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HYDROLOGICAL ASPECTS OF MENDOZA-ARGENTINA

Satellite Images and Numerical Modelling

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nota

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CONTENTS

Page

1. INTRODUCTION

In November 1984, this Author was invited by the Centro Regional de Investigaciones Científicas y Technológicas (CRICYT) and by the Departamento General de Irrigación (DGI), both at Mendoza, Argentina to give a short, introductory course on quantitative analysis of digital satellite images. The course was considered by both Institutions to be the first step towards the organization of a working community, to be built out of the current staff of the participating Institutions and dealing with both research and practical applications.

The physiography and arid climate of the region of Mendoza (Fig. 1, 2) have naturally focussed the aims of research Institutions and of Technical Agencies present in the region on issues closely related to irrigation water management in the extensive cultivated area.

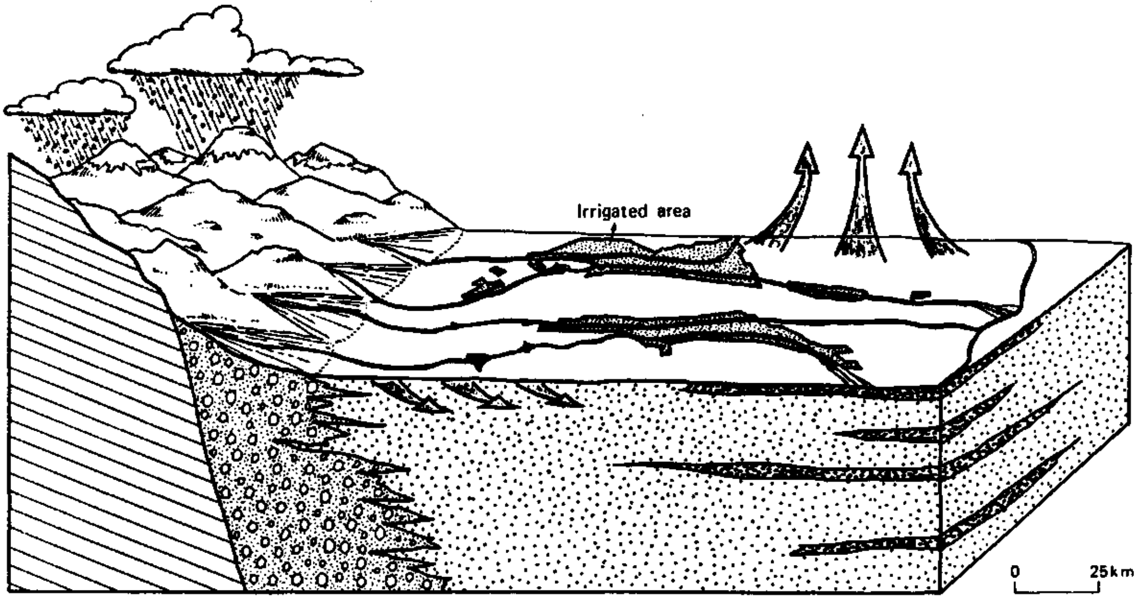


Fig. 1. Sketch of physiography and relevant hydrological processes in the region of Mendoza-Argentina

