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DIGITAL ANALYSIS OF SATELLITE DATA AND NUMERICAL SIMULATION APPLIED TO IRRIGATION WATER MANAGEMENT BY MEANS OF A DATABASE SYSTEM

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ABSTRACT

A procedure is described to combine computational applications, involving several software/hardware configurations, to calculate and map three irrigation performance indices.

The software hardware configuration fulfills five basic functions:

- digital image processing;
- handling of vector data (maps);
- hydrological calculations;
- numerical simulation;
- solution of optimization problems

Each component of the procedure is described in detail.

An example of application, dealing with the Rio Tunuyan Irrigation Scheme is presented. The entire procedure could be developed into a PC-based software package.

INTRODUCTION

In February 1988 NEDECO*, ICW**, ILRI*** and INCYTH**** started cooperation in a project on irrigation water management. It resulted from earlier cooperations between IILA***** and INCYTH (1977-1982) and ICW and INCYTH both involving irrigation water management (Menenti et al., 1982; Menenti et al., 1985) and (since 1984) remote sensing. Its objective is to develop a method to evaluate and optimize the water distribution of large irrigation schemes using satellite remote sensing and (numerical) modelling.

Considering the availability of data at INCYTH the Rio Tunuyan Irrigation scheme, located in the province of Mendoza, Argentina, was chosen to serve as a study area.

The paper describes the results of a research project in which satellite data are used to evaluate and optimize the water distribution of large irrigation schemes. The project contains a variety of computational applications involving several software/hardware configurations.

The map of the scheme's layout and the soil map are digitized using ARC-INFO, a package to create and handle a geographical database. A set of satellite images is classified using the ERDAS image-processing package. The classification can be performed discriminating irrigated and non-irrigated areas or discriminating crops or crop associations. These packages are running both on personal computers (IBM AT) and a VAX computer. In order to be able to combine the three information layers (layout, soil classes, classified image) they are all converted to raster format and transferred to the ERDAS-workstation.

Given the existing water distribution schedule, amounts of water applied per unit of time are calculated using a simple program on the VAX computer. To calculate the potential and actual evapotranspiration for different crops and crop-soil combinations two hydrological models are used, CRIWAR and SWATRE. Both can be run on PC as well as VAX. In order to exchange data between VAX and PC a communication program named KERMIT is used. Finally all information is combined using the LOTUS-123 spreadsheet program, running on an Olivetti-280 PC. All indices

* NEDECO = Association of Engineering Companies for Development,
** ICW = Institute for Land and Water Management Research. ICW is from 1989 onwards part of the Winand Staring Centre for Integrated Land, Soil and Water Research
*** ILRI = International Institute for Land Reclamation and Improvement
**** INCYTH = Insituto Nacional de Ciencias y Tecnicas Hidricas
***** IILA = Instituto Italo-Latino Americano

can now be calculated easily. Given the values of these indices the water distribution can be optimized.

APPROACH

All input point-data, such as meteorological data and soil-physical properties must be referred to the same reference units. These units are defined as the command areas of the tertiary irrigation canals. The processing of these input data results in the following information:

- amount of water needed in each tertiary unit per unit of time (10 days, month);
- amount of water applied in each tertiary unit per unit of time (idem);
- different irrigation performance indices;
- optimized water distribution schedule.

To quantify the performance of irrigation water management three indices were defined (Menenti, 1988):

1. The amount of water applied to one hectare of irrigated land within a specific reference unit divided by the amount of water applied to one hectare of irrigated land in the larger unit of which the reference unit is a part.
2. The amount of water that is needed in a specific reference unit to maintain potential evapotranspiration divided by the amount that is actually applied to that unit.
3. The difference in actual evapotranspiration in situations with and without irrigation within a unit divided by the amount applied to it.

Based on the values of these indices the water distribution schedule can be optimized.

Ad.1. To calculate the value of the first irrigation performance index a classification discriminating irrigated and non-irrigated area is sufficient. The classified image has to be combined with a digitized map of the irrigation infrastructure yielding the irrigated area per unit (Visser, 1987). The volumes of water applied to all reference units have to be calculated on a 10-day or monthly basis from the water distribution schedule. Now the values of the first index can be determined for all units.

