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Irrigation Performance Assessment Tool (IPAT)

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WaterWatch

IrIM

INTA

COMISION NACIONAL DEL AGUA

Irrigation Performance Assessment Tool
(IPAT)

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NATIONAL USER SUPPORT PROGRAMME (NUSP)
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- To supply information to the general public on national and international space-based geo-information applications, new developments and scientific research results.

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Alterra-report 1467

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ABSTRACT

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Currently, the use of remote sensing data in irrigation water management is very limited, due to its low user-friendliness and the limited acquaintance of irrigation engineers with the remote sensing possibilities. To overcome these problems an easy to use GIS/Remote Sensing user interface is developed, called Irrigation Performance Assessment Tool (IPAT), in consultation with the end users. IPAT is successfully tested and demonstrated for three pilot areas in Argentina, Mexico and Ukraine. An economic analysis showed that the use of remote sensing data and IPAT can be very cost-effective.

Keywords: irrigation, performance, water management, GIS, remote sensing, IPAT, SEBAL

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Contents

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IPAT consisted of two projects:
- Local operationalisation of irrigation performance indicators with the use of remote sensing (project code 53403ALT), which focused on prototype development and project leader was Alterra, Wageningen UR.
- Local operationalisation of an irrigation performance assessment tool with the use of remote sensing: Phase II (project code 53503WW), which focused on operationalisation and project leader was WaterWatch.

Summary

The use of remote sensing imagery and processing techniques has proven to have many advantages, to name a few (i) large spatial coverage, (ii) objective information, (iii) applicable to many sectors (water, nature, agriculture, etc.) and (iii) in most cases it is relatively easy and cheap to obtain data, with free downloading from the web as its summum. In the past many scientific efforts have been made to extract useful information from remote sensing data for the use in the water sector. Examples are land use classification, evapotranspiration mapping, precipitation radar, run-off determination. However, the use of this information for operational use in the water management sector is very limited by a number of shortcomings. Two key constraints for the operational use of remote sensing in the water sector are identified:

- Low user-friendliness of remote sensing data. It takes too much effort to incorporate remote sensing data into everyday water management. During the previous projects a lot of attention has been paid on the questions 'what information can be derived from remote sensing?' and not enough attention is being paid to embedding remote sensing technologies into operational use for local counterparts, i.e. the question 'how to use these remote sensing data?'.
- The second constraint is that irrigation engineers are not acquainted with the possibilities of remote sensing. For them, remote sensing stands for land use mapping.

To overcome these problems a basic, easy-to-use ArcGIS user interface, called Irrigation Performance Assessment Tool (IPAT), is developed in consultation with the end users. IPAT can calculate a standardized set of remotely sensed irrigation performance indicators.

The selection of indicators is carried out on the basis of (i) a screening on whether they can be calculated by remote sensing techniques, (ii) the simplicity of the indicator and (iii) wishes and requirements of the knowledge provider (Alterra), the service provider (WaterWatch) and the end users (IHELR, INTA and CNA). A set of four standard indicators is formulated, being the Depleted Fraction, Field Application Ratio, Relative Evapotranspiration and Crop Water Productivity.

The IPAT tool requires an ArcGIS 9.1 (or higher) license and a Spatial Analyst license. The organization of the database of IPAT gives the following possibilities:

- Use of tabular data as well as raster data (such as satellite images) for calculations.
- Spatial selection by use of administrative units. Geodata (either in raster-format or polygon-format) with administrative units is required.
- Spatial and administrative aggregation by use of administrative levels.
- Selection in time by use of period types.
- Aggregation in time by distinguishing period input-types and period output-types.
- Linking spatial vector data such as irrigation lines, irrigation pumps, meteo stations to administrative levels. Links are made in the tables by codes, so that the vector data itself it not obligatory.

- High flexibility for user to add indicators, administrative levels, period types and subelement data (data on rain, irrigation, etc.).

The IPAT tool is tested for three pilot areas: the NCC irrigation system in Crimea, Ukraine, the Yaqui irrigation system in Mexico and the Rio Dulce irrigation system in Argentina. Examples of the four standardized performance indicators show that IPAT is perfectly suited as evaluation tool for the performance of irrigation systems.

A cost-benefit analysis of the use of remote sensing data and the IPAT tool is made to check if the use of remote sensing data in irrigation water management is economically feasible. The IPAT tool is freely available (at http://www.waterwatch.nl/IPAT) and this is no additional financial burden. It proofs that the remote sensing costs are on-average only 0.2 % of the total costs of an irrigation system (or 0.5 % of the O&M costs). Moreover, the remote sensing costs of 0.66 $/ha/yr outweight the average benefits worth $ 79/ha/yr. These benefits include decreased non-beneficial us of water leading to increase of irrigated areas, enhanced food production by better farm management technologies in general, increasing water productivity through saving of applied water and higher revenue collection from all beneficiaries that use water. Non-quantifiable benefits such as increased transparency, conserved groundwater use, implementation of water rights and reduced environmental degradation also exist. They increase the longer term financial and environmental sustainability of the irrigation system.

1 Introduction

1.1 Background

The use of remote sensing imagery and processing techniques has proven to have many advantages, to name a few (i) large spatial coverage, (ii) objective information, (iii) applicable to many sectors (water, nature, agriculture, etc.) and (iii) in most cases it is relatively easy and cheap to obtain data, with free downloading from the web as its summum.

In the past many scientific efforts have been made to extract useful information from remote sensing data for the use in the water sector. Examples are land use classification, evapotranspiration mapping, precipitation radar, run-off determination. However, the use of this information for operational use in the water management sector is very limited by a number of shortcomings. This project tries to overcome these shortcomings.

1.2 Shortcomings previous BCRS projects

The project is a kind of continuation of earlier remote sensing based irrigation projects conducted by Alterra (Argentina), DHV (India, Brazil) and ITC (Sri Lanka), and that were funded by NRSP. Although all these projects have demonstrated that satellite images can help the quantification of the irrigation processes, they are currently - 5 years after project execution - only used by academic researchers in Ph.D. programs. The real implementation with the Irrigation Agencies responsible for the allocation of water has failed, because these entities do not have the tools to 'digest' the pile of remote sensing information. To promote these advantages worldwide in the application field of water management, BCRS/NRSP funded many projects with many partners around the world in the past. In most cases, after project termination, the use of remote sensing techniques was not continued by the local counterparts. Two key constraints for the operational use of remote sensing in the water sector are identified:

- Low user-friendliness of remote sensing data. It takes too much effort to incorporate remote sensing data into everyday water management. During the previous projects a lot of attention has been paid on the questions 'what information can be derived from remote sensing?' and not enough attention is being paid to embedding remote sensing technologies into operational use for local counterparts, i.e. the question 'how to use these remote sensing data?'.
- The second constraint is that irrigation engineers are not acquainted with the possibilities of remote sensing. For them, remote sensing stands for land use mapping.

This project intends to overcome these problems in the field of irrigation water management, a crucial factor for food production in most (semi-)arid countries through:

- creating an easy-to use GIS/Remote Sensing user interface;
- to develop the user-interface in consultation with local engineers to deal with tailor made solutions.

1.3 Objective

Local long-term operationalisation of irrigation performance indicators with the use of remote sensing to improve irrigation water management.
The expected result is the development of a basic, easy-to-use ArcGIS user interface, which can calculate a standardized set of remotely sensed irrigation performance indicators.

1.4 Outline report

Chapter 2 describes the requirements and wishes of the partners in the project consortium, being the knowledge provider (Alterra, Wageningen UR), the service provider (WaterWatch) and the end users from Argentina (INTA), Mexico (CNA) and Ukraine (IHELR).
In Chapter 3 a selection of suitable remotely sensed performance indicators is made. Many irrigation performance indicators for monitoring purposes have been developed worldwide. A selection is made based on suitability of the indicators for operational use with remote sensing, complexity and required data (scales) and user requests.
Hereafter a user interface is developed in which the selected performance indicators are incorporated. The user interface is developed as an ArcGIS tool. Chapter 4 is the manual of this tool.
The required data for the performance indicator calculations (see first step) will be collected (GIS boundaries, meteo, RS data, irrigation schedules and quantities, ground truth) and the satellite images will be processed into ETA and biomass growth with 10-day intervals using the SEBAL algorithm. A land use classification will be made if the Landsat data supports a classification with reasonable accuracy. Chapter 5 describes the results.
In Chapter 6, the user interface will be implemented and tested by the users at three pilot areas: (i) the North Crimea Canal irrigation system in Ukraine, (ii) the Rio Dulce irrigation system in Argentina and (iii) the Yaqui irrigation system in Mexico.
A cost-benefit analysis of the added value of the user use of remote sensing in irrigation water management is carried out in Chapter 7, where after conclusions and outlook are presented in Chapter 8.
The IPAT software, manual and a test dataset are freely available for whomever is interested. It can be downloaded at:

http://www.waterwatch.nl/IPAT.html

2 User requirements

Special attention is paid to the purposes and requirements of the to-be-developed IPAT tool. Within the project these user requirements are based upon three sources of information:

- Literature review is carried out to answer the question why remote sensing data is not used more in (irrigation) water management, as the advantages are evident (i.e. objective information and large aerial coverage). In particular previous BCRS projects are reviewed in this matter. Section 1.2 describes briefly the outcomes of this literature review.
- User consultations have taken place during the project execution. The communication between the knowledge provider (Alterra, Wageningen UR), the service provider (WaterWatch) was relatively easy as they both are situated in Wageningen. The communication with the end users from Argentina (INTA), Mexico (CNA) and Ukraine (IHELR) was through email and a one month workshop in March'06 in the Netherlands. During the workshop the prototype IPAT tool was demonstrated, it was evaluated and final wishes of all end users were identified where after the final version of the IPAT tool was created.
- Project limitations, such as technical possibilities of the ArcGIS software, budget constraints and time limitations, have an impact on the project result as well. However, they should be considered as boundary conditions of the process, instead of requirements.

Based on these three sources of information the user requirements can be formulated by two terms, namely simplicity and flexibility.

2.1 Simplicity

Remote sensing techniques are considered by the end users as rather complicated techniques. It is difficult to extract useful information from remote sensing data and incorporate it into source everyday water management.
The findings of the literature review are in line with this conclusion. During the previous projects a lot of attention has been paid on the questions 'what information can be derived from remote sensing?' and not enough attention is being paid to embedding remote sensing technologies into operational use for local counterparts, i.e. the question 'how to use these remote sensing data?'.
Therefore the KISS (keep it simple and stupid) principle is applied on the development of the IPAT tool. The tool should be easy to use and the results should be easy to understand. That is why a standardized set of remotely sensed irrigation performance indicators are selected, as these indicators are hydrological terms instead of remote sensing terms. Furthermore the strategy is chosen that it is better to have a rather simple, but perfectly working tool, than a complex and hard to operate tool, also given the project limitations as budget and time.

2.2 Flexibility

Besides simplicity, the users put a lot of emphasis on flexibility of the IPAT tool. As all partners in the project consortium had their own wishes, it was impossible to meet all these wishes. Instead a strategy is chosen to make the IPAT software as flexible as possible. This means that the input data is not restricted to a certain set of predefined datasets. It is relatively easy to adapt the IPAT tool to incorporate also specific datasets of the user. It is also possible to create user specific performance indicators besides the standardized set of remotely sensed irrigation performance indicators.

3 Irrigation Performance

3.1 Irrigation performance assessment

Many literatures have been written on the subject of irrigation performance assessment, all with their own definitions and criteria. In this report we follow the work of Bos *et al.* (2005) as it gives an extensive overview of the state of the art in irrigation performance and is published under the umbrella of two of the internationally recognized expertise institutions in the field of water management, namely ICID and IWMI.
Irrigation performance assessment can be defined as the systematic observation, documentation and interpretation of activities related to irrigated agriculture with the objective of continuous improvement. The ultimate purpose is to achieve an efficient and effective use of resources.
Irrigation performance is measured through the use of indicators, for which data are collected and recorded. An indicator should have a scientific basis, should be quantifiable and should refer to a critical or intended value. In general an indicator is a dimensionless ratio of an actual value of a key parameter over reference value of that key parameter:

$$Performance\ Indicator = \frac{actual\ value\ of\ key\ parameter}{reference\ value\ of\ key\ parameter}$$

The temporal or spatial analysis of the indicators then informs us on the level of performance.

The indicators are grouped into four categories:
1. Water balance, water service, and maintenance. The indicators in this group refer to the primary function of irrigation and drainage; the provision of a water service to users.
2. Environment. Both, irrigation and drainage is a man-made intervention in the environment to facilitate the growth of crops. The non-intentional (mostly negative) effects of this intervention are considered in this group.
3. Economics. This group contains indicators that quantify crop yield and the related funds (generated) to manage the system.
4. Emerging indicators. This group gives four indicators that contain parameters which need to be measured by use of satellite remote sensing. This emerging technology enables very cost-effective measurement of data.

3.2 Remote Sensing specific indicators

A selection of indicators from the mentioned four categories is carried out on the basis of the following criteria:

- Indicator parameters are screened on whether they can be calculated by remote sensing techniques. Table 1 gives an overview.
- The KISS (keep it simple and stupid) principle is applied.
- During several meetings and consultations between the knowledge provider (Alterra), the service provider (WaterWatch) and the end users (IHELR, INTA and CNA) the possibilities and wishes are identified and a set of indicators is selected and agreed upon.

Table 1 Overview of key parameters, which can be detected by remote sensing techniques

Key parameter	Symbol	Remote Sensing method	Available within the project
Actual evapotranspiration	*ETA*	SEBAL	√
Potential evapotranspiration	*ETP*	SEBAL	√
Biomass	*Bio*	SEBAL	√
Precipitation	*P*	Radar	-
Land use	*LU*	Classification	√

Based upon the selection criteria the following set of irrigation performance indicators are identified as remote sensing indicators:

<u>Field Application Ratio</u>
The Field Application Ration (*FA*) quantifies the degree to which the crop irrigation requirements are met by irrigation water in the irrigated. Assuming negligible non-irrigation water deliveries to the area, the ratio is defined as:

$$FA = \frac{ETP - P_e}{I}$$

The numerator of this indicator originally contains: 'the volume of irrigation water needed, and made available, to avoid undesirable stress in the crops throughout (considered part of) the growing cycle'. This 'volume' is expressed in terms of m3/ha or in terms of water depth. The numerator equals the potential evapotranspiration by the irrigated crop minus the effective part of the precipitation: $ETP - P_e$.
The value of ($ETP - P_e$) is entirely determined by the crop, the climate and the interval between water applications. Hence, the value of the field application ratio varies with the actual volume of irrigation water delivered to the field. This water delivery depends on the reliability of the 'service' by the water-providing agency, the irrigation know-how of the farmer, and the uniformity with which water can be applied to the field (thus on the water application technology). From a technology point of view the attainable values of the field application ratio are for surface

irrigation ~ 0.7; for sprinkler irrigation ~0.8; and for drip irrigation ~0.95. These in essence provide benchmark values against which targets can be set.

Depleted Fraction

The Depleted Fraction (*DF*) is the ratio that compares three components of the water balance of an irrigated area. This indicator is particularly useful for diagnostic purposes in water-scarce areas. The *DF* relates the actual evapotranspiration from the selected area to the sum of all precipitation on this area plus the surface water inflow (irrigation water) into the area. It is defined as:

$$DF = \frac{ETA}{P + I}$$

Because it is not practical to measure the *ETA* and the precipitation for only the irrigated part of the area, we consider the gross command area. For semi-arid and arid regions the 'critical value' of the depleted fraction ranges between 0.5 and 0.7 (average about 0.6).

Crop Water Productivity

Within many irrigated areas water is an increasingly scarce resource. Hence, it is logical to assess the crop productivity of irrigation in terms of kg/m3. Such an assessment can be made from a variety of viewpoints. Most common used is the productivity in terms of yield over the volume of supplied irrigation water. The crop water productivity (C*WP*) then is defined as:

$$CWP = \frac{Yield}{I}$$

However, it can also be expressed in terms, which can be derived from remote sensing techniques only. By this viewpoint the water productivity is defined as:

$$CWP = \frac{Bio}{ETA}$$

Because of the values of *ETA* and *I* are heavily influenced by local climate, the use of the above two indicators is restricted to 'on project' evaluation.

Relative Evapotranspiration

To evaluate the adequacy of irrigation water delivery to a selected command area as a function of time, the dimensionless ratio of actual over potential evapotranspiration gives valuable information to the water manager. The ratio is defined as:

$$ETR = \frac{ETA}{ETP}$$

The critical for *ETR* is ~0.7 for irrigated crops during the growing season.

Table 2 Remote Sensing specific performance indicators with their function if used to quantify a trend in time or a spatial distribution

Performance Indicator	Information provided if the indicator is used to show:	
	- a trend in time	- the spatial distribution
Field application ratio	Degree to which irrigation water requirements were met of the users and/or the changes of water use by irrigators	Shows difference in water supply to users at various locations within command area. Quantifies the uniformity and equity of water supply
Depleted fraction	Show changes in actual water use by crops	Quantifies differences in the water balance of considered (command) areas
Crop water productivity	Quantifies change in crop yield (or biomass) per m^3 water supplied	Shows spatial variation in productivity (kg/m^3)
Relative evapotranspiration	Quantifies relative reduction in evapotranspiration	Detects water-short areas

4 IPAT Manual

4.1 General framework

The organization of the database of IPAT gives the following possibilities:

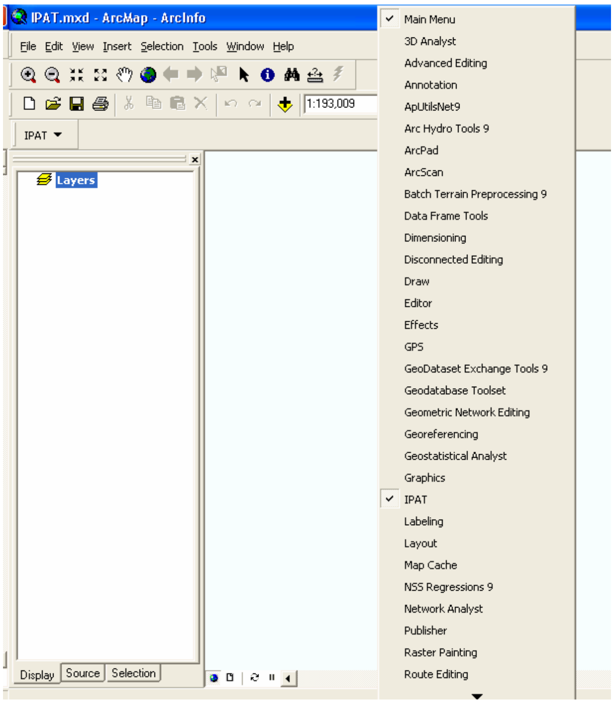
- Use of tabular data as well as raster data (such as satellite images) for measurements.
- Spatial selection by use of administrative units. Geodata (either in raster-format or polygon-format) with administrative units is required.
- Spatial and administrative aggregation by use of administrative levels.
- Selection in time by use of period types.
- Aggregation in time by distinguishing period input-types and period output-types.
- Linking spatial vector data such as irrigation lines, irrigation pumps, meteo stations to administrative levels. Links are made in the tables by codes, so that the vector data itself it not obligatory.
- High flexibility for user to add indicators, administrative levels, period types and subelement data (data on rain, irrigation etc.).

4.2 Working environment

4.2.1 IPAT-toolbar and the map document

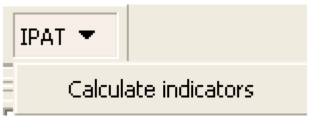
IPAT requires an ArcGIS 9.1 (or higher) license and a Spatial Analyst license.