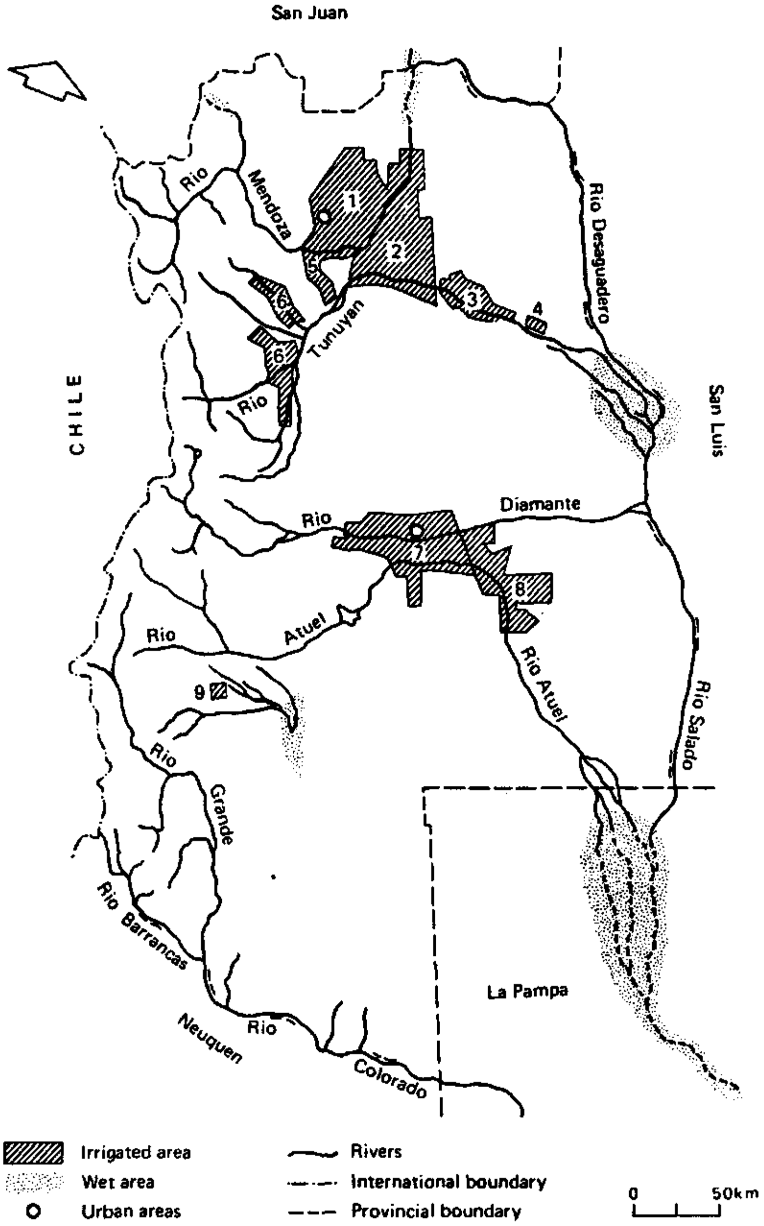


Fig. 2. Main irrigation districts in Mendoza-Argentina

1 = río Mendoza; 2 = río Tunuyán Medio; 3 = Santa Rosa;
4 = La Paz; 5 = Ugarteche; 6 = Valle de Uco; 7 = San Rafael;
8 = General Alvear; 9 = Malargue

The concept of water management implies that optimality (or improvement) is achieved by attuning water delivery or withdrawal to local requirements and constraints. Water management is, however, intrinsically non-local, since water resources are being managed for an area within which both requirements and constraints are actually variable. It appears, therefore, that the quantitative determination of requirements and constraints is essential for solving any water management problem. The ideal determination method should not smooth out the actual variability in space and time.

In principle two classes of methods can be applied to determine the required variables. First, estimation methods (models) involving the calculation of the variables with other data, such as calculation of water requirements by simulating soil-water flow on the basis of soil hydrological properties and weather observations. Second, direct observation of areal patterns of the variables by means of remote sensing.

Models have the advantage that evolution in time can accurately be described, but they are limited in that actual field conditions have to be schematized. This implies establishing grid cells and estimating the required input values for each grid cell. Since remote sensing gives information in terms of patterns, it has the potential to help in establishing the grid cells.

There appeared, therefore, to be a clear scope for fostering quantitative applications of satellite data to study hydrological and water management processes in the region. Accordingly, a research and development program was formulated in 1984 to fully exploit the interdisciplinary potential of a number of narrowly defined research projects aiming at closely interrelated objectives.

In the following sections the stages of the research and development program, as completed so far will be presented. Finally the forthcoming follow up phases of this program will be outlined, after an appraisal of achievements.

2. A RESEARCH AND DEVELOPMENT PROGRAM: 'Regional hydrology and irrigation water management'

2.1. General

Historically, both growth and progress of the population of Mendoza have been made possible by irrigated agriculture. The expansion of irrigated land has by now reached a critical stage from both an economical and physical point of view. A wealth of practical problems have emerged, thus arousing the interest of a broad spectrum of research Institutions and Technical Agencies. There has, therefore, been a natural concentration of efforts to tackle issues related to irrigation water management in the very large irrigated area in the region (500 000 ha having water rigths). A large fraction of current issues may be grouped together under the following headings:

A. Water supply to the irrigated area including glaciology, snowfall mapping, estimation of ice and snow melting, rainfall-runoff relationships, flashfloods in the urban area.

B. Efficient irrigation water management including: monitoring of the actual irrigated area; mapping of irrigation efficiencies; attuning of water allocation to actual crop water requirements.

C. Monitoring and prevention of undesired side-effects of mismanagement of irrigation water.

D. Assessment of the regional impact of irrigation water management, including impact of overirrigation on the vegetation of the arid surroundings of it.

Without going into details (see also MENENTI and NIEUWENHUIS, 1986), it can be understood that all these issues require the determination of spacial patterns of environmental (hydrological) properties. This is necessary to describe quantitatively the processes involved. An usual approach to improve our understanding of hydrological processes is by means of numerical simulation models.

A logical outcome of the above was to organize a joint effort of a number of Institutions in Mendoza to bring to fruition the rather large resources currently spent on many, quite loosely coordinated, efforts. Specifically the objectives of such research and development program were established as being:

A. to augment the applicability of numerical models describing the hydrology of snow, ice-caps and rainfall-runoff by means of satellite data analysis and by adapting the models to use best such data;

B. to improve irrigation water management by improving the quantity, quality and detail of available data on irrigation water use, namely actually irrigated area and crop water requirements, and on the extent of waterlogging and salinization. Such areal data can be collected to a relevant extent by means of satellites and can be fed into models to simulate and to optimize water allocation;

C. to improve current knowledge on growth conditions of natural vegetation (rangeland and forests) in the arid areas downstream of the irrigation districts; this include mapping of phreatofitic vegetation and appraisal of the cattle-raising potential of rangelands, with both issues related to the impact of return flow from the irrigated area on growth conditions in the arid areas. Knowledge of this aspect is quite insufficient as regards both the distribution of vegetation communities and yearly biomass accumulation. Again mapping can be greatly improved with satellite images and crop growth simulation models can be applied to relate growth to soil water balance.