Ad.2. Potential evapotranspiration is crop dependent so a crop classification is needed to be able to calculate the value of the second index for a given reference unit. The potential evapotranspiration of all crops occurring in the area is calculated using the model CRIWAR (Vos et al., 1989) given the necessary meteorological data. CRIWAR is based on the methods described in

FAO (1983). Combination of the classified image and the digitized map results in the area of each crop in a specific reference unit. The total potential evapotranspiration and the value of the second index can now be calculated, again on a 10-day or monthly basis.

Ad.3. To determine the values of the third index the total actual evapotranspiration of the different reference units has to be calculated in situations with and without irrigation. Actual evapotranspiration depends on the type of crop and its growing stage, meteorological circumstances, groundwater level and soil hydraulic properties. Therefore a soil map has to be digitized and data on the soil hydraulic properties of the soil layers in the different soil units have to be gathered. The actual evapotranspiration for the different crop-soil combinations in

Table 1. Definition of irrigation performance indices; for each index the required land use data are indicated explicitly, with their source; the ancillary data necessary to calculate each index are also indicated

Irrigation performance index	Land use data needed	Source	Model	Ancillary data
1. $e_{ij} = \frac{d_{ij}}{d_i} = \frac{V_{ij}/A_{ij}}{V_i/A_i}$	irrigated - non-irrigated area	satellite image		discharges
2. $e_i = \frac{E_{p_k} . A_{ik}}{V_i}$	crops or groups having a similar k_c	satellite image	CRIWAR	discharges meteorological data
3. $e_i = \frac{E_k - \hat{E}_k . A_{ik}}{V_i}$	crops	satellite image	SWATRE	discharges meteorological data soil properties

V_i = volume supplied to unit i ($m^3.month^{-1}$)
V_{ij} = volume received at unit j, within higher order unit i ($m^3.month^{-1}$)
A_i = irrigated area in unit i (m^2)
A_{ik} = area of crop k in unit i (m^2)
E_{p_k} = potential evapotranspiration of crop k ($m.month^{-1}$)
E_k = actual evapotranspiration of crop k, irrigated ($m.month^{-1}$)
$\hat{E}_k$ = idem, non-irrigated ($m.month^{-1}$)
k_c = crop coefficient

situations with and without irrigation can now be determined by simulation using the model SWATRE (Feddes et al., 1978; Belmans et al., 1983). To obtain the area of each crop-soil combination in all reference units three information layers have to be combined; irrigation infrastructure map, soil map, result of crop classification. The total evapotranspiration for the irrigated and non-irrigated situation and the values of the third index can now be determined for all reference units given the volumes applied.

Table 1 shows the formulae of the three irrigation performance indices. It also contains the land use data needed and the models used. The complexity of the calculations increases from the first to the third performance index, as shown by the increasing amount of required ancillary data. Moreover some of the data required, e.g. to calculated the third index, are rather difficult to obtain, like the hydraulic properties of unsaturated soil. This implies that the first index allows a finer spatial resolution in the appraisal of performance than the third index. Therefore, a trade-off has to be established in practice. After the values of the different indices have been calculated the water distribution in the scheme can be optimized based on their values. An optimization model can be applied yielding an improved water distribution schedule.

DESCRIPTION OF STUDY AREA

The Rio Tunuyan Irrigation Scheme is located in the province of Mendoza, Argentina just east of the Andes at an elevation of 650 m. It is an arid region with an average yearly rainfall of about 210 mm. The surface is almost flat with a slight inclination towards the east. The area irrigated by the irrigation scheme is about 70 000 ha.

DESCRIPTION OF SOFTWARE AND HARDWARE CONFIGURATIONS

The operations necessary to apply the approach described in the previous section are briefly described here. Figure 1 shows an overview of all the operations that must be performed including the software-hardware configurations used and the transfer of data between them. The raw data are listed in the upper left corner of the overview. The activities on the right can be characterized as Geographical Information System (GIS)-activities involving three information layers (classified image containing land use classes, map of irrigation infrastructure, soil map). They have to be rectified and combined in order to obtain the information needed: the distribution of land use classes and soil