The IPAT toolbar is available from a ArcGIS Map document (*.mxd). Like any other toolbar in ArcMap it can be added to the visible toolbars by right-clicking on the toolbar-part and selecting IPAT from the list of toolbars.

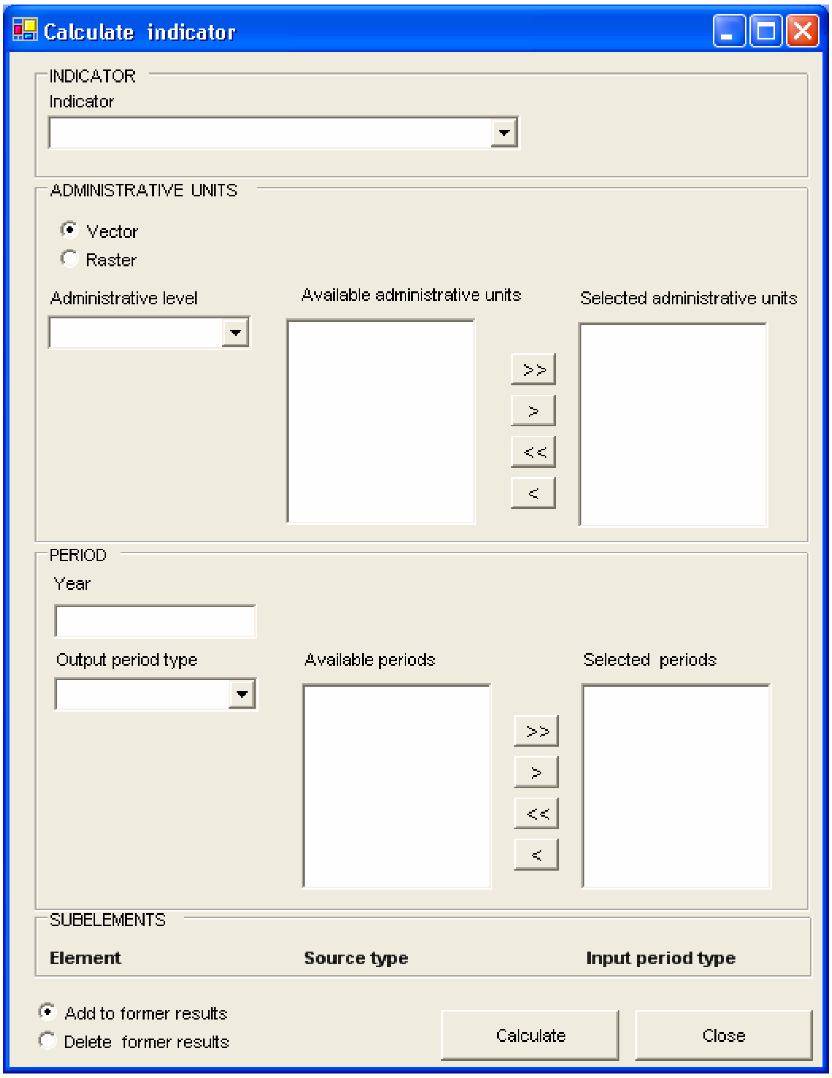


4.2.2 Calculation of indicators - form

The toolbar provides a menu 'Calculate indicators'



This menu will open the 'Calculate indicator' - form



Just before showing the form, settings are read from a file *IPAT.ini*. Information in the *IPAT.ini* -file is used to fill parts of the form. This file should be located in the same directory as the mxd-file. For this reason the form cannot be used from within an unsaved ArcMap - session ('untitled').The map document should be saved, before the menu is clicked.

Explanation of the form:

4.2.3 Indicator

Selection of the indicator that needs to be calculated. Only one indicator at a time can be selected. List of available indicators is taken from table *info_ind_calc,* field *Ind* in de personal geodatabase (pgdb). In this case the user should select from a list 'RWS, RAIN, IRR_EFF, DFRACT').

info_ind_calc : Table

OBJECTID	Ind	Ind_desc	Calc
5	RWS	Relative Water Supply	(Rain + Irr) / ETA
10	RAIN	Rain	Rain
12	IRR_EFF	Irrigation efficiency	(ETA - Rain) / Irr
13	DFRACT	Depleted fraction	ETA/(Rain + Irr)

4.2.4 Administrative Units

Administrative units are read from geodata-layers in the pgdb. Each administrative level needs a separate layer, containing the units for that level. Within that layer a sub selection of the available units can be made from the form. Available levels, corresponding layer names and the fieldnames with unit-codes, are read from the IPAT.ini file. The use of administrative units makes it possible to do spatial selections before performing a calculation. Administrative units are linked (tabularly, by means of code-fields and code-values. See info table *info_link_adm_vct_elem* and information in sections 'tables_link_admin_vector_elements' and 'sources_table_data' in the IPAT.ini-file) to vector elements such as irrigation channel, irrigation pumps or meteo stations. These links are:

4.2.4.1 Vector/Raster - option

Indicates whether the geo-layer with the administrative units is of type 'vector' or 'raster'. Vector layers are stored in a feature dataset in the pgdb, and should be of type 'polygon'. Raster layers are stored in a rastercatalog in the pgdb. Names of the feature dataset and the rastercatalog can be found in section 'level_data_container' in the ini-file:

```
[LEVEL_DATA_CONTAINER]
# dataset = <name_feature_dataset_in_pgdb>
vector = IPAT_levels_vector
raster = IPAT_levels_raster
```

Names of layers for each level and the fieldname from which to get the units are found in section 'vector_admin_levels_and_units' for the vector-option and 'raster_admin_levels_and_units' for the raster-option

```
[VECTOR_ADMIN_LEVELS_AND_UNITS]
# list is extendable
# levels in order of lower detail (f.e: plot, farm, district)
```

# <name_level> = # <name_vectorlayer_in_dataset>, # <name_field_vector_code>
plot = adm_geo_plots, plot_code
farm = adm_geo_farms, farm_code
district = adm_geo_districts, distr_code

[RASTER_ADMIN_LEVELS_AND_UNITS]
# list is extendable
# levels in order of lower detail (f.e: plot, farm, district)
# <name_level> = # <name_raster_in_catalog>, # <name_field_raster_code>
pl = adm_plots_rs, plot_code
frm = adm_farms_rs, farm_code
dstrct = adm_distr_rs, distr_code

4.2.4.2 Administrative level

Selection of the administrative level to run the calculation for. Only one can be selected. This list is taken from the section in the ini-file shown in the former paragraph. The element in front of the '=' - sign will be added to the list of available levels in the form (for example: for the vector - option user should select from a list 'plot, farm district'.

4.2.4.3 Available administrative units

List of all unique values in the corresponding field in the geo-layer for the currently selected level (see par. 'vector/raster - option').

4.2.4.4 Selected administrative units

Selection subset of total 'available administrative units'. Indicator values will only be calculated for the administrative units in this list.

4.2.5 Period

Period information is read from two main sources:
1. table *info_periodsinyear* in the pgdb
2. section 'tables_periodtypes' in the ini-file

1. table info_periodsinyear

In this table subdivision <u>of a year</u> in different period types can be set. Additional period types can be added by adding a new field and establishing the link between the other period types (for example days 1 = dec 1, months 1, years 1, day 32 = dec 4, months 2, years 1).

info_periodsinyear : Table

OBJECTID	DAYS	DECS	MONTHS	YEARS
1	1	1	1	1
2	2	1	1	1
3	3	1	1	1
4	4	1	1	1
5	5	1	1	1
6	6	1	1	1
7	7	1	1	1
8	8	1	1	1
9	9	1	1	1
10	10	1	1	1
11	11	2	1	1
12	12	2	1	1
13	13	2	1	1
14	14	2	1	1
15	15	2	1	1
16	16	2	1	1
17	17	2	1	1
18	18	2	1	1
19	19	2	1	1
20	20	2	1	1
21	21	3	1	1
22	22	3	1	1

Record: 1 of 365

The fieldnames should correspond with information in section tables_periodtypes' in the ini-file (after the '='- sign).

2. section 'tables_periodtypes' in the ini-file

```
[TABLES_PERIODTYPES]
# list is extendable
# <name_period_in_form_list> = <name_period_field_in_database>
day = days
decade = decs
month = months
year = years
```

4.2.5.1 Year

Type in the year for which calculations should be done. Only possible for one year at a time.

4.2.5.2 Output period type

Selection of the period type to run the calculation for. Only one can be selected. This list is taken from the section in the ini-file shown in the upper part of this paragraph. The element in front of the '=' - sign will be added to the list of available period types in the form (in this case the user should select from a list 'day, decade, month, year'). The element behind the '=' - sign should correspond with the fieldname in the table *info_periodsinyear* in the pgdb for the particular period type.

4.2.5.3 Available periods

List of all unique values in the corresponding field in the table *info_periodsinyear* for the currently selected period type.

4.2.5.4 Selected periods

Selection subset of total 'available periods'. Indicator values will only be calculated for the periods in this list.

4.2.6 Subelements

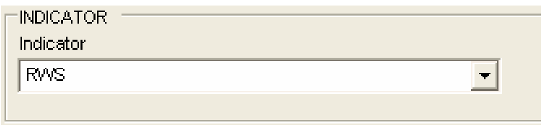
In table *info_ind_calc* in field *Calc* the formula can be found for the calculation of each indicator. Each formula may consist of several subelements. F.e, in the table below the formula for indicator RWS (Relative Water Supply) consists of three subelements: Rain, Irr and ETA.

info_ind_calc : Table

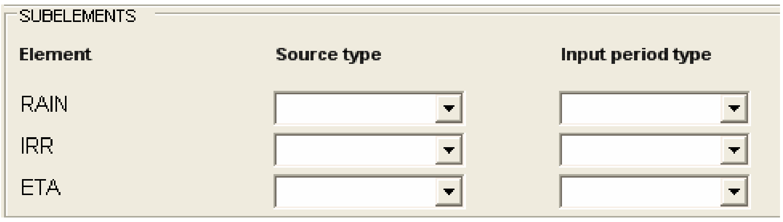
OBJECTID	Ind	Ind_desc	Calc
5	RWS	Relative Water Supply	(Rain + Irr) / ETA
10	RAIN	Rain	Rain
12	IRR_EFF	Irrigation efficiency	(ETA - Rain) / Irr
13	DFRACT	Depleted fraction	ETA/(Rain + Irr)

For each of these subelements a row will be added to the form, with element name, source type and input period type.

Selecting RWS:



Will create three rows in the form:



4.2.6.1 Source type

Set the type of source from which to derive the data for each element. Two options are available:
1. RS
2. Table

1. RS: data provided in raster format, stored in a raster catalog. Rasters could be of any type that is supported by ArcGIS: ESRI GRID, ERDAS IMAGINE, TIFF, MrSID, JFIF (JPEG), ESRI BIL, ESRI BIP, ESRI BSQ, Windows Bitmap, GIF, ERDAS 7.5 LAN, ERDAS 7.5 GIS, ER Mapper, ERDAS Raw, ESRI GRID Stack File, DTED Level 1 & 2, ADRG, PNG, NITF, CIB, and CADRG. A raster catalog can contain a mix of these formats.

2. Table: data provided in table format

Additional information to be able to retrieve the particular data for each subelement is set in the ini-file. Names of the subelements should match the names in the formula (table i*nfo_ind_calc*, field *Ind*).

1. RS: information is read from section 'source_raster_catalogues'.

[SOURCE_RASTER_CATALOGUES]
# list is extendable
# name_element (in calculation) = # name_rastercatalogue
ETA = ETA_DEC

Information consists of the name of the subelement (before the '='-sign), and the name of the corresponding rastercatalog with the data for that element (after the '='-sign).

2. Table: information is read from section 'source_tables_data.

[SOURCE_TABLES_DATA]
# list is extendable
# <Element> = # network, # network feature type, # name datatable, # name_field_code, # name_field_value
# options: # <yes/no>,# <lines/points/none>, # <tablename>, # <fieldname>, # <fieldname>
Rain = no, none, data_meteost, meteost_code, P_meteo
Irr = yes, lines, data_irr_ln, irr_ln_code, Irr
Irr = yes, points, data_irr_pt, irr_pt_code, Irr

Information before the '='-sign consists of the name of the subelement, followed by a list of five elements after the '='-sign:

- Indicates if subelement is linked to a network. Options: yes/no.
- Indicates if values of the subelement are linked to the point - or line elements in a network.
  - If part of a network ('yes'), then options: points/lines.
  - If not part of a network ('no'), then options: none.
- Name of the table that contains the data for this subelement.
- Name of the field with the codes of the corresponding vector-elements (see par. 'info_link_adm_vct_elem' and explanation of section 'Tables_link_admin_vector_elements' of the ini-file).
- Name of the field in the table that contains the values for this subelement.

4.2.6.2 Input period type

Selection of the period type of the input data. This can be the same as the output period type selected before, or any period type of a lower aggregation level. Selection options here are refreshed when an output period type is selected.

4.2.7 Add to/Delete former results - option

The result of the calculation is written to a table in the pgdb. The name of this table is read from the ini-file, section 'tables_data'.

```
[TABLES_DATA]
# table to add the results to
results = results
```

Option 'Add to' will append the new results to the table. Option 'delete' will first remove all existing data, before writing the new results to the table.

4.2.7.1 Calculate

Button to start the calculation.

4.3 IPAT.ini file

4.3.1 General

The IPAT.ini file can be used to make settings considering:

- Path names, such as those for the pgdb and the place to write temporary files to
- Names of data containers such as feature datasets, rastercatalogs, tables, fields
- Links between subelements and their corresponding data containers in the pgdb
- Lists of administrative levels and period types that are used as a selection-list in the 'calculate indicators - form'

4.3.2 Location and moment of loading

Just before showing the 'Calculate indicators' - form, settings are read from the *IPAT.ini* file. Information in this file is used to fill parts of the form. This file should be located in the same directory as the mxd-file. For this reason the form cannot be used from within an unsaved ArcMap - session ('untitled').The map document should be saved, before the menu is clicked.

4.3.3 Content

Example of what the content of the IPAT.ini file might look like:

```
# IPAT parameter file
# --------------------------------------------

[LOCATIONS]
# pgdb = <name of personal geodatabase incl. extension>
# path_dir_pgdb = <path of directory for personal geodatabase> (f.e: D:\USERDATA\IPAT\data)
# path_dir_temp_rasters = <path of directory for temporary raster>
# path_dir_temp_tables = <path of directory for temporary tables>
pgdb = IPAT.mdb
path_dir_pgdb = D:\IPAT\data
path_dir_temp_rasters = D:\IPAT\TEMP_Rasters
path_dir_temp_tables = D:\IPAT\TEMP_Tables

[LEVEL_DATA_CONTAINER]
# dataset = <name_feature_dataset_in_pgdb>
vector = IPAT_levels_vector
raster = IPAT_levels_raster

[SOURCE_RASTER_CATALOGUES]
# list is extendable
# name_element (in calculation) = # name_rastercatalogue
ETA = ETA_CRIMEA

[SOURCE_TABLES_DATA]
# list is extendable
# <Element> = # network, # network feature type, # name datatable, # name_field_code, # name_field_value
# options:  # <yes/no>,# <lines/points/none>, # <tablename>,  # <fieldname>, # <fieldname>
# examples:
# Rain = no, none, data_meteost, meteost_code, P_meteo
# Irr = yes, lines, data_irr_ln, irr_ln_code, Irr
# Irr = yes, points, data_irr_pt, irr_pt_code, Irr
Rain = no, none, data_meteost, meteost_code, P_meteo
Irr = yes, lines, data_irr_ln, irr_ln_code, Irr
Irr = yes, points, data_irr_pt, irr_pt_code, Irr

[VECTOR_ADMIN_LEVELS_AND_UNITS]
# list is extendable
# levels in order of lower detail (f.e: plot, farm, district)
# <name_level> = # <name_vectorlayer_in_dataset>, # <name_field_vector_code>
plot = adm_geo_plots, plot_code
farm = adm_geo_farms, farm_code
district = adm_geo_districts, distr_code
```

```
[RASTER_ADMIN_LEVELS_AND_UNITS]
# list is extendable
# levels in order of lower detail (f.e: plot, farm, district)
# <name_level> = # <name_raster_in_catalog>, # <name_field_raster_code>
pl = adm_plots_rs, plot_code
frm = adm_farms_rs, farm_code
dstrct = adm_distr_rs, distr_code

[TABLES_LINK_ADMIN_VECTOR_ELEMENTS]
# name of the field to check for the vector_codes in the " info_link_adm_vct_elem" table
# <Element> = # network, # network feature type, # name_field_code
# options:  # <yes/no>,# <lines/points/none>, # <fieldname>
Rain = mst_code
Irr = irr_code

[TABLES_PERIODTYPES]
# list is extendable
# <name_period_in_form_list> = <name_period_field_in_database>
day = days
decade = decs
month = months
year = years

[TABLES_INFO]
# names of the info tables in the database
info_periods = info_periodsinyear
info_calc = info_ind_calc
info_link_adm_vct_elem = info_link_adm_vct_elem

[TABLES_DATA]
# name of the table to write the results to
results = results
```

Only the sections of the ini-file that are not discussed in par. 'Calculation of indicators - form' will be discussed more into detail here. These are the sections: 'locations', 'tables_info', 'tables_link_admin_vector_elements', and partly 'source_table_data'.

1. [Locations]
   Settings for the name of the personal geodatabase, the directory where the pgdb is located and the directory names for the location to write temporary raster- and table- data to during a calculation.
2. [Tables_info]
   Names of the info_files in the personal geodatabase. It is advised not to change the names of these tables in the ini-file. But it is possible to do so. Naturally corresponding tables names in the pgdb need to be changed as well in that case. Fieldnames within these tables should not be changed.
3. [Tables_link_admin_vector_elements]
   Fieldname in the table *info_link_adm_vct_elem* where the vector element - code belonging to an administrative unit can be found. For further explanation between the link administrative units and vector elements see par. 'IPAT Personal Geodatabase'. Information in the ini-file should be added for each subelement that is linked to a vector type geodata layer, (source type = 'Table'). It is not needed for subelements that have a source type 'Raster'.

	Adm_code	Adm_level	irr_code	irr_ftype	mst_code	mst_ftype
▶	agar	pl	Irr_01	lines	MS_01	points
	agar	plot	Irr_01	lines	MS_01	points

4. [source_table_data]
See also par. 'source type'
In this section the fourth element in the list after the '=' - sign is the 'name_field_code'. This is the name of the field in the corresponding datatable (name of this table is set in the third element of the list) that contains the vector element - code. Codes in this field should match the codes in the field of table *info_link_adm_vct_elem* as set in section 'info_link_adm_vct_elem'.

Example: the table below is the data table for subelement 'Rain' (name = '*data_irr_ln*'. It has a field called 'Irr_ln_code' with the codes of the vector - elements (features). In table '*info_link_adm_vct_elem*' can be seen which administrative units is linked to which vector - element. In this case information in field 'irr_code' is used.