2.2. Components of the program

This research and development program includes five sub-projects:

1. Management of the irrigation infrastructure: monitoring of the actually irrigated area, flow measurement and control.
2. Monitoring crop water requirements within the irrigation districts of Mendoza, including crop mapping, determination and mapping of evapotranspiration and of crop water stress.
3. Mapping of secondary soil salinity and of very shallow groundwater table, including hydrological analysis of salt accumulation processes.

4. Modeling of snow melting and of rainfall-runoff, including the determination with satellite measurements of input data such as snow and vegetation cover.
5. Analysis of hydrological processes affecting vegetation growth in the arid lands of Mendoza, including mapping of vegetation patterns and of biomass accumulation rate.
6. Improvement and development of numerical methods for satellite data analysis.

Scientific and organizational management of the program is done on the basis of the organizational chart in Fig. 3. Members of the Steering Committees are the Chairman or Directors of the participating Institutions. Their responsibility is to secure the necessary financial resources, to monitor the scientific progress of the projects and to guarantee that project activities keep in line with the operational objectives of each institution. The project adviser operates on the basis of a broad mandata by the Steering Committee to translate guidelines into operational activities. The Project Manager is responsible for the inter-institutional coordination of these activities, while his Assistant takes responsibility for the day - to - day implementation of this inter-institutional cooperation. Specific tasks, as required for this implementation are carried out by members of the Project Operations Committee.

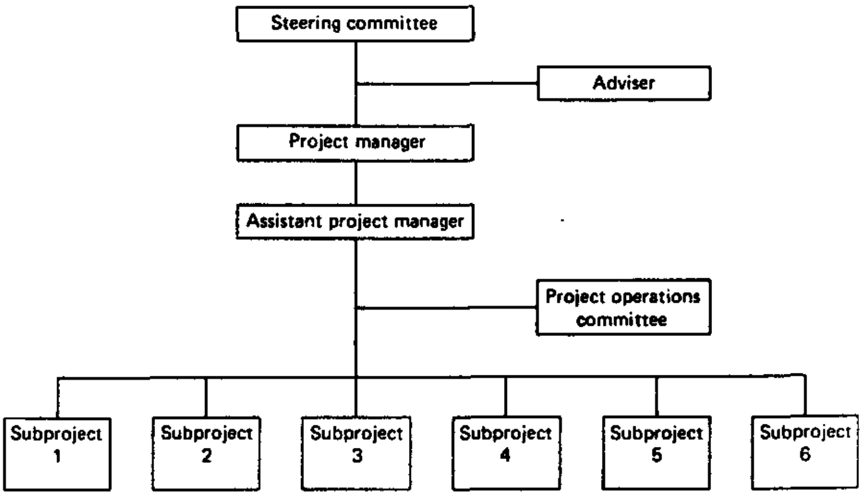


Fig. 3. Organizational chart of management procedure of the Research and Development Program in Mendoza-Argentina

The program is partly funded out of the ordinary budget of the participating Institutions and partly by external Agencies, both National and International.

The Institutions participating to the Program are:

- Instituto Nacional de Ciencia y Técnica Hídricas (INCYTH) - Centro Regional Andino (CRA)
- Centro Regional de Investigaciones Científicas y Tecnológicas (CRICYT)
  - . Area de Electrónica e Informática (IIACE)
  - . Area de Investigaciones en Zonas Aridas (IADIZA)
  - . Area de Ciencias de la Tierra (IANIGLA)
- Departamento General de Irrigación (DGI)
- Instituto Nacional de Tecnología Agropecuaria (INTA)
- Universidad Nacional de Cuyo (UNC) - Facultad de Ciencias Agrarias (FCA)
- Dirección Provincial de Agropecuaria (DPA)
- Dirección Provincial de Catastro DPC).

In the following paragraphs short abstracts will be presented of the six sub-projects.

2.3. Managing the irrigation infrastructure of Mendoza (sub-project 1)

The goal of this project is to develop and apply methods to improve the allocation of irrigation water and, therefore, the overall irrigation efficiency.

The following components can be identified:

- Definition of specific improvements both technological, e.g. automatization of irrigation water conveyance, and organizational, e.g. tasks and scope of irrigation users' associations, necessary to implement particular water management procedures as identified, for example, by means of optimization models.
- Mapping and monitoring of the actually irrigated land by means of satellite data analyses.

- Set up of a Geographic Information System to link maps of irrigated land with maps of the irrigation canal network and of tertiary units.
- Appraisal of the impact of a rapidly changing land use on irrigation water management.

2.4. Monitoring crop water requirements (sub-project 2)

The goal of this project is to develop and test a method to map crop water requirements and to detect eventual crop water stress.
The following components can be identified:

- Crop mapping by means of multitemporal analysis of satellite data, including analysis and collection of phenological observations.
- Calculation of actual and potential evapotranspiration by combining meteorological data and satellite measurements.
- Detection and mapping of eventual crop water stress by relating vegetation indices, as obtained by combining satellite reflectance measurements in the red and near infrared spectral ranges, to surface radiation temperature and to reflectance measurements in the middle infrared (Thematic Mapper bands 5 and 7).

