-irrigated crops reach their maximum spectral response.

When available, a scene of the middle spring is very useful for better discrimination of drylands and spring-irrigated crops.

The definitive crop map used for the project has the following three classes:

- Spring irrigated crops (barley, wheat, garlic, colza, peas, etc.)
- Summer irrigated crops (onion, sunflower, vegetables, corn, sugar beet, etc.)
- Non seasonal irrigated crops (alfalfa, irrigated meadows, etc.) and double annual harvest (barley/green beans, peas/corn, etc.)

Due to the lack of reliable historical field data, it was not possible to estimate the accuracy of the classification. However, the same classification methodology has been validated by another project in the Eastern Llanura Manchega, having climatic features and agricultural practices very similar to those of the ASTIMwR study area (GESMO project, “Design of a system for the integrated management of the 08.29 aquifer - Mancha Oriental”, CALERA *et al*., 1998a). In that project, the confusion matrix obtained by comparing the fieldwork data with the classified image showed that the accuracy of the classification was 84.4% (CALERA *et al.,* 1998b).

2.4.4.4 Evolution of aquifer water table

Other essential information to monitor continental wetlands is that referred to the aquifers. As explained above, many wetlands are deeply influenced by the evolution of the water level. To study the groundwater dynamics and have both a qualitative and qualitative view of the aquifer water table maps were generated.

For this purpose, two methods can be used:

1. Automated methods. Several methods of interpolation of contour lines from point data were tested. The results have been, in all the cases, barely satisfactory. The causes of this are:

    - When interpolating the variable of water table levels it is always important to consider several factors related with this variable such as topography, low-permeability limits... The incorporation of these physical-mathematical characteristics of the variables is very complex, and does not permit to obtain general solutions (SAMPER & CARRERA, 1990).
    - In the ASTIMwR test site there is also the problem of the scarcity and low quality of data, as reported already in previous studies (SGOP, 1986). The lack of good water table levels data is very common even in developed countries, due to the facts that often subterranean waters have been forgotten and prejudged by water managers (SAHUQUILLO, 1994). This fact results in situations where interpolations have to be done with a small quantity of not very reliable data.

2. Manual interpolation. The manual interpolation was the selected method, since it allows the expert to incorporate hydrogeological criteria and the critical use of well data. The integration of the characteristics of the variable (water table heights) generally makes manual results superior to automatic ones (SAMPER & CARRERA, 1990). On the other hand, the subjectivity can produce different interpretations of the same data, which is increased when data are of poor quality.

In this area several problems with data were found:

- In some cases, water level measurements are done in pumping wells. This effect was minimised by delineating the lines of equal water table elevation for dates with no pumping for irrigation.
- Many locations of water level measurements are located close to riverbeds where preferential recharge occurs.
- It was detected that very close locations of water level measurements give very different levels, in places where the difference can be explained only due to the well construction.
- There are a lot of mistakes in data, such as changes of the topographic height of wells.
- In the studied area there are two hydrogeologic units having very different features: the Lower Tertiary unit and the Upper Tertiary unit. The water table elevation maps have been made for the Upper Tertiary unit. Thus, some well data have been not considered, because those close to the limit of the Upper unit also penetrate the Lower unit that has higher or even upsurge levels.

For this, the number of reliable data able to use for each map was reduced to a number ranging between 8 to 20 points for each map and date.

In the software tool, the field data provided by CHG are included. Points of measurement can be plotted on the water table level maps and their data can be displayed in tables and graphics, to enable the operator to compare maps with real data and assess the reliability of the interpolation.

2.4.4.5 Vegetation index evolution

The vegetal coverage associated to a wetland area is both its richness and an element to judge the healthiness of the system. Satellite imagery is a powerful tool to monitor the evolution of this vegetation, and thus the wetland evolution.

The two basic methods to monitor the evolution of vegetation by using remote sensing are image classification and vegetation indexes. The ASTIMwR system includes a tool that manages classified images for irrigation monitoring. In the case of irrigation, classified images are a good option since crops are relatively homogeneous covers usually of several hectares. The system also includes a tool to generate vegetation indexes from Landsat TM images. Those indexes can be very useful for natural wetland vegetation, which is usually very heterogeneous and so it is difficult to group in classes.

The use of these indexes to discriminate vegetal covers is based on the radiometric behaviour of vegetation that shows a clear contrast between visible bands and the near infrared. This principle is the basis of Vegetation Indexes. The most widely employed version is the normalised difference vegetation index (NDVI) (SABINS, 1996), which is defined for Landsat TM images as:

$$NDVI = \frac{Band4 - Band3}{Band4 + Band3}$$

Its values range from -1 to +1. Even persons not trained in Remote Sensing can handle this index because it is easily interpretable. Higher values indicate higher concentrations of green vegetation. Some parameters as the Leaf Area Index, content of water in leafs or photosynthetic activity are clearly co-related with NDVI (CHUVIECO, 1996). In the other hand lower values indicate non vegetated features such as water or barren land.

The methodology based in the analysis of the evolution of values of NDVI has been used for the pilot area of O Sapal de Castro Marím, where little information exists about its evolution and dynamics.

For this area NDVI index was calculated for fourteen Landsat TM images. Whenever possible, a spring image and a summer image for each year were selected, because natural vegetation has the highest values of NDVI in spring and the lowest ones in summer.

The analysis of NDVI values for the whole Castro Marím wetlands is useful only to detect major changes in the land coverage. For areas without significant modification of land uses this kind of analysis of the NDVI gives no results.

To solve this limitation, the evolution of NDVI values has to be studied for smaller areas. In this way, some test plots previously identified in the field were selected. Plots with natural vegetation represent typical assemblages of the area. The main land uses in the Castro Marím wetland areas are represented in the plots selected. Moreover, a parcel of pine woodland, very stable and far from areas susceptible of flooding, has been studied, because it is very useful to compare its evolution with the evolution of the vegetation in O Sapal de Castro Marím.

Once evolutionary data were obtained, they were compared in graphics and tables together with values of other hydrologic parameters that may play an important role in the system dynamics.

The hydrologic data used were:

a) Rainfall.
   Rainfall data were collected from the Castro Marím rainfall station (INAG, 1995), a station having very complete and reliable data. The studied area is very small and so it is possible to extrapolate the data to the whole area.
   Annual, monthly and twice-monthly rainfall data were compared with values of NDVI. The aim was to detect the influence of the rainfall on NDVI in the period previous to the image acquisition.

b) River flows.

The process followed with rainfall data has been applied also to river flow data. Two gauging stations located near the Hispano-Portuguese border were selected due to their closeness to the studied area. The station of Puente Palmas provided the data for the period 1980/81-1993/94. In 1994, this station was substituted by the recently built station of Azud de Badajoz, which recorded the data for 1995/96 - 1996/97. The data were supplied by CHG.

c) Tidal cycles.

Synthetic tidal values were generated using the *Tides and Currents for Windows* software (NAUTICAL SOFTWARE, 1996). Tidal values were compared with NDVI values. The independence of NDVI index values from tidal values in the area was presumed from the visits to the field, because the entry of water in the wetland is artificially regulated. Though, it was interesting to confirm this hypothesis with data graphics.

2.4.5 Results

In order to have a structured description of the results, they are presented according to the sections used in 2.4.4. However, as the interest of the module is in combining several types of data, the results included in each section are based also on data described in other sections.

2.4.5.1 Processing of rainfall data

Completed series of monthly values of rainfall have been obtained. They make it possible to calculate values of area rainfall for the mask selected by the user within the Upper basin of Guadiana River.

By analysing figure 2.43, which shows the values of annual rainfall for the area studied, it can be concluded that:

- The average rainfall for the area is 407 mm, which means an average volume of precipitation in the area of 308 Hm^3.
- As it is characteristic in the South of the Iberian Peninsula, rainfall values show an important dispersion, being the difference between the driest and the wettest year about 400 mm.
- Considering the average values of the whole rainfall data period, it can be concluded that the period considered in ASTIMwR (1978/79 - 1995/96) is not a particularly dry one. However, there are a number of years that, if considered separately, are extremely dry (rainfall about 25% lower than the average): 1990/91, 1992/93, 1993/94 and 1994/95.

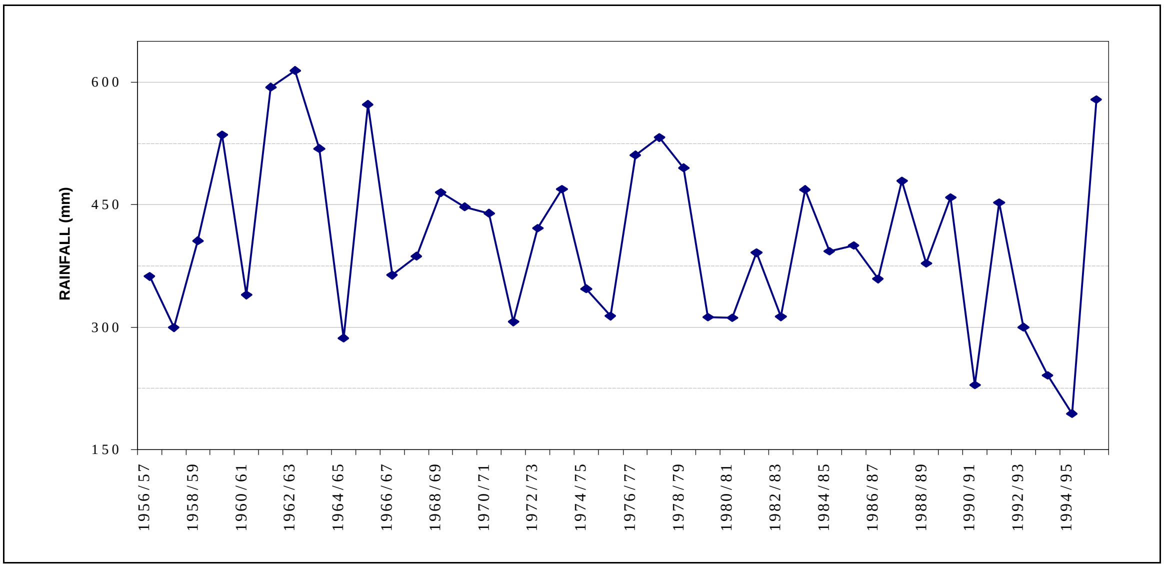

Figure 2.43: Area rainfall for the study area.

2.4.5.2 Wetland (flooded surface) evolution

The flooded surface in Las Tablas de Daimiel for several dates were obtained applying the algorithm described in section 2.4.4.2 to the Landsat TM images. The results are displayed in the table below (see also fig. 2.41):

	Jun 84	Jul 84	Sep 84	May 85	Jul 85	Aug 85	Jun 86	Jul 86	Jul 87	Jul 88
Surface (hectares)	177.2	216.0	67.7	144.7	143.2	143.2	101.8	87.4	17.1	590.9

	Feb 90	May 91	Jul 91	Abr 92	Jul 92	Aug 92	Jul 95	May 96	Jul 96	Aug 96	Jul 97
Surface (hectares)	853.9	486.1	393.1	271.8	163.7	119.8	47.8	426.2	139.0	80.9	418.0

Table 2.24: Remotely sensed flooded surface for available dates.

In 1984, the first year of the studied period, the wetland dynamics were already altered. The rainfall was 470 mm, which is about 40 mm over the average and rainfall during the months of June and July doubles the monthly average. Nevertheless, by the end of the summer of 1984 the flooded surface is very limited (67.7 hectares). This fact is the response of the system to the drawdown of the water table levels of the aquifer that used to feed the wetland.

The Puente Navarro dam, a small dam (of about 8 meters high) built to retain runoff water inside the Park, begins to store water in 1985. This allowed the recovery of a traditionally flooded area with a high environmental value (SÁNCHEZ & CARRASCO, 1996), but its function is nearly none when flows are scarce. Even with the dam, the flooded surface in 1985 is smaller than in 1984, and this trend is maintained during the following years (1986 and 1987), when the draught influences the reduction of water surface.

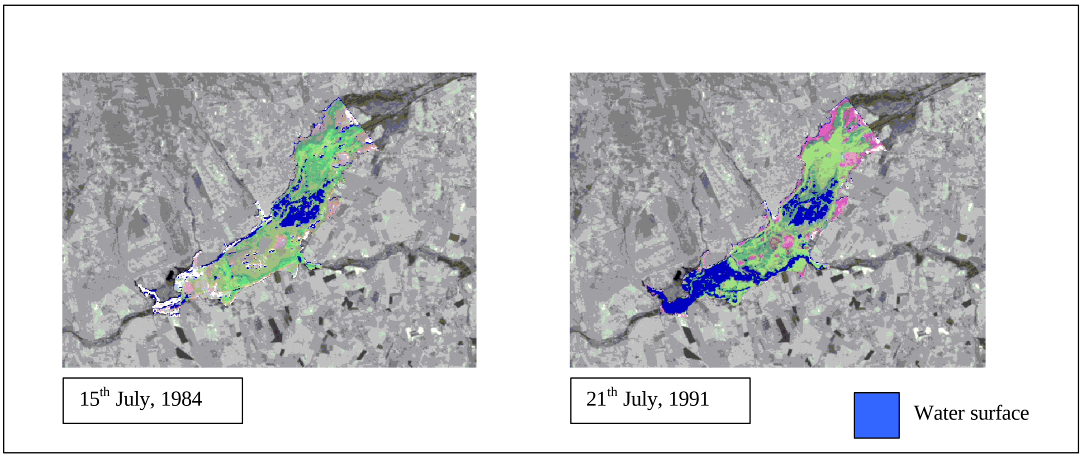

Figure 2.44: Results obtained for the National Park. The area where formula was applied is showed with its own colour table, and it is over the Landsat TM band 5. The Puente Navarro dam has caused a change on the distribution of water in the wetland creating a persistent flooded area downstream.

During the period 1988 - 1991 water transfers from other basins kept levels in acceptable values (fig. 2.44). Water transfers have had a positive influence on the wetland (SÁNCHEZ & CARRASCO, 1996), although they have brought about problems due to the quantity and quality of superficial water. For this reason, between 1992 and 1995 water transfers were reduced and an important part of the water transferred (90% in 1994) was drained directly to the aquifer instead of to Las Tablas de Daimiel. But even in wet years like 1996 (100 mm over the average) and with water transfers (30 Hm^3), the flooded level decreases rapidly in short periods without superficial flows: the flooded surface existing in July is reduced to nearly a half in August of the same year.

This evolution shows that:

- From the beginning of the decade of 1980 Las Tablas de Daimiel does not receive the subterranean waters supply that keeps levels during dry seasons.
- Solving the water supply problem mainly by transferring water from other basins is impossible. Water transfers may have helped the conservation of some flora and fauna of the wetland, but they are not a long-term solution. Changes in water chemistry are a drawback associated with these transfers.

2.4.5.3 Evolution of irrigated surface.

In order to carry out the crop classification, it is preferable to have three images per year distributed in the months of May (or ending of April), July and August. For some years it was not possible to have spring dates, while for others only one summer date was available. There are two reasons for this, the first one is the cloud cover, which limits, mainly in spring, the number of usable images, and the second one has to do with the budget available for data acquisition. To maximise the images budget, also images acquired by other partners of the project for their own module were used.

To avoid misinterpretations of data table 2.25 shows dates of the images used together with the result for each class.

	Dates	**1978**	**1984**	**1985**	**1986**	**1987**	**1991**	**1992**	**1995**	**1996**	**1997**
	April							■			
	May			■		■	■		■	■	
	June		■		■						
	July	■	■	■	■	■	■	■	■	■	■
	August			■				■		■	■
	September		■								
Irrigated (ht)	Summer crops	1,406	4,301	4,425	3,368	3,287	2,858	2,994	2,191	2,729	1,270
	Alfalfa+double crops	no data	620	340	no data	722	400	353	303	130	No data
	Spring crops	no data	480	2,258	no data	2140	7,714	7,327	2,995	5,440	No data

Table 2.25: Available images (top) and irrigated hectares of each crop class for the available images obtained from the supervised classification (bottom).

The first year studied is 1978, by using a Landsat MSS image, when about 1,500 hectares are irrigated in summer, generally distributed in small plots.

The period from 1978 to 1985 is characterised by a constant increase of summer-irrigated lands up to a maximum of 4,425 hectares. The comparison between images of 1978 with those of 1984-85 reveals an important change in the characteristics of irrigated parcels, from small plots in 1978 to more extensive (and automated, as pivots reveal) plots. From 1985 to 1997, there is a decrease of the surface cultivated with summer crops.

For the studied years spring crops show a changing evolutionary trend. From 1985-87 the spring-irrigated surface becomes important (over 2,000 hectares), reaching in 1991-92 values of about 7,500 hectares. In 1995 spring-irrigated surface is only 3,000 hectares, probably as an effect of drought that was in its maximum. However, this seems to be a transitory situation because in 1996 the value of irrigated surface in spring reaches 5,440 hectares.

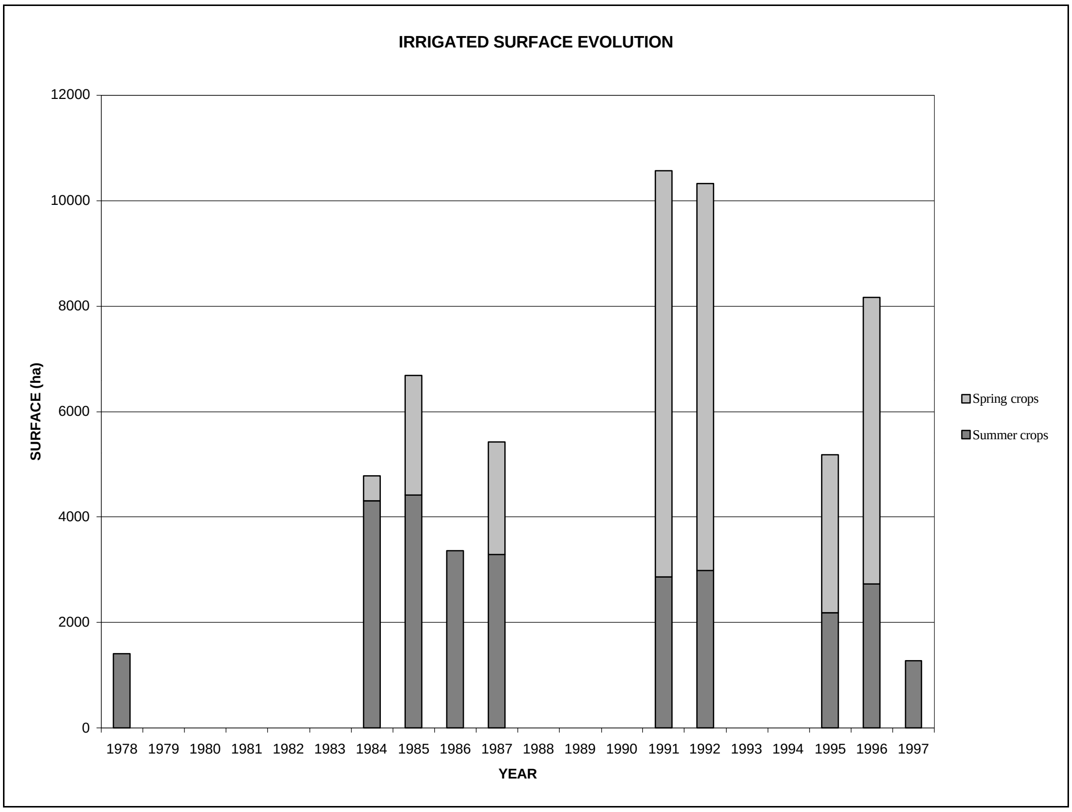

Figure 2.45: Evolution of summer and spring irrigated crops.

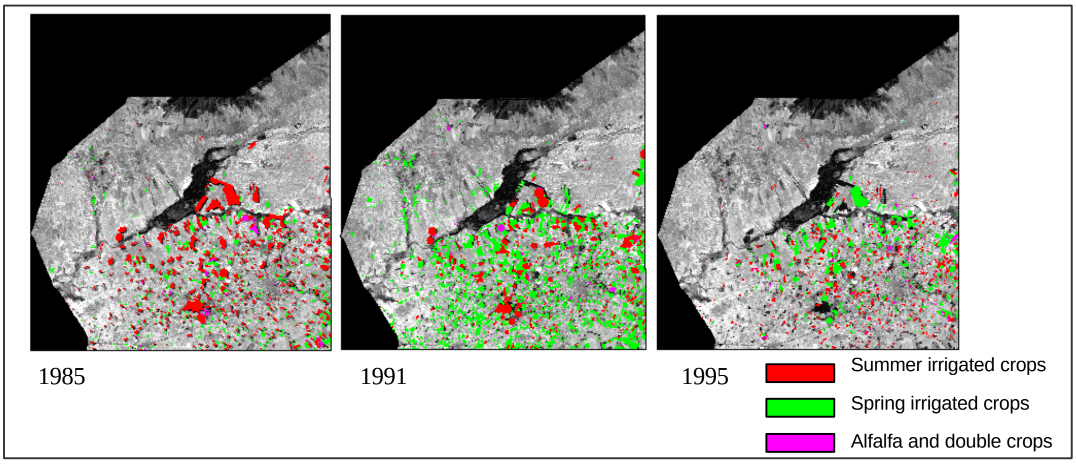

Figure 2.46: Classified images of the study area. Las Tablas de Daimiel can be seen in the middle of the image in dark colour. The three images coincide with three significant moments: 1985 had the maximum summer irrigated surface, 1991 the maximum spring irrigated surface and in 1995, the last year of drought, both summer and spring irrigation surfaces decreased.

Also the evolution of alfalfa and double crops has been monitored. The analysis has showed that this type of crops is not very common in the area in comparison with summer or spring crops. Their evolution is variable, but the general trend is decreasing from the maximum value in 1987.

The conclusions that can be drawn from the evolution of the classes of land use monitored are:

- The areas adjacent to Las Tablas de Daimiel have had similar changes in the agricultural practices to those produced during the last two decades in La Mancha, with no limitations due to their closeness to the National Park. In fact, even inside the Protection Perimeter of the National Park crops have a similar evolution to the rest of the area (table 2.26):

class/year	1978	1984	1985	1986	1987	1991	1992	1995	1996	1997
summer irrigated crops	263	737	854	713	720	441	533	132	171	96
alfalfa+double crops	no data	31	10	no data	46	59	26	5	10	no data
spring irrigated crops	no data	65	191	no data	221	899	1038	554	604	no data

Table 2.26: Irrigated hectares of each crop class within the Protection Perimeter of the Las Tablas de Daimiel National Park.

- The traditional agriculture, based in a model of interrelation between dry land agriculture (mainly cereals) and cattle raising, has changed to irrigation farming (of vegetables and cereal). Though, it is not clear to what extend socio-economic benefits produced by this change have been worth the environmentally negative effects (LÓPEZ SANZ, 1998).
- The decrease of the summer-irrigated surface from 1985 is in contrast with the drastic increase in spring-irrigated surface.
- The effect of drought on the availability of water resources caused a temporal decrease of irrigated surface.
- The decrease of irrigated crops in the past few years could be due to the effects of the *Programa de Compensación de Rentas Agrarias* (Agricultural Incomes Compensation Program). These beneficial effects causing a slight decrease of the irrigated surface do not seem to be enough to achieve the wetland recovery.

2.4.5.4 Evolution of aquifer water table levels

Water table levels maps were elaborated for Upper Tertiary Hydrogeologic Unit (IGME, 1982) with data from the database of the Confederación Hidrográfica del Guadiana (CHG).

The studied period is from 1978 to 1997 according to the availability of wells data and satellite images for irrigated surface maps. When it was possible, water table levels maps were elaborated for months after the irrigation season in order to avoid the effect of dynamic levels, but detecting clearly the effects of pumping in the regional levels.

From 1978 - the year when irrigation begins to increase - to 1993 there was a continuous decrease of the levels of the aquifer. This trend changed as a result of rainfall during 1995/96 and 1996/97. Maps are incorporated to the GIS tool in order to operate with them easily to obtain drawdown maps.