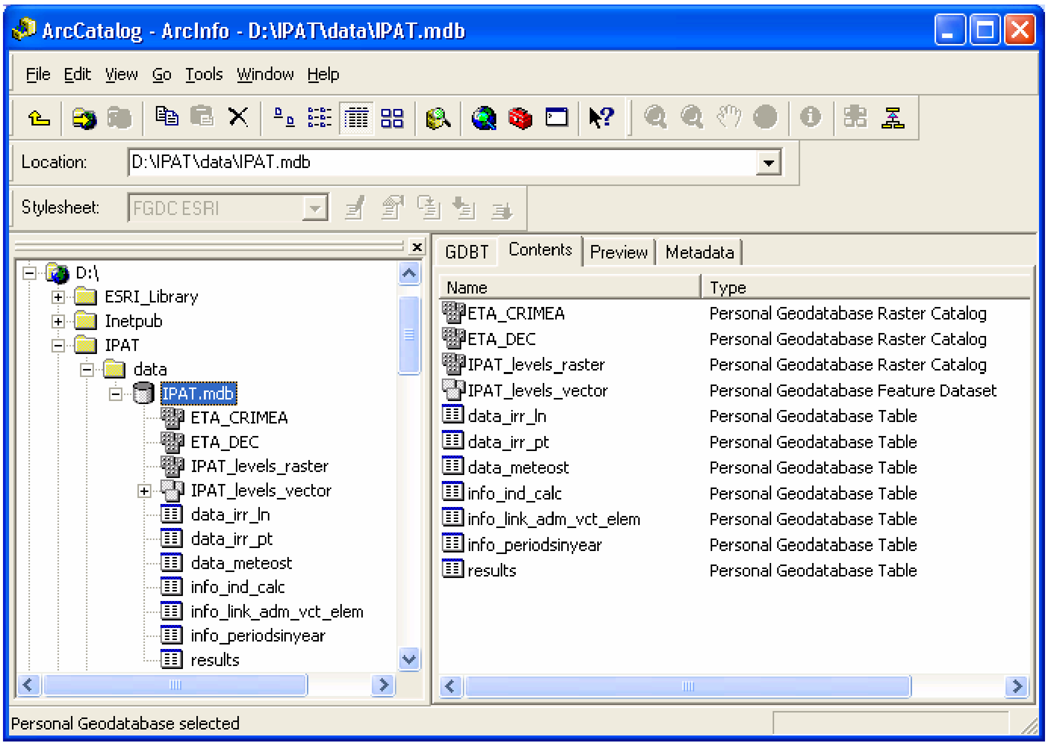
data_irr_ln : Table

	OBJECTID	Irr_ln_code	Period_type	Days	Decs	Months	Years	Irr
▶	2	Irr_01	Decs		1		2001	10
	3	Irr_01	Decs		2		2001	10
	4	Irr_01	Decs		3		2001	10
	5	Irr_01	Decs		4		2001	10
	6	Irr_01	Decs		5		2001	10
	7	Irr_01	Decs		6		2001	10
	8	Irr_01	Decs		7		2001	10
	9	Irr_01	Decs		8		2001	10
	10	Irr_01	Decs		9		2001	10
	11	Irr_02	Decs		1		2001	5
	12	Irr_02	Decs		2		2001	5
	13	Irr_02	Decs		3		2001	5
	14	Irr_02	Decs		4		2001	5
	15	Irr_02	Decs		5		2001	5
	16	Irr_02	Decs		6		2001	5

4.4 IPAT Personal Geodatabase

The data for the IPAT tool should be stored in a personal geodatabase (pgdb) Name and location of this database are flexible. The content of the tables can be edited with the standard ArcGIS tools or by opening the *.mdb - file in MS Access. When editing in MS Access be careful not to edit any tables or field that are typical GIS-fields (such as Shape_Lenght f.e.). In that case data might get corrupted.

The picture below shows an example geodatabase. The required data and data types will be discussed here.



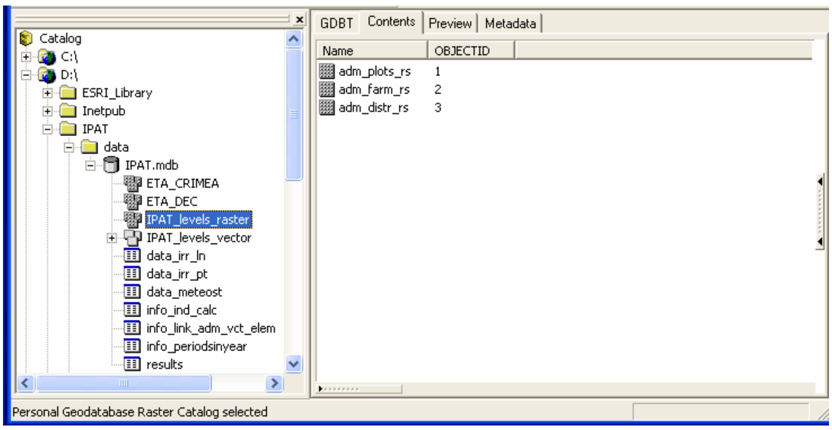
4.4.1 Administrative levels

Geodata for administrative levels can be stored in rasters that are organized in a rastercatalog or in a vector layers within a feature dataset.

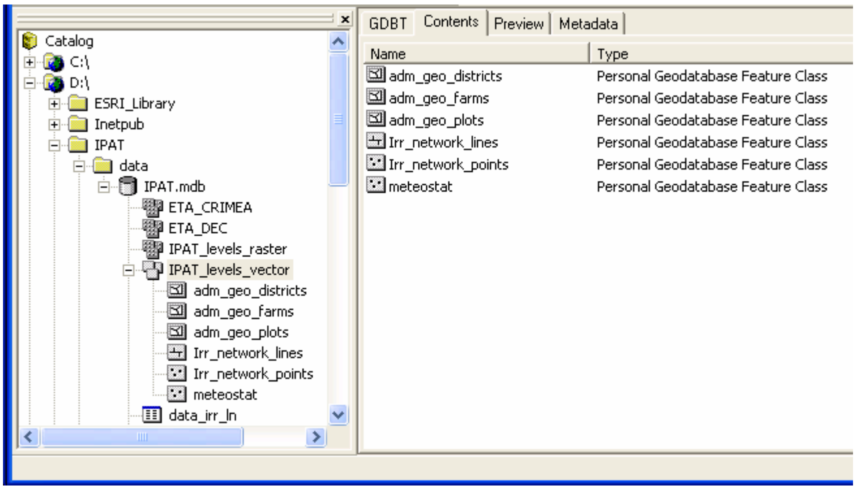
Rastercatalog example: IPAT_levels_raster.

Required fields:

1. Raster field with raster dataset.



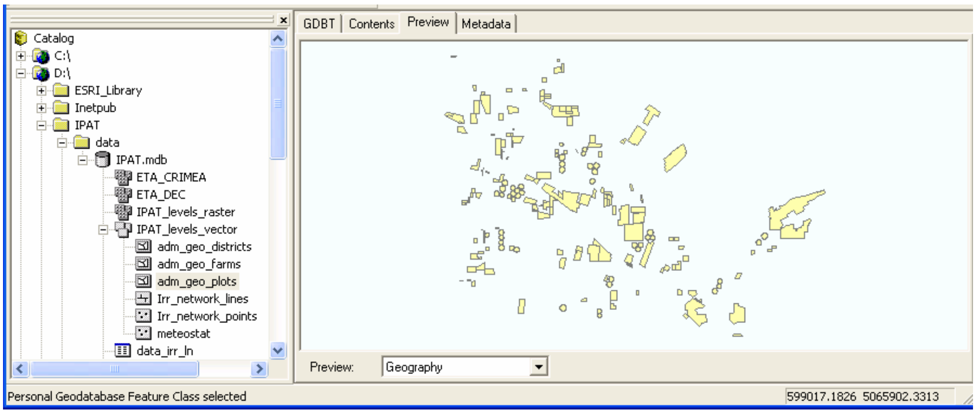
Feature dataset example: IPAT_levels_vector
(example dataset also contains vector data that are not used for adm. Levels)

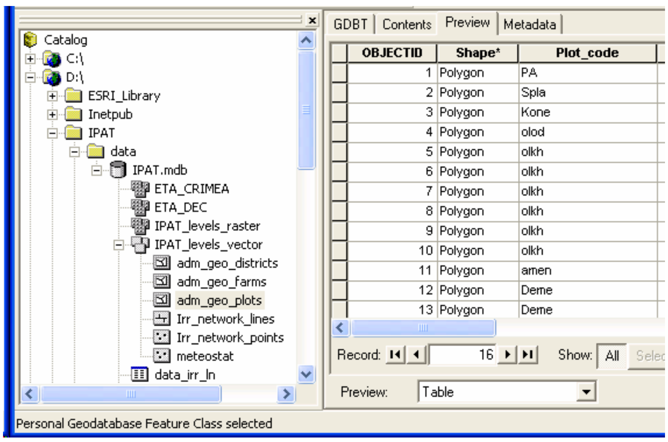


Vector polygon layer within feature dataset: adm_geo_plots (for the plot-level).

Required fields:

1. String field with administrative unit - codes. Name of field is flexible. Setting in ini-file.





4.4.2 Info tables

Three info tables are required: info_ind_calc, info_periods_in_year, info_link_adm_vct_elem.

4.4.2.1 info_ind_calc

Name of this table is flexible, but recommended not to change it. Setting is the ini-file. Required fieldname are not flexible.

Required fields:
1. String field, name ‘Ind’, contains indicator-names. Content of this field appears as selection list in the ‘Calculate indicators - form’.
2. String field, name ‘Calc’, contains formula to calculate indicator with the data of the subelements. The formula is also use to add a row of controls for each subelement in the form (see par. ‘Subelements’).

OBJECTID*	Ind	Ind_desc	Calc
5	RWS	Relative Water Supply	(Rain + Irr) / ETA
10	RAIN	Rain	Rain
12	IRR_EFF	Irrigation efficiency	(ETA - Rain) / Irr
13	DFRACT	Depleted fraction	ETA/(Rain + Irr)

4.4.2.2 info_periodsinyear

This table is used to divide the year into period types. The subdivision is flexible. Each period type is established by adding a numeric field to the table. Relationships between period types is established by the values in the row (for example: Days 2 = Decs 1, Days 11 = Decs 2). Period types should also be added to the ini-file, section ‘tables_periodtypes’. Here the link is set between the period type - names and the corresponding names of the field in this table (see also par. ‘period type’, in chapter about the ini-file).

Required field:
At least one numeric field for the year, because this is the highest aggregation level.

OBJECTID	DAYS	DECS	MONTHS	YEARS
1	1	1	1	1
2	2	1	1	1
3	3	1	1	1
4	4	1	1	1
5	5	1	1	1
6	6	1	1	1
7	7	1	1	1
8	8	1	1	1
9	9	1	1	1
10	10	1	1	1
11	11	2	1	1
12	12	2	1	1

4.4.2.3 info_link_adm_vct_elem

This table is used to make a tabular link from administrative units to elements in other vector data such as irrigation pipes, pumps or meteo stations. Each units can be linked to different vector-layers and because of that for different subelements (for irr to irrigation elements, for rain to meteostations). This can be done by adding fields. This is the only table in the IPAT database where fields have to be added to the table. The names of the fields are set in the ini-file, section 'Tables_link_admin_vector_elements'. For each link two fields should be added: a field for the code of the vector-elements and a field for the feature type of the vector elements (points, lines, polygons).
(fe. Irr_01 is the code of a irrigation pipe in an irrigation layer with line elements. Information of this pipe is linked to the administrative unit 'agar', which belong to the administrative level 'plot').

Adm_code	Adm_level	irr_code	irr_ftype	mst_code	mst_ftype
agar	pl	Irr_01	lines	MS_01	points
agar	plot	Irr_01	lines	MS_01	points

Required fields:
1. String field, name adm_code. Here codes for adm. Units are added. These codes should match the codes in the code-field of the administrative - level - geodata layer (see par. 'administrative units').
2. String field, name adm_level. Indicates to which administrative level the unit-code belongs. Levels should match level -settings in IPAT.ini file.

For each link to a vector layer:
1. String field. With vector-element codes.
2. String field. Feature type of vector elements (options: points\lines\polygons).

See also explanation of section 'Tables_link_admin_vector_elements' of the ini-file.

4.4.3 Subelement values - data per period

Values for subelements can be stored in two formats: raster or table. This is referred to by 'source type' in the 'Calculate Indicator - form'. Rasters are stored in rastercatalogs, which are in fact kind of tables as well. In both cases values need to be linked to a period. This is done by adding period type - fields to the table or the table.
Minimal required fields:
1. Integer field for the 'year'. Name of this field is setting in ini-file.
2. String field, name Period_type. This is used to indicate for which period type the subelement value is valid. The context of this field should match one of the period-types set in the ini-file (see example content ini-file. Values could be day, decade, month or year) Only the corresponding period-type field in the same table will be used to check for the actual period the data is valid for (fe. field Decs = 1).

Additionally other period types fields can be added. Only the fields that are used as 'input period type' for the calculation of an indicator (see explanation of the form - par. 'subelements') are needed in a calculation run. Within one table or rastercatalog, data for different period types can exist. Only the values for the field with the corresponding period type will be used. Field names for the period types are set in the ini-file. These fieldnames should also correspond with the fieldnames in table info_periodsinyear. (see par.' info_periodsinyear').

Example of rastercatalog with values for subelement ETA: name 'ETA_CRIMEA' (see par. about the ini-file for link between subelement and rastercatalog name).

OBJECTID*	Shape*	Raster	Name	Shape_Len	Shape_Area	Period_type	Days	Decs	Months	Years
1	Polygon		2002_nov.img			Month			11	2001
2	Polygon		2002_oct.img			Month			10	2001
3	Polygon		2002dec.img			Month			12	2001
4	Polygon		2003_apr.img			Month			4	2001
5	Polygon		2003_aug.img			Month			8	2001
6	Polygon		2003_feb.img			Month			2	2001
7	Polygon		2003_jan.img			Month			1	2001
8	Polygon		2003_jul.img			Month			7	2001
9	Polygon		2003_jun.img			Month			6	2001
10	Polygon		2003_mar.img			Month			3	2001
11	Polygon		2003_may.im			Month			5	2001
12	Polygon		2003_sep.img			Month			9	2001

Example of table with values for subelement Irr: name 'data_irr_ln'.

OBJECTID*	Irr_ln_code*	Period_type	Days	Decs	Months	Years	Irr
11	Irr_02	Decs		1		2001	5
12	Irr_02	Decs		2		2001	5
13	Irr_02	Decs		3		2001	5
14	Irr_02	Decs		4		2001	5
15	Irr_02	Decs		5		2001	5
16	Irr_02	Decs		6		2001	5
17	Irr_02	Decs		7		2001	5
18	Irr_02	Decs		8		2001	5
19	Irr_02	Decs		9		2001	5
20	Irr_03	Decs		1		2001	1
21	Irr_03	Decs		2		2001	1
22	Irr_03	Decs		3		2001	1
23	Irr_03	Decs		4		2001	1
24	Irr_03	Decs		5		2001	1

4.4.4 Results - table

Results are written to a table in the pgdb. Name of the table is a setting in the IPAT-ini file, section 'Tables_data'. User can choose by option in the form to append new results to the existing data in the table, or to delete old results first.

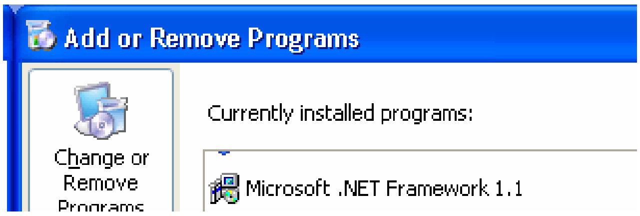
4.5 IPAT_error.log - file

Errors that occur during the use of the form or during calculation of the indicator will be written to file IPAT_error.log. If an error occurs before the stage where IPAT could detect the location of the mxd-file, the log-file will be saved in C:\TEMP. Otherwise it will be in the same directory as the *.mxd - file. New error information will be appended. File will be automatically created if it doesn"t exist yet.

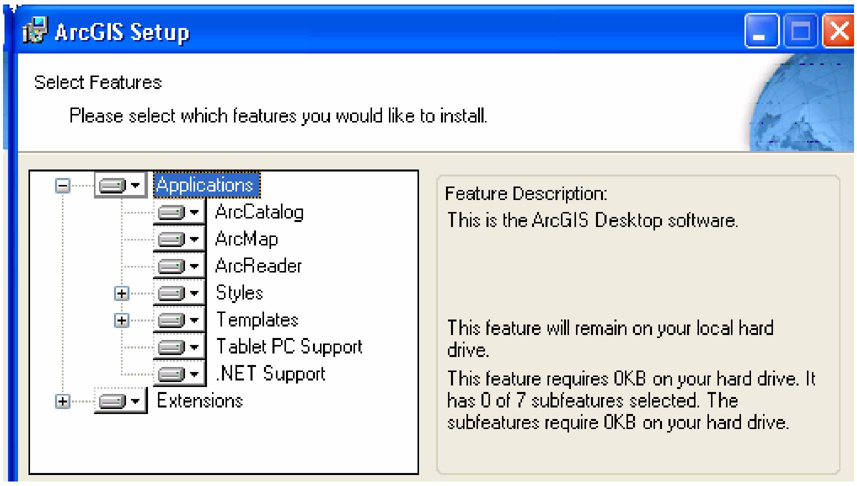
4.6 Set up

IPAT can be installed by using the setup.exe file. When this is done the IPAT-toolbar will be automatically available in ArcMAP. Requirements for installation:

- MS.NET Framework 1.1 or higher (can be freely downloaded from internet)



- ArcGIS 9.1, including.NET Support



- IPAT_Setup.zip containing the setup.exe

4.7 Internet link

The IPAT software, manual and a test dataset are freely available for whomever is interested. It can be downloaded at:

http://www.waterwatch.nl/IPAT.html

5 Remote Sensing input

For the calculation of various irrigation performance indicators the IPAT tool requires both point specific data like irrigation flows and spatial data like the actual evapotranspiration (ETA), biomass production (or crop yield) and land use.
The Surface Energy Balance Algorithm for Land (SEBAL) was applied in the three case studies to quantify evapotranspiration and biomass production spatially. Data from NOAA, MODIS and Landsat are selected because they both have a visible, near infrared and a thermal infrared band. These bands are required to compute the major land surface parameters (i) albedo, (ii) vegetation index and (iii) temperature. These 3 parameters form the basis for the computation of the surface energy balance.
Several other earth observation satellites do not contain a thermal infrared band, and are not suitable for energy balance modeling.
NOAA and MODIS images are characterized by a relatively high temporal resolution (once a day), but a low spatial resolution of approximately 1 kilometer. On the other hand, Landsat images have a high spatial resolution of 30 meter, but a low temporal resolution of 16 days. An analysis of the growing season solely based on Landsat images is practically impossible as the chance of almost all acquisitions during the season being cloud-free is very low in most areas. On the other hand an analysis using only NOAA-AVHRR images would not give sufficient spatial detail. Therefore the advantages of both sensors are combined in this methodological framework where high and low resolution products are integrated to calculate total seasonal evapotranspiration and biomass production at field level.

5.1 SEBAL methodology

Satellites measure spectral radiance and no evapotranspiration or crop growth. These spectral radiances are employed in SEBAL that converts radiances into surface energy balances including evapotranspiration. The theoretical and computational approach of SEBAL is well documented in Bastiaanssen *et al.* (1998; 2005). The initial work on SEBAL was carried out in the Qattara depression in 1986.
SEBAL has 25 computational steps that calculate the actual (ETA) and potential evapotranspiration rates (ETP) as well as other energy exchanges between land and atmosphere. The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum. Satellite radiance will be converted first into land surface parameters such as surface albedo, leaf area index, vegetation index and surface temperature and the ranges of these parameters will be used to assess the ranges of ETA.