2.5. Mapping of secondary soil salinity and of drainage requirements (sub-project 3)

The goal of this project is to map areas of exceedingly high soil salinity and to assess the actual impact of overirrigation on salts build-up in the soil and on shallow groundwater.
The following components can be identified:

- application of a numerical model of salt and water balance in the soil to simulate the effects of actual allocation of irrigation water;
- analysis of satellite data to map areas affected by very high salt contents and by very shallow groundwater table and to assess the temporal variability of these areas;
- collection of field data on soil salinity, depth of shallow groundwater table and crop conditions.

2.6. Modeling of hydrological processes

The goal of this project is to validate and apply numerical models of hydrological processes such as snow melting in relation with forecasts of water supply, rainfall-runoff in the small basins of the piedmont and flash floods in the immediate surroundings of the urban area of Mendoza.

The following components can be identified:

- improvement of the current method to forecast streamflow during summertime by mapping snowcover and estimating snowaccumulation with satellite data;
- determination of curve number, required as input to rainfall-runoff models, by assessing vegetation cover with satellite data;
- determination of land use in the urban areas of Mendoza to apply hydrological models of flash floods;
- morfometric analysis of natural drainage pattern to obtain the required input data to apply a model relating rainfall to runoff on the basis of density and architecture of the drainage patterns.

2.7. Hydrology and vegetation growth in the arid lands of Mendoza (sub-project 5)

The goal of this project is to improve the current understanding of the interrelation between the hydrological regime of the arid surroundings of Mendoza, with special attention to the impact of return flow from the irrigated land, and growth of natural vegetation.

The following components can be identified:

- mapping with satellite data of paleohydrography of the arid, flat portion of Mendoza to identify potential drainage channels and wet areas;
- detailed vegetation mapping with Thematic Mapper data in relation with paleohydrography to verify the existence of a hydrological connection between the irrigation districts and natural vegetation, via rivers or groundwater; mapping with satellite data of vegetation growth conditions to asses rangeland potential for exploitation;
- application of crop growth simulation models to relate quantitatively hydrological conditions to biomass accumulation.

2.8. Numerical methods for satellite data analysis (sub-project 6)

The goal of this project is to provide better methods for digital satellite data analysis to the scientists working on specific application-oriented projects within the framework of the program.
The following components can be identified:

- implementation of a few numerical classification algorithms;
- intercomparison of these classification algorithms;
- development of a geometric correction algorithm;
- development of procedures to combine maps with images.

3. INTRODUCTORY SHORT COURSE ON QUANTITATIVE ANALYSIS OF SATELLITE IMAGES (November 1984)

3.1. Outline of the course

The first step of the R/D program described in Chapter 2 was to provide a number of scientific and professional staff members of different institutions in Mendoza (see Appendix I) with basic, elementary knowledge of remote sensing by satellites. The introductory course took place from November 26 through December 12, 1984. The following lectures were given by this Author:

- capabilities of systems of satellite-borne sensors;
- radiation in the atmosphere;
- interaction mechanisms between radiation and land surface;
- shortcomings of systems of satellite-borne sensors;
- satellite data collection systems;
- direct vs indirect information: the integration of satellite data with ground-measurements;
- energy balance of the land-surface;
- measuring terms of the land-surface energy balance by means of satellites: approximations;
- multi-spectral analysis of satellite images;
- multi-temporal analysis of satellite images.

Two lectures were given by ing. S. Leguizamon of IIACE as an introduction to digital image processing by means of the systems (COMTAL VISION ONE/20) available at CRICYT/IIACE.

To carry out the hands-on training, included in the course on digital image processing, five topical working groups were established. Selection of topics and membership of working groups were the outcome of a preparatory meeting (16 nov. 1984) with the participants. During this meeting an inventory of the tasks of all participants could be made. The topical working groups were:

1. Multitemporal analysis of satellite data applied to crop mapping;
2. Multispectral analysis of satellite data applied to land use mapping;
3. Vegetation resources of the arid lands of Mendoza;
4. Vineyards census, including unrooting and abandonment;
5. Mapping of soil salinization and shallow groundwater.

Besides the hands-on training, practical work by participants included field-checks of the image products obtained by means of digital processing. Each group spent at least four hours working with the digital processor and at least one day in the field.
A workshop presentation of final results by the participants concluded the course.

3.2. Highlights

The most important outcome of the course was the proof that digital analysis of satellite data was a workable concept in Mendoza and that there was a well structured user community in Mendoza, with clearly identified practical applications. The image processor COMTAL VISION ONE/20 of CRICYT/IIACE had been largely underused till the course and no organized effort had been deployed to promote applications of this technique.
Furthermore a number of basic image processing techniques were for the first time tested and applied on behalf of the course.
Too little time could be dedicated by the working groups to their specific topics for the final results to be of any relevance. It is worth mentioning, however, that even the analysis of Landsat MSS images gave some improvements of the topografic maps with respect to the main irrigation canals. Another positive result was that saline soils did show up clearly in the usual MSS color composition (MSS7, red; MSS5, green; MSS4, blue). The same simple band combination did allow for a rather accurate delimitation of seepage sites in the south-western portion of the area irrigated by the río Mendoza. Finally, field checks done by the participants of working groups 1, 2 and 4 did confirm the reliability of Landsat MSS as regards mapping of irrigated land.