The main results obtained from the analysis of water table level maps are:

- The increase of pumping for irrigation has been the main cause of the continuous decrease of the water table levels, reaching values of about 25 meters in this area.

  The following graphic shows the evolution that measurement points have in the area close to Las Tablas de Daimiel (fig. 2.46).

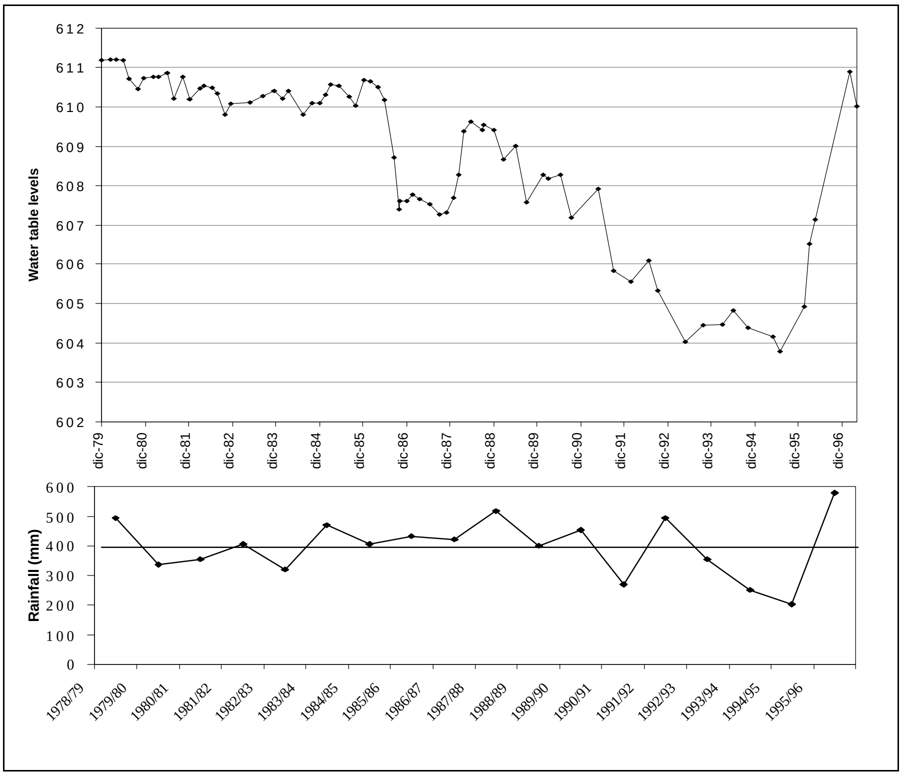

Figure 2.46: Evolution of the water table levels in a well close to Las Tablas de Daimiel (top) and rainfall volumes for the period 1980 - 1996. The horizontal line in the rainfall graphic is the annual average for a series of 40 years. The graphic shows that the water level decline is not only due to drought.

- The change of summer-irrigated crop to spring-irrigated crops has not produced water saving. This is because spring crops have increased proportionally much more than summer crops have decreased, and this effect has balanced the possible saving due to the lower water consumption of spring crops.

- Volume extracted in the period 1987-90 is bigger than the one extracted from the aquifer reservoirs for the period 1990-93 (fig. 2.47). Paradoxically, this slowing down in the rate of decrease in a drier period of years could be explained by the lack of water in wells (many of them went dry and for others the cost of pumping grew) that makes farmers stop irrigation.

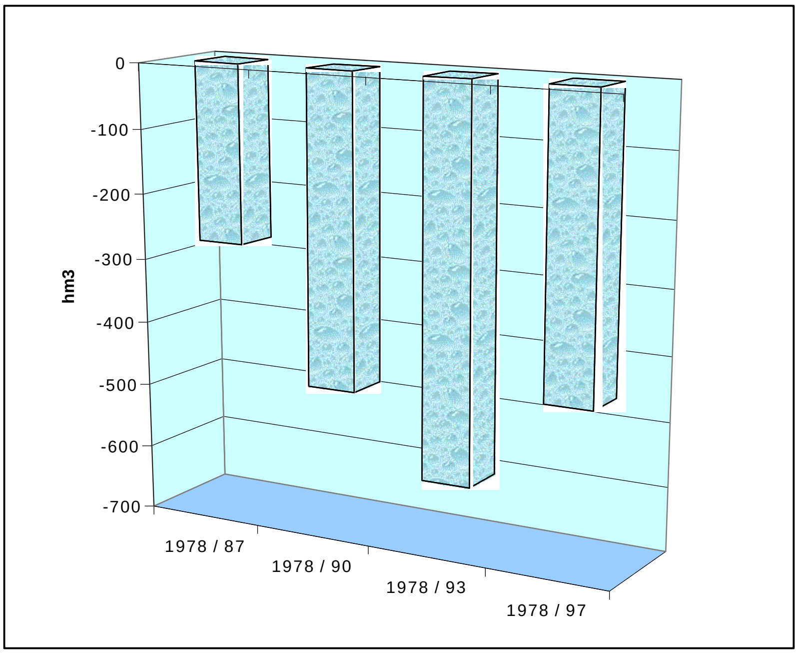

Figure 2.47: Changes in storage of aquifer 04-04 in the study area (supposed an average storage coefficient c=0.05)

- For 1996 and 1997, two very wet years, there is a recuperation of water table levels. This recuperation should not lead to erroneous interpretations. Indeed, it does not mean that the aquifer has recovered its original state (fig. 2.47). The effect is magnified by the fact that this area is close to the border of the aquifer and has a lot of superficial streams and ponds that infiltrate into the aquifer. Many measurement points of water table levels are close to these streams and ponds, and so, recharge effects are magnified (fig. 2.48). For areas far away from places of preferential infiltration and closer to the central areas of the aquifer the recovery of levels is much smaller.
- It is patent that the different behaviours of the Miocene-Pliocene and confined Oligocene aquifers. The latter one, not very exploited until 1990 decade, has maintained nearly constant its heads (and higher than for Miocene-Pliocene) until the beginning of its exploitation during draught (1990-1995) and its recovery has been also fast.

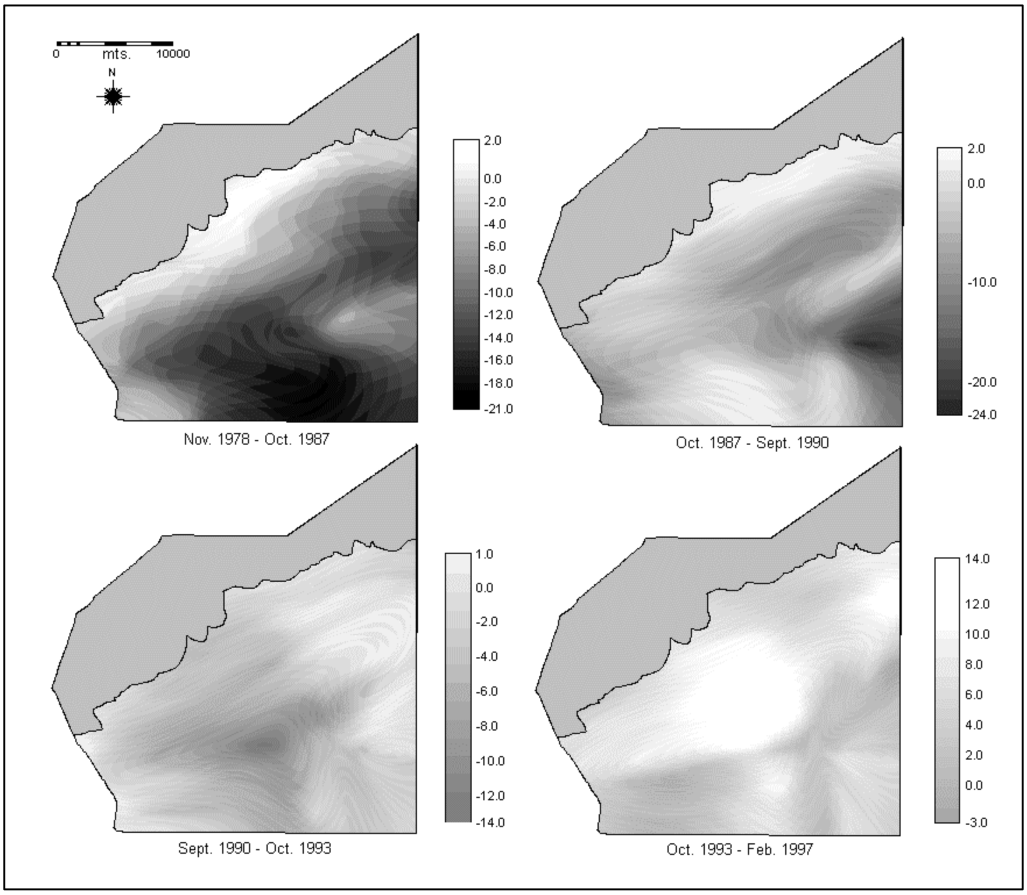

Figure 2.48: Maps showing changes of Miocene-Pliocene aquifer water table levels in meters for different years. These maps have been obtained by crossing the water table levels maps in the GIS. The area coloured in homogeneous grey belongs to the Oligocene aquifer.

2.4.5.5 Vegetation index evolution

The results obtained for O Sapal de Castro Marím confirmed the interest of the NDVI as a change detection indicator. In this area image classification, both supervised and unsupervised, was tried and no satisfactory results were obtained due to the natural system complexity. Whereas, NDVI has been very useful to study the sensibility of the system to certain hydrologic parameters.

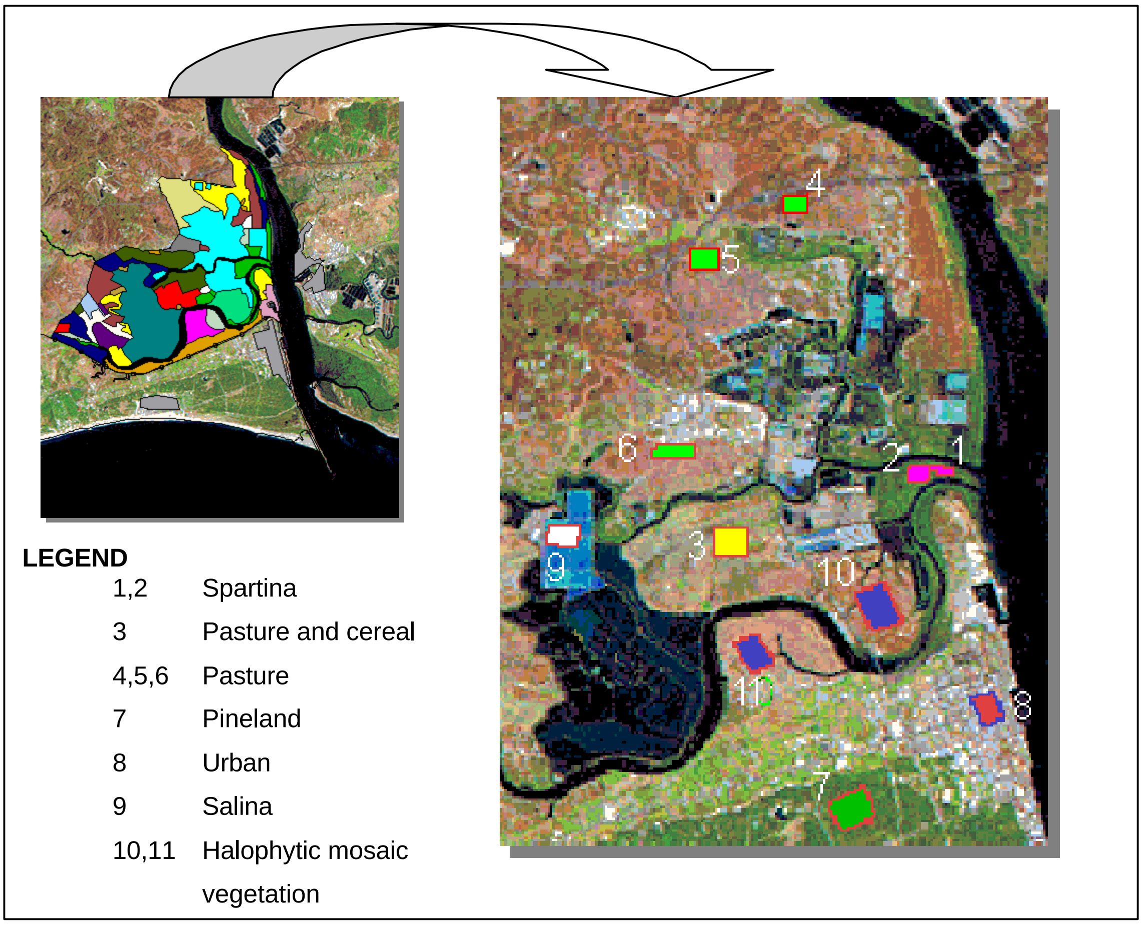

Figure 2.49: Some of the test plots monitored and the land use map (from 1997 fieldwork) that was the basis to select them.

From the analysis of the NDVI index for the whole area, it was detected that there have not been major changes in the land use of this area since 1984 until 1997.

From the analysis of the evolution of the NDVI in the test plots it can be concluded that:

- No relationship exists between tidal cycles and the evolution of the vegetation index.
- The correlation between annual rainfall data and NDVI is low.
- The correlation between monthly and twice-monthly rainfall with NDVI is very good, especially for plots with pines, mosaic wetland vegetation (fig. 2.49) and Spartina (a halophytic plant), but it is not always good for pastures, no doubt owing to farming practices. The range of fluctuation of NDVI with rainfall values varies linearly with the seasonal nature of each vegetal cover. For example, for pine woodland the effect of rainfall can be clearly observed, even when it always has NDVI high values. It also can be observed how during the growth of the woodland NDVI increases progressively (1984-90) until the stabilisation (1990-97) when it reaches its maximum biomass. On the other hand, NDVI of wetland mosaic vegetation ranges between nearly zero values when rainfall is low for a couple of months to 0.2-0.4 values for wet months.

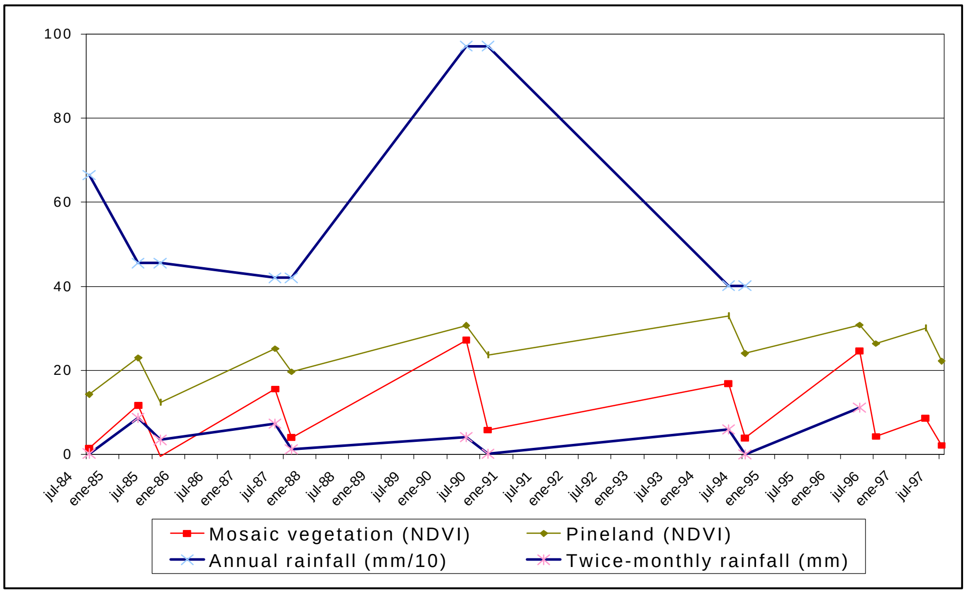

Figure 2.50: Comparison between rainfall data and NDVI values (from 0 to 100) for two test plots.

- There is not a good correlation between the Guadiana River flow data and changes in NDVI. Although higher river flows are coincident with high NDVI values, there is no proportionality between river flow and NDVI. The observed relation is due to the fact that usually wet months in the Guadiana river basin are also wet in the river mouth area where O Sapal is located.

O Sapal de Castro Marím has suffered drastic changes in its landscape due to the human action in this century. For example, part of its natural value as a bird area is linked to the creation of pools for salt mining. No major changes in the land use have been detected during the last fifteen years, since the registered variations in the natural vegetal coverage are directly related to seasonal rainfall.

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2.5 System Implementation

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2.5.1 Introduction

The objectives of the Centre for Earth Observation programme of the European Commission include the wish to make the tools and techniques as developed in academia useful for organisations in charge of the management of the natural resources.

The ASTIMwR project intends to bring the worlds of research institutes and private consultants together with public agencies in charge of water management.

The technology of remote sensing and geo data processing through GIS and other software has to be made manageable and operational in the daily routine of the ‘users’, in this project the Confedaración Hidrográfica del Guadiana, the Instituto da Água, the Instituto de Hidráulica, Engenharia Rural e Ambiente and the Consorcio di Bonifica di Paestum.

This objective was translated in the wish to design and build a “system”, that is to say a computerised data set and functionalities, which the users would be able to use without having to go deeply in the techniques of Remote Sensing, GIS and databasing.

The first phase of the project comprised the information analysis of the users and the first design of the system. Reports on these studies have been presented in the ’ASTIMwR Interim Report’ of February 98. In the following some elements of that report will be repeated.

2.5.2 Requirements, priorities and constraints formulated in the first phase

The first inventory of wishes and requirements was a lot more than what the project would be able to realise. It also showed that developing an information system for an organisation, such as the users in the project represent, implies a lot more than developing a tool for easy access to information derived from base data and (processed) images. The word *system* as software package should thus not be confused with the concept of an entire information system of an organisation. Unfortunately the boundary between the two concepts has been difficult to explain and draw. The two meanings of system have caused some confusion during the execution of the project. Users tended to have ever increasing and higher expectations than what could be realised in the frame of the project.

Priority was given to the provision of data on the state of the resources as could be detected with the use of earth observation techniques and specialised knowledge combined with other (field and administrative) data. This is reflected in the themes of the modules that were implemented during the project (chapter 2.1, 2.2, 2.3 and 2.4). Special care was given to the user's demand to be able to locate groundwater irrigation (by remote sensing) in known parcels and to estimate the actual water use versus the licenced water use. This functionality provides a direct information source for the management of the decreasing groundwater levels. Visualisation of the information in the form of maps and graphs also received a high priority.

A major constraint encountered in the user's organisations was the limited human and technical resources. This was translated into the need for an easy and structured interface that would allow fast access to the most commonly and frequently used data and information products. The system should run on available hardware (that means PC – Windows technology).

2.5.3 First design

A first design was presented to the users whereby access to the information would be given on each of the themes of the modules and to the general source data, the images, the administrative and management units handled by the user organisations. Each theme has a spatial, thematic and temporal component. Menus should lead the user to the selection of the elements, the themes and the time period from which data had to be retrieved.

Technically the system was designed to be able to receive data in different formats as determined by the software environments in which the users and the research institutes were working.

The handling of the graphical data required operations ranging from pure retrieval to geo data processing as can only be done in GIS environments. The system was originally thought of as independent of commercial software but would still have to provide data base and GIS type functionalities. This turned out to be unfeasible. The amount of time and money which would have been required to develop such software could not be justified against the cost of using already available GIS software. The project thus decided to use the ILWIS software (*Integrated Land and Water Information System*, version 2.2), which requires a hard-key, as the database manager for the graphic data. Access was selected as database manager for the meta database and Access formats for all attribute tables.

The presentation of the design to the user communities led to a series of new requirements for access to data and more complex data combinations. These requirements were incorporated for the further development.

2.5.4 Architecture of the system

The system is also referred to as the User Interface (UI) as it should provide easy access to frequently used data in the routine operations of the organisations. Access to the data by pointing at a location, or by selecting the name of a location was required.

As stated before, the underlying data base management software would be ILWIS for the graphic data. Non graphic data will be managed in Access table format but do not require the software itself.
ILWIS supports the Dynamic Data Exchange (DDE) standard. The programming of the interface itself was done in Visual Basic that, through the DDE, would be able to invoke operations in the underlying software.

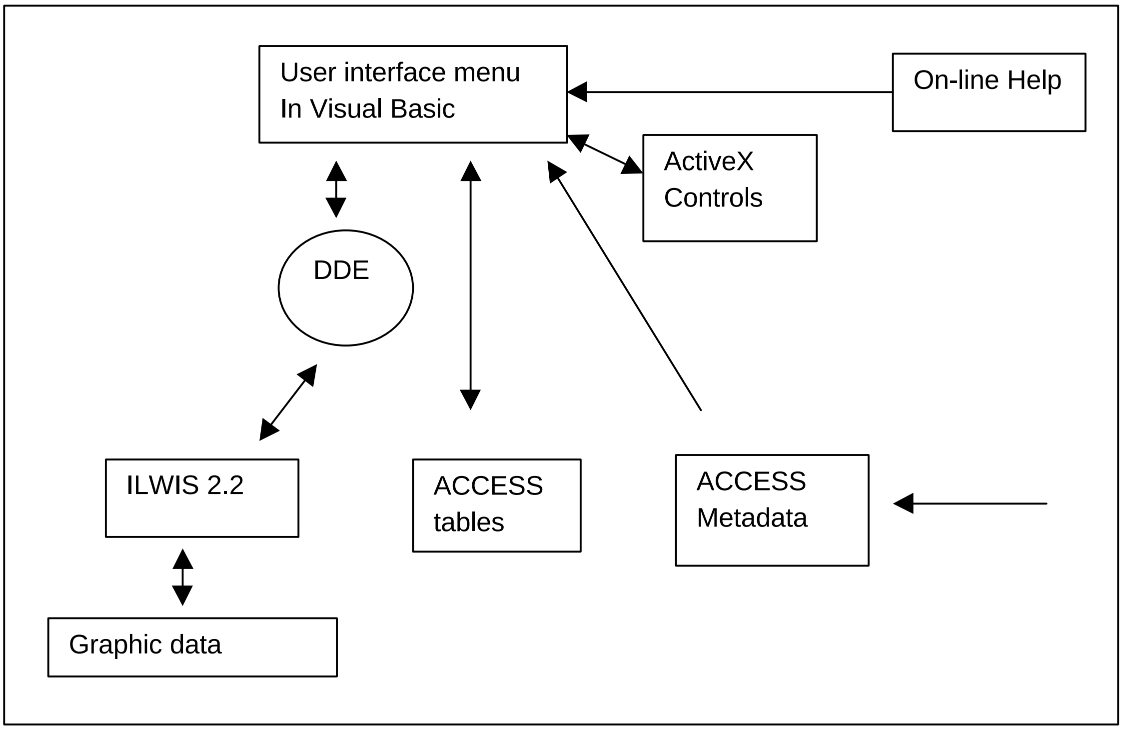

Figure 2.51: System Design flow chart.

Visual Basic invokes functions of Active X control to facilitate the development of the interface and invokes ILWIS 2.2 functions through DDE for GIS and RS operations (including the visualisation and hardcopy output functions).

The Visual Basic programme can access directly other tables, which are designed in an Access format to read, edit and create new tables without having to run ACCESS software. An on line Help is provided on all the items of the interface and can access the Help file of ILWIS.

The manual of the system shows all the components of the program and explains how they should be operated.

2.5.5 The Meta Database

A very important component of the system is the meta database in which all information on the capture, processing and output of the information is maintained. The user can access the meta database via the interface and see how combinations are made and products presented. The names, dates and institutions that relate to the processed data can be traced so that new users can find their way to the source of the data and assess their quality.

If new data sets are to be incorporated by the users, then also the metadata on these new data should be added. This meta database does require the Access software for updates. The meta data can be read via the interface without having the Access software installed.