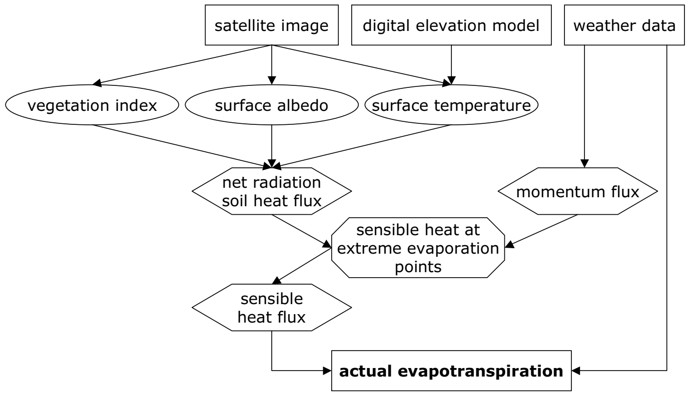


Figure 1 Schematic overview of energy balance and ET computations with SEBAL

The resulting actual evapotranspiration is the sum of evaporation from bare soil or open water bodies and the transpiration of crops. It is important to understand that the evapotranspiration is the amount of water lost into the atmosphere and thus it cannot be reused but is lost from the hydrological basin. The actual evapotranspiration from the SEBAL algorithm is crop type independent which makes SEBAL applicable in areas were the land use is unknown. It is important to realize that the actual evapotranspiration cannot be compared to the reference evapotranspiration calculated by other methods and kc factors.

Basically, actual evapotranspiration for each image pixel is computed from the energy balance equation: ET=Rn-G-H, where Rn is the net radiation, G is the soil heat flux and H is the sensible heat flux. Rn is computed from satellite-measured broadband surface albedo and surface temperature, along with ground measurements of global radiation. G is estimated as a fraction of Rn, surface temperature and vegetation index. And, H is estimated from surface temperature, surface roughness, and wind speed, with a correction for atmospheric buoyancy using the Monin-Obukhov similarity hypothesis. The role of surface temperature from satellites is crucial as it determines the amount of sensible heat flux H (besides Rn and G), and thus, the energy being available for actual evapotranspiration.

This approach is novel as it computes the real and actual situation of the soil-water-plant-atmosphere system, which may deviate substantially from the optimal and ideal growing condition, and the computations are based on radiances and crop and soil types with a priori fixed properties don't need to be known. SEBAL has been applied and tested in more than 25 countries worldwide in a broad range of climatic conditions from humid to hyper-arid.

After solving ETA for every pixel, SEBAL inverts the surface resistance (r_s) to evapotranspiration, i.e. the resistance due to stomatal closure (for plants) or surface moisture (for fallow land). This resistance is then subsequently used to compute ETA and biomass production for a prolonged period using the one-step Penman-Monteith equation for actual field conditions (Monteith, 1965). The basic assumption is that r_s will not change in between subsequent satellite acquisition dates.

The biomass production is calculated according to the principles of the ecological production model of Monteith (1972). This model is based on total Active

Photosynthetically Absorbed Radiation (APAR) and a light use efficiency (ε) that converts the radiation absorbed into a dry matter production value. The sunshine duration of the meteorological data is used to compute global radiation on a day-to-day basis. The interception of this radiation by biological active canopies is derived from the vegetation index. The light use efficiency is approximated as a maximum value for c3 crops (2.5 gr/MJ) and a reduction factor depending on the opening of the stomata's (Bastiaanssen and Ali, 2003). The opening of the stomata's is inversely proportional related to the canopy resistance rs.

SEBAL requires the following input data:
- visible, near-infrared and thermal infrared data from satellite images
- routine weather measurements: temperature, relative humidity, wind speed and solar radiation
- simple land use map
- digital elevation model (DEM)

To obtain periodical values of evapotranspiration and biomass production the following computational steps are required: first, SEBAL is applied on daily images to compute the different components of the energy balance at the instantaneous moment of overpass (acquisition time). Secondly, SEBAL is re-run to compute daily values using daily average meteo data. Thirdly, SEBAL is re-run again, but now using average meteorological inputs that are representative for the corresponding period and with the assumption that certain bio-physical parameters from the day computations remain constant during this entire period. This framework requires that meteorological data must be prepared for the moment of overpass (acquisition time), for the daily average and averaged for each period. The bio-physical parameters that are kept constant during a period are:
- Surface albedo
- Normalized Difference Vegetation Index
- Evaporative fraction
- Bulk Surface Resistance

The NOAA/MODIS products can be disaggregated to field level by means of Landsat images. The NOAA/MODIS results can be split into periods that correspond with one of the Landsat dates. For each of these periods the NOAA/MODIS-based product can be summed and averaged for the entire area. These average values were then multiplied with a relative map that is created by dividing the Landsat product with the average value for the area. In this way the spatial patterns are taken from Landsat and the accumulated values from NOAA/MODIS. The total seasonal values can be calculated by summing the downscaled products of the respective periods.
The number of used high and low resolution satellite images depended on the length of the growing season and the availability of cloud free images. In combination with a land use map the crop yield can be determined by multiplying the cumulative seasonal biomass production with the harvest index.

6 Case studies

6.1 Ukraine

6.1.1 NCC irrigation system

Large irrigation systems were built in the Southern part of Ukraine in Soviet times. One of the largest systems is the North Crimea Canal (NCC) system. It is the oldest still functioning system, constructed during the sixties and seventies to secure water delivery to Crimea. The water originates from the Dnieper River and is used for agriculture (83%), municipalities (10%), fishery (4%) and industry (3%). The system was designed for a command area of 357,800 ha in Crimea, however, nowadays about half of this area is still irrigated. In the remote Southern and Eastern parts, the water has to be lifted to a 100 m elevation. Sprinkler irrigation is the most common field application method, although substantial areas (rice fields) are under surface irrigation.

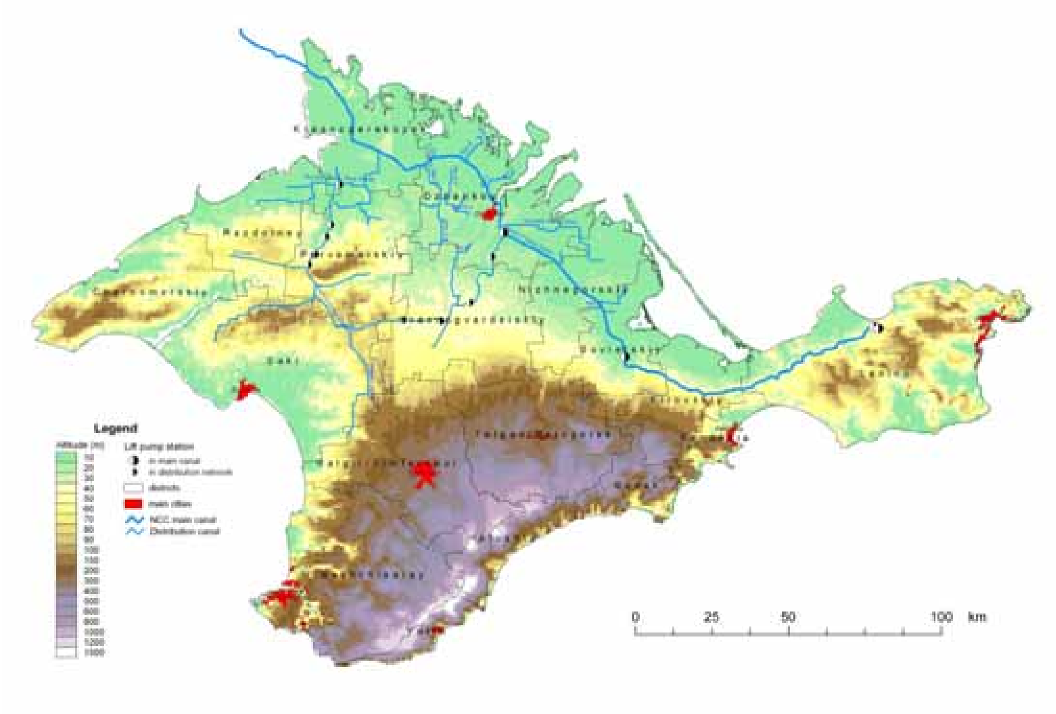


Figure 2 NCC irrigation system in Crimea, Ukraine

The NCC irrigation system is located in the steppe zone of Crimea, which borders in the North on the Sivash Sea and wetlands, which are internationally recognised as important nature preservation areas for their unique hyper-saline ecosystem. Drainage of large amounts of excess irrigation water caused serious pollution and

freshening of the Sivash. It must be noted that due to the current poor performance of irrigated agriculture, NCC causes less ecological problems than during Soviet times.
The NCC system is managed by the Government. Water distribution is delegated to 14 Irrigation Departments, responsible for water delivery up to the farm intake. The entire infrastructure was designed for irrigation of large fields. Since independence the performance of irrigated agriculture has decreased, due to the problematic transformation from command to market economy (Roerink & Zhovtonog, 2005).

Dzhankoy pilot district
Dzhankoy district covers 266,600 ha, of which more than 90% is used for agricultural purposes. It borders on the Sivash wetlands and has a population of 126,000. The Irrigation Department manages 200 km of distribution canals and 71 pumping stations and serves a command area of 72,100 ha, of which 31,000 ha was irrigated in 2003. Since independence the situation at farm level in Dzhankoy has changed drastically. In Soviet times there were 28 kolkhozes and sovkhozes, which in the 1990s were transformed into more than 150 farms of different types and sizes. The former collective farms were privatized and transformed into farm enterprises. Also, land shareholders separated from the former collective farms and started as peasants of family farms. The process of farm restructuring is continuing till today (Roerink & Zhovtonog, 2005).

For the NCC irrigation system, besides remote sensing data, also meteorological and irrigation flow data were available. They were used to calculate with IPAT the performance indicators for several administrative levels. In the section below IPAT results are given for field, farm and district level.

6.1.2 IPAT results

SEBAL was applied for the 2002-2003 hydrological year on images from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. It was decided to calculate the evapotranspiration (ETA) for 12 months running from October 1st (2002) to September 30th (2003).
Thirteen MODIS acquisition days were selected for further ET analysis and are specified in Table 3. It was attempted to use one cloud free image for each month. Moreover two extra days (May 10th and July 5th) were added to compare those results with the Landsat results from exactly the same two days. There are two MODIS sensors operational, the MODIS Terra and MODIS Aqua. The overpass time of the Terra sensor is approximately between 10 and 11 a.m. local time, while the Aqua acquires images between noon and 1 p.m. The MODIS Aqua data is more favourable for ET studies and was thus used for this study. The major contribution of the daily evapotranspiration originates from midday and the afternoon. However, in the selection of cloud free images it was unavoidable that Terra images were used; usually clouds appear late in the morning so that only Terra images are useable. For the months December and February no cloud free images were available. This was

solved by averaging the biophysical parameters of the preceding and succeeding image.

Table 3 MODIS acquisition days and time (GMT) and corresponding period

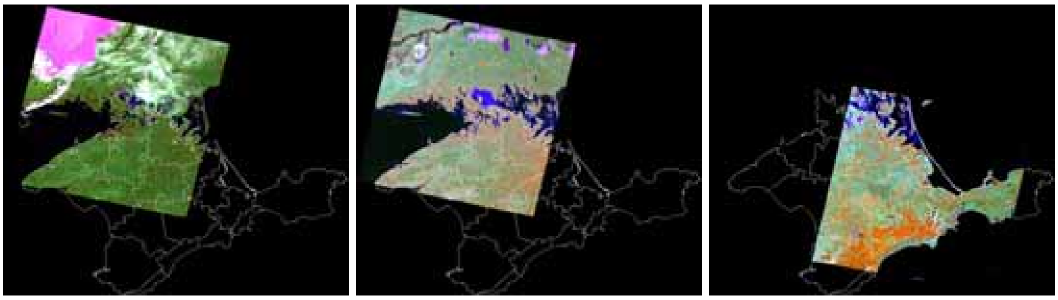
Date	Julian Day Number	Sensor	Acquisition Time (GMT)	Corresponding month
21-01-02	288	aqua	1035	October
13-11-02	319	aqua	1040	November
17-11-02	349	aqua	1015	-
18-01-03	15	terra	0850	January
18-03-03	46	terra	0830	March
26-04-03	74	aqua	1015	April
10-05-03	105	terra	0845	Landsat day
15-05-03	135	aqua	1045	May
13-06-03	166	aqua	1015	June
03-07-03	196	terra	0810	July
05-07-03	227	terra	0800	Landsat day
30-08-03	258	aqua	1025	August
23-09-03	288	aqua	1115	September

Table 4 MODIS image characteristics

MODIS bands	Resolution	Parameter
1-2	250m	NDVI
1-2, 3-7	500m	broadband albedo
31-32	1000m	surface temperature

The MODIS satellite had 36 bands, but not all of them are required to prepare the inputs for SEBAL (Table 4). The Normalized Difference Vegetation Index (NDVI), broadband albedo and surface temperature can be calculated using only 9 out of 36 bands, which are in different precision: bands 1 and 2 (from which the NDVI is calculated) are in 250 m resolution, bands 3 to 7 (from which the broadband albedo is partially derived) are in 500 m resolution and the temperature bands 31 and 32 are in 1000 m resolution. After downloading, the ordered data were imported and automatically reprojected to the Universal Trans Mercator (UTM) system (zone 36, WGS84) with the MODIS reprojection Tool 3.3. An example is given in Figure 3. Before deriving the NDVI and surface albedo, the reflective solar bands 1 to 7 were atmospherically corrected band-by-band using a methodology proposed by Tasumi *et al.* (accepted).
MODIS satellite images have a moderate resolution of minimum 250 m. To obtain more detail for analysis of e.g. individual fields three Landsat images were ordered and analysed. Landsat images have a spatial resolution of 30 m at nadir and the size is approximately 180 by 200 km. Three cloud free images were available for the period that was analysed May 10th, July 5th and August 15th (2003) (Figure 4).

Figure 3 Crimea and Ukraine's mainland as seen on a MODIS image (band 7-2-1) dated August 30th, 2003



May 10th (2003) Path/row 178/28 | *July 5th (2003) Path/row 178/28* | *August 15th (2003) Path/row 177/28.5*

Figure 4 Landsat ETM images (RGB: 4,5,3)

Figure 5 depicts the total annual ETA that was estimated by SEBAL, which was calculated from the monthly MODIS maps of ETA. High ETA values are found in the irrigated rice growing areas in the north near Krasnoperekopsk and east of Dzhankoy. Annual ETA here is approximately between 700 and 800 mm. Also the forested mountain areas in the south and the wetlands in the north and north-east have high ETA values up to 850 mm per year. The irrigated areas around Dzhankoy are amongst the most intensively irrigated in Crimea, two irrigation seasons are recorded here and average ETA values are between 400 and 600 mm per year. In general higher ETA values are found along the section of the Northern Crimea Canal that goes up to Kerch in the ultimate east. Further to the west and south-west over the higher steppe lands, up to the southern mountain range, ETA is much lower between 200 and 400 mm. SEBAL produced similar maps for biomass production.

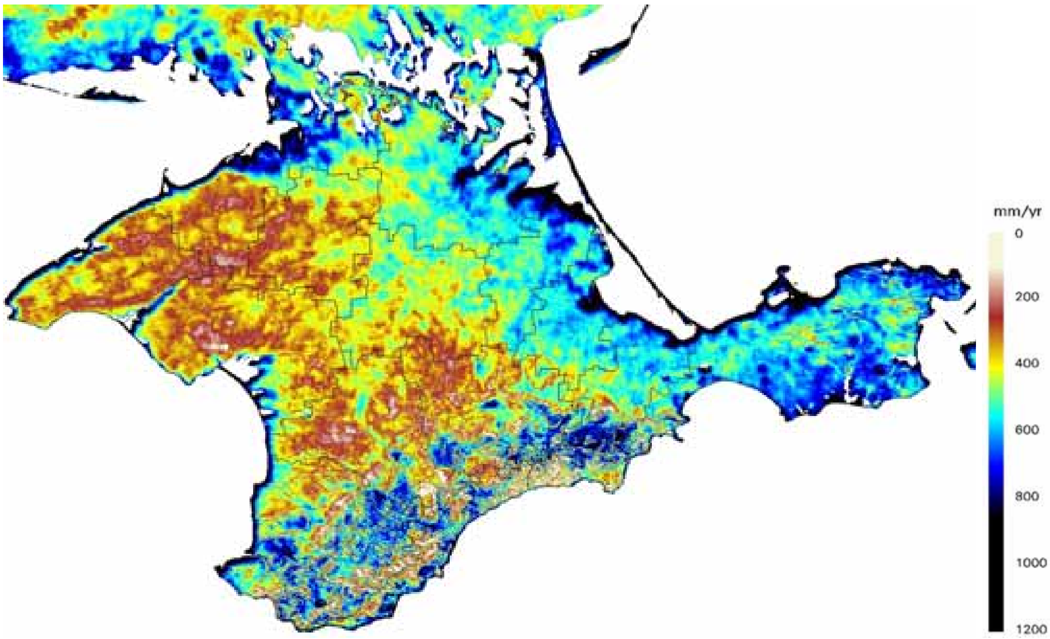


Figure 5 Annual evapotranspiration October 2002 till September 2003 by SEBAL

<u>District level</u>

IPAT calculated for whole Crimea the relative evapotranspiration and the crop water production per district. Figure 6 shows the ETR values per district with minimum values around 0.4 in the mountainous forested area in the South of Crimean and maximum values around 0.9 for the districts located along the Northern coastline of Crimea. It is obvious that this is caused by the NCC irrigation canal that is flowing through these districts.

Figure 7 shows the CWP per district. It is calculated as biomass production over ETA and looks like a kind of inverse image of the ETR image in Figure 6. This can be explained by the fact that Crimea is not a very dry area (like the other two case studies in Argentina and Mexico). Only by the end of June, July and August severe water problems exist. In spring whole Crimea is covered green vegetation and biomass values are more or less equal all over Crimea. Consequently irrigation gives lower instead of the expected higher CWP values.

In conclusion, one can say that the irrigation performance at district level is characterized by high ETR values for irrigated areas, so water is not a limiting factor in Crimea. Secondly, one can conclude that the CWP indicator is not suitable to compare different district with each other for the specific case of Crimea.