An evident shortcoming of the image processing system at CRICYT/IIACE was that no software was available to digitize maps and to superimpose them onto satellite images. This has been a major difficulty when attempting to relate local field observation with the images.

At the end of this short course the five working groups acquired a permanent character through formal agreements between the participating Institutions. The task set out for the working groups for the following period, i.e. until October 1985, was basically to gather a better practical experience with the image processing system.

4. WORKSHOP ON 'APPLICATION OF SATELLITE DATA TO HYDROLOGY AND WATER MANAGEMENT' 28 OCTOBER TO 15 NOVEMBER 1985, MENDOZA-ARGENTINA

4.1. Outline of the workshop

After the first introductory course, it was a mandatory next step to focuse the attention of the participants to the program on specific applications of satellite data to some aspects of regional hydrology. This was essentially done in the form of in-depth follow-ups of the work done by the working groups during the Introductory short course in 1984.
It was felt that it was not useful and effective to have a separate working group on mapping of vineyard conditions. Accordingly the following working groups were established:
1. Crop mapping.
2. Mapping of irrigated land and of irrigation infrastructure.
3. Mapping of soil salinization and of shallow groundwater.
4. Vegetation resources of the arid lands of Mendoza.

The list of participants is given in Appendix II.
During the workshop no formal lectures were given. An outline of the 1984 course was presented to a restricted group of newcomers by means of a four hour seminar. The activity of the working groups was organized according to a fixed schedule (see Table 1).

Tabel 1. Schedule of working groups activity; workshop on 'Application of satellite data to hydrology and water management', 28 October to 15 November 1985, Mendoza-Argentine

Schedule	Image processing (8 to 12 a.m.)	Appraisal of results/field work (8 to 12 a.m.)
Day 0		W.G. 1
Day 1	W.G. 1	W.G. 2
Day 2	W.G. 2	W.G. 3
Day 3	W.G. 3	W.G. 4
Day 4	W.G. 4	W.G. 1

This schedule was repeated throughout the duration of the workshop. In the afternoon extra-time was available to come with unforseen difficulties or to further in-depth analysis of eventually arisen issues. The meetings with each working group on the day preceeding each session proved quite effective to improve the overall progress of each mini-project.

As done in 1984, the results obtained by the working groups were presented by means of a seminar. A rather large audience (about 80 people) attented the seminar. Special attention was given to the preparation of the material to be used during the presentation. This preparation was an integral part of the training provided to the participants, since such presentations were a novelty for most of them.

4.2. Highlights

In comparison with the 1984 course, relatively much time could be spent this time on actual work. All participants got acquainted with the procedure to be applied to correct the raw Landsat data for sun zenith angle and sensor calibration. Since no measurements of atmospheric properties were available, atmospheric effects were accounted for by making use of reference targets to obtain correction factors. Although this does not give absolute correction factors, this procedure does allow for relative corrections to be applied, thus making multitemporal analyses techniques feasible.

The working group 1, dealing with crop mapping, focussed its activity on gathering spectral reflectance data of a number of crops at different growth stages by picking out the corrected MSS image pixels included in a number of plots, large enough to be identified in the MSS images.

These results will be presented in detail in Chapter 6. Here it will only be mentioned that a multitemporal analysis procedure to discriminate different intercropping schemes involving vineyards was identified. Furthermore a multitemporal discrimination scheme was established for the 8 crops or crop associations considered in this preliminary work.

Working group 2 set forth the activity initiated during the Introductory course, by carrying out field work to assess the geometrical properties of MSS images, particularly of hard copies made locally. It could be established that accuracy of the MSS images was about 5%. It is worthwhile to mention that the MSS images did point out a few errors in the available maps of the irrigation infrastructure. The overall conclusion otbe drawn from this work is that mapping irrigated land in conjunction with the irrigation infrastructure could be done with MSS data only for primary and secondary canals. A preliminary assessment was done by comparing the boundaries of large farms as established with MSS data respectivily airphotographs.

Working group 3 met major problems in establishing suitable ground truth sites. The problem was not so much pinpointing seriously affected crops, as the delimination of broader patches of irrigated land affected by salinity and/or shallow groundwater. A major complicating factor is that farmers tend to switch to more salt resistent crops, when increasing salinity starts to affect production. Spectral reflectance values extracted from corrected MSS images, anyhow did clearly show the effect of high salinity on crops. Areas affected by very shallow groundwater were easily identified.

The results obtained by working group 4, dealing with vegetation and hydrology of the arid lands of Mendoza were of particular interest. As a case-study, vegetation index values were related to vegetation cover within a small catchment (Divisadero Largo, 5 km^2). Because of the small size of the catchment, numerical arrays of individual pixel values were applied as row data.

The data arrays were colocated with the topographic, vegetation and soil maps by taking ground control points along a fault, which is quite evident in the satellite images. Sun zenith angle correction factors were tentatively calculated by taking into account surface dip and exposure.