2.5.6 Data Input

The interface provides also facilities for data input. Here a differentiation has to be made in data that can be inserted directly, such as administrative data, and data that require pre-processing by specialised institutions or consultants.

A lot of effort has been given to loading into the system of the data sets as they became gradually available from the different technical partners. As stated above, different formats for graphical and attribute data would be used as each partner uses its own digital infrastructure for the processing of data. Data have been received in Erdas, Arc-info, Excel and other formats. The conversion of these data to the formats of the ASTIMwR system required a carefully planned procedure whereby the quality of the data was monitored. Indeed, the fact that data from many different domains have to be combined, generally through their spatial attributes, means that standards for the quality of the geo-referencing have to be set according to the scale of the data. The meta data is here of prime importance.

Loading data of this nature shows that the database requires rules for data management and administration. This is a separate task for which one person/division should be made responsible. In the present system there are no privileges defined for different users. This makes it possible that any user can change or even delete data. The user organisation will have to describe and assign the responsibilities for access to and maintenance of the data. Standards for the quality of new data will have to be defined and the data base administrator will have to control the quality of the data before loading. Management of backups, version management, documentation and training of staff on the system will be related tasks. Only in this way the system will become a useful component in the entire information system of the (user's) organisation.

2.5.7 Testing the different versions of the system

In month 18 a Pre-alpha version of the system was provided to the partners in the project and a testing round started. A series of bugs was encountered and new requirements were formulated. A part of these bugs related to the ILWIS software, which was still under development during the execution of the project. These bugs were solved with the release of the version 2.2 in approximately month 22 of the project. Programming bugs were solved in the Alpha version, which was released in month 20 and new functionalities for multi temporal analysis of NDVI data were added to the programme.

Testing was done with limited data-sets sent by the technical partners, since the delivery of the complete data-set ended only shortly before the final meeting of the project.

The Beta version was released in month 23 and the 1.0 version was delivered to the partners in month 24 of the project, tested and discussed during the final meeting with all the partners.

2.5.8 Conclusions

User requirements have been evolving during the execution of the project. This made it necessary to follow a prototyping approach for the development of the system. The final product does satisfy the requirements as stated in the System Design Document and even extends on that as a result of the interactions with the partners during the project.

The version 1.0 is delivered with all the data as provided in the different work-packages and can be used for demonstration and production purposes.

The software is capable of receiving Geo data from different formats. Nonetheless expert knowledge is advisable to incorporate new data when transformation of formats have to be done. Tabular data are easily incorporated from the standard formats in which they are generally delivered.

If the system is being incorporated in the daily routines of the (user’s) organisations, additional rules and responsibilities will have to be defined for the operation and maintenance of the system. A data base administrator will have to be appointed and rules of access and authorities for updates will have to be defined.

As the demonstration proved the functionalities, ease of operation and speed of processing, it is believed that the prototype of the systems provides a good platform for further development and use in water management in river basins.

The fact that a full-grown GIS software package is incorporated in the system does generate the possibility that users can expand on their geo data management using the functionalities of this software. This can be accompanied by further development of the interface, or be done separately in the GIS environment.

The meta database is an very important component of the system. Users should realise that any modification of the data or adding of new data should be accompanied by an update of the meta database. Especially when data will be exchanged within and between organisations, the metadata will turn out to be of prime interest.

3 EVALUATION OF SUCCESS CRITERIA

The success criteria for the ASTIMwR were identified during the first year of the project and were taken into account throughout the duration of the project to assess the progress of the work and, where necessary, to refocus the activities.

The success criteria have been categorised into the following three groups:

a) Organisational Criteria, namely:
- Commitment of all the partners
- Involvement of the users in all phase of the project
- Fulfilment of the contractual commitments
- Creation of new contacts with potential EO customers
- Advertisement and dissemination of the project

b) Technical, namely:
- Positive evaluation of the ASTIMwR system
- Positive evaluation of the information generated

c) Economic, namely:
- Cost-effectiveness of EO data
- Interest of the partners in following the research/development

In the following subchapters, the success of ASTIMwR is assessed against these criteria.

3.1 Organisational Criteria

3.1.1 Commitment of all the partners

The project has run reasonably smoothly over its lifecycle and no major problems have affected its progress. The difficult task of maintaining efficient communication and collaboration between the partners was successfully. Indeed, the Consortium has worked in a good environment and its members have been solicitous in carrying out their tasks, in accordance with their capabilities and resources.

3.1.2 Involvement of the users in all phase of the project

From the beginning of ASTIMwR, the users have been actively involved in the project. They have collaborated in the selection of the test sites, the cataloguing of the available data and the organisation of the fieldwork. They have provided the technical partners with images, maps and alphanumeric data in their possession, thus facilitating the work of the other partners and optimising the ASTIMwR budget. Moreover, the users have made staff available for the fieldwork and have provided support to the technical partners when they have needed to stay in the test site during long periods.

The users have expressed their needs and requirements both during personal interviews and during the project meetings. This was facilitated by the fact that it was possible to talk in Spanish, Portuguese and Italian. Thanks to this positive co-operation it was possible to elaborate a comprehensive user requirements document.

The users have participated in all the project meetings. The meeting venues rotated among the user' organisations in order to provide opportunities to get to know their organisations and the area managed by them. In all three countries the head of the user organisations officially welcomed the meeting participants. In Spain and Italy, the meeting was opened in presence of the press, who had been invited by the users.

3.1.3 Fulfilment of the contractual commitments

The successful co-operation by the partners enabled the fulfilment of contractual commitments (deliverables and cost statements) to the European Commission.

Although a delay occurred in the delivery of the definitive draft of the User Requirements Document, mainly due to internal staff changes in ITC (the responsible partner), this delay didn't affect the good progress of the project because the users were able to clarify orally their requirements to the Consortium.

3.1.4 Creation of new contacts with potential EO customers

New potential users have expressed their interest in ASTIMwR. The expected usefulness of the ASTIMwR results led IHERA (*Instituto de Hidráulica, Engenheria Rural e Ambiente*) of the Portuguese Ministry of Agriculture to participate in the project activities and events as a member of the Portuguese team.

The research was received with enthusiasm by the irrigation districts selected as test sites and, due to the interest excited by the project, a new test area was selected in Portugal.

IHERA produced a video to present ASTIMwR and the results of the Portuguese test area, while SC-DLO prepared a report for the Spanish irrigation districts that collaborated in the irrigation performance module.

Through its participation in the CEO programme, GEOSYS S.L. had the unexpected opportunity to extend its market into Equatorial Africa. In September 1997 it carried out a project for the quality control of a set of SPOT images on behalf of the Ministry of Foreign Affairs of Guinea-Bissau and submitted a project proposal for the generation of ortho-images to a restricted Invitation to Tender issued by the same African Organisation.

3.1.5 Advertisement and dissemination of the project

ASTIMwR has widely fulfilled this success criterion, since the project has been advertised throughout the project lifecycle through the initiative of all the members of the Consortium.

The ASTIMwR project was presented to the scientific community in the following official events:

- Workshop on Sustainable Water Use in Agriculture, - 3 June 1997, Albacete, Spain.
- VII Congreso Nacional de Teledetección - June 1997, Santiago de Compostela, Spain
- Congresso Nazionale di Ingegneria Agraria - 12 September 1997, Ancona, Italy.
- II Simposio sobre el Margen Continental Ibérico Atlántico, - 17-20 September 1997, Cádiz, Spain
- ILRI ICMAD workshop - 18 December 1997, Wageningen, The Netherlands.
- Riunione Gruppo Studi Irrigazione del C.N.R. - 12 January 1998, Roma, Italy.
- Jornadas sobre la medida y evaluación de las extracciones de agua subterránea - 25-27 March 1998, Alicante, Spain.
- 1st International Conference and Exhibition on Geographic Information, 7-11 September 1998, Lisbon, Portugal.
- Convegno Nazionale di Idraulica e Costruzioni Idrauliche - 9-12 September 1998, Catania, Italy.
- 1st Inter-regional Conference on Environment-Water: Innovative Issues in Irrigation and Drainage - ICID - 16-18 September 1998, Lisbon, Portugal.
- The European Symposium on Remote Sensing, Agriculture and Ecosystems (EARSeL) - 21-25 September 1998, Barcelon, Spain.
- Colloquium: Space Techniques for Environmental Management in the Mediterranean, EURISY - 19-20 October 1998, Athens, Greece.
- Curso de Especialización en Sistemas de Información Geográfica Aplicada a la Evaluación del Impacto ambiental y a Las Auditorías Ambientales, Colegio Oficial de Ingenieros Agrónomos de Castilla y León y Cantabria – 20-21 November 1998, Palencia, Spain.

In October 1998, the ASTIMwR project was presented as an example of a successful shared-cost action project at the workshop '*Earth Observation for Resource Management – Regional and National Scale'*, held at the Joint Research Centre (Ispra, Italy).

The Consortium members produced the following publications related to ASTIMwR:

MONTESINOS S., DE STEFANO L., CASTAÑO, S. NAVARRO. E., QUINTANILLA A., VELA A., ARAGON, J.R. & LUNA E. (1997). *Aplicación de técnicas de observación de la Tierra a la gestión integral de los recursos hídricos de una cuenca (ASTIMwR)*, Presented at VII Congreso Nacional de Teledetección, Santiago de Compostela, Spain.

AMBAST S.K. (1997). *Monitoring and evaluation of irrigation system performance in saline irrigated command using satellite remote sensing and GIS*, Interne mededeling 471, DLO-Winand Staring Centre, Wageningen, p.p.106The Netherlands.

CASTAÑO, S., FERNÁNDEZ-MEJUTO, M. & VELA, A. (1997). *Proyecto Europeo ASTIMwR. Zona piloto de estudio: desembocadura del Guadiana y zona costera asociada*, Poster presented at II Simposio sobre el Margen Continental Ibérico Atlántico, Cádiz, Spain.

BOSS M., JACOBS C. (1997). *Irrigation performance monitoring in the Guadiana basin by remote sensing*. Internal Report n. 450, SC-DLO, Wageningen, The Netherlands.

SOMMA G., DE ZEEUW C.J., SU Z. & MENENTI M. (1998). *Application of Space Techniques to derive energy fluxes for water management in arid zones*. EARLSeL Symposium proceedings, 11-15 May 1998, ITC Enschede, The Netherlands.

SU Z., M. MENENTI, H. PELGRUM, B.J.J.M. VAN DEN HURK AND W.G.M. BASTIAANSSEN (1998). *Remote sensing of land surface fluxes for updating numerical weather predictions*, EARSeL symposium proceedings, 11 – 15 may 1998.

CASTAÑO, S. (1998). *Aplicaciones de la Teledetección y Sistemas de Información Geográfica al control y cuantificación de las extracciones de aguas subterraneas.* En Jornadas sobre la medida y evaluación de las extracciones de agua subterránea. Alicante.

DE ZEEUW C.J. (1998). *SEBAL calculations and Eta mapping for the Bullaque irrigated area based on Landsat TM images of 1989, 1991, 1996 and 1997*. Internal Report nº 528, SC-DLO, Wageningen, The Netherlands.

PERDIGAO A. (1998). *Precision farming as an integration of GIS-Remote Sensing and agro-meteorological models*. 1st International Conference and Exhibition on Geographic Information, September 1998, Lisbon, Portugal.

SOMMA G., DE ZEEUW C.J., SU Z. & MENENTI M. (1998). Application of Space Techniques to derive energy fluxes for water management in (semi) arid zones. Proceedings of the National Symposium of Hydraulics, September 1998, Catania, Italy.

MONTESINOS S., DE STEFANO L. & D'URSO G. (1998). *Application of Space Techniques to the Integrated Management of Water Resources: the ASTIMwR Project*. Additional Papers of the 1st Inter-regional Conference on Environment-Water: Innovative Issues in Irrigation and Drainage, September 1998, Lisbon, Portugal.

BASILE A., COPPOLA A. & D'URSO G. (1998). *Methodological approach for soil hydrological classifications*. Additional Papers of the 1st Inter-regional Conference on Environment-Water: Innovative Issues in Irrigation and Drainage, September 1998, Lisbon, Portugal.

SANTINI A. & D'URSO G. (1998). *Sviluppo di un sistema di supporto alle decisioni nella gestione dei comprensori irrigui.* Atti Convegno Nazionale di Idraulica e Costruzioni Idrauliche, September 1998, Catania, Italy.

VELA A., CALERA A., MEJUTO M.F., CASTAÑO, S. & RUIZ J.R. (1998). *Application of remote sensing techniques to the evaluation of water consume* Conference on Remote Sensing, Agriculture and Ecosystems, Barcelona.

BOS I. (1998). *The efficiency of irrigation. Torre de Abraham, Spain* , Interne mededeling 537, DLO-Winand Staring Centre, Wageningen, The Netherlands.

SERRAO, M. & D. VOS (1999). *Irrigation performance monitoring in the Lucefecit Basin, Portugal, by Remote Sensing*. Interne mededeling, DLO-Winand Staring Centre, Wageningen, The Netherlands.

D'URSO G., MENENTI M. & SANTINI A. (in press, 1999). *Regional application of one-dimensional water flow models for irrigation management*. Agricultural Water Management, Elsevier Sci. Pub.

ROERINK G. J., M. MENENTI & W. VERHOEF (in prep.) *Reconstruction of cloud-free time series using Fourier analysis of time series*. Submitted to Int. Journal of Remote Sensing.

The Spanish users highlighted the importance of the project for their water policy by promoting a press conference at the kick-off meeting in Ciudad Real (Spain). The President of the Confederación del Guadiana and the Vice-Rector of the Universidad de Castilla-La Mancha took part in the presentation of the project before the press. The event had diffusion in newspapers, local radio and television. At the second progress meeting, held in Paestum (Italy) in February 1998, the Italian User organised an official presentation of ASTIMwR, where representatives of local and regional Organisms were invited. At the final progress meeting (Albacete, Spain, January 1999) the Universidad de Castilla-La Mancha summoned a press conference to present the final results of the project. Through these initiatives, ASTIMwR and the CEO Programme was promoted at local and national level, in newspapers, radio and television. Annex 14 gathers together the newspaper articles concerning ASTIMwR published during the two years of the project.

The ASTIMwR project was registered in the following services of the Commission:

- EWSE/INFEO, the information service of the Centre for Earth Observation.
  The progress and the initial achievements of the project were published in the 'CEO Newsletter' (Issue 8, January 1998).
- CORDIS, the European Commission's R&D information service.
  In particular, the project co-ordinator was requested by the CORDIS service to fill in a questionnaire to have ASTIMwR presented in the 'Planet Earth' Special edition published in December 1998 by CORDIS.

Moreover, the ASTIMwR achievements will be presented in the promotional brochure issued by DG XII and containing the best of the Theme-3 projects related to EO in the Environment and Climate Programme.

ASTIMwR generated interest in several research institutes and companies that contacted the Consortium asking for information about the project. Moreover, the project co-ordinator provided information to the following studies:

- "Survey of Data Use in Theme 3 -Shared Cost Projects" of DGXII.
- "New Application Feasibility Study" funded by CEO.
- "Industry and Market Snapshot Study" funded by CEO.
- "Survey of EC funded GIS Projects" of DGIII.

Some of the partners devoted a space on their Web sites to the ASTIMwR project:

- www.geosys.es/proyectos/astimwr/home.htm, which presents the ASTIMwR project according to the CEO Project Web page templates. Links with the EWSE and CEO are given.
- www.geosys.es/proyectos/astimwr/socios.htm, where the ASTIMwR partnership is presented, with contact details and Hyperlinks to the partners and their Web site.
- www.geosys.es/proyectos/astimwr/astitext.htm, that describes in detail the ASTIMwR objectives and activities. This includes a section that presents the state of the art, which has been progressively updated.
- www.cc-ab.uclm.es/idr, where the objectives of ASTIMwR are briefly presented.

3.2 Technical Criteria

3.2.1 Positive evaluation of the ASTIMwR User Interface

The characteristics and functionalities of the User Interface were considered satisfactory, and fulfilled the specifications agreed at the beginning of the project: integration of EO data with other data (table and maps) in a user friendly environment; customised menus, to supply information to non-EO-expert staff; and easy-to-use functionalities of data management (input, output and storage).

The structure of the main menu and the sub menus is clear and enables the users to easily look up topics of the modules, in maps, tables and graphs. The main menu enables users to look at each module and its sub-products, and to compare data for various years to get a complete overview.

The import/export dialogues are easy-to-use at a user level and support most prevailing formats. A meta database allows the operator to keep a record of the data input operations (name of the operator, date of the data input, characteristics of the new data, etc.). This database, whose update is optional but recommended, is considered as an added value of the system, since it guarantees a transparent management of the data.

The data management catalogue makes it easy to add and delete images, maps and masks, to update the database and to display maps. It allows directories to be created where maps related to a specific area are stored, and to include/exclude masks and images in them. This functionality helps the operator to use and store maps in a structured way and is essential for ensuring the extrapolation of the User Interface to other areas, since it enables new customers to introduce their data into the system.

The process for choosing and opening a map is completely user-friendly. Once the map window is open, there are many display options of ILWIS that can be used from the UI if the operator has some basic knowledge of this software.

The presence of ILWIS 2.2 in the background enables water managers to benefit from the quality of this commercial software, although, at the same time, limits the possibility of fully customising the fuctionalities of the UI. Indeed, some recommendations for the UI enhancement could not be implemented because they didn't match with the characteristics of ILWIS. These suggestions concerned mainly the formats imported by the UI, the map display options, the generation of 2D maps from attribute tables. Moreover, the need for owning a hard key per system limits the number of UI that can be distributed to local users such as irrigation districts.

The help function contains both the ASTIMwR on-line help and the ILWIS help. The ASTIMwR on-line help gives extensive documentation and clear descriptions about the subjects of the different modules. Users can easily find answers to questions about specific modules, since multiple help buttons directly link the module that is used to the relevant chapter of the help.

The User Interface was structured in modules to guarantee the independence of the thematic applications and allow possible customising of the UI according to the specific needs of the customers. Nevertheless, in a consolidated system it would be useful to have an overview map of the river basin where the masks used in each module can be displayed, so that map results at different scales can be compared.

3.2.2 Positive evaluation of the information generated

The quality of the information generated within the User Interface is considered satisfactory in relation to the current scientific state of the art and the quality of the available data.

The evapotranspiration maps obtained from low resolution EO data are considered of interest for planning at river basin scale, although the dependence on the SEBAL software for producing the input data links the update of these maps to the module provider. From a scientific point of view, ASTIMwR enabled the SEBAL model to be upgraded for application in situations where very little field measurements are available. Simplification of the SEBAL algorithm towards a so-called SEBI algorithm might improve its applicability. However, the price paid is a reduction in accuracy and reliability.

The irrigation performance methodology performs well although the efficient application of the module in other areas depends on the quality and the periodicity of the available data. The results of this module can be used as an indication “a posteriori” for the farmers and an assessment of water management at irrigation district level. Whether the information obtained can be used for better water fees application should be carefully considered. The module developers highlighted that the comparison between the “on demand” system and the “gravity” system in Spain showed a clear difference in terms of uniformity and matching of crop water requirements.

Using EO data for monitoring groundwater extraction is of high interest, since the control of irrigation is an important task in the routine work of water managers. The results comply with the requirements of the users and the linkage of administrative data with raster information is considered particularly valuable. The information generated has been employed by CHG for monitoring the fulfilment of water restrictions for 1997. The application will benefit from the higher resolution multispectral data available in the near future and is dependent on the quality of the available ancillary data.

The information produced by the 'wetland evolution monitoring' module can be assumed to be a good thematic basis for other studies. Indeed this application has generated several maps and tables that complement the existing information for the studied areas. In particular, the data corresponding to 15-year evolution of the studied area, the NDVI-derived data and the possibility of generating Thiessen polygons from rainfall data are considered of high interest. The results would benefit from the integration of aerial photography and further ground survey studies.

3.3 Economic Criteria

3.3.1 Cost-effectiveness of EO data

When assessing the cost effectiveness of EO-related applications, the ASTIMwR users pointed out that this is determined by the importance of the information in the work priorities, its reliability and the possibility of obtaining the same information by other means. The water extraction monitoring module represents a good compromise between these three factors. Also the generation of evapotranspiration maps with NOAA AHVRR data is positively considered for water resources management at watershed scale. The use of EO data in the other applications are only considered cost-effective if satellite images are acquired for other priority actions. Indeed, due to their high costs, EO data are not affordable when used only for small areas or when they request a high temporal periodicity. The ASTIMwR modules have the important advantage that they all use the same type of satellite images (except for the NOAA data). In this way, water managers can obtain information about different hydrological and land use issues after acquiring a reduced number of high-resolution mutispectral images.

3.3.2 Interest of the partners in following on the development

All the partners expressed their deep interest in following up the opportunities opened by ASTIMwR.

The user organisations plan to invest in implementing the ASTIMwR applications in other sites within their jurisdiction. This will imply both the preparation of new input data and the customisation of the UI for case-specific issues that are not considered in the existing UI.

Already during the execution of the project, the Spanish user (*Confederación Hidrográfica del Guadiana*, CHG) has invested its own funds into two EO-supported projects that complemented the activities of ASTIMwR:

- “*Elaboración del catastro digital de los aprovechamientos de regadío en las UU.HH 04.04 y 04.06*” (“Elaboration of digital cadastre for the irrigation exploitation in the Hydrological Units 04.04 and 04.06”), which included the evaluation, by means of EO data, of the irrigated area in 1997 in both hydrological units.
- “*Generación de ortofotos digitales de la U.H. 04.04 para inventario de recursos hídricos destinados al viñedo*” (“Generation of othophotos of H.U. 04.04 for inventory of water resources devoted to the irrigation of vineyard”).

In 1998, CHG funded the project *ARYCA* (“*Aprovechamientos en Regadío y Catálogo de Aguas*”), aimed at analysing, using satellite images, the water rights demands submitted to CHG from 1993 to 1998. In the same year, the Ministry of Environment decided to implement in the Upper Part of the Guadiana river basin an investment plan of about 6 MECU that includes monitoring of ground water extraction using EO data and implementation of decision-support tools based on EO data, orthophotos and cadastral data.

Also the technical partners are eager to participate in future development of the ASTIMwR application. The applicability in similar semi-arid regions is the main focal point of interest in this respect, as the requirements tackled by the ASTIMwR project are considered relevant worldwide to a variety of institutes.

The possibility of continuing the development of the software to convert it into a stand-alone application (without commercial software behind) is also under consideration by some of the partners.

4 CONCLUSIONS

The main goals of the ASTIMwR project have been successfully achieved. The ASTIMwR system has been developed in response to the customers' need for more effective monitoring of the availability and consumption of water, in accordance with the social, economic and environmental importance of this natural resource. This has been done by moving Remote Sensing and GIS techniques from the research world to the offices of water managers, whilst the user-friendliness of the system has guaranteed the transparency of these technologies for non-specialised staff.

The products developed by the project still suffer from technical limitations, mainly due to the level of currently available data and technology. Nevertheless, these products have already been shown to be directly useful for management purposes in a "real-world" context.

ASTIMwR has shown that Remote Sensing and GIS techniques represent a valuable alternative to the classical data gathering methods. At both basin and local level, EO data are a source of information for land use change monitoring and the geographical analysis of meteorological data. EO not only increases the quality and quantity of data available for sustainable management of water resources, but also provides, when used within routine management task, an added value to pre-existing data that are available but often under used.

The ASTIMwR Consortium has worked well. The users group has shared with enthusiasm its knowledge of water resources management and has thus constantly stimulated the technical partners towards the operationalisation of EO techniques. The non-overlapping but complementary scientific specialisations of the technical partners have made it possible to cover a wide area of EO applications. Several activities have been carried out that were not foreseen in the original project plan as part of a constant effort to find viable solutions to the limitations set by the existing techniques and data.