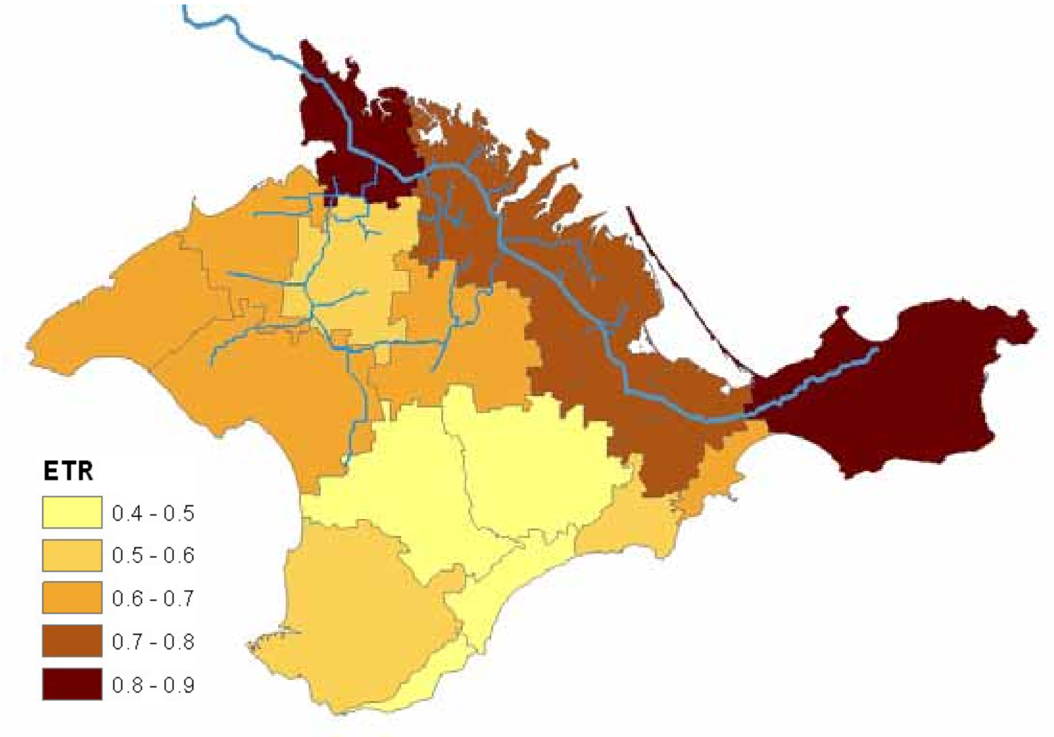


Figure 6 Relative evapotranspiration per district in Crimea for the irrigation season 2002/2003

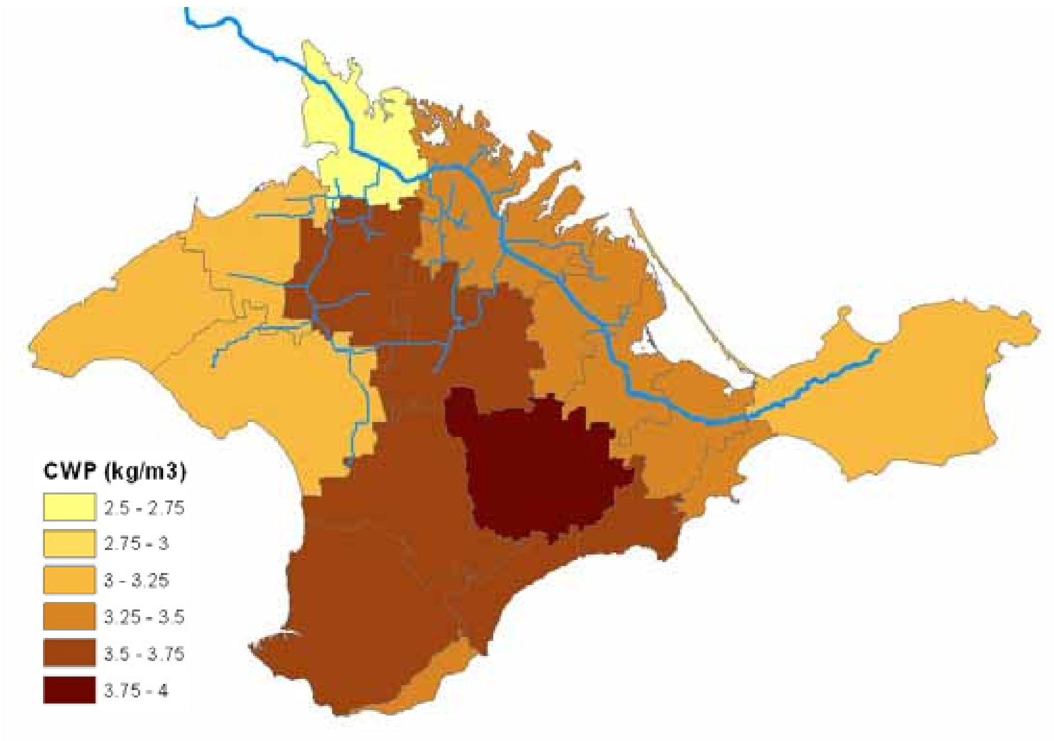


Figure 7 Crop water production per district in Crimea for the irrigation season 2002/2003

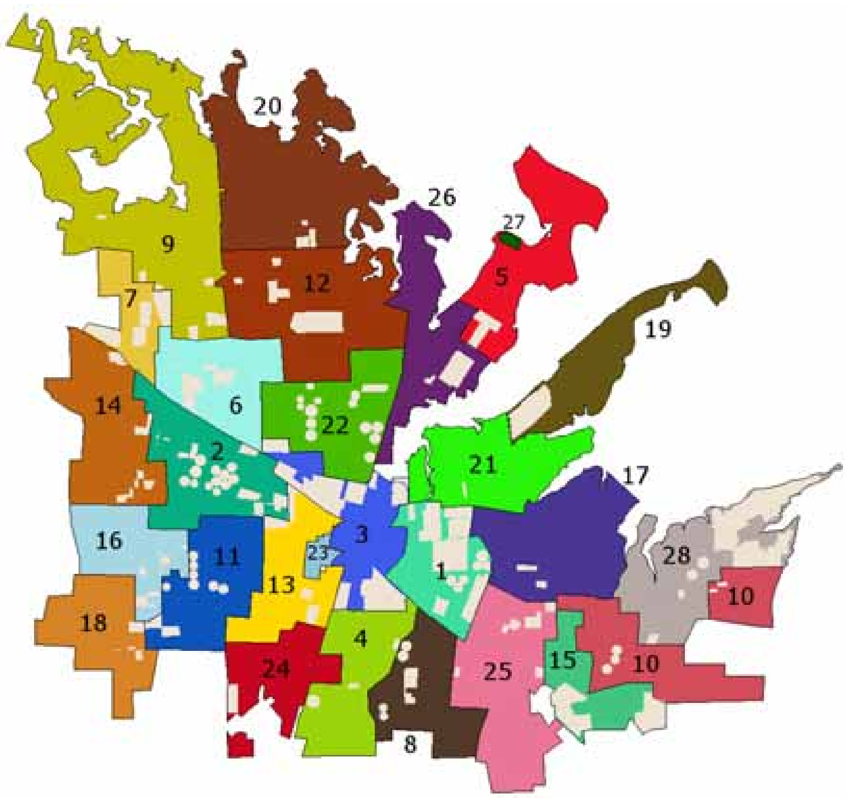


Figure 8 Farm boundaries superimposed with the irrigated area in 2003 (beige)

Farm level

In the Dzhankoy area there are 28 farms that range in size from 150 to 20173 ha. Most of the farms only irrigated for a minor part during the 2002/03 season. The figure below displays the boundaries of the farms and the areas within the farms that were allocated to receive irrigation water.

With the IPAT tool the average biomass production and evapotranspiration has been calculated for each farm and for the irrigated area in the farm. In the table below the values are given including the ratio between the whole farm and the irrigated area within that farm.

During the spring season the biomass production for the whole farm is even higher than for the irrigated areas within the farms. During the summer season the production is higher for the irrigated areas for most farms as can be expected. On average the production for the irrigated areas is 17% higher. There are however, farms where the irrigated areas show a lower production as compared to the whole farm. For Semennoy and Lenina the production within the irrigated area is 30% less than the average for the whole farm. For these farms the irrigation has a negative impact on the production levels. One of the reasons might be that the area that was allocated for irrigation did not receive the water.

The farms that show the highest ratios are putting their irrigation in good use. Obilniy, Mayak and Perekopskiy have a biomass production that is 60% or more in the irrigated area as compared to the average of the whole farm.

Table 5 Biomass production (kg/ha)

ID	Farm	Whole farm		Irrigated area		Ratio	
		spring	summer	spring	summer	spring	summer
21	Zarechniy	9,279	10,582	8,812	12,610	95	119
6	Sovkhoz Ukraina	7,922	10,515	6,630	11,051	84	105
28	Kolkhoz Ukraina	9,766	9,802	8,022	7,677	82	78
1	Dzhankoy	9,296	9,642	10,205	10,932	110	113
23	Magarach	9,145	9,624				
19	Chongarskiy	9,129	9,259	10,743	11,538	118	125
26		9,545	8,887	9,041	12,893	95	145
3	Izumrudniy	7,696	8,728	6,692	8,948	87	103
24	Obilniy	8,598	8,711	6,745	14,034	78	161
18	Semennoy	7,837	8,684	7,184	6,067	92	70
8	Azov	7,863	8,629	8,589	11,188	109	130
17	Lenina	9,031	8,576	8,136	6,102	90	71
10	Molodaya Gvardiya	9,205	8,225	7,879	7,090	86	86
25	Rossiya	9,807	8,203	9,765	10,067	100	123
11	Progress	7,650	8,156	6,952	10,255	91	126
12	Zavet Lenina	8,611	7,890	7,040	8,076	82	102
4		8,162	7,880	7,512	6,616	92	84
5	Severniy Krim	7,671	7,516	6,986	10,284	91	137
22	Pobeda	8,704	7,503	9,002	7,332	103	98
13	Michurinets	8,144	7,497	7,047	9,257	87	123
15	Zarya	11,288	7,395	11,963	7,191	106	97
20	Yasnaya polyana	7,585	7,079	6,448	6,829	85	96
2	Rodina	7,208	6,657	9,168	8,578	127	129
27		6,119	6,629				
16	Mayak	7,441	6,456	8,988	11,556	121	179
14	Novokrimskoye	7,195	6,167	6,084	7,381	85	120
7		8,355	5,273	7,931	6,789	95	129
9	Perekopskiy	7,704	4,446	5,592	9,014	73	203
	Average	8,427	8,022	8,044	9,206	95	117

Plot level

The irrigated plots at farm level in the previous section are now analysed in detail. With additional irrigation flow measurements per plot and meteorological data the depleted fraction and the field application ratio are determined per plot. Figure 9 and Figure 10 show the results.

Taking into account a critical DF value of 0.6, one can conclude that most plots in Dzhankoy district have higher values. Only the plots located nearby the side branch of the main NCC canal have lower values (left on the figure). This is explained by the fact that in this region the land are intensively cultivated by small privatized farmers. In their enthusiasm they over-irrigate and this results in low DF values.

A similar trend can be found for the FAR values. The plots with low DF values have also low FAR values, indicating again over-irrigation. On the other side there are a lot of plots with values higher than one, which indicates that too less water is diverted to the plant, as ETP-P is much larger than the irrigated volume. This is caused by the extensive cultivation practice of the former kolkhozes and sovkhozes in this part of the district.

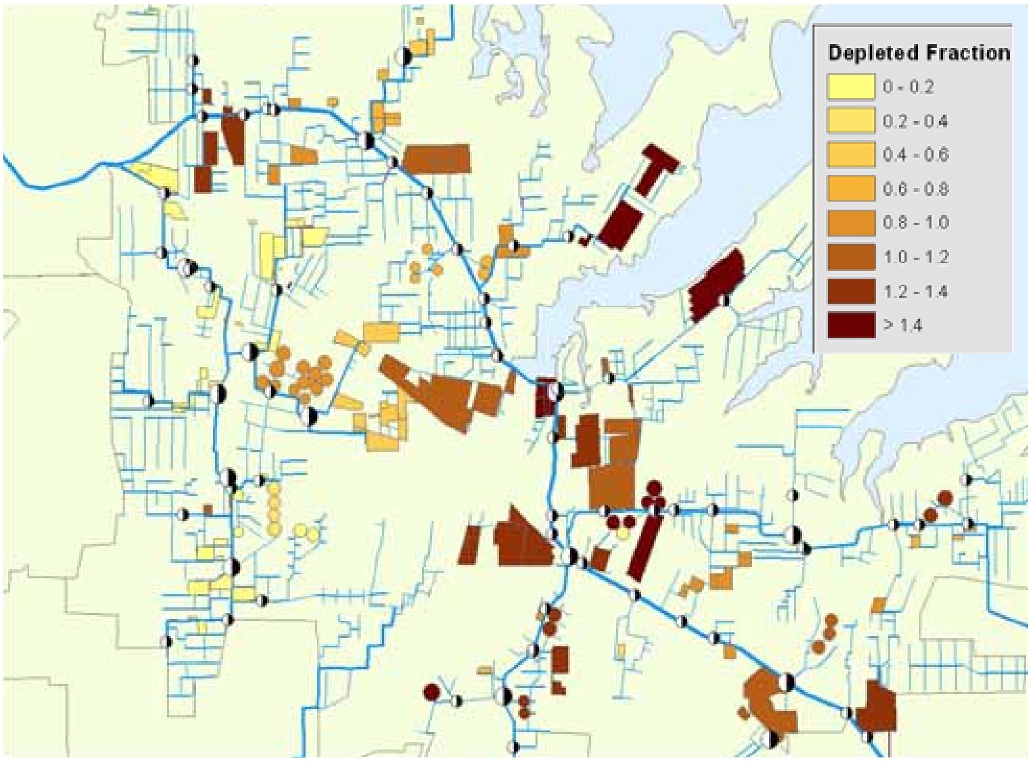


Figure 9 Depleted fraction per irrigated plot in Dzhankoy district for the irrigation season 2002/2003

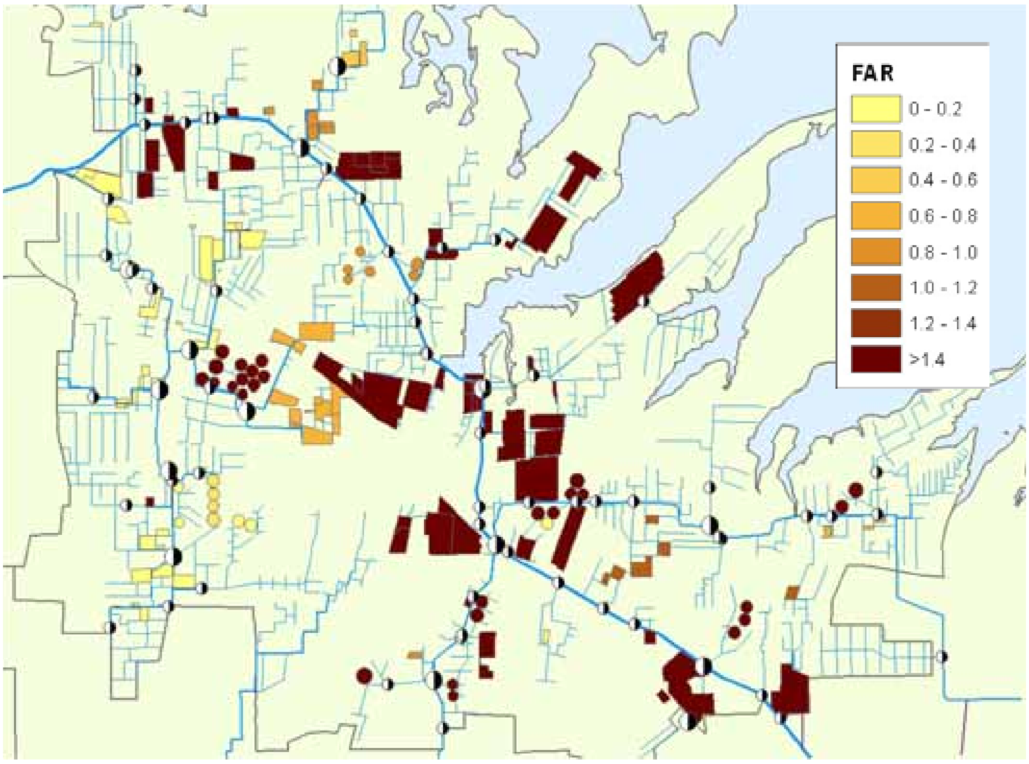


Figure 10 Field application ratio per irrigated plot in Dzhankoy district for the irrigation season 2002/2003

6.2 Mexico

6.2.1 Yaqui irrigation system

The Yaqui River coastal plain is a highly productive agricultural region in the state of Sonora, Mexico, situated adjacent to the Gulf of California. The Yaqui valley is representative climatically for the rest of the Sonoran desert, and is classified as arid to semi-arid, with average rainfall of less than 300mm and mean annual temperatures above 22°C.

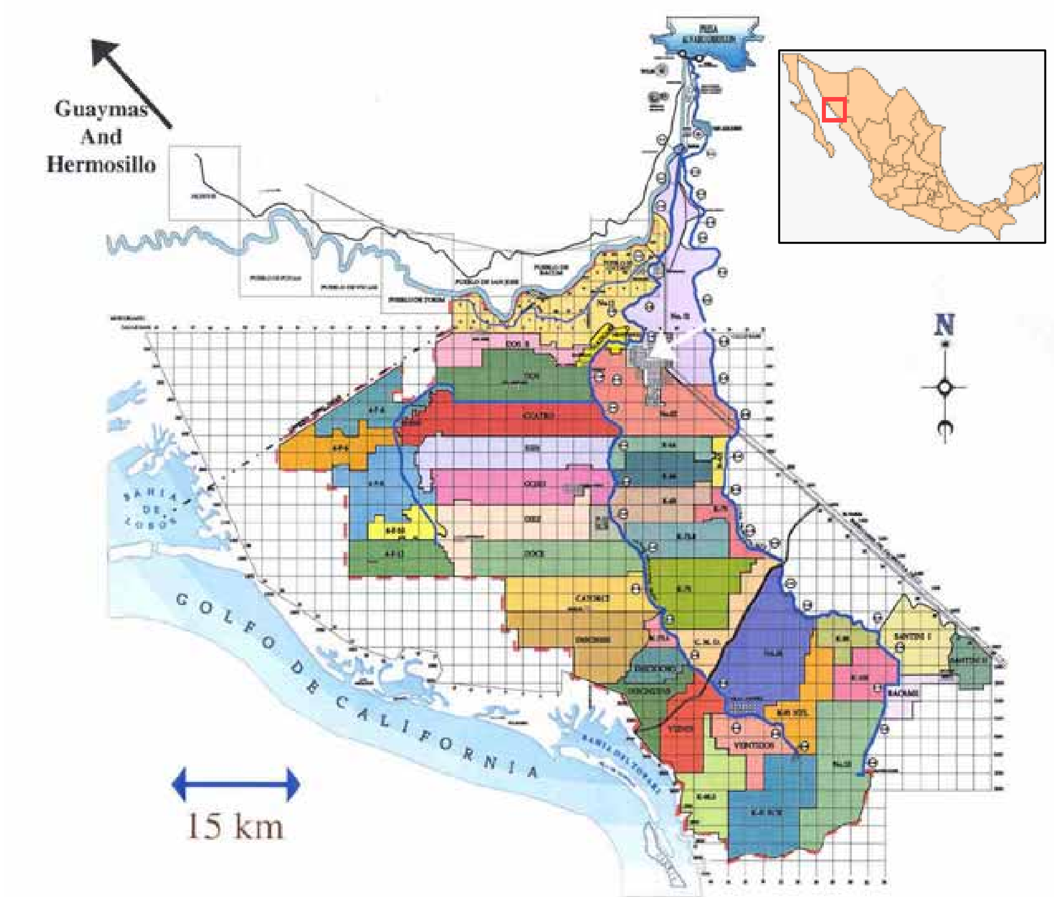


Figure 11 Yaqui irrigation system in Sonoro, Mexico

As one of the first agricultural districts to enjoy state-subsidized water, the Irrigation District has an extensive distribution network. A total of 2774 kilometers of canals, laterals, and branches distribute over 2,000 Mcm of Yaqui water annually to producers in the Irrigation District. Two main canals, Canal Alto and Canal Bajo, have a capacity of 100 m3/sec and 120 m3/sec, respectively (Figure 4). Average diversions from the Yaqui River basin have been steadily increasing since 1970, and most recently, surface water composes nearly 95% of the total withdrawn water.