It was established that areal patterns of surface reflectance were not affected by morphology to a great extent, probably because of the small length scale of relief in the catchment area. Temporal profiles of vegetation indices were obtained for the three main vegetation communites in the catchment area. These temporal profiles were tentatively related to rainfall and estimated actual evapotranspiration with promising results.

4.3. Organization of follow-up projects

At this stage this Author felt that a further step had to be under taken. Especially because of the many in-depth discussions with each workshop participant, which took place during the 'Appraisal of results' - sessions (see Table 1), a much better and detailed picture emerged of the individual needs and capabilities. So specific terms of reference were drafted for a number of participants, while still keeping the organizational framework in Fig. 3.

Between November 1985 and February 1986 a package of project proposals was prepared for submission to CONICET (Consejo de Investigaciones Científicas y Técnicas) as a three years multi-disciplinary and cooperative effort of the participating institutions (see also Section 2.2). Because of overall budgetary constraints, CONICET did not issue a call for proposals applying to multi-year projects. This had the consequence that the progress of the project did depend on gentleman's agreements between the parties concerned. Because of this unclear cooperation framework, many project activities were significantly delayed.

5. FIRST SYMPOSIUM: 'THE HYDROLOGY OF MENDOZA: SATELLITE IMAGES AND SIMULATION MODELS' (5 NOVEMBER 1986, MENDOZA-ARGENTINA)

5.1. Outline of the Symposium

As the 1985 workshop had shown, each of the four eastablished working groups did adress a number of different issues. These issues could better be adressed by individual scientists, with the working groups still having a clear organizational scope as regards field work, funding and exchange of practical knowledge on the use of the COMTAL image processing system.

Between November 1985 and October 1986 relatively little progress was achieved. So, at the beginning of my 1 month visit, a work programme was outlined for each one of the mini-projects which had been conceived as a result of the 1985 workshop. Each programme was aimed at obtaining some preliminary results within a four weeks period. This First Symposium was intended, therefore, to give a first, real, overview of the work being done by several individuals and institutions in the framework of the cooperative project.

Because of the rather narrowly defined issues being adressed by individual research efforts based on the analysis of satellite data, the time was ripe, in the opinion of this Author, to introduce the use of numerical simulation models to study different hydrological processes, having satellites as an important source of input data.

The full Program of the Symposium is given in Appendix III, here it is only mentioned that papers were grouped together by topic:

1. Introduction: to illustrate the hydrological consequences of over-irrigation, due to insufficient knowledge of the actually irrigated land;
2. Water supply: mountain and piedmont hydrology, with emphasis on snow melting forecasting and real time warning of flash-floods;
3. Irrigation water use: mapping of crop water requirements and monitoring of soil salinization and waterlogging;
4. Vegetation and hydrology of arid lands: mapping of vegetation communities and assessment of their dependence on hydrological conditions, including numerical simulation of water-limited biomass accumulation.

To better understand the interrelations between all these issues, one should re-consider Figs. 1 and 2. It can be appreciated that the Symposium was a first opportunity to illustrate a number of parts of that complex piecework which is the hydrological setting of Mendoza.

5.2. Highligths

In Chapter 6 a detailed overview of the most interesting results presented during the Symposium will be given. Furthermore, the Proceedings volume is in preparation and will be published during 1988. In this Section only general comments will be given.

The Symposium, and especially the preparatory work leading to it, was the first occasion to give shape to the individual research projects. This clearly appears by comparing the list of papers presented at the Symposium (Appendix III) with the general field of activity of each working group (Section 4.1). The set of papers does also properly illustrate how many facets have to be considered when dealing with the regional hydrology of Mendoza.

The single, most important result presented was, in this Author opinion, the determination of actually irrigated land in the entire province of Mendoza (see Figs. 1 and 2), as done with Landsat MSS data (Thomé). This opinion is based on the followings:

- the difference between actually irrigated land and the estimation of the Departamento General de Irrigación (see Table 2) did clearly indicate the potential impact of overirrigation on regional hydrology;
- this case study underscored the cost-effectiveness of using full MSS scenes on behalf of studies involving such large areas.

The results presented by Abraham should also be mentioned, since the natural drainage pattern, as mapped with MSS data does vividly illustrate the hydrological interrelation between irrigated land and the arid lands surrounding it.

6. APPRAISAL OF RESULTS

6.1. Results

6.1.1. Mapping irrigated land in Mendoza

The entire project is based on the concept that the huge water requirements and the excessive water allocation in the irrigation districts are the main driving factor of the regional hydrology (Figs. 1 and 2). This concept is supported by the data in Table 2.

When taking an irrigation project efficiency of 40% into account, the 477 520 ha having water rights require 8.5 10^9 m^3 a^{-1}. Since the actually irrigated area is 302 140 ha only, the actual gross water requirement are 5.4 10^9 m^3 a^{-1}. The Irrigation Water Authority at Mendoza (Departamento General de Irrigación) is since long applying an own estimation of actually irrigated land, namely 358 520 ha, with gross water requirements being 6.4 10^9 m^3 a^{-1}. This implies that over-irrigation is 1.10^9 m^3 a^{-1}. How real is this problem, is apply illustrated by a Landsat MSS scene of the southern part of Mendoza, which clearly indicates that downstream of the irrigation districts, natural vegetation cover is high with water supply being essentially return flow from the irrigation districts.