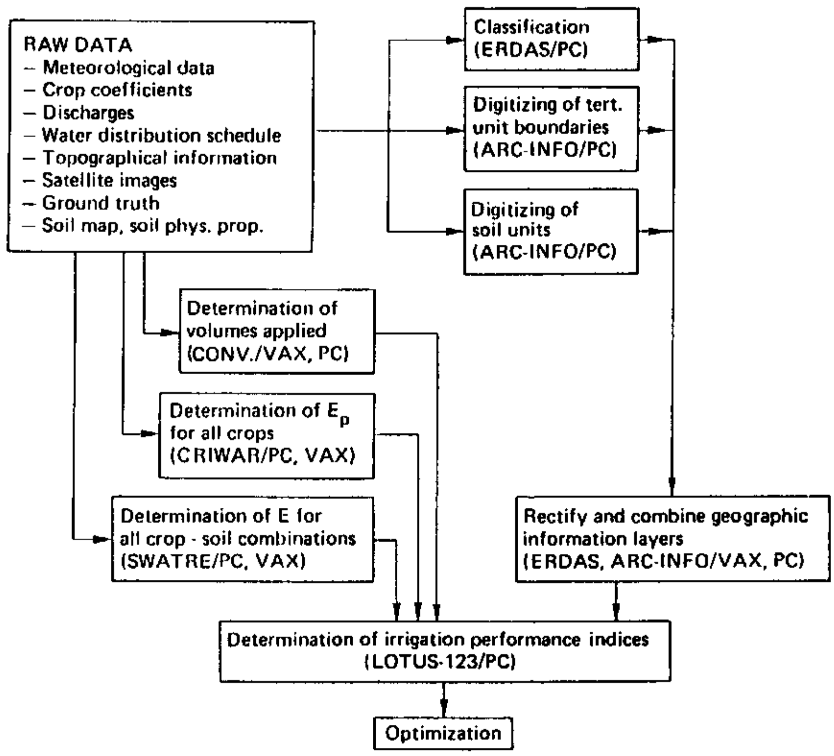

Fig. 1. Chart showing raw data and operations as required to calculate irrigation performance indices and to optimize water allocation

units in the different reference units. The activities on the left consist of the calculation of the volumes applied to each reference unit and the hydrological modelling. The use of the models results in the potential (CRIWAR) and the actual (SWATRE) evapotranspiration of all crops or crop-soil combinations. All information is combined in a LOTUS-123 worksheet to calculate the values of the irrigation performance indices.

Raw data

A short list of the required input data is given to emphasize that satellites provide only part of the information, although accurate land use data are essential to improve irrigation management.

Classification of land use

To map land use, automatic classification of satellite images is performed by means of the ERDAS image processing software package. Three methods to map irrigated areas using LANDSAT-TM images were tested:

- Ratios method

  An artificial image was created consisting of:

  $$\frac{\text{band 4}}{\text{band 3}} \cdot \frac{\text{band 4}}{\text{band 5}} \cdot \text{constant}$$

  The values in this image were separated in two groups supposing the pixels having the lower values not to be irrigated and the ones having a higher value to be irrigated. The threshold value between the two classes was chosen in such a way that an area of about 200 ha with a known land use was classified optimally.
- Principal components method
  A principal component analysis was performed on bands 3, 4, 5 and 7. The same procedure as described above was applied to the first principal component.
- Automatic classification method
  A supervised automatic classification was performed using two training sets for the irrigated and the not irrigated area both of about 200 ha.

Table 2 shows the irrigated area of five tertiary units resulting from the different classification methods - obtained by combining the classified image and the map of the irrigation infrastructure - and the results of a field survey done in March 1988. Table 3 shows the difference between the results of the three methods and the ground truth. It must be noted that the image was taken in 1986 but as almost all crops in the area are perennial the comparison - albeit with care - could still be

Table 2. Irrigated areas of five tertiary units according to three different classification models and field survey

Tertiary unit	Irrigated area (ha)			
	ratios method	PC method	automatic classification	field survey
Gonzales	126.9	115.5	124.8	139.2
Alcaraz	86.6	97.6	73.8	79.9
Orrego	88.6	87.8	93.7	102.7
Day	112.1	109.3	113.8	125.4
Segundo Razgo	325.4	328.2	336.1	356.0

Table 3. Accuracy of classification methods given as: (irrigation.area (class) - irrigation.area (survey)) / irrigation.area (survey)

Tertiary unit	Classification accuracy (%)		
	ratios method	PC method	automatic classification
Gonzales	8.8	17.0	11.5
Alcaraz	8.4	22.2	7.6
Orrego	13.7	14.5	8.8
Day	10.6	12.8	9.3
Segundo Razgo	8.6	7.8	5.6
Mean	10.0	14.9	8.6

made. It indicates that the results of the method using a PC-analysis are less accurate than those resulting from the two remaining methods. For all three methods the comparison was done for an area six times larger than the area considered as a reference for the classification of the satellite images.