The remaining percentage comes from local groundwater. Though groundwater use is low in comparison to other regions, there is a growing consensus that groundwater will contribute more to the irrigation budget, especially during drought years. To counter locally high water tables and resulting soil salinization, the Irrigation District maintains 451 km of principal collector drains and operates pumps to recover this drainage water for re-use. In addition to the substantial Yaqui surface water delivered, nearly 700 extraction wells discharge to the distribution canals totaling approximately 354 Mcm annually (some of these wells assist in lowering high water levels near main canals) (Adams, 2006).

As the original centre for the Green Revolution for wheat in Mexico, the basin has rapidly grown to over 225,000 cultivated hectares. The area is dominated by wheat cultivation in the winter period, which was reported to be 85 per cent of the total cropped area (Lobell *et al.*, 2003). Wheat is sown in late November - early December and is harvested in late April - early May. Farmers usually irrigate four to five times within the season.

The Yaqui irrigation system is administratively divided in 42 districts, which are called Modulos (see Figure 11 and). The IPAT pilot study focused on these Modulos. With the use of remote sensing data, IPAT calculated several performance indicators for the Modulos and the differences are analyzed and explained.

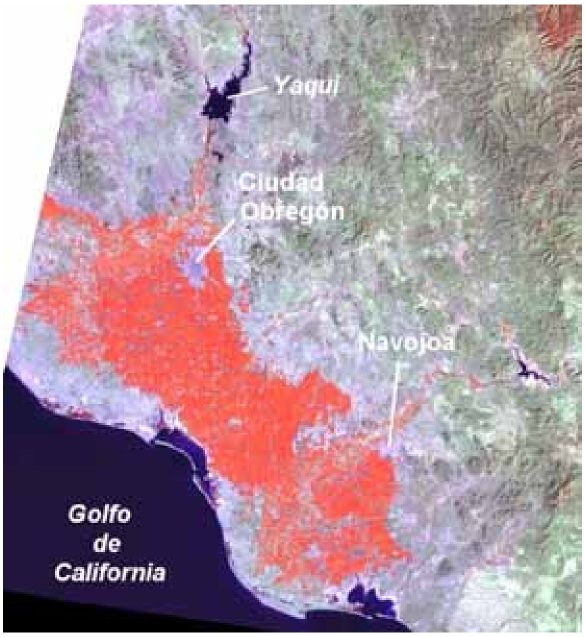


Figure 12 The Yaqui irrigation district as seen on a false-colour Landsat image acquired on February 26, 2000. Green vegetation appears red on the image

6.2.2 IPAT results

The SEBAL model was applied for the 1999-2000 winter season using both National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer (NOAA-AVHRR) and Landsat satellite images.
Twelve NOAA images (Table 6) were used to calculate evapotranspiration (ET) and biomass production over 10 day periods (decades) for 1 km pixels with the SEBAL algorithm. These low resolution products were then disaggregated to field level by means of high resolution SEBAL generated ETA and biomass production maps of three Landsat ETM scenes (path/row: 34/41) that were acquired during the growing season (Table 7).
Based on the biomass yield and seasonal ETA the crop water productivity of wheat was calculated spatially. The average CWP of wheat for the entire Yaqui irrigation district equals 1.37 kg/m^3.
As can be observed from Figure 4 CWP not only varies within the system, but also within fields. This indicates that, besides climatology and regional soil physical and hydrological properties, specific management decisions by farmers, such as irrigation amount and timing, fertilization, weeding, choice of seed variety, etc., play an important role in the level of CWP that is reached.
SEBAL estimated wheat yields in Yaqui Valley depict a large range varying between 3 and 8 ton ha-1. Large variations in ET are also observed, ranging from 250 to 450 mm. High yields can only be obtained when ET is high as well. This agrees with the general opinion that high yielding varieties from the Green Revolution consume relatively larger amounts of water.

Table 6 NOAA-AVHRR image acquisition dates

Image #	Date
1	January 4 (2000)
2	January 12 (2000)
3	January 28 (2000)
4	February 17 (2000)
5	February 19 (2000)
6	February 23 (2000)
7	March 12 (2000)
8	March 16 (2000)
9	March 20 (2000)
10	April 1 (2000)
11	April 10 (2000)
12	April 10 (2000)

Table 7 Landsat image acquisition dates and related decades for the integration

Landsat-7 (p/r: 34/41)	Decade	Date
January 25	1-4	January 1 - February 9
February 26	5-9	February 10 - March 31
April 24	10-12	April 1 - April 30

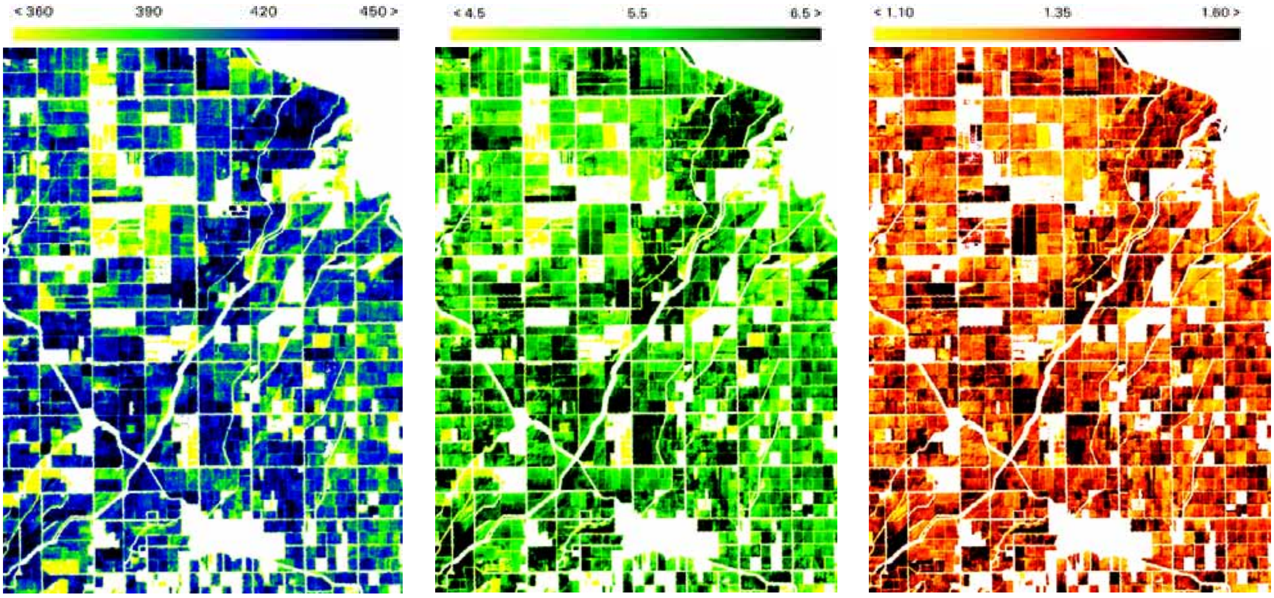


Figure 13 Detailed maps of seasonal evapotranspiration (mm - left), yield (ton/ha - middle) and water productivity (kg/m³ - right) of wheat in Yaqui irrigation district.

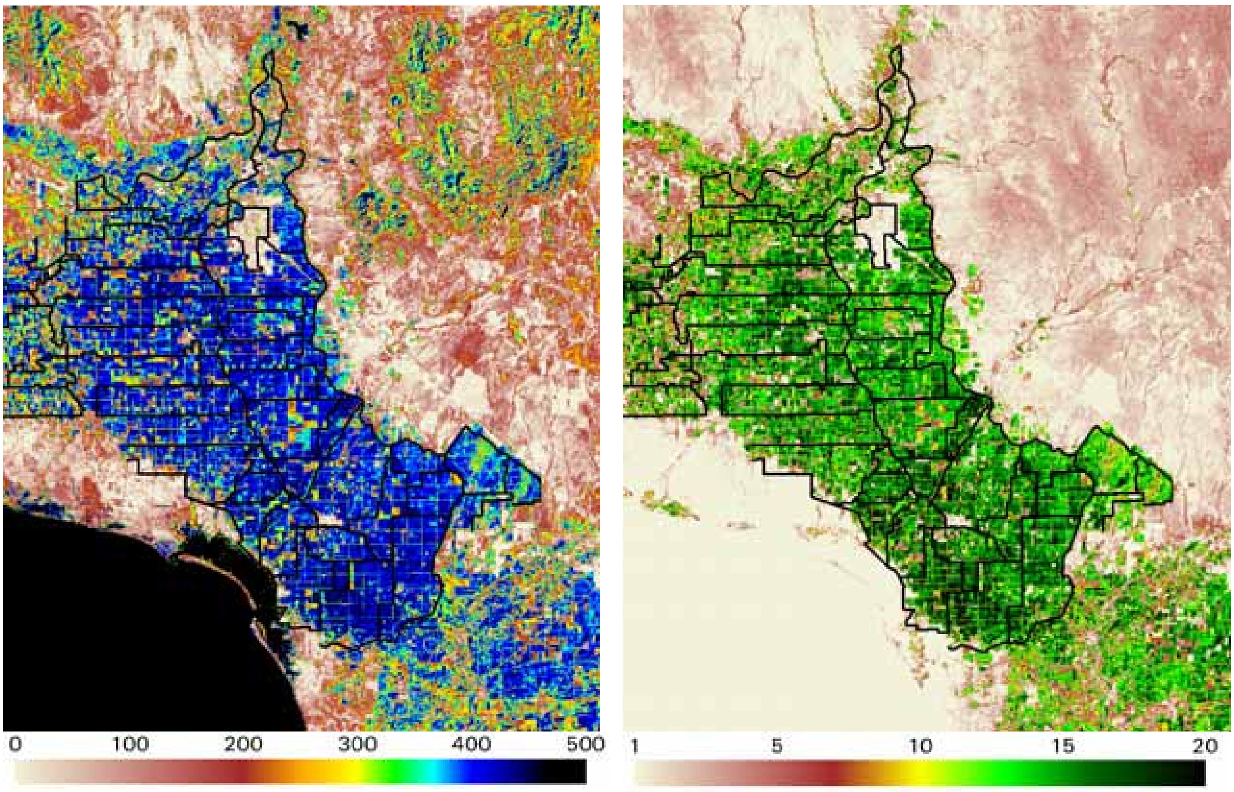


Figure 14 Total evapotranspiration (mm) and biomass growth (ton/ha) of the wheat season 2000 superimposed with the boundaries of the Módulos

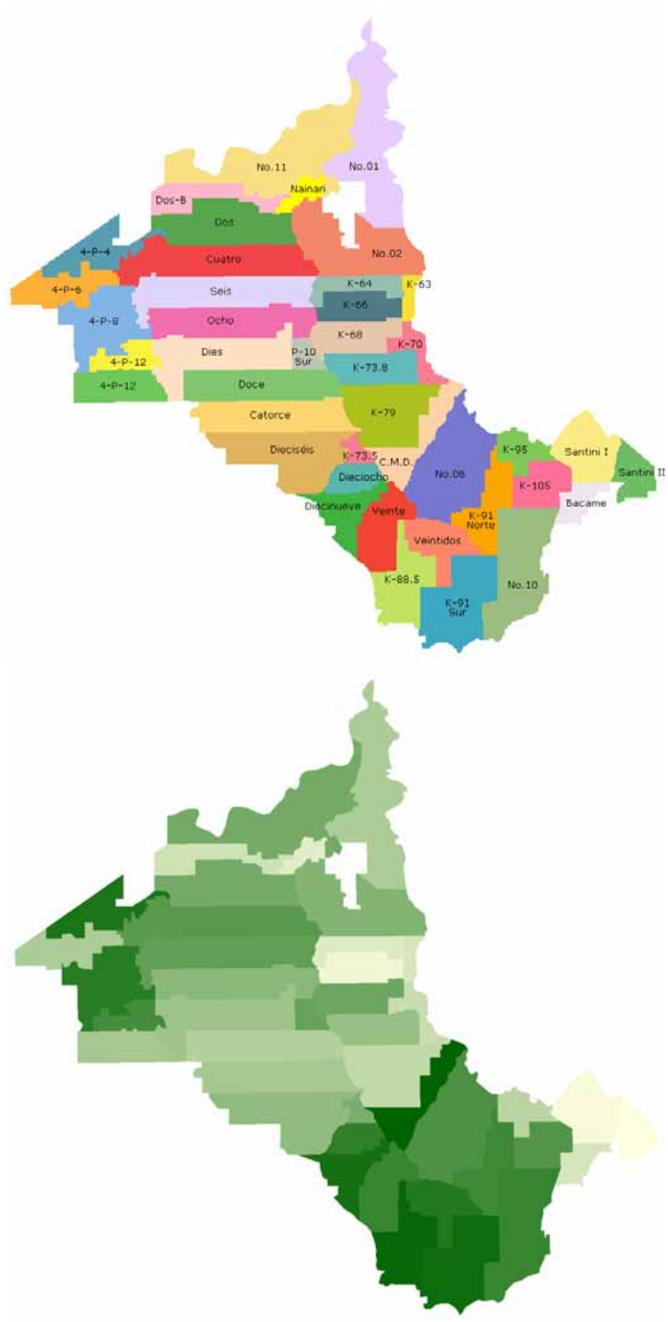


Figure 15 Módulos (above) and the average wheat yield (light yellow 5000 kg/ha; dark green 6100 kg/ha)

The total evapotranspiration was calculated for the wheat season 2000. Figure 14 gives the spatial pattern of evapotranspiration and biomass growth for the Yaqui irrigation district.
Within the IPAT tool the pervious data can be easily combined with the Módulos boundaries to calculate for example the average wheat yield (Figure 15). Table 8 gives the complete IPAT results for the Modulos in Yaqui irrigation system.

Table 8 Avarage values per Módulo as produced with IPAT

Módulo	Total area (ha)	ETA (mm)	Total ETA (MCM)	Wheat area (ha)	Wheat yield (kg/ha)	ETA wheat (mm)	CWP heat (kg/m³)	Wheat area (%)
4-P-4	4,752	331	15.7	1,173	5,956	409	1.45	25
4-P-6	4,884	327	16.0	1,826	5,518	397	1.39	37
4-P-8	7,444	308	23.0	1,604	5,862	408	1.43	22
4-P-12 Norte	2,598	311	8.1	803	5,753	407	1.41	31
4-P-12 Sur	4,687	280	13.1	1,150	5,532	401	1.38	25
No. 11	14,401	293	42.1	4,162	5,587	396	1.41	29
Dos - B	4,406	331	14.6	1,639	5,415	379	1.43	37
Nainari	1,454	313	4.5	515	5,366	402	1.34	35
Dos	8,671	344	29.8	3,838	5,587	405	1.38	44
Cuatro	10,263	353	36.2	5,396	5,634	413	1.37	53
Seis	9,574	371	35.5	5,549	5,628	415	1.35	58
Ocho	8,391	361	30.3	5,264	5,553	410	1.35	63
Diez	8,774	349	30.6	4,728	5,536	407	1.36	54
P-10 Sur	1,341	383	5.1	981	5,614	410	1.37	73
Doce	8,056	378	30.5	5,298	5,508	411	1.34	66
Catorce	8,028	374	30.1	5,604	5,529	410	1.35	70
Dieciséis	9,471	328	31.1	4,503	5,551	409	1.36	48
K-73.5	957	380	3.6	542	5,577	413	1.35	57
Dieciocho	2,381	399	9.5	1,770	5,852	417	1.40	74
Diecinueve	4,086	346	14.1	2,139	6,008	411	1.46	52
Veinte	5,399	362	19.6	3,041	5,848	408	1.43	56
K-88.5	6,120	354	21.7	3,814	6,053	420	1.44	62
Veintidos	4,448	382	17.0	3,227	5,882	416	1.41	73
No. 01	13,008	251	32.6	3,736	5,518	395	1.40	29
No. 02	10,534	321	33.8	5,425	5,557	409	1.36	52
K-64	2,863	379	10.8	2,033	5,374	404	1.33	71
K-66	3,955	361	14.3	2,600	5,312	405	1.31	66
K-63	1,075	389	4.2	772	5,389	401	1.35	72
K-68	4,464	384	17.1	3,204	5,606	412	1.36	72
K-73.8	4,688	393	18.4	3,766	5,546	411	1.35	80
K-70	2,233	392	8.7	1,798	5,447	407	1.34	81
K-79	7,993	370	29.6	5,449	5,471	403	1.36	68
C.M.D.	4,787	384	18.4	2,674	6,065	423	1.43	56
No. 06	11,555	358	41.4	7,891	5,708	407	1.40	68
K-95	2,805	388	10.9	2,350	5,492	400	1.37	84
K-91 Norte	4,911	382	18.7	3,675	5,780	407	1.42	75
K-105	3,826	388	14.9	3,203	5,703	404	1.41	84
K-91 Sur	9,007	400	36.0	5,824	6,048	428	1.41	65
No. 10	10,357	395	40.9	7,321	5,848	419	1.39	71
Santini I	5,651	354	20.0	3,364	5,210	392	1.33	60
Bacame	2,215	354	7.8	1,129	5,388	402	1.34	51
Santini II	2,997	354	10.6	1,741	5,032	391	1.28	58

6.3 Argentina

6.3.1 Rio Dulce irrigation system

The Rio Dulce irrigation system is one of the most important irrigation systems in Argentina. The gross command area is 350,000 ha, of which the maximum irrigable area is 120,000 ha, due to the limited volume of available water. It has contributed more than 40% of the gross agriculture product of Santiago del Estero province for many years and supports the livelihoods of more than 50% of its population. Irrigation in the area of the Rio Dulce started before 1900 by spontaneous actions of local settlers, developing small canals for irrigation. During the twentieth century large interventions took place from the side of the Government, which resulted in the construction of a water conveyance (reservoir) and distribution (canals, gates, etc.) infrastructure.
The main canal La Matriz starts at the Los Quiroga diversion dam. The objective of the dam is to guide the water of the Río Dulce into the irrigation system and to regulate the level of the river. In the summer the river produces sufficient water and during the winter, all water that is available is used for the irrigation system. The main canal is 21,8 km long and completely lined; its discharge capacity is 100 m^3/sec.
The Rio Dulce irrigation system is a jointly managed system, with a provincial agency being responsible for the continuous water distribution at primary and secondary level of the system and water users (associations) being responsible for a fixed rotational water distribution at the lower levels of the system. The water users are only farmers, however, they range from small peasants (< 10 ha, the majority) to large (>100ha) farm enterprises (Prieto, 2006).