For all the members of the partnership, the end of the project represents the starting point for exploiting the products developed and the expertise gained beyond ASTIMwR's original goals and user groups. The users are already willing to invest their own resources in improving the quality of water management by using the ASTIMwR products in their work as water managers. This experience will undoubtedly identify new technical requirements, which will be the basis for enhancing both the models used for information production and the efficacy of the software tools. As well as trying to meet the emerging needs of the users as clients, all the technical partners now aim to improve the quality of the services they provide and to take advantage of the expertise gained as a result of ASTIMwR. An especially important task for all of them will be to extrapolate the applied methodologies in other watersheds affected by similar problems. This will provide opportunities to carry out further methodological development and to include new functionalities adapted to the requirements of new users.

Besides the global objective of facilitating the sustainable management of water, the ASTIMwR project had as an objective the integration of different entities managing water in the frame of different legal and administrative conditions. The pursuit of this objective has led to a deepening of the knowledge of the organisational and constitutional context of water management in Portugal, Spain and Italy, which will facilitate the involvement of the ASTIMwR partners in new activities related to water management in Southern Europe. The heterogeneity of the Consortium has also revealed the amount of work still needed to achieve greater standardisation in order to minimise the difficulties in information exchange between organisations and countries.

ASTIMwR has contributed to the scientific knowledge and technical competence in the European Union in water resources management. It has promoted the scientific and technological co-operation and integration between European universities, research institutes and industry, thus enabling the transfer of technology among countries, the mobility of scientific researchers and the training of young scientists in a European context. In this way the project has made its own small contribution to strengthening the social and economic cohesion of the Union.

At the start of the ASTIMwR project a number of criteria were established for assessing the project's success within the context of the European policy objectives of the Environment and Climate Programme. The global goal was summarised in that the ASTIMwR system should strive to be “the most important expert system available in Europe, for the management of water at basin level for agriculture purposes, using Earth Observation satellites”. Only time will tell whether this objective has been successfully achieved, but ASTIMwR has certainly already proven to be an important solution to real water management problems in a number of European contexts.

ANNEXES

Annex 1: List of Addresses

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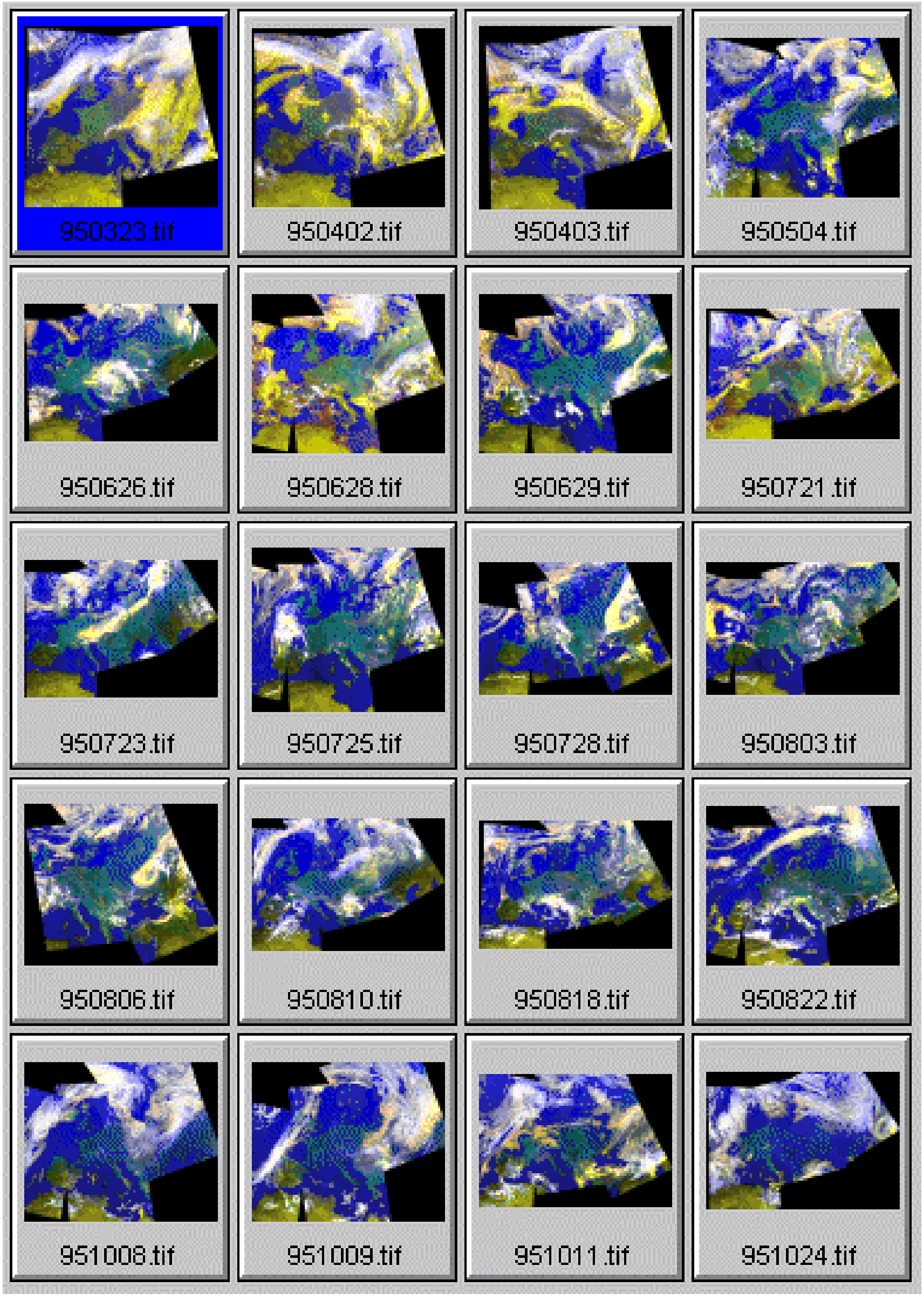
ANNEX 2: Overview of NOAA-AVHRR images available for 1995



ANNEX 3: Theoretic approach of image processing for NOAA data

Albedo and NDVI
The algorithm for deriving surface albedo and NDVI consists of:

1. Calculate surface bidirectional reflectance of AVHRR band 1 & 2,
2. Derive surface broad-band albedo from the above surface reflectance,
3. Derive NDVI from the same surface reflectance.

The band-integrated radiance received at the satellite I^s can be modeled as the sum of five terms (applying atmospheric and viewing angle correction), i.e.:

$$I^s = I^{dir} + I^{sca} + I^{sky} + I^{ind} + I^{mul}$$

where I^{dir} is the radiation directly reflected by the ground from the solar beam towards the satellite; I^{sca} the radiation singly scattered directly to the satellite by the molecules and particles within the atmosphere; I^{sky} the radiation singly scattered into a diffuse flux which impinges on the ground and is reflected directly to the satellite; I^{ind} the radiation reflected by the ground and subsequently scattered towards the satellite, and I^{mul} the contribution from all orders of molecular multiple scatter.

The surface bidirectional reflectance is given by (Paltridge and Mitchell, 1990):

$$r = \frac{K(1-M) - \sec f_s \sum_{j=0}^{1} \Phi_j Q_j(m)}{4 \cos q \cdot g(m) e^{-mt} (1+mt)}$$

which is expressed in terms of the AVHRR-measured K, the relevant angles associated with the measurement (q, f_s, Ψ_0, Ψ_s), and an given value of aerosol optical depth appropriate to the wavelength of the particular channel. Where M is the contribution by molecular multiple scatter, Q_j are the integrated source function, *g(m)* are functions related to air mass m (m is the total air mass from the sun to ground to satellite), t is the aerosol optical depth. $_j$ are the scattering phase functions for molecular and aerosol scatter.

Having obtained the AVHRR band 1 and 2 surface reflectance**,** surface broad-band albedo can be obtained as follows (Valiente et al., 1995):

$$a = 0.545 \cdot r_1 + 0.320 \cdot r_2 + 0.035$$

Accordingly, we can also derive NDVI from AVHRR band 1 & 2 surface reflectance as

$$NDVI = \frac{r_2 - r_1}{r_2 + r_1}$$

Surface temperature

The algorithm for deriving surface temperature is as follows:

1. Land surface temperature derived from NOAA/AVHRR using a theoretical split-window algorithm;

2. Adiabatically corrected Land surface temperature using temperature lapse rate (a typical value is 6.5 K/km).

By introducing atmospheric dependence of the split-window coefficients, the final quadratic split-window algorithm for land surface temperature (T_0 : in k) is (Coll and Caselles, 1997):

$$\begin{aligned} T_0 &= T_4 + [1.34 + 0.39 \cdot (T_4 - T_5)](T_4 - T_5) \\ &\quad + 0.56 + a \cdot (1 - e) - b \cdot \Delta e \\ a &= W^3 - 8W^2 + 17W + 40 \\ b &= 150(1 - W/4.5), \\ &(W : g/cm^2) \end{aligned}$$

where T_i is the brightness temperature in band i; $\varepsilon = (\varepsilon_4+\varepsilon_5)/2$ the mean surface emissivity, $\Delta\varepsilon = \varepsilon_4-\varepsilon_5$ the spectral emissivity difference of AVHRR band 4 & 5 and (W) the atmospheric water vapor content.

The derived surface temperature is said to be accurate to 0.5 K given the actual atmospheric water content.

Emissivity

The emissivity is calculated using the vegetation cover method of Caselles and Sobrino (1989) (see also Valor and Caselles, 1995) as follows

$$e = e_v P_v + e_g (1 - P_v) + de$$
$$de = (1 - e_g) e_v F (1 - P_v) + [(1 - e_v) e_g G + (1 - e_v) e_v F^{'}] P_s$$

where F, G, F’ are shape parameter that take into account of radiation with respect to vegetation structure, subscripts v, g, s refer to observed vegetation top, ground, side respectively.

The shape factors are give as:

$$F = 2\frac{H}{S}F_{s-g} = \left(1+\frac{H}{S}\right) - \sqrt{1+\left(\frac{H}{S}\right)^2}$$
$$G = \frac{S}{H}F_{g-s} = \frac{1}{2}\left\{\left(1+\frac{S}{H}\right) - \sqrt{1+\left(\frac{S}{H}\right)^2}\right\}$$
$$F' = F_{s-s} = \sqrt{1+\left(\frac{S}{H}\right)^2} - \frac{S}{H}$$

where F_{s-g}, F_{g-s}, F_{s-s} are shape factors for energy transfer between side-ground, ground-side, and side-side, S and H are separation and height of the vegetation rows.

If no information on vegetation structure is available, the emissivity can be approximated as:

$$e = e_v P_v + e_g(1-P_v) + 4\langle de\rangle P_v(1-P_v)$$

$\langle de\rangle$ in this case is a regional representative value (0.000 ~0.020), and additionally in the spectral 10.5- to 12.5 um spectral region, we have:

$$e_v = 0.985 \pm 0.007$$
$$e_g = 0.960 \pm 0.010$$

Roughness

The total roughness is calculated as a superposition of vegetation and orographic roughness according to the following:

$$z_0 = \sqrt{z_{0or}^2 + z_{0vg}^2}$$

The orographic roughness is calculated as

$$z_{0or} = \frac{1}{p_{size}} \cdot v$$

where ν is the variance of a neighbourhood of a group of DEM grid points and P_{size} the size of a DEM grid.

The vegetation roughness can be derived from land use classification (each land use is assigned a specific roughness value, e.g. Wieringa, 1993) or from an empirical function of the following form:

$$z_{0vg} = f(NDVI) \quad (e.g.\, z_{0vg} = \exp[-6.65 + 6.38 \cdot NDVI])$$

ANNEX 4: Maps

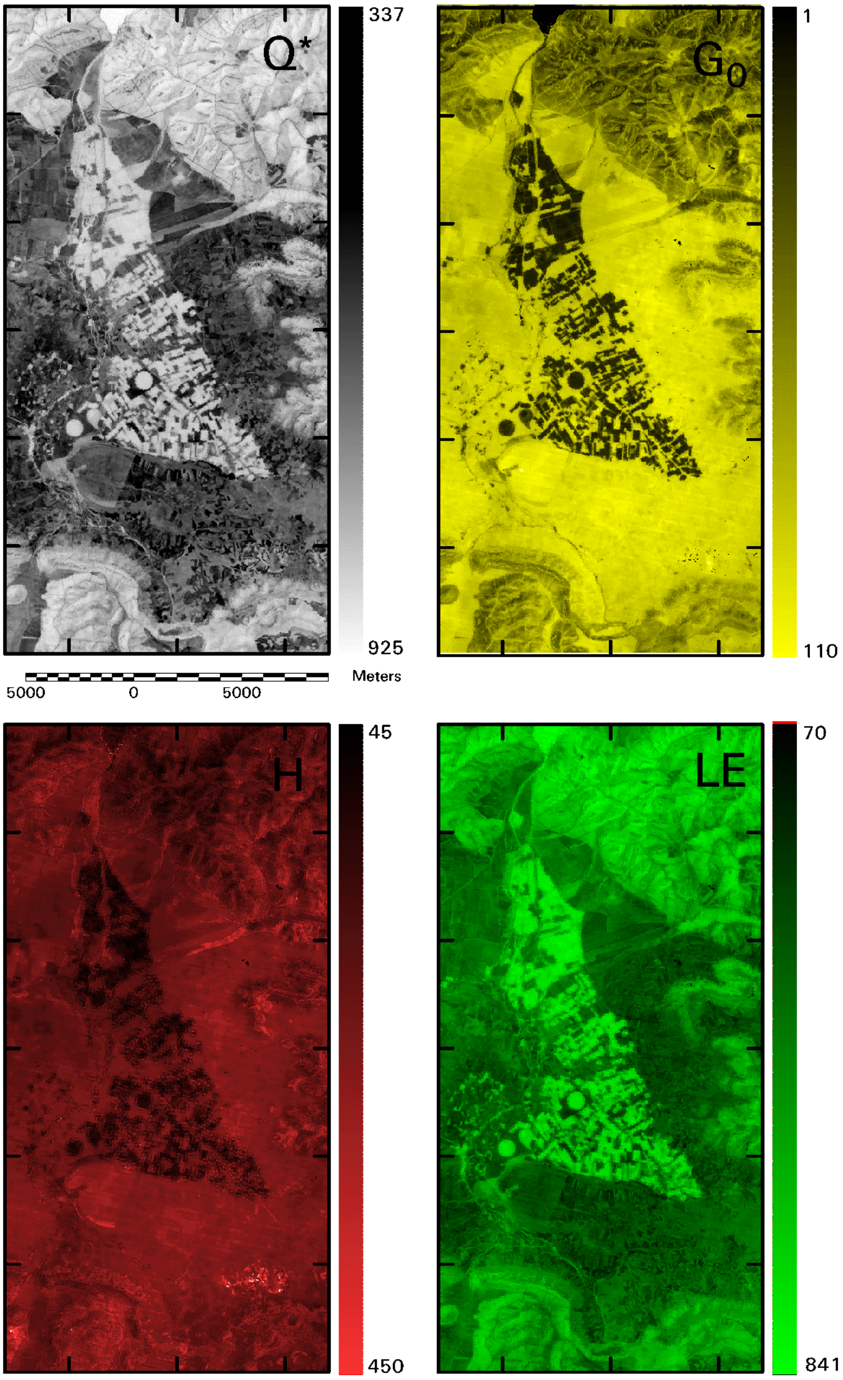
Map 1. Example of the results of the surface energy balance calculations with SEBAL for the Bullaque irrigated area on 21 July, 1991.

Map 2. SEBAL results and calculated net radiation, evaporative fraction and ETa for the Bullaque irrigated area on 21 July, 1991.

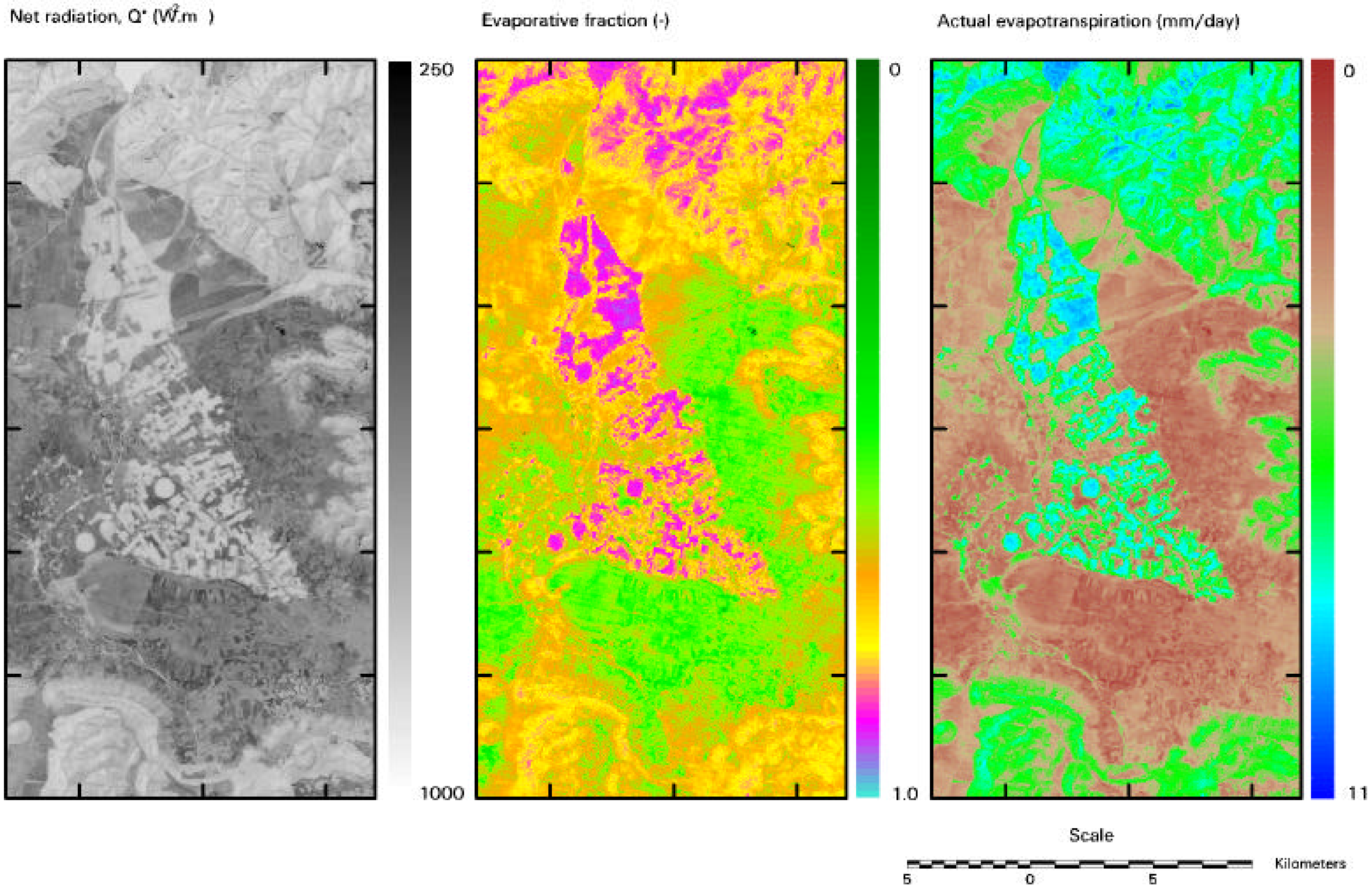
Map 3. Guadiana river basin (March 23, 1995): Q, evaporative fraction and ETa.*

Map 4. Low resolution ETa maps of the Guadiana river basin at six dates in 1995.

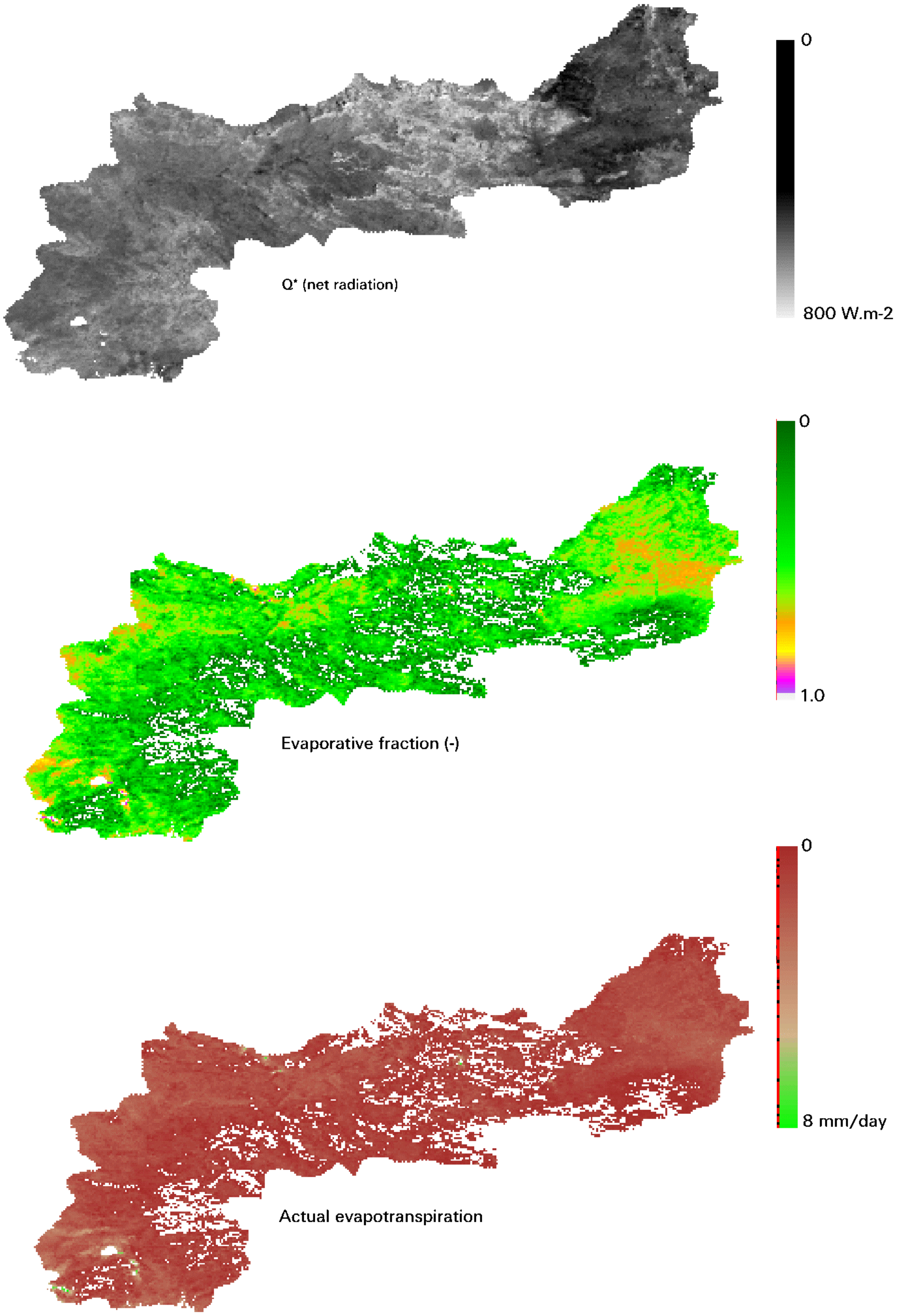
Map 5. NDVI map 1995 versus NDVI map 1996 for Spain and Portugal.