Digitizing of tertiary unit boundaries

The available maps of the scheme's layout appeared to be inadequate as indicated and improved by Pieters (1988). Tertiary canals had been located in the maps very roughly and the boundaries of their area of influence were not indicated. Therefore the exact location of the tertiary canals and the boundaries of their area of influence were determined during an extensive field survey covering the area of influence of the Viejo Retamo. Table 4 shows a comparison between area having water rights within the Viejo Retamo according to the tomero (person in charge of the water distribution) and the area having water rights according to the DGI (Departamento General de Irrigacion). It also shows the total area of influence of the Viejo Retamo resulting from a map made at the INCYTH and the same area resulting from the survey.

The boundaries of the tertiary units as determined during the survey were digitized using the ARC-INFO package.

Table 4. Area having water rights and total area according to different sources

Source	Area with water rights (ha)	Total area (ha)
Tomero	4789	
DGI	4435	
INCYTH		5006
Field survey		4902

Determination of volumes of water applied to each tertiary unit

From the tomero of the Viejo Retamo secondary unit, data on the water distribution were obtained for the period August '87 - February '88. Each tertiary unit has its own intake structure including a measuring weir, almost all with a known Q-h relation (Bos, 1987). The raw data consist of the opening time of the structure, the closing time and the head over the weir crest at both moments. A computer program was developed to convert these data to volumes of water applied per turn and per period of 10 days.

The figures on amounts applied per 10 days tend to fluctuate a lot. If a certain unit receives water on the 8th and 9th of the month and again on the 22th the amount applied in the second decade will still be zero. Therefore in further processing the amounts are added up to amounts applied per month.

Determination of potential evapotranspiration, E_p, for all crops

A crop classification was made using a multi-temporal method (Menenti et al., 1986) on images taken in the growing season '85-'86. This classification appeared to be inadequate. Two reasons can be given for this inadequacy:

- the high variability of soil cover within each crop class;
- the lack of enough reliable ground truth data.

In March '88 crops were mapped in several tertiary units. For several plots a more detailed survey was made concerning soil cover, age and condition of the crop, undergrowth etc. Two TM-images acquired on 15-3-'88 and 11-1-'88 have been ordered and will be analysed using these data. This, to determine if a crop classification is feasible for this area.

CRIWAR is a program that calculates, among other things, the potential evapotranspiration of a crop if its k_c and some meteorological data are known. The program is based on FAO (1983). Values of the k_c throughout the season for all crops occurring in the area were obtained (J.A. Morabito, 1989.

Table 5. Values of the crop coefficient k_c to obtain crop specific potential evapotranspiration as $E_p = k_c.E_0$ with E_0 being the reference evapotranspiration (Rio Tunuyan area, Mendoza, Argentina)

Crop	Crop coefficient k_c (-)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Grapes (Vina)	0.74	0.73	0.68	0.59					0.37	0.52	0.64	0.71
Grapes (Parral)	0.93	0.93	0.83	0.64					0.37	0.71	0.79	0.89
Peach	1.02	0.94	0.82	0.65					0.74	0.89	0.99	1.03
Pear	0.94	0.89	0.79	0.64					0.63	0.78	0.89	0.94
Apricot	1.02	0.94	0.82	0.65					0.74	0.89	0.99	1.03
Olive	0.68	0.67	0.64	0.60	0.55	0.49	0.44	0.51	0.57	0.62	0.65	0.68
Tomato	0.95	1.10	1.00	0.60					0.35	0.45	0.58	
Onion	0.90	0.75							0.55	0.75	0.85	0.90

Personal communication, INCYTH, Argentina). They are shown in Table 5. The necessary meteorological data are also available so the potential evapotranspiration can be calculated for all crops. Once a crop classification is made the total water requirement of all reference units can be determined.