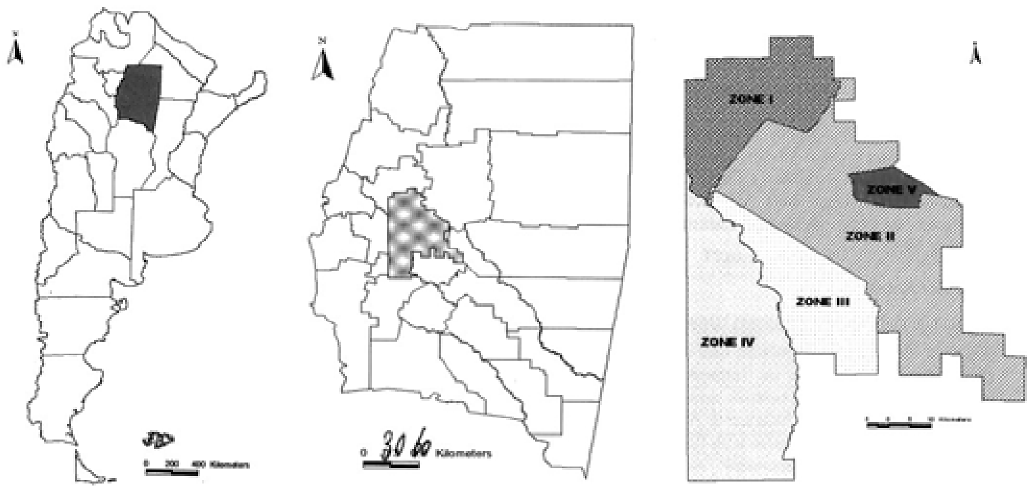


Figure 16 The 5 irrigation zones in the Rio Dulce irrigation system (right), which is located in the Santiago del Estero province (middle) in Argentina (left)

The scheme is divided administratively in 5 zones. Due to historical reasons, these zones have a very uneven development of their water infrastructure and control. In order of level of modernization:

- In Zone I (19,000 ha) the irrigation network was completely modernized during the last decades. Canals were lined to quaternary level and a dense drainage network was constructed. Water measurement devices were installed in the head end of all canals.
- Zone V (7,500 ha) is similar to Zone I. However, canals are not lined in this area.
- In Zone IV (19,000 ha) the modernization process reached the tertiary level and a dense drainage network was constructed as well. However, at quaternary level water flow is not measured anymore.
- In Zone II (46,000 ha) nothing was modernized. Old earthen canals are still being used. Nevertheless they have received high maintenance over the last years. Measuring devices are only available at the head of secondary canals. Few drains have been built in these areas.
- Zone III (15,000 ha), as Zone II, is not modernized.

The IPAT pilot study focused on these 5 zones. With the use of remote sensing data only, IPAT calculated several performance indicators for the 5 zones and the differences are analyzed and explained.

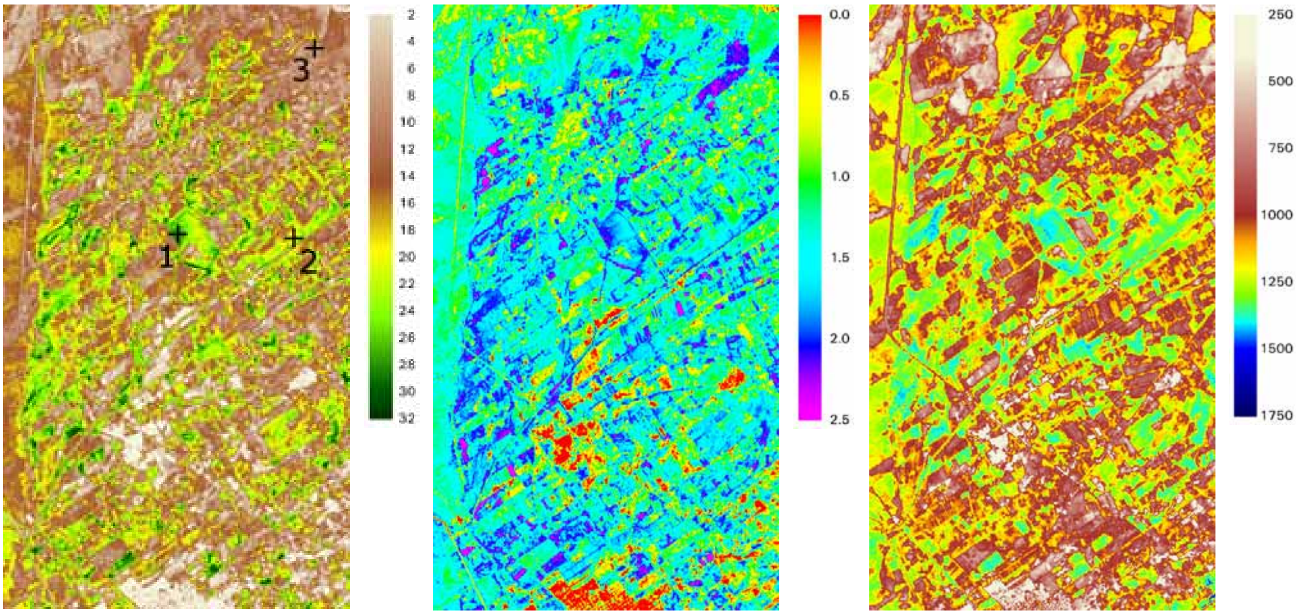
6.3.2 IPAT results

For the SEBAL calculations of the Rio Dulce 10 Landsat TM7 images have been processed from June 20th, 2002 till May 6th, 2003 to generate monthly high resolution maps from June 2002 till May 2003. Time series have been generated for the evapotranspiration and the biomass production and thus the crop water productivity expressed as biomass production per cubic meter of water consumed.

Table 9 Used Landsat7 images in the Argentina case

#	Date
1	June 20th, 2002
2	September 8th, 2002
3	September 24th, 2002
4	October 26th, 2002
5	November 11th, 2002
6	January 30th, 2003
7	February 15th, 2003
8	March 19th, 2003
9	April 20th, 2003
10	May 6th, 2003

A subset of the total annual values is displayed in the figure below to show the diversity in evapotranspiration and biomass production. The area is located North of Santiago del Estero (just visible at the bottom of the maps). From Figure 17 it is clear that not the whole area is cultivated. On the biomass production map can be seen that large areas have a biomass production of less than 10 ton/ha. These areas are probably left fallow and were not used for agriculture.



Biomass production (ton/ha) *Crop water productivity (kg/m³)* *Evapotranspiration (mm)*

Figure 17 SEBAL results of the total annual values (June 2002 till May 2003)

Figure 18 Field boundaries within the 5irrigation zones of Rio Dulce irrigation system

A field map with around 650 fields was used in IPAT to generate average values for each field. In order to present the data in this report the 650 fields were divided into the 5 zones, which are described in paragraph 6.3.1. Figure 18 displays the 650 fields and Table 10 describes the results.

Table 10 Average annual results (June 2002 till May 2003) per irrigation zone

Zone #	BIO (kg/ha)	CWP (kg/m3)	ETA (mm)	Area (ha)
I	12,664	1.296	941	14,786
II	11,918	1.264	893	48,239
III	12,922	1.303	957	17,171
IV	16,451	1.497	1,074	20,929
V	9,854	1.088	871	12,972

It is expected that zone I and V would have the highest irrigation performance, as they are the most modern equipped irrigation zones. However, Table 10 tells us that zone I is doing average, while zone V is doing worst in terms of crop production (BIO=9,854 kg/ha) and water productivity (CWP=1.088 kg/m^3).
The non-modernized zones II and II are performing also more or less average, while the partly modernized zone IV is performing best. This could be explained by the fact that in zone IV only the main water distribution system is modernized, while at tertiary level, the traditional water distribution system exists. So the benefits are combined from lined canals in the main system with the large experience of the farmers at tertiary level.
If one takes a closer look on the figures in Table 10 one can conclude that increasing ETA rates result in increasing crop production and water production rates. Questions should be asked why zones I, II, III and IV do not irrigate more and if zone IV will irrigate more, will the crop and water production still increase. The answer to these questions lies in the fact that the irrigation system is a water limited system, i.e. the crop production is limited by the volume of water instead of other limiting factors, such as land. The resulting high demand for water has the consequence that the limited water resources are used by too many farmers on too many lands, and the optimal crop water production is not reached. Zone IV is located besides the main canal, has relatively easy access to water and therefore has the highest ETA value.

6.4 IPAT evaluation

All partners in the project consortium (Alterra, WaterWatch, IHELR, INTA and CNA) tested and evaluated the IPAT tool. The main conclusion is that IPAT is a perfect tool for evaluation of the performance of irrigation systems. More specific the advantages of IPAT are:

- The ability to create new performance indicators very easily is praised. By simply changing or adding a formula, a new performance indicator can be created.

- If remote sensing data only are available, IPAT proofs to provide still a lot of useful indicators (ETA, ETR, CWP, biomass production).
- Once the input data is entered in IPAT, it works relatively easily, which means it can be used in a operational way by irrigation engineers.

Disadvantages are of course also mentioned by the project partners. First of all, a piece of software as IPAT is never finished. It can always be improved and users always have their specific requirements and wishes. However, the following issues were mentioned a drawbacks in the operational use of IPAT:

- The software costs to run IPAT are high. ArcGIS 9.1 (or higher) together with the Statial Analyst extension is needed to run the IPAT user interface. Currently, ArcView is used in general as the standard GIS platform all over the world. To purchase a ArcGIS licence costs more than 5000 Euros. However, as ArcGIS will replace ArcView as the standard GIS analysis software, it is foreseen that in future all organisations working with GIS will change to ArcGIS. A short term solution is found by the purchase of a demo ArcGIS license, which costs about 100 Euro, but the license is limited to 6 months.
- IPAT only has a small data availability check. If necessary data is missing to run IPAT, a short message is given that data is missing and the model stops. No clear insight is given in which data is missing.
- Data input is not automated yet. Data has to be imported in IPAT model by means of opening the corresponding access database, which is a time consuming and precise work.

All partners expressed their wish and committed themselves to continue the further development of IPAT, taking into account the comments above.

7 Cost-benefit analysis of remote sensing in irrigation management

7.1 Possible contributions of remote sensing in irrigation management

Flow measurements and accounting for water - as well as the crucial distinction between water applied to the field and water consumed by the crop - is technically and administratively complex. Because of this fact, water distributions in irrigation systems are often disputed, and there are arguments about water volumes received in head and tail end. Hence, there is a need for an independent, direct, and standardized method that can describe water distribution in irrigation systems.

The thermal-infrared application in remote sensing has, after 20 years of research and applications, reached a level that it can be operationally applied to quantify water consumption in irrigation and drainage systems, as well as for the analysis of entire river basins (Bastiaanssen and Bos, 1999; Menenti, 2000). Allen and Bastiaanssen (2005) said that water shortages reduces food production, and that it is imperative that water managers, planners and hydrologists determine the spatial and temporal distribution of evapotranspiration. They also mention that the technique is now sufficiently accurate.

In a summary of a workshop devoted to remote sensing and irrigation, Vidal and Sagardoy (1995) attributed the limited application of satellite image remote sensing to poor technology transfer and to the large investments required, among others. In an additional Expert Consultation on Remote Sensing and Drainage, Bos *et al.* (2001) concluded that '.. *user-friendly tools are needed to help water managers in their decision making of water allocation and to increase the productivity of water. Considering that the accuracies of drainage related parameters are acceptable, and the costs being affordable, the workshop concluded that the core activity in remote sensing sciences during he next decade should focus on making products. A product oriented approach is needed that produces easily accessible information to clients*'. Such product oriented approach can be launched only if the stakeholders of remote sensing products in irrigation management are properly identified:

- irrigation districts
- irrigation departments
- irrigation service delivery agencies
- river basin authorities
- departments of water resources
- catchment management agencies

These line agencies are usually under the auspices of federal water governors are responsible for the supply side of irrigation water. They should operationally bring the proper amounts of water to certain distribution points in the irrigation district network. Transfer of the management and responsibility of the irrigation water resources usually starts from the distributary or secondary irrigation canal. Beyond this points, the water recipients are responsible themselves for the further downstream division of flow and field irrigations. The members of Water Users Associations (WUAs) and Water Boards are selected by individual recipients and they thus represent the beneficiaries of the irrigation system. These groups are also potential clients of remote sensing data.

The potential benefits of using remote sensing data in conjunction with IPAT for line agencies and recipient water groups are:

- Improving transparency and building trust between water supply agencies and water user groups
- Decreasing non-beneficial use of water resources
- Enhancing food production
- Increasing crop water productivity
- Reduce applied water
- Conserve groundwater use
- Water revenue collection
- Implementation of water rights
- Environmental sustainability
- Gaining insight in cost recovery studies

Remote sensing technology cannot be manipulated and fraud can be excluded. Satellite measurements are suitable to compare variability among villages, aquifers, and sub-basins especially in cases in which there is conflict and distrust among water using groups. The satellite serves as a watchdog, because electronic sensors are unbiased and politically neutral.

7.2 Remote Sensing costs

Successful introduction of remote sensing does not depend solely on technical capabilities. Irrigation managers and policy makers will shift to advanced information technologies if the they get better results at equal or lower costs. The value of remote sensing data relies therefore on the balance of costs and benefits. The financial consequences of using remote sensing technologies becomes apparent only after investing in equipment, devices, and skilled labor necessary to process and interpret the images.

7.2.1 Material and software costs

Material and software costs consist of (i) image purchases and (ii) the purchase of software licenses. Technological breakthroughs in digital imaging systems and high speed computers are making the purchase and processing of satellite images more affordable. Irrigation performance can be the best explored by means of thermal infrared satellites. The following earth resources satellites, or a combination of them, are found suitable:

- MODerate resolution Imaging Spectrometer (MODIS) (http://modis-land.gsfc.nasa.gov/)
- Advanced Very High Resolution Radiometer (AVHRR) (http://www.oso.noaa.gov/poes/)
- Landsat (http://landsat7.usgs.gov)
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (http://asterweb.jpl.nasa.gov)

These four satellites can be divided into lower resolution (MODIS and AVHRR) and higher resolution images (Landsat and ASTER). The advantages of daily available low-resolution 1 km images (MODIS, AVHRR) are as follows:

- Vast coverage, suitable for huge irrigated alluvial plains
- Short time intervals (if clouds permit)
- Suitable for describing dynamic irrigation processes
- No costs for raw image data

The advantage of high-resolution satellite images (Landsat/ASTER) with a pixel resolution of 30 m are as follows:

- Ability to spot individual fields and thus smallholder irrigation processes
- Potential to link crop water consumption to specific fields and crop types
- Insight in spatial context of irrigation systems, notably non-uniformities in access to water and production opportunities

Low resolution data are free of charge available. For Landsat images, a contribution for the re-production of the data is charged. This fee is usually in the order of € 400 to 600, depending on the type of supplier. A Landsat image covers an area of 185 km x 185 km, hence the purchasing costs per unit of land are low (€ 0.00015/ha). ASTER images are technically superior to Landsat. There is however no systematic data acquisition, data archiving and data distribution policy in place. This limits the operational applicability of ASTER data. The purchasing costs for an ASTER image are typically € 70 for an area of 60 km x 60 km. The latter brings the image costs per unit of land at € 0.00019 /ha, being slightly more than for Landsat.

A full irrigation analysis study with high resolution images will require minimally one Landsat or ASTER image per month to capture the dynamic changes in irrigation systems. For a growing season of 6 months, image purchasing costs will thus be € 3600 for an area maximally comprising 185 km x 185 km.
The costs of software packages varies highly between virtual free software to commercial packages (IDL, Erdas Imagine) of € 10,000 to € 25,000, depending on the optional tools selected.

7.2.2 Labor costs

Image analysis require a remote sensing laboratory within existing water management institutes. Alternatively, the work is executed by external consultants. In both cases, specialized labor is an essential component of the total remote sensing costs.

An external consultant can work more effectively and in a shorter time span, but the daily rates will be relatively high. Recruiting a remote sensing specialist by the water management institute is for instance in first notice cheaper (only gross salaries need to be paid), but not necessarily a saving of costs, because it may require more time to complete a certain image processing task.

Bastiaanssen (1998) summarized the costs of land use mapping for five countries. Table 11 indicates that these costs range from $0.03/ha (India) to $0.20/ha (Morocco), and the range is essentially controlled by national or foreign staff doing the analysis, besides the size of the area and the type of imagery selected. The average cost to conduct a land use study is $ 0.14/ha.

Table 11 Costs of land use mapping with remote sensing data

Country	Annual costs (incl. labor and images) ($ / ha)
Philippines	0.08
Maldives	0.03
Morocco	0.20 to 0.80
Indonesia	0.08 [1]
Indonesia	0.13 [2]
India	0.10 [3]
India	0.03 [4]
Average	0.14

Costs of conducting remote sensing studies were also discussed and summarized during the World Bank Expert Consultation on Remote Sensing and Drainage held in Ede/Wageningen in May 2001 (Bos *et al.* 2001). The group of 20 experts concluded that the price for monitoring irrigation and drainage performance is approximately $ 0.80/ha for an irrigation scheme of 20,000 ha, but that the price drops to $ 0.08/ha for an area of 500,000 ha.

The annual costs for properly operating an irrigation performance program in a remote sensing unit for an irrigation country like Sri Lanka has been discussed and estimated at $180,000/yr (~$ 0.23/ha/yr). This number is based on using a mixture of high and low resolution images and on local salaries and wages (Dr. Palitha Bandara, personal communication).

Bastiaanssen and Hellegers (2007) reviewed the opportunities to provide operational remote sensing services in groundwater-borne irrigation projects. They concluded that the cost for an irrigation and groundwater abstraction study is approximately $ 2.00 ha for a high-resolution 30 m product and a study area of 15,000 to 30,000 ha.

[1] National staff involved in image processing
[2] International staff involved in image processing
[3] Study area smaller than 100,000 ha
[4] Study area larger than 250,000 ha

For, a low-resolution 1000 m product, the cost will not be more than $0.2 and cover 100,000 to 200,000 ha. This consistent statement on spatial scale vs. costs, was also recognized in the earlier reviews.

Since the IPAT tool is developed and made freely available to users, the total costs for irrigation performance studies will not be affected.

In conclusion, it can be summarized that the costs of remote sensing varies essentially between higher resolution (30 m) and lower resolution (1000 m) satellite data. Also the size of the irrigated area has a strong effect. In none of the historic studies, the costs have exceeded $ 2/ha. The lowest minimum costs are $ 0.08/ha. In the majority of the remote sensing studies, the costs for land use mapping are $ 0.14/ha and for irrigation performance are $ 0.66/ha.

7.3 Irrigation management costs

7.3.1 Investment costs

These costs of irrigation systems consist of fixed costs for capital investments and variable operation and maintenance (O&M) costs (such as energy and labor costs), which increase with the volume of water delivered through the canal network or extracted from aquifers. Table 12 shows - as an example - the fixed and variable costs of alternative irrigation technologies considered in the planning of the Crimea irrigation project in the Ukraine. The fixed costs consists of the investment and fixed maintenance costs. The variable costs relate to energy, petrol and labor.

Table 12 Costs of the various on-farm irrigation technologies including equipment and canals in Ukraine (after Hellegers and Perry, 2004)

Technology	Fixed costs ($/ha/yr)	Variable costs ($/ha/yr)
Surface irrigation	80	20
Mechanised surface irrigation	85	20
Drip irrigation	600	6
Hose piple	250	40
Average	254	22

A comparative analysis of investment costs in US-borne sprinkler systems is provided in (http://www.ag.ndsu.edu/pubs/ageng/irrigate/ae91w.htm). The capital costs included the purchase of the irrigation system, the well-pump-motor, the pipe, valves and the electric panel. The capital costs are $ 280/ha, $ 293/ha, $ 309/ha, $ 291/ha, $ 242/ha for center pivot, pivot with corner, linear move, big gun and side rolls. Further, the owner will experience depreciation costs, interest on investment and insurance costs. Considering an economic lifetime of 25 years, the annual investment costs for a center pivot system are $ 11.2 /ha/yr. For a center pivot, the total annual operating and ownership costs are $ 41/ha/yr. The total annual fixed and variable costs are thus $ 52/ha/yr, being considerable lower than the data suggested in Table 12 for Ukraine.

The World Bank reviewed irrigation investments achieved in the period between 1950 and 1993, and concluded that the average investment in sub-sahara Africa is $ 18,000/ha or $ 720/ha/yr if a period of 25 years is considered. Over against that, South Asia had a 13 times lower investment of $ 55/ha/yr.