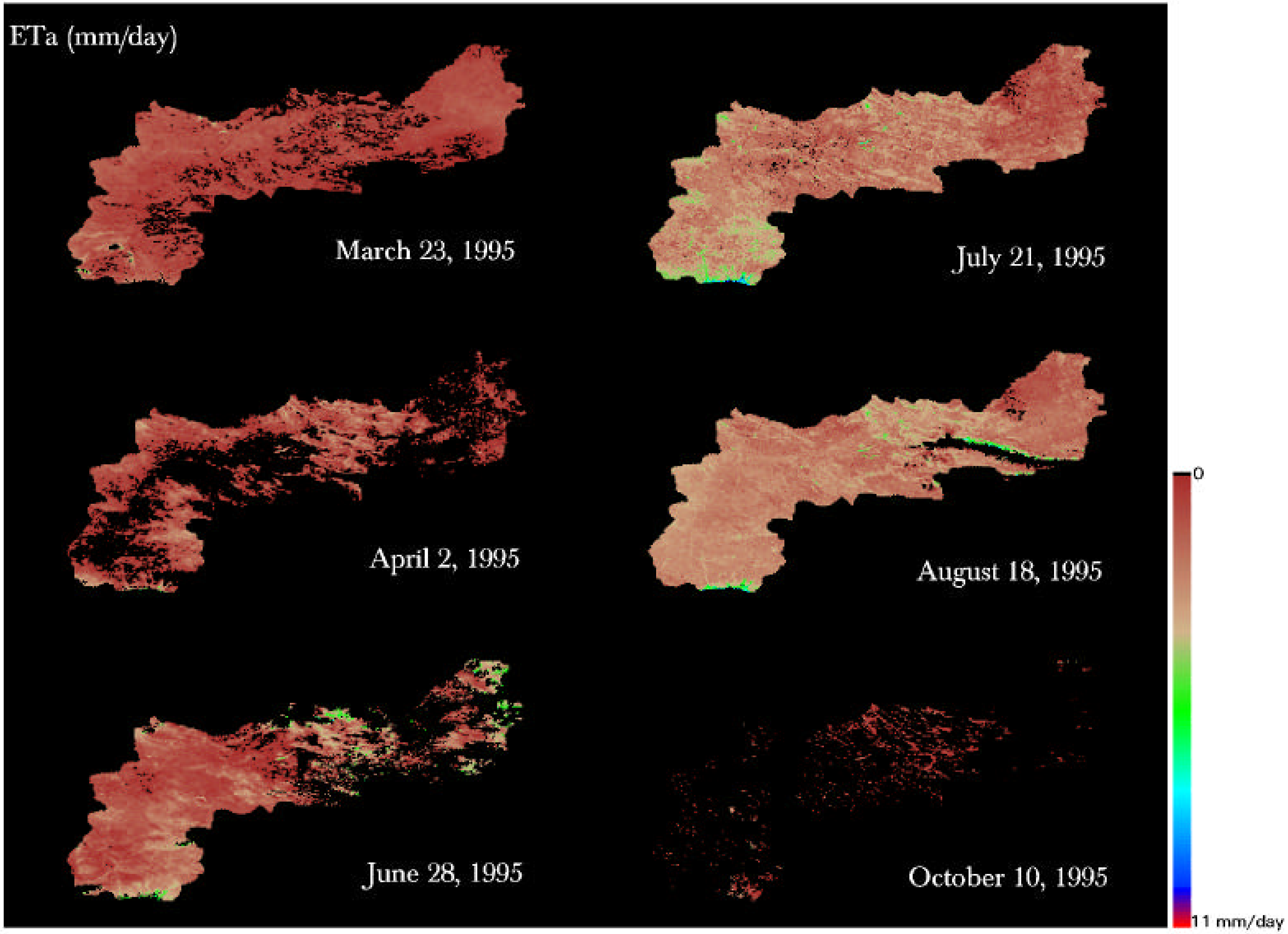
Map 1. Example of results of Surface Energy Balance result for the Landsat5-TM image of July 21, 1991. The energy balance reads: Q* = G0 + H + LE.



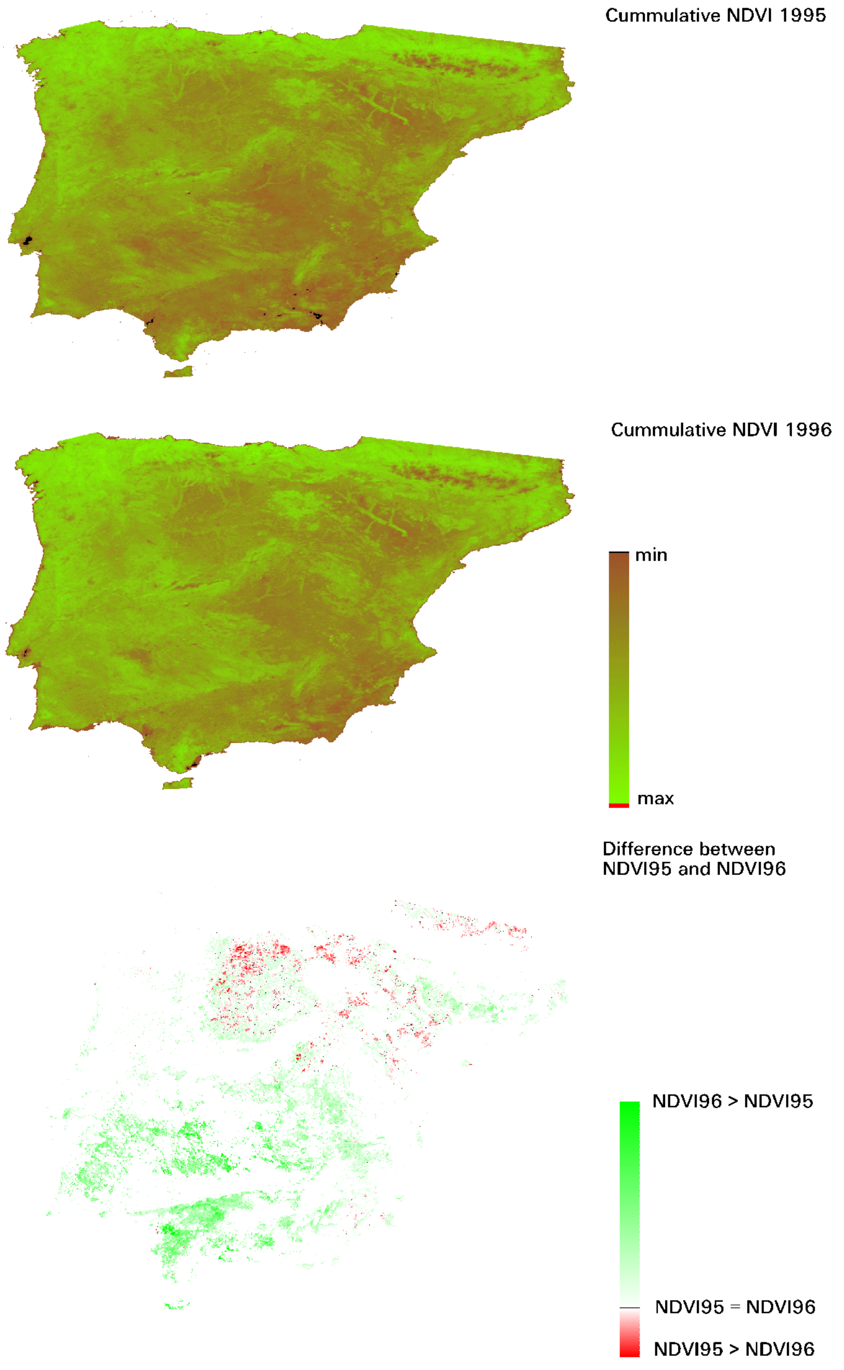
Map 2. SEBAL results and calculated net radiation, evaporative fraction and ETa for the Bullaque irrigated area on July 21, 1991.



Map3. Guadiana river basin (March 23, 1995). Q*, evaporative fraction and ETa.



Map 4. Low resolution ETa maps of the Guadiana river basin at six dates in 1995.



Map 5. NDVI map 1995 versus NDVI map 1996 for Spain and Protugal.

ANNEX 5: Procedure to estimate background reflectance

From Jacobs and Azzali (1998):

Suppose the average DN value of the area is x, then the Gain and Offset values are interpolated in a linear mode:

G(x) = (1-x)G(0) + xG(1), and
O(x) = (1-x)O(0) + xO(1).

The minimal background reflectance values Rmin (0%) and the maximal values Rmax (100%) are used as a starting point to calculate new Rmin' and Rmax' values:

Rmin' = G(1)*DN + O(1), and
Rmax' = G(0)*DN + O(0).

Substitution for Rmax' and Rmin' gives:

G(Rmax') = (1-Rmax')G(0) + Rmax'G(1);
O(Rmax') = (1-Rmax')O(0) + Rmax'O(1);
G(Rmin') = (1- Rmin')G(0) + Rmin'G(1);
O(Rmin') = (1- Rmin')O(0) + Rmin'O(1).

This results in new estimations:

Rmax'' = G(Rmin')x + O(Rmin'), and
Rmin'' = G(Rmax')x + O(Rmax').

Rmax and Rmin values converge each step and the iterations are continued until they are the same (i.e. deviate not much than 0.1%). The background reflectance $r_{b,\lambda}$ can now be calculated (*Omgtest.f* model) and consequently the ground reflectance r_g for each pixel can be determined.

ANNEX 6: Potential evapotranspiration results from CRIWAR 2.0

ETpot Bullaque 1997

Guadiana, ASTIMwR, Spain Meteo file: TOR97.MTF Cropping pattern file: TOR97.PAT								
Class		Etp (mm/10 days)						**Total Etp (mm/season)**
	decade	month						
		Apr	May	Jun	Jul	Aug	Sep	
1	1	0	14	26	48	52	31	**512**
	2	0	11	34	46	43	23	
	3	11	34	41	57	40	0	
2	1	0	17	28	52	55	31	**544**
	2	0	13	37	49	45	23	
	3	13	37	44	61	40	0	
3	1	0	20	31	63	57	24	**595**
	2	16	32	40	55	37	0	
	3	15	40	56	67	43	0	
4	1	0	20	31	66	60	24	**608**
	2	16	32	40	57	37	0	
	3	15	40	58	71	43	0	
5	1	19	42	31	66	43	0	**614**
	2	18	32	49	57	37	0	
	3	17	40	65	66	31	0	

ETpot Peñarroya 1997

Guadiana, ASTIMwR, Spain Meteo file: PENA97.MTF Cropping pattern file: PENA97.PAT								
Class		Etp (mm/10 days)						**Total Etp (mm/season)**
	decade	month						
		Apr	May	Jun	Jul	Aug	Sep	
A Vine	1	19	25	19	28	27	26	**438**
	2	19	20	24	25	28	27	
	3	18	25	28	31	34	15	
B Vine	1	19	28	21	31	30	26	**470**
	2	20	22	27	28	28	27	
	3	20	28	32	34	34	15	
C Vine	1	19	39	28	41	39	31	**603**
	2	25	31	35	37	35	33	
	3	28	39	41	44	41	18	
D Maize	1	0	17	30	51	55	30	**548**
	2	0	13	337	51	45	23	
	3	12	39	44	61	40	0	
E Maize	1	0	20	31	66	60	24	**613**
	2	16	33	40	59	37	0	
	3	14	42	59	71	43	0	
F Melon	1	0	0	34	59	34	0	**401**
	2	0	22	47	54	0	0	
	3	0	37	60	54	0	0	

ANNEX 7: Bullaque Performance indicators, primary unit level

		1989				1991				1996			
Primary unit	Area (ha)	Aij (ha)	Vij (m3)	IP1	IP2	Aij (ha)	Vij (m3)	IP1	IP2	Aij (ha)	Vij (m3)	IP1	IP2
Sector 1	1481	636	5163000	0.93	0.76	1104	11983000	0.9	0.61	786	8143000	1.01	0.68
Sector 2	1220	449	3500000	0.9	0.79	563	6973000	1.03	0.53	422	4391000	1.01	0.68
Sector 3	2851	1237	11518000	1.07	0.66	1602	20278000	1.05	0.52	1170	11876000	0.99	0.69
Total	5552	2323	20181000			3269	39234000			2377	24410000		

		1997												
Primary unit	Area (ha)	Class 1 (ha)	Class 2 (ha)	Class 3 (ha)	Class 4 (ha)	Class 5 (ha)	Aij (ha)	Vij (m3)	IP1	IP2 values				
										Seasonal	20-May	20-Jun	10-Jul	10-Aug
Sector 1	1481	400	232.4	242.1	140	75.8	1090	7337256	0.96	0.83	0.91	0.7	0.77	0.85
Sector 2	1220	60	162.8	175.8	115.4	69.9	584	4463626	1.09	0.76	0.73	0.62	0.7	0.76
Sector 3	2851	307	486.3	500.4	116.5	88.8	1499	10406794	0.99	0.81	0.88	0.69	0.76	0.83
Total	5552	767	881.5	918.3	371.9	234.5	3174	22207676						

ANNEX 8: Bullaque Performance Indicator 1 & 2, secondary unit level

		1996			1997													
Unit	Area (ha)	Aij (ha)	Vij (m2)	IP1	CI 1 (ha)	CI 2 (ha)	CI 3 (ha)	CI 4 (ha)	CI 5 (ha)	Aij (ha)	Vij (m3)	IP1	IP2 values				
													total	May	Jun	Jul	Aug
1	26	11	142400	1.45	16	0	0	0	0	16	156998	1.37	0.52	1.1	0.47	0.5	0.55
2	81	44	373289	0.93	40	6	14	0	0	60	427393	1.01	0.74	1.03	0.65	0.7	0.77
3	132	55	648920	1.28	63	12	8	0	0	83	437480	0.74	1	1.71	0.89	0.95	1.04
4	107	59	691227	1.28	68	18	9	0	0	95	422850	0.62	1.18	2.03	1.05	1.12	1.23
5	88	6	474752	1.6	8	1	3	0	0	12	105292	1.28	0.59	0.74	0.51	0.55	0.61
6	394	334	1545848	0.5	94	82	79	7	0	262	1196901	0.66	1.2	1.48	1.01	1.11	1.21
7	196	117	4004000	1.6	2	0	31	61	42	137	730193	0.75	1.13	0.88	0.86	1.01	1.1
8	332	37	139255	0.41	17	20	47	31	9	124	521698	0.59	1.38	1.28	1.11	1.27	1.39
9	59	32	294889	1.02	7	3	24	18	2	53	375663	0.99	0.83	0.73	0.66	0.75	0.83
10	49	22	230101	1.13	7	19	7	0	0	32	392650	1.7	0.45	0.67	0.4	0.43	0.47
11	41	12	140593	1.23	14	12	0	0	0	26	210011	1.13	0.65	1.44	0.6	0.63	0.69
12	58	37	374799	1.1	42	41	8	19	11	120	590213	0.69	1.13	1.35	0.97	1.06	1.16
13	61	32	414746	1.42	15	16	8	3	10	52	524407	1.42	0.55	0.58	0.47	0.52	0.56
14	69	39	376880	1.06	3	9	11	13	15	51	551112	1.51	0.55	0.46	0.43	0.5	0.54
15	57	22	192588	0.94	10	13	6	7	0	37	465035	1.63	0.44	0.57	0.41	0.45	0.49
16	89	43	325900	0.83	3	0	29	14	7	53	449897	1.19	0.7	0.58	0.54	0.63	0.69
17	113	39	370466	1.04	7	21	14	12	7	62	453019	1.02	0.78	0.79	0.65	0.73	0.8
18	122	45	478192	1.15	1	0	16	33	7	56	440062	1.1	0.77	0.62	0.59	0.69	0.76
19	104	38	369024	1.06	4	29	14	1	0	47	406006	1.21	0.65	0.86	0.57	0.62	0.67
20	61	9	83415	0.98	1	0	10	0	0	11	100642	1.51	0.64	0.47	0.43	0.5	0.55
21	85	33	246403	0.81	10	23	20	0	0	53	866414	2.21	0.34	0.43	0.3	0.33	0.36
22	134	47	413359	0.96	10	21	14	14	21	79	837676	1.49	0.54	0.5	0.44	0.5	0.54
23	118	54	395000	0.79	8	21	21	7	10	68	380014	0.79	1.02	0.99	0.84	0.94	1.03
24	258	57	468874	0.89	4	27	18	12	0	60	687532	1.6	0.5	0.55	0.42	0.47	0.51
25	158	62	372183	0.65	7	51	35	0	0	93	472068	0.71	1.1	1.35	0.95	1.04	1.14
26	219	62	548766	0.96	33	39	18	0	0	90	474516	0.74	1.03	1.53	0.92	0.99	1.08
27	124	64	473265	0.81	9	33	8	4	0	54	648965	1.69	0.46	0.67	0.41	0.44	0.48
28	90	28	122164	0.48	10	29	18	0	0	57	442595	1.09	0.72	0.93	0.63	0.68	0.74
29	114	51	376316	0.8	8	21	17	1	10	56	674614	1.68	0.47	0.48	0.4	0.44	0.48
30	176	88	586325	0.73	0	8	29	0	61	98	946264	1.35	0.63	0.48	0.48	0.56	0.6
31	193	74	676333	1	6	17	30	3	6	62	357890	0.81	1	0.96	0.82	0.92	1.01
32	243	108	773120	0.78	31	41	54	15	0	140	696914	0.7	1.13	1.25	0.96	1.06	1.16
33	206	73	557656	0.84	30	47	20	7	7	110	838983	1.07	0.73	0.91	0.63	0.69	0.75
34	71	35	258172	0.79	14	19	17	0	1	51	511374	1.41	0.55	0.66	0.47	0.52	0.57
35	188	72	593045	0.9	8	25	46	3	0	82	685870	1.18	0.68	0.69	0.57	0.63	0.69
36	135	51	424804	0.91	23	8	27	5	0	63	701009	1.57	0.5	0.54	0.42	0.47	0.51
37	111	41	363431	0.97	17	26	12	11	3	69	650607	1.32	0.59	0.69	0.51	0.56	0.61
38	183	73	545218	0.82	20	20	35	30	0	105	668694	0.89	0.9	0.9	0.74	0.84	0.92
39	153	57	356049	0.68	12	18	42	6	0	77	492659	0.89	0.9	0.9	0.74	0.83	0.91
40	187	86	620254	0.78	13	19	62	18	0	111	525058	0.66	1.22	1.16	0.99	1.13	1.24
41	263	119	888428	0.81	60	55	21	13	0	150	690438	0.65	1.18	1.67	1.04	1.12	1.23
total	5649	2369	21730449		751	868	900	367	231	3117	22207676						

ANNEX 9: Bullaque Performance Indicator 3, secondary unit level

Secondary unit	IP3	Secondary unit	IP3	Secondary unit	IP3	Secondary unit	IP3	Secondary unit	IP3
1	0.76	41	0.61	81	0.23	121	0.34	161	0.67
2	0.40	42	0.75	82	0.59	122	0.35	162	0.68
3	0.68	43	0.73	83	0.63	123	0.30	163	0.67
4	0.62	44	0.76	84	0.00	124	0.83	164	0.71
5	0.39	45	0.40	85	0.04	125	0.83	165	0.62
6	0.70	46	0.52	86	0.00	126	0.45	166	0.61
7	0.51	47	0.80	87	0.14	127	0.25	167	0.31
8	0.60	48	0.80	88	0.08	128	0.00	168	0.92
9	0.54	49	0.76	89	0.09	129	0.33	169	0.66
10	0.63	50	0.13	90	0.06	130	0.34	170	0.81
11	0.83	51	0.00	91	0.06	131	0.10	171	0.64
12	0.74	52	0.45	92	0.00	132	0.17	172	0.00
13	0.67	53	0.79	93	0.01	133	0.25	173	0.00
14	0.71	54	0.89	94	0.00	134	0.71	174	0.77
15	0.71	55	0.24	95	0.58	135	0.46	175	0.75
16	0.62	56	0.25	96	0.44	136	0.40	176	0.45
17	0.10	57	0.46	97	0.64	137	0.40	177	0.82
18	0.48	58	0.80	98	0.46	138	0.38	178	0.63
19	0.69	59	0.29	99	0.48	139	0.21	179	0.68
20	0.36	60	0.56	100	0.00	140	0.40	180	0.00
21	0.75	61	0.68	101	0.78	141	0.42	181	0.00
22	0.56	62	0.80	102	0.52	142	0.00	182	0.00
23	0.76	63	0.79	103	0.00	143	0.37	183	0.00
24	0.80	64	0.79	104	0.04	144	0.33	184	0.00
25	0.62	65	0.50	105	0.06	145	0.47	185	0.00
26	0.61	66	0.71	106	0.32	146	0.77	186	0.83
27	0.72	67	0.78	107	0.70	147	0.41	187	0.76
28	0.75	68	0.00	108	0.19	148	0.26	188	0.70
29	0.86	69	0.62	109	0.74	149	0.40	189	0.00
30	0.25	70	0.71	110	0.77	150	0.42	190	0.49
31	0.43	71	0.45	111	0.28	151	0.38	191	0.81
32	0.00	72	0.47	112	0.13	152	0.24		
33	0.66	73	0.31	113	0.23	153	0.01		
34	0.81	74	0.17	114	0.72	154	0.56		
35	0.70	75	0.59	115	0.58	155	0.40		
36	0.41	76	0.60	116	0.61	156	0.33		
37	0.77	77	0.43	117	0.46	157	0.52		
38	0.73	78	0.68	118	0.43	158	0.36		
39	0.73	79	0.65	119	0.12	159	0.72		
40	0.77	80	0.00	120	0.33	160	0.82		

ANNEX 10: Peñarroya Performance indicators, primary unit level

		1989				1991				1996			
primary unit	**Area (ha)**	**Aij (ha)**	**Vij (m3)**	**IP1**	**IP2**	**Aij (ha)**	**Vij (m3)**	**IP1**	**IP2**	**Aij (ha)**	**Vij (m3)**	**IP1**	**IP2**
sector 1	651	218	1217160	1.29	0.85	189	771012	0.93	1.35	230	301860	0.94	3.91
sector 2	1174	396	1671084	0.98	1.13	331	1467612	1.01	1.26	246	424332	1.23	3.11
sector 3	584	190	1044900	1.27	0.87	149	709777	1.09	1.19	86	129168	1.07	3.57
sector 4	974	387	1522692	0.91	1.17	258	1062828	0.94	1.28	166	253800	1.09	3.5
sector 5	889	303	1214784	0.93	1.17	204	1027620	1.15	1.12	226	251208	0.8	4.82
sector 6	650	304	1090476	0.83	1.33	204	803088	0.9	1.42	156	190728	0.87	4.38
Total	4922	1798	7761096			1335	5841937			1110	1551096		

		1997									
primary unit	**Area (ha)**	**ClassA* (ha)**	**ClassB (ha)**	**ClassC (ha)**	**ClassD (ha)**	**ClassE (ha)**	**ClassF (ha)**	**Aij (ha)**	**Vij (m3)**	**IP1**	**IP2**
sector 1	651	37	60	44	15	0	2	158	602208	0.93	1.33
sector 2	1174	76	102	72	36	30	34	350	1322244	0.94	1.33
sector 3	584	66	37	5	23	14	8	154	629964	1.02	1.17
sector 4	974	68	131	74	31	3	9	316	1379376	1.09	1.15
sector 5	889	65	55	29	11	7	5	172	744336	1.08	1.13
sector 6	650	47	47	21	14	16	26	171	640548	0.94	1.3
Total	4922	360	433	244	130	70	84	1320			

ANNEX 11: Peñarroya Performance indicators, secondary unit level

		1989			1991			1996		
secondary unit	Area (ha)	Aij (ha)	Vij (m3)	IP1	Aij (ha)	Vij (m3)	IP1	Aij (ha)	Vij (m3)	IP1
T1-1	361	109	486700	1.12	116	315800	0.69	113	98064	0.74
T1-2	239	104	640300	1.54	68	398100	1.49	105	189324	1.53
T2-1	719	161	534700	0.83	172	587400	0.87	127	214596	1.44
T2-2	435	239	1013300	1.06	161	771500	1.22	122	140832	0.98
T3-1	323	66	366400	1.39	50	230700	1.17	39	57780	1.26
T3-2	258	127	601100	1.19	100	426500	1.09	47	53892	0.97
T4-1	301	227	803600	0.89	141	499600	0.9	150	193104	1.09
T4-2	346	160	608800	0.95	116	484500	1.06	16	8316	0.44
T5-1	394	165	659000	1	90	508700	1.44	55	59184	0.91
T5-2	501	127	467000	0.92	116	342900	0.75	171	152604	0.76
T6-1	616	146	514200	0.88	124	435100	0.89	55	40500	0.63
T6-2	373	170	494300	0.73	97	308500	0.81	101	87588	0.74
Total	4866	1801	7189400		1351	5309300		1101	1295784	