A great deal of attention is being given to assess the accuracy of the figures on irrigated land obtained with MSS data. Different image sampling methods have been compared (Thomé) and the relationship between land use classification accuracy, image texture and sensor resolution has been assessed (Dijk en Van Eijk). Particularly the accuracy of a classification algorithm has been compared by applying MSS and Thematic Mapper data to three land use patterns, the latter having a rather different typical agricultural field size. As illustrated by the graphs in Fig. 4 the three land-use types, i.e. large plots, small plots and diffuse land use have a clear season dependent texture. The work of Dijk and Van Eijk did show that results obtained with either MSS or TM are comparable as regards the large-sized-farms type of land-use.

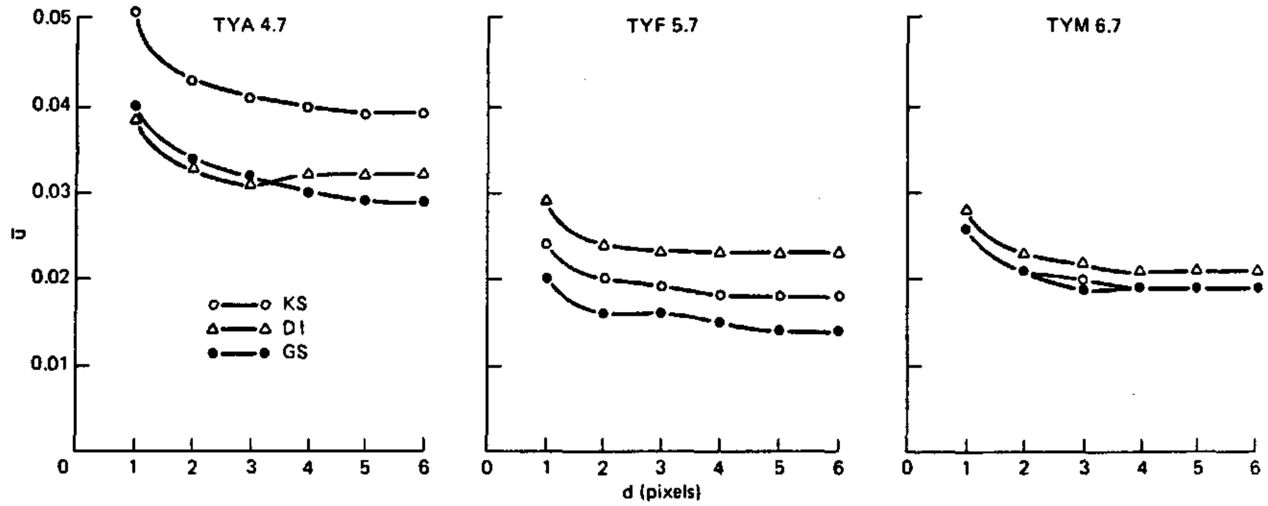


Fig. 4. Multitemporal texture analysis of uniformity of Landsat MSS data (Mendoza-Argentina)
(A) August 1984 (wintertime); (B) February 1985 (full vegetation cover); (C) March 1985 (end of growing season) (Dijk en Van Eijk)

The advanced characteristics of Thematic Mapper are badly needed, however, when one seeks to map irrigated land within individual irrigation water managements units (tertiary units).

It has been proven (Visser) that mapping of irrigated land within individual tertiary units is feasible. A case-study has been completed by mapping and digitizing the boundaries of a number of tertiary units in the Tunuyán irrigation scheme (Fig. 5). By means of a numerical classification algorithm, the land use pattern in the area has been obtained. Next, by applying an affine transformation to the elements of the classified image, the latter is overlaid on the digitized map of the tertiary units. Finally, pixels within each tertiary unit are counted for the class 'cultivated land'. The results obtained for the tertiary units shown in Fig. 5 (definitely) prove (see Fig. 6) that the actually irrigated land is much less than irrigable land.

Moreover other results presented by Visser do confirm that much less land is being irrigated than land having water rights. The overall figures in Table 2 are, therefore, confirmed with obvious implications about the urgency of improving irrigation water management by updating the data currently applied to establish water allocation schemes to tertiary units.