As a first approximation, the average capital investment of Ukraine, USA, sub-Saharan Africa and Asia yields to $ 260/ha (linear average of 4 values)

7.3.2 Operation & Maintenance Costs

The financial objective related to the operation of irrigation schemes is to establish financially sound mechanisms of cost-recovery. This implies that staff salary costs, logistics and supplies need to be self-sufficient and collected from water service fees. Hellegers and Perry (2004) summarized the O&M costs of five irrigation systems in different countries with diverging infrastructures (see Table 13). These costs relate to surface water systems. The O&M costs vary between $12 /ha/yr (Indonesia) and $165 ha/yr (Egypt). The average value of) & M costs in operational irrigation systems is $ 70/ha/yr.

Table 13 Cost Structure to Operate Irrigation Schemes in Various Parts of the World

Irrigation Scheme	Country	Total O&M Costs ($/m^3)	Water Consumption (m^3/ha)	Total O&M Costs ($/ha)
Kemry	Egypt	0.01	16,500	165
Haryana	India	0.0013	10,000	13
Tadla	Morocco	0.017	7,400	125
Brantas	Indonesia	0.001	12,000	12
Crimea	Ukraine	0.012	3,000	36
Average				70

7.3.3 Price of water

The costs of water can be virtually nothing, but there is a certain price for making the resource available to the users. Wahaj (2001) mentioned that pumped groundwater in Punjab in a particular distributary is sold between $ 0.03 to $ 1.67/1000 m^3. Kloezen (2002) investigated the production costs in the Lerma-Chapala basin in Central Mexico. In Lerma-Chapala, water trading is established among WUAs, and the prices vary with season and year. In the summer of 1995, the price varied between $ 0.40 to $ 0.93/1,000 m^3, but in the summer of 1997, these prices rose to $ 3.44 and $ 3.50/1,000 m^3 (a factor of 4 to 10 higher). Because of the high water applications

(20,000 m^3/ha/yr) - that exceed crop water needs by 100 percent - total water charges in this part of Mexico can reach $70/ha/yr.

Hellegers and Perry (2004) found a price paid by irrigators of $4.00/1,000 m^3 in Egypt, $5.00/1,000 m^3 in India, $200/1,000 m^3 in Morocco, $2.00/1,000 m^3 in Indonesia, and $20.00/1,000 m^3 in Ukraine. This water price is based on the volume of water depleted by consumptive use. The cost for annual water consumption for these five global systems is on average $34.00/ha. Assuming that these irrigation systems have an average efficiency of 50 percent, the amount of water supplied needs to be doubled. This implies that the price of water can be $68.00/ha, similar to Kloezen's findings (2002).

7.4 Cost-benefit evaluation

Water policymakers and water managers are expected to use advanced information technologies, if the associated gains and results exceed the additional costs. The value of remote sensing data relies on the balance between costs and benefits. When combined with economical profits from using remote sensing technologies, it becomes feasible to quantify some key aspects of costs (Table 14) and benefits (Table 15), although no complete monetary flows can be obtained.

Table 14 Benchmark results of costs in irrigation systems

Item	Average costs ($/ha/yr)	Range costs ($/ha/yr)	Average costs (%)
Investment costs	260	11 to 720	65.2
O&M costs	70	12 to 165	17.6
Costs of water	68	2 to 200	17.1
Remote Sensing costs	0.66	0.02 to 2	0.2
Total	398,66		100

Hence, by inclusion of remote sensing monitoring of irrigation systems, the total costs will increase by $ 0.66 /ha or 0.2 %. Since it is more plausible to be self-reliant on operational costs, a remote sensing dimension will increase the variable costs by 0.5 %. These values are a relatively low component of the operational costs, and in fact negligible small. The costs of water are for instance 100 times higher than remote sensing costs.

The benefits of remote sensing can be divided into the category of (i) reducing operational costs and (ii) increasing the benefits (see Table 15). Although all stakeholders will agree that improving transparency and trust will be beneficial for the management of irrigation systems, especially large scale systems, trust is non-quantifiable. The same applies for the conservation of groundwater extractions, implementation of water rights to ensure legal access to irrigation water resources and environments with sustainable soil fertility, soil salinity and controlled water table fluctuations.

Nevertheless, it turns out that for the other issues the economical benefits vary between 14 to 180 $/ha/yr with an average value of $ 79/ha/yr if only one of the items becomes a success. The overall cost benefit ratio is thus 0.66 : 79. Benefits are more than 100 times the costs necessary to make these benefits possible.

Table 15 Benchmarking benefits in irrigation systems after inclusion of remote sensing data. The data is based on two cropping seasons per year, 12,000 m^3/ha/yr of actual evapotranspiration, a water productivity of 1.0 kg/m^3 per unit of water consumed, a crop yield of 12 ton/ha/yr for two crops and a gross return of $ 1800/ha ($ 0.15/m^3)

Results from remote sensing technologies	Relative change (%)	Reducing costs ($/ha/yr)	Increasing benefits ($/ha/yr)
Improved transparency	Non-quantifiable	Non-quantifiable	Non-quantifiable
Decreased non-beneficial use of water	+10	-	180
Enhanced food production	+5	-	90
Increased crop water productivity	+5	-	90
Reduced applied water	- 20	14	-
Conserved groundwater use	Non-quantifiable	Non-quantifiable	Non-quantifiable
Higher water revenue collection	+30	21	-
Implemented water rights	Non-quantifiable	Non-quantifiable	Non-quantifiable
Environmental sustainability	Non-quantifiable	Non-quantifiable	Non-quantifiable

Because of the increasing crisis in water and food security, the preparedness for investment in remote sensing technology is growing. By further promoting the technical advances, the trend of increasing interest may continue. The availability of the IPAT tool will help to get access to, and interpret the remote sensing data. The lack of awareness of both the technological contribution and the limited costs, are the main source for low applicability.

8 Conclusions and outlook

8.1 Conclusions

The use of remote sensing imagery and processing techniques has proven to have many advantages, to name a few (i) large spatial coverage, (ii) objective information, (iii) applicable to many sectors (water, nature, agriculture, etc.) and (iii) in most cases it is relatively easy and cheap to obtain data, with free downloading from the web as its summum. In the past many scientific efforts have been made to extract useful information from remote sensing data for the use in the water sector. Examples are land use classification, evapotranspiration mapping, precipitation radar, run-off determination. However, the use of this information for operational use in the water management sector is very limited by a number of shortcomings. Two key constraints for the operational use of remote sensing in the water sector are identified:

- Low user-friendliness of remote sensing data. It takes too much effort to incorporate remote sensing data into everyday water management. During the previous projects a lot of attention has been paid on the questions 'what information can be derived from remote sensing?' and not enough attention is being paid to embedding remote sensing technologies into operational use for local counterparts, i.e. the question 'how to use these remote sensing data?'.
- The second constraint is that irrigation engineers are not acquainted with the possibilities of remote sensing. For them, remote sensing stands for land use mapping.

To overcome these problems a basic, easy-to-use ArcGIS user interface, called Irrigation Performance Assessment Tool (IPAT), is developed in consultation with the end users. IPAT can calculate a standardized set of remotely sensed irrigation performance indicators.

The selection of indicators is carried out on the basis of (i) a screening on whether they can be calculated by remote sensing techniques, (ii) the simplicity of the indicator and (iii) wishes and requirements of the knowledge provider (Alterra), the service provider (WaterWatch) and the end users (IHELR, INTA and CNA). A set of four standard indicators is formulated, being the Depleted Fraction, Field Application Ratio, Relative Evapotranspiration and Crop Water Productivity.

The IPAT tool requires an ArcGIS 9.1 (or higher) license and a Spatial Analyst license. The organization of the database of IPAT gives the following possibilities:

- Use of tabular data as well as raster data (such as satellite images) for calculations.
- Spatial selection by use of administrative units. Geodata (either in raster-format or polygon-format) with administrative units is required.
- Spatial and administrative aggregation by use of administrative levels.
- Selection in time by use of period types.

- Aggregation in time by distinguishing period input-types and period output-types.
- Linking spatial vector data such as irrigation lines, irrigation pumps, meteo stations to administrative levels. Links are made in the tables by codes, so that the vector data itself it not obligatory.
- High flexibility for user to add indicators, administrative levels, period types and subelement data (data on rain, irrigation, etc.).

The IPAT tool is tested for three pilot areas: the NCC irrigation system in Crimea, Ukraine, the Yaqui irrigation system in Mexico and the Rio Dulce irrigation system in Argentina. The main conclusion is that IPAT is a perfect tool for evaluation of the performance of irrigation systems. More specific the advantages of IPAT are:

- The ability to create new performance indicators very easily is praised. By simply changing or adding a formula, a new performance indicator can be created.
- If remote sensing data only are available, IPAT proofs to provide still a lot of useful indicators (ETA, ETR, CWP, biomass production).
- Once the input data is entered in IPAT, it works relatively easily, which means it can be used in a operational way by irrigation engineers.

A piece of software as IPAT is never finished. It can always be improved and users always have their specific requirements and wishes. However, during the pilot studies the following issues were recognized as drawbacks in the operational use of IPAT:

- The software costs to run IPAT are high. ArcGIS 9.1 (or higher) together with the Spatial Analyst extension is needed to run the IPAT user interface. Currently, ArcView is used in general as the standard GIS platform all over the world. To purchase a ArcGIS license costs more than 5000 Euros. However, as ArcGIS will replace ArcView as the standard GIS analysis software, it is foreseen that in future all organisations working with GIS will change to ArcGIS. A short term solution is found by the purchase of a demo ArcGIS license, which costs about 100 Euro, but the license is limited to 6 months.
- IPAT only has a small data availability check. If necessary data is missing to run IPAT, a short message is given that data is missing and the model stops. No clear insight is given in which data is missing.
- Data input is not automated yet. Data has to be imported in IPAT model by means of opening the corresponding access database, which is a time consuming and precise work.

A cost-benefit analysis of the use of remote sensing data and the IPAT tool is made to check if the use of remote sensing data in irrigation water management is economically feasible. The IPAT tool is freely available (at http://www.waterwatch.nl/IPAT) and this is no additional financial burden. It proofs that the remote sensing costs are on-average only 0.2 % of the total costs of an irrigation system (or 0.5 % of the O&M costs). Moreover, the remote sensing costs of 0.66 $/ha/yr outweight the average benefits worth $ 79/ha/yr. These benefits include decreased non-beneficial us of water leading to increase of irrigated areas, enhanced food production by better farm management technologies in general, increasing water productivity through saving of applied water and higher revenue collection from all beneficiaries that use water. Non-quantifiable benefits such as increased transparency, conserved groundwater use, implementation of water rights and reduced environmental degradation also exist. They increase the longer term financial and environmental sustainability of the irrigation system.

8.2 Outlook

Over the last decades water management became more and more important as the threats of water, whether from sea, river or rain, became more and more obvious. Various water relates catastrophes, such as floodings and droughts, illustrated the fact that good water management is of crucial importance for mankind. Policy makers are aware of the importance of good water management and are currently working out new policies (water framework directive, etc.) to deal with these issues. Consequently, financial resources for water management are created or enlarged.
However, this policy making process and also the implement of it should be based on objective information over large areas and time spans. Traditional data information sources, such as meteorological data and flow measurements, are not sufficient to cover the need for information. Remote sensing data can overcome this problem as it strength is the large spatial coverage. However, as observed in this report, the use of remote sensing data is currently very limited, due to a lack of tool to 'digest' the pile of remote sensing information.
The IPAT tool is developed to overcome these problems. The project consortium evaluated the IPAT tool positively as a easy-to-use tool with understandable outcomes and wishes to inform the wider community of water managers and related experts of the existence of IPAT. The following strategy will be handled:

- The IPAT software, manual and test dataset will become freely available at internet (done within the current project).
- The project consortium will support the use of IPAT and adapt it, if bugs or other unforeseen errors are still present in the current software.
- Several promotional and informative papers will be published in water magazines, such as H2O.
- A scientific paper about IPAT will be publishes in a water related journal in 2007 and presented at a water related seminar.
- The project partners will look permanently for new sources of finance to further develop the IPAT tool.
- A cooperation with international water institutions like FAO, ICID and IWMI will be sought after to investigate the joint possibilities for further development and promotion of IPAT.

Literature

Adams, L., 2006. http://pangea.stanford.edu/~addams/yaqui/index.htm.

Allen, R.G. & W.G.M. Bastiaanssen, 2005. 'Editorial: Special Issue on Remote Sensing of Crop Evapotranspiration for Large Regions', Irrigation and Drainage Systems 19: 207-10.

Allen, R.G., L.S. Pereira, D. Raes & M. Smith, 1998. 'Crop evapotranspiration - Guidelines for computing crop water requirements', FAO Irrigation and drainage paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 p.

Bakker, M. & W.G.M. Bastiaanssen, 1999. 'Earth observation for environmental impact assessment in irrigation and drainage projects - a demostration project for the Tungabhadra irrigation pilot project II, India', NRSP-2 report 99-13, Delft, The Netherlands, 42 p.

Bastiaanssen, W.G.M., 1998. 'Remote Sensing in Water Resources Management: The State of the Art', International Water Management Institute, Colombo, Sri Lanka.

Bastiaanssen, W.G.M. & L. Chandrapala, 2001. 'Remote sensing aided water resources management in Sri Lanka', NRSP-2 report 00-29, Delft, The Netherlands, 30 p.

Bastiaanssen, W.G.M. & M.G. Bos, 1999. 'Irrigation Performance Indicators Based on Remotely Sensed Data: A Review of Literature,' Irrigation and Drainage Systems 13: 291-311.

Bastiaanssen, W.G.M. & P.J.G.J. Hellegers, 2007. 'Satellite Measurements to Assess and Charge for Groundwater Abstraction', in (eds.) Dinar, Safwat and Agwe, Cost Recovery of Irrigation and Drainage Projects: Wishful Thinking or Difficult Reality?, World Bank (in press).

Bastiaanssen, W.G.M., D.J. Molden & I.W. Makin, 2000. 'Remote sensing for irrigated agriculture: examples from research and possible applications', Agricultural Water Management, 46, 137-155.

Bastiaanssen, W.G.M., E.J.M. Noordman, G. Hiemstra & A.C.W. Lambrechts, 2001. 'Naar remote sensing ondersteunende beregeningsbesluiten', NRSP-2 report 01-13, Delft, The Netherlands, 27 p.

Bastiaanssen, W.G.M., E.J.M. Noordman, H. Pelgrum, G. Davids & R.G. Allen, 2005. 'SEBAL for spatially distributed ET under actual management and growing conditions', Journal of Irrigation Drainage Engineering 131, 85-93.

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes & A.A.M. Holtslag, 1998. 'The Surface Energy Balance Algorithm for Land (SEBAL): Part 1 formulation', Journal of Hydrology 212-213, 198-212.

Bastiaanssen, W.G.M. & S. Ali, 2003. 'A new crop forecasting model based on satellite measurements applied across the Indus Basin, Pakistan', Agric. Ecosyst. Environ. 94, 321-340 (2003).

Belmonte, A.C., A.M. Jochum & A.C. García, 2003. 'Space-assisted irrigation management: towards user-friendly products', ICID Workshop on Remote Sensing of Crop Evapotranspiration, Montpellier, 17 Sep 2003, 12 p.

Bos, M.G., M.A. Burton & D.J. Molden, 2005. 'Irrigation and drainage performance assessment: practical guidelines', CABI Publishing, Wallingford, UK. 158 p.

Bos, M.G., S. Abdel-Dayem, W.G.M. Bastiaanssen & A. Vidal, 2001. 'Remote Sensing for Water Management: the Drainage Component', Report World Bank Expert Consultation, Ede-Wageningen, May 15 to 16, 2001. The World Bank, Washington, DC.

D'Urso, G., 2001. 'Simulation and management of on-demand irrigation systems: a combined agrohydrological and remote sensing approach', PhD thesis, Wageningen University, Wageningen, The Netherlands, 174 p.

Del Blanco, I.A., Rajaram, S., Kronstad & W.E., Reynold, M.P., 2000. 'Physiological performance of synthetic hexaploid wheat-derived populations', Crop Sci. 40, 1257-1263.

DEMETER, 2002. 'Demonstration of earth observation advisory services', http://www.demeter-ec.net

FAO, 1999. 'SIMIS - Scheme Irrigation Management Information System', FAO Land and Water Digital Media Series 6.

Garatuza-Payan, J. & C.J. Watts, 2005. 'The use of remote sensing for estimating ET of irrigated wheat and cotton in Northwest Mexico', Irr. Drain. Syst. 19, 301-320.

Hellegers, P.J.G.J. & C.J. Perry, 2004. 'Water as an Economic Good in Irrigated Agriculture, Theory and Practice', Agricultural Economics Research Institute (LEI), Report 3.04.12, The Hague, The Netherlands

Hoedjes, J.C.B., R.M. Zuurbier & C.J. Watts, 2002. 'Large aperture scintillometer used over a homogeneous irrigated area, partly affected by regional advection', Boundary-Layer Meteorol. 105, 99-117.

Kloezen, W.H., 2002. 'Accounting for Water, Institutional Viability and Impacts of Market-Oriented Irrigation Interventions in Central Mexico', Ph.D. Thesis, Department of Water Resources, Wageningen University, ISBN 90-5808-657-7.

Lobell, D.B., G.P. Asner, J.I. Ortiz-Monasterio & T.L. Benning, 2003. 'Remote sensing of regional crop production in the Yaqui Valley, Mexico: estimates and uncertainties', Agric. Ecosys. Environ. 94, 205-220.

Lobell, D.B., J.I. Ortiz-Monasterio, C.L. Addams & G.P. Asner, 2002. 'Soil, climate, and management impacts on regional wheat productivity in Mexico from remote sensing', Agric. For. Meteor. 114, 31-41.

Menenti, M., 2000. 'Irrigation and Drainage', in G.A. Schultz and E.T. Engman (eds), Remote Sensing in Hydrology and Water Management, 377-400. Berlin: Springer Verlag.

Molden, D., R. Sakthivadivel, C.J. Perry, C. Fraiture & W. Kloezen, 1998. 'Indicators for comparing performance of irrigated agricultural systems', Research report 20, IWMI, Sri Lanka.

Pavlov, S.S., 2004. 'Analysis of the irrigation management institutions in North Crimea Canal System, Ukraine', MSc thesis, Wageningen University, 126 p.

Prieto, D.R., 2006. 'Modernization and the evaluation of irrigation practices in the Rio Dulce irrigation project, Santiago del Estero, Argentina. Una tarea de todos', PhD Thesis, Department of Irrigation, Wageningen University, Wageningen, The Netherlands, 292 p.

Roerink, G.J. & O.I. Zhovtonog, 2005. 'Towards Sustainable Irrigated Agriculture in Crimea, Ukraine: A Plan for the Future', Alterra, Wageningen, 138 p.

Sakthivadivel, R., C. Fraiture, D. Molden, C.J. Perry & W. Kloezen, 1999. 'Indicators of Land and water productivity in irrigated agriculture', Water resource development, Vol. 15, Nos. 1/2, 161-179.

Tasumi, M., R.G. Allen & R. Trezza. 'Rapid operational estimation of at-surface reflectance and albedo from Landsat and MODIS satellites', Remote Sensing of Environment (accepted).

Vidal, A. & J.A. Sagardoy, 1995. 'Use of remote sensing techniques in irrigation and drainage', Water Report 4, FAO, Rome, Italy: 201 pp.

Wahaj, R. 2001. 'Farmer Actions and Improvements in Irrigation Performance below the Mogha', Ph.D. Thesis, Department of Irrigation, Wageningen University, Wageningen, The Netherlands.