		1997									
secondary unit	Area (ha)	ClassA (ha)	ClassB (ha)	ClassC (ha)	ClassD (ha)	ClassE (ha)	ClassF (ha)	Aij (ha)	Vij (m3)	IP1	IP2
T1-1	361	25	29	17	5	0	2	77	243000	0.76	1.57
T1-2	239	10	31	27	10	0	0	78	359208	1.13	1.13
T2-1	719	25	47	41	7	13	8	141	489780	0.87	1.48
T2-2	435	53	55	31	29	17	27	211	832464	0.97	1.26
T3-1	323	25	11	2	10	8	1	56	209304	0.92	1.33
T3-2	258	41	26	4	13	6	8	97	420660	1.07	1.10
T4-1	301	49	66	26	20	0	6	167	775332	1.19	1.05
T4-2	346	19	66	48	11	3	3	150	604044	1.00	1.28
T5-1	394	9	3	2	9	5	5	33	316332	2.40	0.53
T5-2	501	55	51	24	2	1	1	134	428004	0.79	1.51
T6-1	616	10	13	11	11	5	20	70	307152	1.09	1.11
T6-2	373	38	36	13	3	11	5	106	333396	0.78	1.54
Total	4866	359	433	244	130	70	84	1319	5318676		

ANNEX 12: Paestum Performance indicators, primary unit level

Primary units	Aij (ha)	Epot (mm / day; season)				Vij (m3)			
		May	Jul	Aug	Total	May	Jul	Aug	Total
8	240	2.97	4.10	2.09	641	51850	68630	40770	839341
9	236	3.09	3.62	2.18	600	67120	75630	74990	1172626
10	215	3.00	3.59	2.12	602	40850	58450	45460	758230
11	225	3.16	2.92	2.23	549	45750	51560	59870	1029628
12	195	2.90	2.82	2.05	538	40938	60221	45208	805818
13	214	2.63	2.87	1.86	539	60320	67620	62010	927908
14	211	3.12	2.50	2.20	524	31400	63830	58530	951475
15	216	2.78	3.78	1.96	594	63440	93180	49500	1178181
16	208	2.99	3.77	2.11	619	30880	68600	45260	789473
17	218	3.12	3.30	2.20	581	50030	80380	46320	954117
18	286	3.21	3.02	2.26	570	56350	100620	61880	902344

Primary units	IP1			IP2				Eact, n (mm)	Eact, I (mm)	Vsim (m3)	IP3
	May	Jul	Aug	May	Jul	Aug	Total				
8	0.99	0.89	0.71	1.24	1.44	1.23	1.92	241	378	1251212	0.27
9	1.30	1.00	1.33	0.98	1.13	0.69	1.29	183	345	1220414	0.33
10	0.87	0.85	0.88	1.42	1.32	1.00	1.80	186	357	1375565	0.28
11	0.93	0.72	1.11	1.40	1.28	0.84	1.51	211	317	689376	0.35
12	0.96	0.97	0.97	1.24	0.91	0.88	1.29	203	292	444265	0.43
13	1.29	0.99	1.21	0.84	0.91	0.64	1.15	178	227	304391	0.42
14	0.68	0.94	1.16	1.89	0.83	0.80	1.33	176	302	575011	0.53
15	1.34	1.35	0.96	0.85	0.88	0.86	1.19	224	316	948444	0.23
16	0.68	1.03	0.91	1.81	1.14	0.97	1.69	192	342	856396	0.40
17	1.05	1.15	0.89	1.23	0.90	1.04	1.37	196	306	915124	0.30
18	0.90	1.10	0.90	1.47	0.86	1.05	1.48	189	331	1249857	0.37

ANNEX 13: Paestum Performance indicators, secondary unit level

Sec. units	Aij (ha)	Epot (mm / day; season)				Vij (m3)				IP1			IP2				Eact, n (mm)	Eact, l (mm)	Vsim (m3)	IP3
		May	Jul	Aug	Total	May	Jul	Aug	Total	May	Jul	Aug	May	Jul	Aug	Total				
801	24	2.45	5.06	1.73	525.0	8748	11579	6878	140698	1.80	1.63	1.29	0.61	1.06	0.61	1.88	273	399	112921	0.27
802	7	4.04	4.47	2.85	637.7	1096	1451	862	17627	0.75	0.68	0.54	2.43	2.26	2.42	2.16	189	400	34102	0.45
803	7	3.00	3.66	2.11	523.1	2142	2835	1684	34450	1.59	1.44	1.14	0.85	0.87	0.85	0.47	256	421	36295	0.31
804	5	4.26	2.42	3.01	636.9	552	731	434	8881	0.59	0.54	0.42	3.25	1.55	3.24	1.47	220	411	29030	0.31
805	5	3.41	4.10	2.41	503.3	807	1068	634	12972	0.87	0.79	0.62	1.78	1.79	1.77	5.83	235	388	25574	0.28
806	4	3.26	3.38	2.30	456.1	1252	1657	984	20137	1.45	1.31	1.04	1.02	0.89	1.01	2.07	251	399	22993	0.28
807	7	1.29	4.59	0.91	599.4	1939	2567	1525	31192	1.39	1.26	0.99	0.42	1.25	0.42	0.79	166	409	57615	0.30
808	15	2.53	4.47	1.79	661.6	5325	7049	4187	85655	1.80	1.63	1.29	0.64	0.94	0.63	1.05	246	402	79778	0.29
809	9	3.00	3.07	2.11	612.0	1960	2595	1542	31532	1.14	1.04	0.82	1.18	1.02	1.18	1.00	166	373	60674	0.29
810	9	2.46	4.09	1.74	514.1	2799	3705	2201	45020	1.49	1.35	1.06	0.75	1.04	0.75	1.34	167	386	76998	0.27
811	5	2.78	5.09	1.96	513.8	456	603	358	7328	0.48	0.43	0.34	2.64	4.06	2.63	0.92	271	411	25276	0.27
812	7	3.66	5.01	2.58	405.2	497	658	391	7991	0.35	0.32	0.25	4.67	5.37	4.66	3.58	323	490	45658	0.26
813	4	3.37	4.68	2.38	441.2	791	1047	622	12719	0.93	0.85	0.67	1.63	1.91	1.63	1.95	336	387	16866	0.13
814	7	3.85	4.64	2.72	568.8	1011	1339	795	16266	0.72	0.66	0.52	2.40	2.43	2.40	0.25	281	455	43025	0.28
815	28	2.69	4.19	1.90	628.4	5048	6682	3969	81192	0.90	0.81	0.64	1.35	1.77	1.35	1.60	261	377	113567	0.29
816	7	3.80	4.26	2.68	635.6	1043	1380	820	16773	0.75	0.68	0.54	2.28	2.15	2.27	2.17	272	436	39384	0.29
817	6	3.31	4.14	2.33	618.0	719	951	565	11557	0.57	0.52	0.41	2.60	2.74	2.60	3.28	276	376	29134	0.22
818	6	3.58	4.69	2.53	644.2	1283	1699	1009	20642	1.03	0.94	0.74	1.57	1.72	1.56	3.26	289	402	29384	0.24
819	6	2.80	4.01	1.98	658.8	372	492	292	5976	0.31	0.28	0.22	4.08	4.90	4.07	2.99	268	430	36662	0.27
820	2	4.65	5.34	3.58	676.7	1340	1774	1054	21555	3.56	3.24	2.55	1.41	1.06	1.79	3.80	271	403	41731	0.26
821	6	2.20	5.34	1.56	658.2	1092	1446	859	17566	0.91	0.82	0.65	1.10	2.24	1.10	2.63	240	374	26968	0.30
822	17	3.09	4.37	2.18	650.9	3112	4119	2447	50049	0.91	0.83	0.65	1.52	1.81	1.52	1.04	272	366	77304	0.21
823	5	3.09	4.09	2.18	531.3	1049	1389	825	22266	1.05	0.96	0.75	1.33	1.48	1.32	0.97	282	435	28495	0.27
824	7	3.93	3.75	2.77	591.1	875	1158	688	14074	0.63	0.57	0.45	2.82	2.26	2.81	0.60	269	412	38908	0.26
825	6	4.60	2.90	3.24	560.5	1558	2062	1225	25062	1.36	1.24	0.97	1.53	0.81	1.52	1.24	242	400	30773	0.30
826	5	1.91	2.22	1.35	493.2	335	443	263	5387	0.31	0.28	0.22	2.80	2.73	2.79	4.49	36	50	3674	0.21
827	9	3.70	2.62	2.61	561.4	2489	3295	1957	40033	1.45	1.32	1.04	1.15	0.68	1.14	2.00	195	273	27648	0.24
828	5	3.30	2.85	2.33	592.0	566	749	445	9104	0.54	0.49	0.39	2.76	2.01	2.75	2.69	182	277	17217	0.29
829	6	2.34	2.85	1.65	710.7	474	627	372	7616	0.39	0.36	0.28	2.70	2.75	2.69	8.40	190	284	23663	0.24
830	6	2.23	3.62	1.58	556.4	1120	1483	881	18021	1.02	0.92	0.73	0.99	1.35	0.99	1.76	195	279	19894	0.23
901	9	2.73	3.62	1.93	660.5	1657	1868	1852	28956	0.96	0.74	0.98	1.29	1.68	0.90	4.01	175	391	60753	0.31
902	7	3.53	3.02	2.49	690.5	1372	1546	1533	23968	0.97	0.75	0.98	1.64	1.39	1.15	0.64	185	436	52871	0.34
903	6	3.13	3.94	2.21	626.6	1019	1149	1139	17809	0.89	0.69	0.90	1.59	1.98	1.12	1.99	165	345	34406	0.30
904	5	2.89	3.59	2.04	577.0	1048	1181	1171	18308	0.99	0.77	1.01	1.32	1.61	0.93	1.62	174	363	35537	0.28
905	9	3.59	4.40	2.53	611.4	2223	2505	2483	38833	1.18	0.91	1.20	1.37	1.65	0.96	1.08	167	375	57788	0.34
906	4	3.09	3.80	2.18	573.7	437	493	489	7639	0.51	0.39	0.52	2.75	3.34	1.93	0.94	180	382	28442	0.31
907	7	2.48	2.82	1.75	502.6	1113	1254	1243	19443	0.81	0.62	0.82	1.39	1.56	0.97	3.05	143	311	40955	0.28
908	6	4.18	1.91	2.95	538.6	4806	5416	5370	83969	3.82	2.96	3.89	0.49	0.22	0.35	2.62	162	351	43722	0.27
909	5	2.88	4.02	2.03	489.2	983	1108	1098	17177	0.98	0.76	1.00	1.32	1.82	0.93	2.07	129	247	24706	0.24
910	5	3.62	3.68	2.55	615.5	1123	1265	1254	19613	1.07	0.83	1.09	1.52	1.52	1.07	1.69	168	338	31291	0.28
911	7	3.39	3.93	2.39	557.0	2134	2405	2384	37285	1.46	1.13	1.48	1.05	1.20	0.74	1.03	162	360	50191	0.29
912	7	2.09	4.21	1.47	565.1	5286	5956	5905	92341	3.82	2.96	3.89	0.25	0.49	0.17	3.05	173	408	54586	0.30
913	6	2.44	3.80	1.72	567.4	1569	1768	1753	27407	1.34	1.04	1.36	0.82	1.26	0.58	4.26	160	391	46363	0.29
914	8	2.29	4.49	1.62	605.9	1957	2205	2187	34194	1.16	0.90	1.18	0.89	1.71	0.62	2.29	166	419	69074	0.31
915	7	3.21	2.57	2.27	494.4	428	483	479	7486	0.33	0.26	0.34	4.40	3.46	3.09	2.43	170	416	52342	0.31
916	5	3.26	3.74	2.30	633.3	1430	1611	1597	24978	1.39	1.08	1.42	1.06	1.19	0.74	4.41	168	416	40205	0.32
917	9	2.05	4.45	1.45	509.9	1278	1441	1428	22335	0.72	0.56	0.73	1.29	2.76	0.90	0.83	168	350	60277	0.27
918	6	5.54	1.81	3.91	697.0	1651	1860	1844	28841	1.34	1.03	1.36	1.87	0.60	1.31	1.14	164	349	39554	0.29
919	6	2.59	2.84	1.83	606.4	521	587	582	9094	0.42	0.32	0.43	2.79	3.02	1.96	1.32	124	238	28732	0.25
920	7	2.93	4.29	2.07	518.9	1550	1746	1731	27075	1.08	0.83	1.10	1.23	1.77	0.86	1.28	159	302	43628	0.24
921	9	2.03	4.55	1.43	638.4	6588	7423	7360	115089	3.82	2.96	3.89	0.24	0.53	0.17	1.15	174	381	61572	0.29
922	7	1.35	2.82	0.96	593.8	1111	1252	1242	19418	0.75	0.58	0.76	0.81	1.67	0.57	1.28	88	108	5630	0.26
923	7	1.70	3.92	1.20	559.1	1769	1993	1976	30897	1.20	0.93	1.22	0.64	1.45	0.45	2.67	204	340	18431	0.55
924	8	1.82	3.24	1.28	473.8	1284	1447	1435	22434	0.80	0.62	0.82	1.02	1.79	0.72	2.42	200	257	8610	0.52
925	6	2.30	2.27	1.62	531.7	552	622	617	9646	0.45	0.35	0.46	2.30	2.24	1.61	1.91	158	333	38154	0.28
926	4	2.63	3.79	1.86	713.6	1109	1250	1239	19379	1.32	1.02	1.34	0.90	1.28	0.63	0.98	174	241	5090	0.56
927	13	3.24	2.79	2.28	614.7	9778	11018	10924	170827	3.82	2.96	3.89	0.38	0.33	0.27	1.68	151	249	26009	0.48
928	21	3.60	4.07	2.54	561.6	2941	3314	3286	51383	0.71	0.55	0.72	2.29	2.55	1.61	0.92	242	358	53946	0.45
929	24	4.17	4.69	2.95	546.0	1330	1499	1486	23239	0.28	0.21	0.28	6.83	7.58	4.80	1.12	258	367	63315	0.42
930	8	3.15	2.18	2.22	639.6	1970	2220	2201	34421	1.18	0.91	1.20	1.21	0.82	0.85	0.67	198	355	20276	0.65
931	7	5.31	3.28	3.75	634.9	5102	5749	5700	89140	3.82	2.96	3.89	0.63	0.38	0.44	2.19	249	467	23958	0.61
1001	6	2.88	3.52	2.03	639.5	1074	1536	1195	19931	0.92	0.90	0.93	1.42	1.34	1.00	1.10	177	361	36849	0.29
1002	6	2.67	3.88	1.88	569.9	1241	1775	1381	23029	1.04	1.03	1.06	1.15	1.30	0.81	2.68	171	406	47664	0.29
1003	6	3.24	3.68	2.29	595.0	967	1383	1076	17940	0.84	0.83	0.85	1.74	1.53	1.22	2.24	187	397	38737	0.31
1004	10	2.71	4.93	1.91	499.9	1384	1980	1540	25689	0.70	0.68	0.71	1.76	2.48	1.24	2.71	218	443	78515	0.28
1005	6	3.59	3.54	2.53	722.0	712	1019	792	13216	0.60	0.59	0.61	2.71	2.08	1.91	4.27	197	459	45689	0.34
1006	7	3.68	2.92	2.59	658.7	394	563	438	7304	0.27	0.26	0.27	6.19	3.82	4.36	3.90	170	370	50850	0.29
1007	9	2.17	4.43	1.53	590.0	984	1407	1095	18256	0.58	0.57	0.59	1.69	2.68	1.19	3.49	161	426	71943	0.31
1008	7	2.49	2.97	1.76	611.0	1364	1952	1518	25323	0.96	0.94	0.97	1.17	1.08	0.83	1.66	134	331	47394	0.30
1009	6	3.23	2.78	2.28	587.0	245	350	273	4546	0.22	0.22	0.22	6.61	4.42	4.66	0.20	166	316	32612	0.26
1010	6	1.68	4.83	1.19	572.1	1234	1765	1373	22900	1.06	1.04	1.08	0.72	1.59	0.50	0.65	163	387	45636	0.29
1011	7	3.30	1.34	2.33	641.8	1300	1860	1447	24134	1.00	0.98	1.01	1.50	0.47	1.06	1.45	158	325	39084	0.28

Sec. units	Aij (ha)	Epot (mm / day; season)				Vij (m3)				IP1			IP2				Eact, n (mm)	Eact, l (mm)	Vsim (m3)	IP3
		May	Jul	Aug	Total	May	Jul	Aug	Total	May	Jul	Aug	May	Jul	Aug	Total				
1012	5	2.26	4.28	1.60	627.8	1029	1472	1145	19095	1.03	1.02	1.05	0.99	1.45	0.70	5.48	164	323	30902	0.25
1013	7	3.30	3.42	2.33	652.1	1532	2192	1705	28433	1.06	1.04	1.07	1.41	1.13	0.99	2.63	185	407	48772	0.33
1014	7	2.54	3.10	1.79	661.5	937	1341	1043	17391	0.64	0.63	0.65	1.78	1.69	1.25	2.31	165	345	41665	0.32
1015	7	2.61	3.24	1.84	552.2	3453	4940	3842	64086	2.38	2.34	2.41	0.49	0.48	0.35	3.39	159	292	38986	0.25
1016	6	2.08	2.87	1.47	596.8	1674	2395	1863	31071	1.48	1.45	1.50	0.64	0.68	0.45	3.08	138	285	29583	0.28
1017	6	2.62	3.18	1.85	657.3	1338	1914	1489	24828	1.10	1.08	1.12	1.07	1.01	0.76	1.04	175	317	32552	0.27
1018	7	2.56	3.16	1.81	642.3	1193	1707	1328	22143	0.86	0.85	0.88	1.33	1.28	0.94	4.64	114	220	30278	0.24
1019	6	3.09	3.37	2.18	600.8	850	1216	946	15773	0.69	0.68	0.70	2.01	1.70	1.42	3.49	173	383	43957	0.29
1020	7	3.47	3.05	2.45	528.3	503	720	560	9337	0.39	0.38	0.39	4.07	2.78	2.86	2.91	157	380	44013	0.33
1021	5	2.60	2.64	1.84	532.5	979	1401	1089	18170	0.95	0.93	0.96	1.24	0.98	0.87	1.71	110	284	28992	0.31
1022	7	3.47	3.18	2.45	562.9	1292	1849	1438	23988	0.88	0.87	0.89	1.78	1.27	1.25	0.79	177	361	46715	0.29
1023	4	2.21	2.88	1.56	604.2	1805	2583	2009	33502	2.38	2.34	2.41	0.42	0.42	0.30	2.52	161	313	20295	0.28
1024	6	2.83	3.46	1.99	668.4	965	1381	1074	17919	0.76	0.75	0.77	1.68	1.60	1.18	1.59	221	290	23506	0.19
1025	9	4.02	2.60	2.83	613.4	1617	2314	1800	30020	0.89	0.87	0.90	2.03	1.02	1.43	1.88	167	402	70295	0.30
1026	7	3.02	5.05	2.13	626.1	1157	1656	1288	21484	0.83	0.82	0.84	1.64	2.13	1.16	1.76	216	438	48799	0.32
1027	8	2.94	4.69	2.07	663.5	1030	1474	1146	19116	0.66	0.65	0.67	2.01	2.50	1.42	2.20	250	395	41489	0.27
1028	8	3.55	3.33	2.51	609.4	871	1246	969	16162	0.55	0.54	0.56	2.91	2.12	2.05	3.52	202	296	27802	0.27
1029	8	3.49	3.98	2.46	653.5	1305	1867	1452	24216	0.84	0.82	0.85	1.88	1.66	1.32	1.33	266	323	26554	0.17
1030	3	3.31	2.63	2.34	532.3	408	584	454	7580	0.78	0.77	0.79	1.92	1.18	1.35	3.15	225	336	10102	0.29
1031	8	4.23	4.43	2.99	604.3	835	1195	930	15507	0.55	0.54	0.56	3.48	2.82	2.45	1.80	268	386	37313	0.24
1032	7	3.10	3.90	2.19	583.9	1407	2014	1566	26123	0.99	0.97	1.00	1.41	1.38	1.00	1.34	231	305	27031	0.20
1033	10	2.72	4.72	1.92	546.7	2758	3946	3069	51186	1.36	1.33	1.38	0.91	1.22	0.64	0.80	239	329	44215	0.21
1034	6	3.34	3.70	2.36	732.9	1014	1452	1129	18830	0.79	0.78	0.81	1.90	1.63	1.34	4.34	184	403	46774	0.30
1101	7	3.00	2.15	2.12	592.2	1681	1894	2199	32210	1.19	0.92	1.42	1.14	0.80	0.68	2.27	164	311	39704	0.26
1102	7	2.75	4.38	1.94	627.5	1572	1772	2057	30129	1.05	0.82	1.26	1.18	1.85	0.71	0.95	205	334	34344	0.28
1103	6	2.66	3.25	1.88	618.3	1252	1411	1639	24000	0.98	0.76	1.17	1.23	1.47	0.74	1.02	156	296	32800	0.27
1104	6	1.41	3.23	1.00	571.6	1406	1585	1840	26952	1.15	0.89	1.37	0.55	1.25	0.33	1.49	151	400	50186	0.30
1105	4	3.83	2.46	2.70	602.2	858	967	1123	16445	0.97	0.75	1.15	1.79	1.13	1.07	1.51	158	310	27106	0.25
1106	6	3.69	1.35	2.60	467.2	1031	1162	1349	19759	0.90	0.69	1.07	1.86	0.67	1.11	3.31	164	392	43133	0.30
1107	5	4.26	2.29	3.00	462.6	709	799	928	13595	0.70	0.54	0.83	2.74	1.46	1.64	1.27	173	376	35948	0.29
1108	7	3.78	2.94	2.67	613.2	634	715	830	12157	0.44	0.34	0.53	3.85	2.95	2.31	1.20	168	372	50666	0.29
1109	8	2.82	2.87	1.99	670.4	4003	4512	5239	76721	2.60	2.01	3.10	0.49	0.49	0.29	1.34	173	355	48249	0.29
1110	4	3.68	4.63	2.60	454.8	867	977	1134	16608	1.00	0.77	1.19	1.66	2.06	1.00	1.01	275	419	11660	0.54
1111	7	3.46	2.87	2.44	569.5	1850	2084	2420	35449	1.25	0.97	1.49	1.25	1.02	0.75	3.52	232	354	18848	0.48
1112	6	3.13	2.55	2.21	662.3	1003	1131	1313	19225	0.81	0.63	0.97	1.74	1.39	1.04	2.34	190	265	12869	0.36
1113	6	2.61	4.75	1.84	750.7	1282	1445	1678	24568	1.03	0.80	1.23	1.14	2.04	0.68	2.65	165	298	31775	0.26
1114	4	1.93	5.04	1.36	659.2	1808	2037	2366	34645	2.09	1.62	2.49	0.42	1.07	0.25	2.52	212	291	7004	0.49
1115	5	2.60	5.28	1.84	499.3	852	961	1116	16337	0.94	0.72	1.11	1.26	2.51	0.75	6.35	245	357	11521	0.44
1116	5	2.25	3.97	1.59	614.8	1240	1398	1623	23767	1.35	1.04	1.61	0.75	1.31	0.45	2.95	218	303	7923	0.49
1117	4	2.76	4.72	1.95	635.9	1637	1844	2142	31366	1.88	1.45	2.24	0.66	1.12	0.40	2.17	228	332	9700	0.47
1118	4	2.83	2.99	2.00	595.6	604	681	791	11579	0.72	0.55	0.85	1.78	1.86	1.07	2.60	231	382	11742	0.54
1119	5	3.48	3.31	2.45	541.9	1081	1219	1415	20724	1.20	0.93	1.43	1.31	1.23	0.79	1.62	233	365	13286	0.45
1120	4	2.93	3.21	2.07	590.9	1179	1329	1543	22599	1.48	1.15	1.77	0.89	0.97	0.53	2.00	230	371	11828	0.48
1121	4	3.05	3.34	2.15	692.8	1034	1166	1353	19822	1.19	0.92	1.42	1.15	1.25	0.69	2.44	207	292	7016	0.53
1122	5	3.85	3.10	2.72	624.7	2471	2785	3234	47359	2.60	2.01	3.10	0.67	0.53	0.40	1.75	249	359	10665	0.49
1123	5	2.32	2.65	1.64	628.4	1682	1896	2202	32245	1.61	1.25	1.92	0.65	0.73	0.39	####	227	333	11315	0.49
1124	5	2.95	3.44	2.08	639.2	517	582	676	9905	0.53	0.41	0.64	2.49	2.86	1.49	1.76	243	297	7650	0.34
1125	5	2.62	2.80	1.85	690.0	610	687	798	11685	0.62	0.48	0.74	1.91	2.01	1.14	1.15	156	197	4013	0.50
1126	5	2.61	2.97	1.84	540.4	1494	1684	1955	28630	1.59	1.23	1.89	0.74	0.83	0.44	2.34	125	138	538	1.09
1127	5	3.42	1.71	2.41	678.6	762	858	997	14597	0.78	0.61	0.93	1.97	0.97	1.18	0.25	241	325	7647	0.54
1128	5	3.22	2.67	2.27	517.8	1208	1361	1581	23149	1.26	0.97	1.50	1.15	0.95	0.69	1.20	236	321	8276	0.49
1129	7	4.81	1.64	3.39	660.5	523	589	684	10015	0.40	0.31	0.47	5.48	1.84	3.29	1.92	232	279	10500	0.30
1130	8	2.95	2.98	2.08	504.5	1068	1204	1398	20467	0.68	0.52	0.81	1.96	1.95	1.18	4.30	254	322	13770	0.39
1131	5	3.38	1.81	2.39	569.6	623	702	816	11944	0.69	0.53	0.82	2.21	1.17	1.32	2.01	238	325	7304	0.54
1132	7	3.34	2.98	2.35	580.6	1778	2004	2327	34079	1.19	0.92	1.42	1.26	1.11	0.76	1.35	253	277	5066	0.35
1133	4	4.07	1.74	2.87	655.1	1906	2148	2494	36522	2.60	2.01	3.10	0.71	0.30	0.42	2.31	192	239	5994	0.29
1134	7	3.79	2.20	2.67	671.5	1130	1274	1479	21661	0.86	0.67	1.03	1.98	1.13	1.19	1.63	253	321	9319	0.48
1135	7	3.23	1.40	2.28	649.7	1086	1224	1422	20819	0.81	0.63	0.97	1.80	0.77	1.08	1.25	182	247	7600	0.58
1136	9	3.33	2.40	2.35	582.2	1811	2041	2370	34702	1.06	0.82	1.26	1.42	1.01	0.85	1.06	207	294	24599	0.30
1137	9	3.46	1.75	2.44	559.8	694	782	908	13304	0.41	0.31	0.49	3.84	1.92	2.30	1.83	202	245	8283	0.45
1138	0				644.0	0	0	0	0							0.10			0	0.00
1139	4	3.32	3.23	2.34	449.8	1031	1162	1349	19756	1.23	0.95	1.46	1.22	1.17	0.73	1.59	269	353	7736	0.46
1140	5	1.77	3.95	1.25	583.1	443	499	580	8494	0.49	0.38	0.58	1.64	3.59	0.98	4.04	228	254	3209	0.37
1141	10	3.74	2.68	2.64	466.0	5303	5977	6940	101634	2.60	2.01	3.10	0.65	0.46	0.39	3.18	277	366	18584	0.49
1201	6	1.97	3.33	1.39	712.5	815	1199	900	17726	0.73	0.73	0.73	1.22	1.56	0.87	2.51	154	280	26169	0.27
1202	8	3.07	3.15	2.17	603.7	892	1312	985	19393	0.58	0.58	0.58	2.41	1.87	1.71	2.67	140	290	41285	0.28
1203	7	1.98	3.64	1.39	678.3	1373	2019	1516	34448	0.94	0.95	0.95	0.95	1.32	0.67	2.09	174	398	54101	0.30
1204	6	3.82	2.54	2.70	535.1	1005	1478	1110	21849	0.84	0.85	0.85	2.04	1.02	1.45	1.37	199	250	6691	0.46
1205	10	2.11	4.02	1.49	539.1	1992	2930	2200	34533	1.03	1.04	1.04	0.92	1.33	0.66	1.44	178	232	12408	0.42
1206	7	1.72	2.99	1.22	566.9	1333	1961	1472	28990	1.00	1.01	1.01	0.78	1.02	0.55	4.48	129	175	8902	0.34
1207	7	2.02	4.22	1.43	563.6	970	1426	1071	21083	0.72	0.73	0.73	1.26	1.99	0.90	0.67	247	308	7922	0.52