Determination of actual evapotranspiration, E, for all crop-soil combinations with and without irrigation using SWATRE

SWATRE is a numerical model on water transport in the unsaturated zone. It needs a variety of input data among which the $h(\theta)$ and $K(h)$-relations of the different soil layers in the profile. According to a soil survey done in 1975 by INCYTH and INTA two soil units can be distinguished in the area of the Viejo Retamo. Data on the soil hydraulic properties of the layers occurring in those soil units consisted of five measurements of the volumetric water content of the soil at 0.1, 0.3, 0.5, 3, and 15 bar. The program RETC (Van Genuchten, 1986) was used to fit an analytical function to these measurements yielding an estimation of the different pF-curves. It also offers the possibility of estimating the K(h)-relation based on the same data given the saturated conductivity (Van Genuchten and Nielsen, 1985). All further necessary input data have been gathered as well and SWATRE can be run for all crop-soil combinations in the pilot area for both the irrigated and the non-irrigated situation.

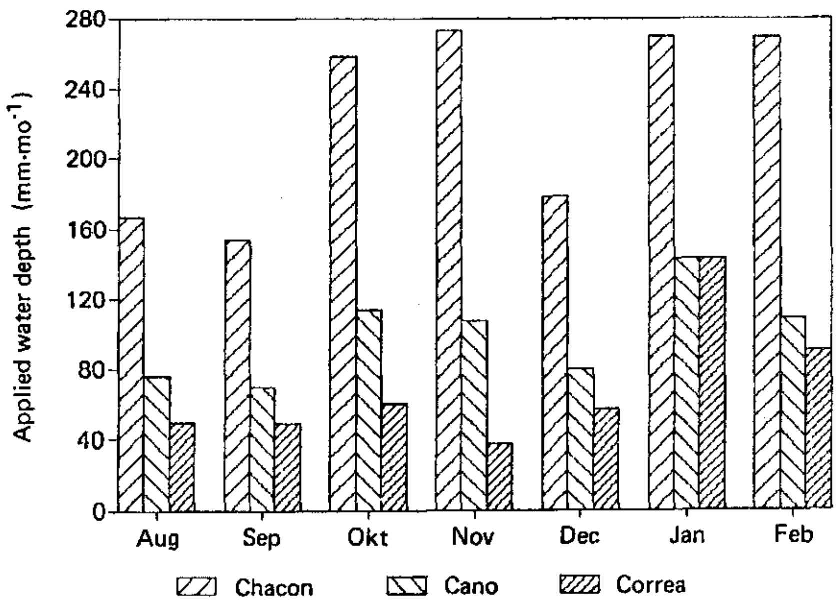

Fig. 2. Water depth (mm.month^{-1}) applied to one hectare of irrigated land for three tertiary units, Chacon, Cano and Correa, within the secondary unit Viejo Retamo. Large differences indicate deviations from the prescribed uniform water allocation policy

Determination of performance indices

Based on the irrigated areas in all tertiary units and the amounts of water applied to them the value of the first irrigation performance index has been calculated for all tertiary units in the pilot area. For this purpose a LOTUS-123 worksheet was developed. Fig. 2 shows the layer of water applied to one hectare of irrigated land in three tertiary units of the Viejo Retamo. Differences in supplied layers are caused by the fact that the actually irrigated area differs from the area with water rights according to which the water is supplied. Another worksheet has been developed to calculate the second index given the E_p for all crops and the crop distribution per tertiary unit.

Optimization of water distribution

To improve the water distribution in the scheme the values of the different performance indices have to be optimized. At this moment two software packages are available for the optimization of water allocation:

- An irrigation water management optimization package developed by Menenti et al. (1982);
- MINOS, a software-package to handle optimization problems based on linear programming.

CONCLUSIONS

Given the results that have been achieved within the project until now it can be concluded that the combined use of satellite data and hydrological modelling offers an adequate approach to assess the performance of large irrigation schemes.

Combination of geographical information derived from the satellite data, the results of the hydrological modelling and some additional information offers the possibilty to quantify the performance of the current water supply. The LOTUS-123 spreadsheet program has shown to be a very practical tool in performing the necessary calculations.

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