Sec. units	Aij (ha)	Epot (mm / day; season)				Vij (m3)				IP1			IP2				Eact, n (mm)	Eact, l (mm)	Vsim (m3)	IP3
		May	Jul	Aug	Total	May	Jul	Aug	Total	May	Jul	Aug	May	Jul	Aug	Total				
1208	7	2.99	2.34	2.11	550.0	494	726	545	10731	0.37	0.38	0.37	3.63	2.15	2.58	0.85	148	337	39559	0.32
1209	7	3.16	1.63	2.23	542.1	737	1084	813	16017	0.56	0.57	0.57	2.54	0.99	1.80	1.13	206	250	7226	0.40
1210	7	2.68	4.05	1.89	431.5	1214	1786	1341	26400	0.91	0.92	0.92	1.32	1.51	0.94	1.13	251	312	7315	0.56
1211	7	2.84	5.53	2.17	500.0	1307	1923	1444	28426	0.98	0.99	0.99	1.30	####	####	1.44	231	286	6331	0.58
1212	7	2.91	2.45	2.06	454.6	816	1200	901	17741	0.62	0.63	0.62	2.12	1.34	1.50	0.54	240	292	6064	0.57
1213	7	3.44	3.17	2.43	559.3	1191	1752	1315	25899	0.92	0.92	0.92	1.69	1.18	1.20	1.60	224	265	5773	0.46
1214	5	2.88	4.32	2.03	481.0	1099	1616	1213	23888	1.04	1.05	1.05	1.24	1.41	0.88	2.06	236	273	2763	0.70
1215	7	2.55	2.43	1.80	456.1	1335	1964	1475	29037	0.98	0.99	0.99	1.17	0.84	0.83	1.78	192	210	2720	0.44
1216	6	3.68	1.67	2.60	401.7	389	573	430	8467	0.30	0.31	0.31	5.48	1.88	3.89	0.73	192	234	7299	0.37
1217	6	1.75	0.84	1.23	445.5	3107	4571	3431	32388	2.41	2.43	2.42	0.33	0.12	0.23	2.16	51	57	1586	0.24
1218	6	3.42	2.86	2.41	543.8	950	1397	1049	20648	0.75	0.76	0.76	2.05	1.30	1.46	2.07	244	282	5128	0.48
1219	6	2.50	2.90	1.76	539.3	658	968	727	14306	0.52	0.52	0.52	2.18	1.91	1.55	1.44	179	299	13251	0.58
1220	8	2.74	3.42	1.93	689.9	3959	5824	4372	41264	2.41	2.43	2.42	0.51	0.48	0.36	2.80	232	432	30945	0.53
1221	8	2.07	3.01	1.46	631.3	1432	2107	1582	31147	0.92	0.93	0.92	1.02	1.12	0.72	3.47	221	379	22384	0.55
1222	7	3.01	2.24	2.12	514.1	1034	1521	1142	22481	0.76	0.77	0.77	1.78	1.00	1.26	2.06	234	292	10442	0.38
1223	7	3.10	2.19	2.19	593.2	1384	2035	1528	30084	0.96	0.97	0.97	1.46	0.78	1.03	1.64	241	325	13230	0.46
1224	8	3.30	2.08	2.33	521.1	718	1056	792	15604	0.43	0.43	0.43	3.50	1.66	2.49	0.62	220	382	25283	0.54
1225	6	2.04	3.82	1.44	527.7	1147	1687	1267	24943	0.93	0.94	0.94	0.99	1.40	0.70	1.31	208	220	900	0.77
1226	6	4.13	2.34	2.92	499.3	4482	6594	4950	97466	3.54	3.57	3.56	0.53	0.23	0.37	1.01	233	264	3758	0.52
1227	6	4.08	3.52	2.88	494.0	1023	1505	1130	22248	0.85	0.86	0.85	2.17	1.42	1.54	1.11	234	261	5541	0.30
1228	6	4.91	1.46	3.47	456.0	1212	1783	1338	26349	0.99	1.00	0.99	2.24	0.50	1.59	2.91	226	267	5505	0.46
1229	7	2.95	3.33	2.08	596.6	1018	1498	1124	22137	0.69	0.70	0.70	1.92	1.64	1.37	1.82	224	369	21861	0.49
1230	7	3.40	1.64	2.40	445.4	500	736	553	10880	0.37	0.38	0.37	4.13	1.51	2.93	1.42	232	412	20923	0.58
1231	8	3.36	1.77	2.37	617.4	1345	1978	1485	29244	0.86	0.87	0.86	1.77	0.70	1.26	1.96	219	369	21000	0.56
1301	7	1.94	4.02	1.37	702.5	1351	1514	1388	20974	0.96	0.74	0.89	0.92	1.88	0.70	1.54	200	268	9938	0.49
1302	9	2.46	3.57	1.74	448.6	1618	1814	1663	28602	0.93	0.71	0.87	1.20	1.72	0.91	1.33	225	280	9290	0.52
1303	9	2.76	2.11	1.95	532.2	1302	1459	1338	23018	0.76	0.59	0.72	1.63	1.23	1.24	1.08	119	157	6116	0.53
1304	8	2.61	2.96	1.84	442.4	3102	3478	3189		1.86	1.43	1.74	0.63	0.71	0.48	1.94			5122	0.51
1305	10	2.36	2.28	1.67	470.4	2293	2571	2357	54849	1.14	0.87	1.06	0.94	0.90	0.72	2.19	163	194	5956	0.58
1306	7	2.91	3.03	2.05	534.1	1268	1422	1304	40544	0.86	0.66	0.80	1.53	1.58	1.17	1.75	211	245	11688	0.47
1307	8	2.87	2.05	2.02	520.8	1757	1970	1806	22424	1.14	0.87	1.06	1.14	0.81	0.87	0.62	255	329	2592	0.47
1308	8	2.09	2.44	1.48	519.2	1304	1462	1341	31065	0.81	0.63	0.76	1.16	1.34	0.88	0.62	163	179	8545	0.46
1309	9	2.03	2.13	1.43	579.9	629	705	646	23059	0.37	0.28	0.34	2.50	2.60	1.91	1.32	185	234	4286	0.31
1310	7	4.26	2.16	3.00	441.3	1833	2055	1885	11117	1.23	0.95	1.15	1.56	0.78	1.19	3.29	161	176	10662	0.50
1311	9	2.19	1.76	1.54	494.4	553	620	569	32414	0.32	0.24	0.30	3.11	2.49	2.37	0.98	146	217	0	0.00
1312	6	3.00	2.31	2.12	509.5	3045	3413	3130	9781	2.43	1.87	2.27	0.56	0.43	0.43	2.55	0	0	11065	0.39
1313	7	2.84	3.14	2.01	574.0	1587	1779	1631	53827	1.14	0.87	1.06	1.13	1.23	0.86	1.86	129	198	16709	0.39
1314	8	2.36	2.14	1.67	580.3	554	621	570	28049	0.36	0.28	0.34	2.92	2.62	2.23	2.57	171	265	2435	0.41
1315	6	2.77	2.14	1.95	640.6	1031	1156	1060	9798	0.81	0.62	0.76	1.54	1.18	1.18	1.60	57	70	11377	0.40
1316	8	2.04	2.79	1.44	667.0	2654	2975	2728	18230	1.73	1.33	1.62	0.53	0.72	0.41	1.30	120	191	29811	0.44
1317	6	2.28	3.05	1.61	581.3	1589	1781	1634	46916	1.24	0.95	1.16	0.83	1.10	0.63	1.36	183	353	22776	0.34
1318	4	3.12	3.07	2.20	580.5	841	943	865	28095	1.14	0.87	1.06	1.24	1.21	0.95	1.67	208	327	4568	0.33
1319	5	2.67	3.29	1.88	566.2	1139	1277	1171	14871	1.14	0.87	1.06	1.06	1.30	0.81	1.63	234	275	10374	0.36
1320	7	2.65	3.23	1.87	454.5	1487	1667	1528	20141	1.14	0.87	1.06	1.05	1.27	0.80	1.85	147	221	12507	0.34
1321	7	2.29	4.08	1.62	485.5	1648	1848	1695	26284	1.14	0.87	1.06	0.91	1.60	0.69	6.00	214	280	15435	0.37
1322	9	2.66	2.85	1.88	591.0	837	938	861	29143	0.44	0.34	0.41	2.71	2.88	2.07	0.92	238	317	1773	0.40
1323	6	2.56	4.29	1.80	501.6	962	1079	989	13404	0.82	0.63	0.77	1.40	2.33	1.07	7.11	131	138	5469	0.45
1324	7	2.18	4.05	1.54	600.7	1753	1966	1803	17012	1.21	0.93	1.13	0.81	1.50	0.62	1.50	220	262	10453	0.37
1325	7	3.54	1.95	2.50	538.8	902	1012	928	31001	0.62	0.47	0.58	2.60	1.42	1.98	0.82	250	303	3989	0.49
1326	7	3.16	2.64	2.23	490.3	2609	2925	2682	15955	1.87	1.44	1.75	0.76	0.63	0.58	2.26	222	248	0	0.00
1327	6	3.71	2.38	2.62	631.3	1306	1465	1343	46132	1.14	0.87	1.06	1.47	0.94	1.13	1.48	212	224	5275	0.33
1328	6	2.34	2.32	1.65	642.0	258	290	265	23097	0.20	0.15	0.19	5.28	5.19	4.03	2.21	239	269	1445	0.60
1329	4	1.80	4.03	1.27	558.1	1591	1784	1636	4566	1.81	1.40	1.70	0.45	0.99	0.34	3.58	180	194	4376	0.21
1330	7	1.58	2.57	1.12	612.1	342	383	351	28132	0.23	0.18	0.22	3.11	5.01	2.38	1.53	215	236	0	0.00
1331	6	1.97	2.31	1.39	526.7	852	955	876	6038	0.70	0.54	0.65	1.27	1.48	0.97	1.31	0	0	0	0.00
1332	9	2.38	3.82	1.68	554.9	1776	1991	1826	15069	0.99	0.76	0.92	1.09	1.73	0.83	1.38	87	89	17118	0.31
1333	8	3.68	3.14	2.60	591.2	1568	1758	1612	31396	0.98	0.76	0.92	1.69	1.43	1.29	1.47	260	318	5614	0.39
1334	7	3.71	2.66	2.62	577.1	1794	2011	1844	27723	1.22	0.94	1.14	1.38	0.98	1.05	1.32	232	260	3620	0.44
1335	7	1.99	4.67	1.41	585.2	1958	2195	2012	35487	1.45	1.12	1.36	0.62	1.44	0.47	0.96	218	239	10053	0.37
1336	6	3.46	3.56	2.44	490.1	1419	1591	1459	34610	1.14	0.87	1.06	1.37	1.40	1.05	1.71	218	273	23955	0.54
1401	7	2.80	3.53	1.98	470.2	523	1063	975	25086	0.38	0.53	0.65	3.30	2.28	1.39	3.66	272	478	45270	0.28
1402	5	2.81	3.50	1.98	587.3	565	1148	1053		0.52	0.73	0.89	2.42	1.65	1.02	1.46			41504	0.29
1403	6	2.86	2.61	2.02	521.6	371	753	691		0.34	0.47	0.57	3.82	1.91	1.61	0.61			26495	0.35
1404	5	2.67	2.33	1.88	425.2	848	1723	1580	15484	0.85	1.19	1.45	1.41	0.67	0.59	3.80	180	368	24139	0.34
1405	7	3.07	1.64	2.16	526.6	305	619	568	19222	0.23	0.32	0.39	6.09	1.78	2.56	1.21	215	436	6916	0.58
1406	6	1.52	3.22	1.07	442.0	843	1714	1571	10972	0.74	1.04	1.26	0.92	1.07	0.39	3.42	199	367	10892	0.58
1407	6	4.58	2.06	3.24	461.6	1654	3362	3082	25105	1.42	1.98	2.40	1.46	0.36	0.61	1.61	153	317	11824	0.68
1408	5	3.21	2.56	2.27	459.7	1548	3147	2886	9018	1.42	1.98	2.40	1.02	0.45	0.43	1.15	187	247	6129	0.53
1409	5	2.54	3.02	1.79	540.1	524	1066	977	24966	0.52	0.72	0.88	2.22	1.44	0.93	1.79	248	359	14176	0.75
1410	6	3.96	1.74	2.80	463.9	414	842	772	48970	0.36	0.51	0.62	4.91	1.18	2.06	1.16	227	364	4642	0.52

Sec. units	Aij (ha)	Epot (mm / day; season)				Vij (m3)				IP1			IP2				Eact, n (mm)	Eact, I (mm)	Vsim (m3)	IP3
		May	Jul	Aug	Total	May	Jul	Aug	Total	May	Jul	Aug	May	Jul	Aug	Total				
1411	8	3.73	1.04	2.63	515.5	596	1212	1112	45846	0.39	0.54	0.65	4.37	0.67	1.84	0.79	245	304	6987	0.59
1412	4	3.16	2.75	2.23	485.5	734	1492	1368	15527	0.83	1.16	1.41	1.72	0.81	0.72	1.80	188	396	7894	0.78
1413	5	3.46	1.16	2.44	599.4	516	1048	961	12266	0.57	0.80	0.97	2.73	0.50	1.15	1.83	186	229	11452	0.74
1414	5	2.85	5.06	2.01	604.2	770	1565	1435	17663	0.77	1.07	1.31	1.67	1.62	0.70	1.79	151	204	14692	0.62
1415	5	3.93	3.22	2.77	482.3	576	1171	1074	21740	0.53	0.74	0.91	3.32	1.49	1.40	1.30	168	307	13215	0.59
1416	6	2.20	1.76	1.55	466.2	601	1221	1119	15271	0.53	0.74	0.90	1.86	0.81	0.78	2.89	155	344	6237	0.82
1417	7	3.11	2.99	2.20	567.5	725	1475	1352	22795	0.55	0.77	0.94	2.53	1.33	1.07	1.89	254	435	18330	0.78
1418	4	3.02	1.61	2.13	501.5	196	398	365	17057	0.27	0.37	0.45	5.13	1.49	2.16	1.17	260	403	4932	0.70
1419	6	2.23	2.39	1.58	696.9	852	1732	1589	17783	0.76	1.05	1.28	1.34	0.78	0.56	1.90	108	198	12211	0.70
1420	5	4.34	1.68	3.06	540.6	792	1609	1476	21481	0.84	1.17	1.42	2.34	0.49	0.98	0.35	188	405	12021	0.74
1421	5	2.86	3.01	2.02	574.5	743	1511	1386	5805	0.68	0.95	1.16	1.89	1.09	0.79	1.42	115	208	8805	0.57
1422	5	3.59	2.07	2.53	491.2	1402	2851	2614	25237	1.42	1.98	2.40	1.14	0.36	0.48	2.66	159	309	10222	0.73
1423	4	3.52	3.01	2.49	479.6	526	1069	980	23442	0.61	0.85	1.04	2.59	1.21	1.09	1.15	192	378	9080	0.69
1424	5	2.93	2.40	2.07	512.1	458	930	853	22016	0.42	0.59	0.72	3.12	1.40	1.31	1.55	194	286	9151	0.27
1425	5	2.82	3.89	1.99	527.5	294	598	549	41530	0.31	0.43	0.52	4.13	3.12	1.74	1.32	137	288	25238	0.34
1426	5	3.77	4.03	2.66	582.5	393	798	732	15569	0.42	0.58	0.71	4.09	2.39	1.72	1.16	194	339	27766	0.29
1427	5	2.66	3.11	1.88	521.7	577	1173	1076	13551	0.63	0.89	1.08	1.89	1.21	0.80	2.32	71	117	3691	0.55
1428	8	3.17	3.19	2.24	556.6	670	1362	1249	8717	0.44	0.62	0.75	3.22	1.77	1.36	1.71	191	372	14322	0.73
1429	5	3.70	1.47	2.61	381.3	326	663	608	11632	0.35	0.49	0.59	4.78	1.04	2.01	0.76	290	462	11116	0.72
1430	7	2.32	1.28	1.63	483.0	1293	2629	2411	17092	0.93	1.30	1.59	1.12	0.34	0.47	3.67	193	237	5506	0.69
1431	6	2.63	2.14	1.86	488.6	482	980	899	19847	0.44	0.61	0.74	2.73	1.21	1.15	1.15	177	316	12028	0.69
1432	7	3.26	1.91	2.30	664.4	547	1112	1020	9665	0.40	0.55	0.67	3.72	1.19	1.56	1.47	177	347	15252	0.56
1433	8	3.07	3.03	2.16	556.6	901	1831	1679	38300	0.59	0.83	1.00	2.34	1.26	0.98	1.40	87	142	14260	0.48
1434	7	2.82	2.03	1.99	507.2	1855	3771	3458	14277	1.42	1.98	2.40	0.90	0.35	0.38	1.88	167	316	12023	0.50
1435	5	4.77	1.70	3.37	611.4	570	1159	1063	16200	0.59	0.82	0.99	3.68	0.72	1.55	1.43	168	291	12666	0.71
1436	6	2.71	1.45	1.91	625.9	828	1682	1543	26667	0.65	0.90	1.10	1.89	0.55	0.80	1.58	154	243	5127	0.73
1437	7	1.62	2.83	1.14	456.8	1071	2177	1996	54935	0.81	1.13	1.37	0.90	0.86	0.38	1.87	100	192	11524	0.74
1438	8	3.70	2.66	2.61	485.2	1654	3361	3082	16888	1.10	1.53	1.86	1.52	0.60	0.64	3.01	173	357	15713	0.59
1439	6	3.15	3.09	2.22	589.0	1574	3199	2933	24510	1.42	1.98	2.40	1.00	0.54	0.42	1.88	74	132	11583	0.71
1440	11	3.66	2.60	2.58	488.7	460	934	857	31714	0.21	0.30	0.36	7.70	2.99	3.24	1.12	135	262	11676	0.68
1441	7	3.26	2.28	2.30	599.9	824	1676	1536	48970	0.64	0.89	1.08	2.32	0.89	0.98	1.34	178	299	11841	0.74
1501	5	2.45	3.33	1.73	557.7	1037	1523	809	46603	1.06	1.07	0.76	1.04	1.07	1.04	1.52	194	341	16462	0.19
1502	5	3.42	4.26	2.41	584.2	839	1232	655	13612	0.88	0.89	0.63	1.75	1.65	1.75	1.43	128	202	15612	0.15
1503	4	3.09	3.58	2.18	549.5	521	765	407	24410	0.62	0.62	0.44	2.26	1.99	2.28	2.20	180	314	12748	0.13
1504	5	2.09	5.49	1.47	547.5	784	1152	612	19121	0.77	0.78	0.55	1.22	2.43	1.23	1.74	203	266	20477	0.23
1505	5	1.95	2.95	1.38	549.0	414	608	323	15467	0.40	0.40	0.28	2.21	2.53	2.22	0.55	254	304	8874	0.23
1506	5	2.99	3.34	2.11	543.2	415	610	324	9608	0.39	0.40	0.28	3.43	2.91	3.45	2.90	262	303	28167	0.28
1507	8	2.76	1.93	1.95	603.2	1219	1791	951	14460	0.77	0.78	0.55	1.62	0.85	1.62	1.29	259	350	25808	0.27
1508	4	2.86	4.30	2.02	0.0	15796	23201	12325	7629	####	####	####	0.07	0.08	0.07	0.00	94	132	14122	0.23
1509	7	4.16	2.60	2.93	451.3	1166	1712	910	7655	0.83	0.84	0.59	2.25	1.07	2.26	2.90	255	406	25326	0.19
1510	7	2.31	4.75	1.63	507.3	1956	2872	1526	22480	1.50	1.51	1.06	0.70	1.08	0.70	1.25	208	294	29454	0.27
1511	4	3.34	3.75	2.36	452.9	1242	1825	969	291214	1.41	1.42	1.00	1.07	0.91	1.08	1.46	194	267	15714	0.16
1512	5	2.04	4.99	1.44	508.6	1218	1789	950	21492	1.12	1.13	0.79	0.82	1.52	0.83	1.54	240	310	25505	0.25
1513	5	2.78	4.73	1.96	479.7	725	1065	566	36053	0.77	0.78	0.55	1.63	2.09	1.64	0.48	210	334	30553	0.27
1514	6	2.84	4.71	2.00	582.2	1462	2147	1141	22901	1.17	1.17	0.83	1.10	1.38	1.10	1.28	247	305	33041	0.27
1515	5	2.96	3.69	2.09	469.2	844	1240	659	22455	0.77	0.78	0.55	1.73	1.64	1.74	1.77	238	353	15803	0.21
1516	5	2.24	2.95	1.58	567.7	332	487	259	13370	0.32	0.32	0.23	3.17	3.15	3.19	2.19	268	440	18663	0.24
1517	7	2.44	4.62	1.72	507.8	1264	1856	986	26951	0.93	0.94	0.66	1.18	1.69	1.19	3.36	245	385	33839	0.22
1518	5	1.97	2.89	1.39	540.7	1067	1567	833	15562	1.17	1.18	0.83	0.76	0.84	0.76	1.12	230	290	12083	0.19
1519	4	1.64	4.95	1.16	453.6	6212	9124	4847	6117	7.45	7.51	5.30	0.10	0.23	0.10	1.51	248	335	17803	0.22
1520	5	2.84	3.08	2.00	557.6	590	867	461	23301	0.63	0.63	0.45	2.04	1.67	2.05	0.92	261	370	18183	0.25
1521	4	2.15	4.81	1.51	548.6	1428	2098	1114	19674	1.63	1.64	1.16	0.60	1.01	0.60	2.31	168	218	20108	0.24
1522	5	4.00	4.21	2.83	586.2	886	1301	691	114526	0.99	1.00	0.70	1.83	1.46	1.84	2.87	226	321	26921	0.28
1523	6	3.39	3.79	2.39	506.9	869	1276	678	10883	0.77	0.78	0.55	1.98	1.68	1.99	0.82	198	293	30821	0.29
1524	5	2.44	4.11	1.72	604.8	893	1312	697	26329	0.97	0.98	0.69	1.13	1.44	1.14	0.61	236	343	23419	0.24
1525	5	3.36	4.72	2.37	536.0	705	1036	550	16327	0.77	0.78	0.55	1.96	2.09	1.97	1.18	285	454	21276	0.25
1526	5	3.74	3.11	2.64	566.5	845	1241	659	16018	0.80	0.81	0.57	2.10	1.32	2.11	1.00	268	424	22091	0.20
1527	5	2.48	2.94	1.75	587.7	861	1265	672	16462	0.91	0.91	0.65	1.23	1.11	1.24	1.28	239	363	22877	0.29
1528	7	2.95	3.58	2.08	491.8	824	1210	643	13002	0.62	0.63	0.44	2.13	1.96	2.15	1.79	206	320	25788	0.20
1529	7	3.08	4.12	2.17	673.0	1084	1593	846	15579	0.80	0.80	0.57	1.75	1.77	1.76	0.94	272	355	37163	0.23
1530	5	3.74	3.58	2.64	607.0	515	757	402	15878	0.57	0.57	0.40	2.98	2.15	2.99	1.18	239	376	19981	0.17
1531	6	2.90	2.33	2.05	701.1	237	348	185	15183	0.21	0.22	0.15	6.12	3.71	6.15	1.96	216	294	16009	0.25
1532	4	2.18	4.68	1.54	675.4	594	873	464	19990	0.71	0.72	0.50	1.38	2.25	1.39	0.84	250	378	16504	0.24
1533	5	4.05	5.15	2.86	656.4	693	1017	540	9501	0.77	0.78	0.55	2.37	2.28	2.39	1.66	306	381	25196	0.26
1534	6	3.58	3.98	2.52	492.7	917	1347	716	4370	0.77	0.78	0.55	2.09	1.76	2.10	1.58	152	223	29378	0.23
1535	6	1.88	4.12	1.33	550.8	506	744	395	10960	0.44	0.44	0.31	1.92	3.19	1.93	1.15	230	325	31824	0.25
1536	4	1.51	2.70	1.07	668.0	947	1391	739	12769	1.23	1.24	0.87	0.56	0.75	0.56	1.75	296	442	18111	0.25
1537	5	2.97	4.58	2.09	516.2	1461	2145	1140	16908	1.36	1.37	0.96	0.99	1.15	0.99	0.52	252	366	20102	0.17
1538	4	2.86	4.61	2.02	559.9	1118	1642	872	9334	1.38	1.40	0.98	0.93	1.14	0.94	3.30	252	393	19646	0.22
1539	6	2.02	2.26	1.42	540.3	1210	1778	944	26066	0.99	1.00	0.70	0.92	0.78	0.92	2.02	216	332	4987	0.16

Sec. units	Aij (ha)	Epot (mm / day; season)				Vij (m3)				IP1			IP2				Eact, n (mm)	Eact, I (mm)	Vsim (m3)	IP3
		May	Jul	Aug	Total	May	Jul	Aug	Total	May	Jul	Aug	May	Jul	Aug	Total				
1540	6	1.97	2.13	1.39	447.1	422	620	329	26930	0.38	0.39	0.27	2.32	1.90	2.33	1.30	238	302	6476	0.18
1541	6	3.05	3.41	2.15	541.0	1370	2012	1069	20611	1.09	1.10	0.77	1.27	1.07	1.27	1.47	258	363	18817	0.11
1542	5	2.06	3.46	1.45	560.6	1075	1579	839	22315	1.04	1.05	0.74	0.89	1.14	0.90	1.27	59	73	13790	0.25
1543	7	2.78	4.10	1.96	561.0	2460	3614	1920	7785	1.65	1.66	1.17	0.76	0.85	0.76	1.50	68	89	33163	0.26
1544	7	3.55	4.14	2.50	642.7	2415	3547	1884	25251	1.79	1.81	1.28	0.89	0.79	0.90	1.59	251	285	25762	0.17
1601	25	2.86	3.83	2.02	494.7	2429	5395	3560	19819	0.49	0.75	0.66	2.63	1.76	1.41	1.09	167	233	103451	0.34
1602	15	3.02	5.15	2.13	663.9	976	2169	1431	45356	0.32	0.49	0.42	4.29	3.65	2.30	2.26	238	351	93317	0.31
1603	12	1.95	2.89	1.37	674.4	1782	3959	2612	44520	0.75	1.15	1.00	1.17	0.87	0.62	1.34	252	317	49851	0.37
1604	5	3.23	3.18	2.28	650.0	845	1878	1239	64696	0.82	1.25	1.09	1.78	0.88	0.95	1.77	149	291	29121	0.30
1605	5	2.99	3.69	2.11	727.7	634	1409	930	26006	0.63	0.96	0.84	2.14	1.32	1.14	3.58	180	370	21522	0.28
1606	5	2.99	2.24	2.11	537.0	299	664	438	47477	0.32	0.49	0.42	4.24	1.59	2.27	1.86	102	259	20103	0.30
1607	5	4.40	3.72	3.11	639.1	875	1943	1282	22517	0.92	1.40	1.23	2.16	0.91	1.15	2.06	219	386	30760	0.32
1608	5	3.19	3.64	2.25	594.4	356	790	521	16894	0.33	0.50	0.44	4.42	2.52	2.36	2.91	219	338	27871	0.32
1609	5	3.03	4.36	2.14	680.3	569	1263	833	7967	0.57	0.86	0.76	2.42	1.74	1.29	2.79	180	309	33143	0.33
1610	6	2.72	3.92	1.92	717.2	820	1821	1202	23299	0.67	1.02	0.90	1.83	1.32	0.98	2.33	263	470	14482	0.61
1611	5	3.08	3.17	2.17	572.8	575	1277	843	9474	0.61	0.94	0.82	2.27	1.17	1.21	1.74	197	360	22398	0.26
1612	6	4.49	3.36	3.17	550.6	967	2148	1417	15146	0.79	1.20	1.05	2.57	0.96	1.37	1.96	182	400	20295	0.72
1613	7	2.83	3.68	1.99	460.1	655	1454	959	21839	0.45	0.69	0.60	2.83	1.84	1.52	0.52	167	311	19514	0.78
1614	5	3.51	2.92	2.48	578.2	1340	2977	1964	15313	1.33	2.03	1.78	1.19	0.50	0.64	1.77	162	284	7318	0.67
1615	9	2.89	2.66	2.04	489.7	1012	2248	1483	25756	0.59	0.89	0.78	2.23	1.03	1.19	1.40	194	431	12729	0.69
1616	9	3.17	2.70	2.24	552.3	643	1428	942	17436	0.34	0.52	0.46	4.19	1.79	2.24	3.87	141	350	6070	0.71
1617	6	3.29	3.38	2.33	602.1	403	895	591	35700	0.32	0.49	0.43	4.59	2.36	2.46	2.35	176	273	15167	0.70
1618	6	2.56	4.30	1.81	567.4	337	748	494	26957	0.26	0.40	0.35	4.43	3.72	2.37	1.77	139	240	16256	0.45
1619	6	2.05	3.79	1.45	547.1	1448	3216	2122	17123	1.18	1.81	1.58	0.78	0.72	0.42	1.34	169	215	44200	0.39
1620	5	2.47	3.65	1.74	526.2	379	841	555	10733	0.36	0.56	0.49	3.06	2.26	1.64	0.96	206	376	7739	0.49
1621	5	2.16	3.34	1.53	546.9	281	625	412	8972	0.31	0.47	0.41	3.18	2.46	1.70	0.62	278	390	8949	0.49
1622	7	3.74	4.23	2.64	546.8	765	1700	1122	38568	0.54	0.82	0.72	3.12	1.77	1.67	2.29	183	463	24586	0.45
1623	6	3.48	4.17	2.46	601.8	580	1289	850	10087	0.47	0.71	0.62	3.37	2.01	1.80	1.54	178	250	10313	0.38
1624	5	3.84	3.63	2.71	617.0	234	519	343	7497	0.22	0.33	0.29	8.03	3.81	4.30	1.61	192	287	3837	0.30
1625	10	3.50	4.01	2.47	457.4	1612	3580	2362	20384	0.83	1.27	1.11	1.90	1.09	1.02	1.24	281	437	18394	0.43
1626	4	2.88	3.59	2.03	661.9	1179	2620	1728	15451	1.67	2.54	2.22	0.78	0.49	0.42	1.68	265	327	4537	0.61
1627	5	3.52	3.27	2.48	515.8	5213	11580	7640	6227	5.62	8.57	7.50	0.28	0.13	0.15	6.32	226	247	5201	0.50
1628	4	3.23	3.85	2.28	533.1	581	1290	851	42930	0.69	1.05	0.92	2.11	1.26	1.13	1.50	259	341	9968	0.49
1629	5	4.02	3.58	2.83	656.7	308	684	451	31414	0.32	0.49	0.42	5.70	2.54	3.05	3.06	189	267	12434	0.67
1630	12	1.91	3.96	1.35	587.2	763	1695	1118	138870	0.32	0.49	0.42	2.71	2.81	1.45	5.92	221	277	86322	0.40
1631	12	2.54	5.44	1.79	633.8	779	1731	1142	15466	0.32	0.49	0.42	3.61	3.86	1.93	2.87	251	368	76551	0.35
1701	7	2.69	2.15	1.90	681.6	670	1076	620	8198	0.47	0.52	0.40	2.56	1.42	2.17	2.65	195	368	18450	0.27
1702	6	3.07	3.56	2.17	627.0	858	1379	794	20322	0.68	0.75	0.57	2.04	1.63	1.73	2.01	188	472	18219	0.16
1703	5	3.60	2.95	2.54	617.6	594	954	550	20754	0.54	0.60	0.46	2.98	1.69	2.52	1.60	217	436	29559	0.28
1704	6	2.47	4.05	1.75	604.8	1729	2778	1601	13088	1.48	1.64	1.25	0.75	0.85	0.64	1.78	149	219	22828	0.19
1705	5	2.30	4.74	1.62	701.6	685	1100	634	16770	0.74	0.82	0.63	1.40	1.99	1.19	0.53	188	236	22403	0.23
1706	6	2.30	4.67	1.63	482.8	2736	4395	2533	11605	2.43	2.68	2.05	0.43	0.60	0.36	1.18	254	404	20153	0.20
1707	6	2.40	3.19	1.70	721.4	1453	2335	1345	33789	1.25	1.38	1.05	0.87	0.80	0.74	7.51	243	317	18722	0.22
1708	6	3.52	3.07	2.49	662.9	1782	2863	1650	13381	1.57	1.73	1.32	1.01	0.61	0.86	2.68	248	361	21326	0.23
1709	7	3.19	4.00	2.25	547.2	1324	2128	1226	53465	0.94	1.04	0.79	1.53	1.33	1.30	0.41	250	321	19951	0.20
1710	6	4.43	4.14	3.13	593.6	2143	3444	1985	28402	1.87	2.06	1.58	1.07	0.69	0.90	1.29	204	274	21476	0.22
1711	5	2.96	2.56	2.09	465.4	731	1175	677	34829	0.71	0.79	0.60	1.87	1.12	1.59	2.96	203	290	6088	0.19
1712	4	2.79	2.05	1.97	542.6	427	686	395	25882	0.50	0.55	0.42	2.50	1.28	2.12	1.94	225	281	10889	0.26
1713	4	3.28	2.68	2.31	591.1	451	725	418	41891	0.54	0.59	0.45	2.75	1.56	2.33	1.41	226	309	18039	0.26
1714	7	2.52	3.44	1.78	427.9	1576	2532	1459	14292	1.19	1.31	1.00	0.96	0.91	0.81	1.63	71	94	20485	0.18
1715	7	2.84	3.89	2.00	552.7	1994	3204	1846	8346	1.43	1.58	1.21	0.90	0.85	0.76	0.41	150	217	39698	0.24
1716	6	2.80	2.35	1.98	621.0	1173	1885	1086	8819	1.04	1.15	0.88	1.22	0.71	1.03	1.65	227	339	15859	0.26
1717	7	2.44	3.98	1.72	526.5	1594	2561	1476	30797	1.17	1.30	0.99	0.94	1.06	0.79	3.60	186	241	27878	0.23
1718	18	3.20	4.79	2.26	544.0	5611	9014	5195	38970	1.57	1.73	1.32	0.92	0.95	0.78	1.17	274	412	65100	0.21
1719	14	4.04	2.27	2.85	633.5	4238	6809	3924	22933	1.57	1.73	1.32	1.16	0.45	0.98	2.53	158	230	57773	0.31
1720	12	4.53	3.35	3.20	685.4	877	1409	812	31153	0.37	0.41	0.31	5.55	2.84	4.70	1.41	194	290	51151	0.31
1721	14	3.32	2.21	2.34	526.4	1453	2334	1345	109653	0.52	0.57	0.44	2.87	1.33	2.43	4.58	245	322	51446	0.36
1722	8	2.42	4.03	1.71	667.0	1053	1691	975	82826	0.68	0.75	0.57	1.61	1.86	1.37	1.64	236	367	25547	0.34
1723	6	2.55	2.85	1.80	655.1	409	657	379	17138	0.34	0.38	0.29	3.36	2.60	2.85	1.40	250	385	16429	0.36
1724	7	2.23	3.62	1.57	640.6	638	1025	591	28388	0.48	0.52	0.40	2.11	2.38	1.79	0.48	152	286	16500	0.37
1725	8	2.45	2.90	1.73	601.5	2155	3462	1995	20574	1.39	1.54	1.17	0.79	0.65	0.67	1.18	147	258	33971	0.39
1726	6	2.24	4.47	1.58	585.3	1037	1667	960	7995	0.94	1.03	0.79	1.08	1.49	0.91	1.56	137	235	23158	0.35
1727	9	3.86	2.08	2.73	531.9	1062	1706	983	12465	0.61	0.67	0.51	2.88	1.07	2.44	1.55	112	202	29994	0.40
1728	7	4.01	2.43	2.83	496.7	717	1152	664	42119	0.53	0.58	0.44	3.43	1.44	2.91	0.37	185	354	26222	0.42
1729	12	3.40	2.31	2.40	528.1	985	1582	912	20273	0.42	0.47	0.36	3.63	1.70	3.08	1.88	190	337	35764	0.41
1730	5	3.63	2.80	2.56	662.2	1617	2597	1497	20750	1.57	1.73	1.32	1.04	0.56	0.88	3.75	161	299	20467	0.39
1731	6	3.01	3.94	2.13	684.8	1614	2593	1494	14014	1.45	1.60	1.22	0.94	0.85	0.79	1.66	174	336	22508	0.31
1732	7	2.09	3.68	1.48	603.3	1194	1918	1105	19249	0.92	1.01	0.77	1.03	1.26	0.87	1.75	126	253	20610	0.40
1733	14	3.26	3.84	2.30	592.0	2241	3600	2075	31596	0.81	0.89	0.68	1.83	1.49	1.55	1.91	182	338	66461	0.37

Sec. units	Aij (ha)	Epot (mm / day; season)				Vij (m3)				IP1			IP2				Eact, n (mm)	Eact, I (mm)	Vsim (m3)	IP3
		May	Jul	Aug	Total	May	Jul	Aug	Total	May	Jul	Aug	May	Jul	Aug	Total				
1801	5	3.56	4.56	2.52	563.7	2466	4403	2708	31538	2.56	3.14	2.56	0.63	0.50	0.45	1.67	187	312	33443	0.37
1802	11	3.02	4.17	2.13	587.7	888	1586	975	23331	0.39	0.48	0.39	3.50	3.01	2.50	1.76	139	266	72547	0.33
1803	10	2.55	2.91	1.80	590.4	1460	2607	1603	43796	0.75	0.91	0.75	1.54	1.09	1.10	1.81	262	437	22853	0.21
1804	5	3.94	4.53	2.78	570.7	192	343	211		0.20	0.25	0.20	8.91	6.36	6.36	4.54			32529	0.32
1805	9	3.32	3.26	2.34	581.0	843	1505	925		0.49	0.60	0.49	3.07	1.88	2.19	3.36			42124	0.23
1806	22	3.18	3.19	2.25	548.9	2961	5287	3252	52316	0.66	0.81	0.66	2.17	1.35	1.55	1.18	297	554	116201	0.30
1807	24	3.26	2.31	2.30	478.6	1230	2195	1350	18840	0.26	0.32	0.26	5.67	2.50	4.05	4.84	233	441	121685	0.39
1808	13	2.49	3.58	1.76	602.4	2668	4765	2930	30973	1.07	1.31	1.07	1.05	0.94	0.75	1.38	104	152	51800	0.26
1809	5	4.13	2.74	2.92	663.8	2195	3919	2410	4076	2.34	2.87	2.34	0.80	0.33	0.57	3.29	287	505	13793	0.49
1810	10	5.00	1.36	3.53	681.7	2662	4754	2924	19095	1.29	1.59	1.29	1.74	0.30	1.24	2.02	244	354	40598	0.46
1811	8	2.72	4.32	1.92	640.6	2376	4243	2609	62821	1.48	1.82	1.48	0.83	0.82	0.59	2.18	179	337	36263	0.41
1812	14	3.70	4.04	2.61	710.6	1625	2902	1784	26086	0.59	0.72	0.59	2.83	1.92	2.02	2.45	140	338	57654	0.43
1813	6	2.37	4.83	1.67	610.9	502	897	551	56613	0.42	0.52	0.42	2.54	3.22	1.81	0.53	220	327	9700	0.49
1814	18	3.45	3.90	2.43	693.2	1736	3099	1906	46570	0.49	0.60	0.49	3.19	2.25	2.28	6.97	252	396	78605	0.47
1815	9	4.41	3.36	3.11	713.2	811	1448	890	56486	0.47	0.57	0.47	4.26	2.02	3.04	2.15	183	363	18089	0.48
1816	3	3.19	3.57	2.25	667.5	310	554	341	50416	0.45	0.55	0.45	3.24	2.26	2.31	3.63	205	389	2556	0.34
1817	6	3.79	3.49	2.67	657.5	783	1398	860	34476	0.69	0.85	0.69	2.47	1.42	1.76	2.73	255	434	5674	0.32
1818	5	4.61	2.80	3.25	627.2	922	1646	1012	5740	0.93	1.14	0.93	2.24	0.85	1.60	2.18	165	244	3863	0.36
1819	12	2.97	1.94	2.10	726.7	6301	11251	6919	39330	2.54	3.11	2.54	0.53	0.21	0.38	3.13	278	484	48397	0.31
1820	4	3.86	1.35	2.72	707.0	415	741	456	17202	0.53	0.66	0.53	3.26	0.71	2.33	2.37	268	367	13392	0.37
1821	4	1.72	1.77	1.21	734.8	235	419	258	6583	0.27	0.33	0.27	2.90	1.86	2.07	6.48	202	227	0	0.00
1822	4	4.79	1.77	3.38	712.3	1098	1961	1206	16613	1.32	1.61	1.32	1.64	0.38	1.17	4.67	243	275	14490	0.34
1823	7	3.79	2.11	2.68	607.2	1261	2252	1385	19562	0.91	1.11	0.91	1.88	0.65	1.34	1.27	244	272	31927	0.47
1824	6	3.14	3.54	2.22	537.2	1678	2997	1843	0	1.44	1.76	1.44	0.99	0.69	0.70	1.46	137	257	22474	0.28
1825	6	2.33	4.82	1.64	677.9	1804	3221	1981	0	1.49	1.83	1.49	0.70	0.91	0.50	1.17	184	311	20097	0.30
1826	6	1.62	3.93	1.14	633.7	1982	3540	2177	4976	1.80	2.20	1.80	0.41	0.61	0.29	1.42	0	0	27530	0.39
1827	8	2.97	1.65	2.09	592.2	759	1356	834	23304	0.49	0.60	0.49	2.75	0.95	1.96	1.28	183	301	8560	0.35
1828	5	3.09	2.09	2.18	633.3	217	388	238	26756	0.20	0.25	0.20	6.84	2.87	4.89	2.28	193	407	20108	0.31
1829	5	1.57	4.41	1.11	540.2	1032	1843	1134	35611	1.03	1.26	1.03	0.69	1.21	0.50	2.84	230	339	25940	0.38
1830	4	3.23	2.66	2.28	588.1	2125	3795	2334	38268	2.63	3.22	2.63	0.56	0.28	0.40	1.15	211	309	15344	0.34
1831	16	2.52	3.87	1.78	710.7	2193	3916	2408	42057	0.70	0.86	0.70	1.63	1.56	1.16	2.95	207	403	83279	0.49
1832	12	2.40	2.46	1.69	687.0	1520	2714	1669	17203	0.66	0.81	0.66	1.64	1.05	1.17	1.19	60	98	49880	0.31

ANNEX 14: Newspapers articles on the ASTIMwR project