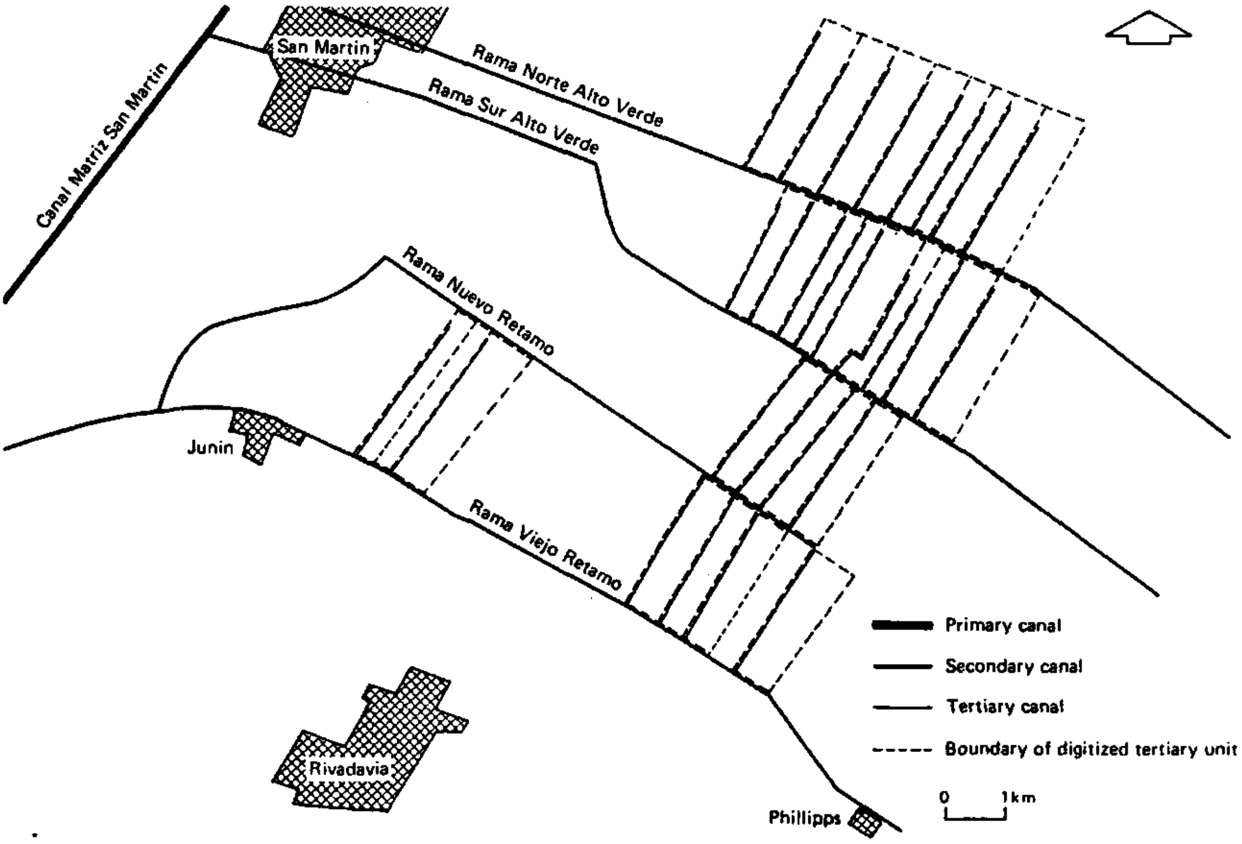


Fig. 5. Part of lay-out of río Tunuyán Irrigation Scheme showing digitized tertiary units (Visser)

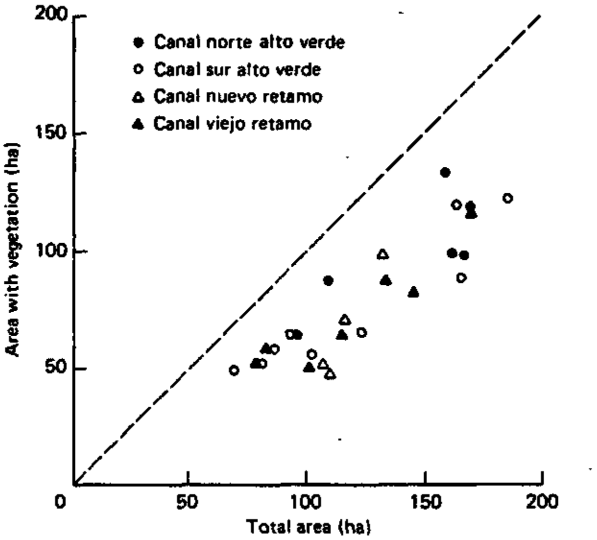


Fig. 6. Plot of cultivated land vs irrigable area by tertiary unit (Visser)

Table 2. Irrigated land, as obtained with Landsat MultiSpectral Scanner (MSS) data; irrigated land, as estimated by the Departamento General de Irrigación (DGI) and land having water rights; Mendoza-Argentina (Thomé)

Region	Irrigated land MSS (ha)	Irrigated land DGI (ha)	Water rights (ha)
North	178 040	202 680	265 360
South	129 100	155 840	212 160

6.1.2. Water supply

Snowmelting provides, through the rivers of Mendoza (see Fig. 2) most of the water needed to meet crop water requirements. To forecast total water supply for any given growing season, the most important piece of information is the snow covered area which can be easily mapped with satellite data (Maza, Cobos). The enhanced multispectral capabilities of the Thematic Mapper do allow for discrimination of snow and ice.

A rather more complicated issue is the contribution of rainfall in the piedmont area to water supply. Beside the case of the río Tunuyán upper basin, a trade off between adding runoff water to irrigation water, by using canals as reservoirs, and coping with flash-floods caused by storms in summer time must be established.

To this purpose a real time hydrological network has been established (see Fig. 7). Numerical models are being applied and evaluated to now-casting of flash floods. One of the most important parameters of such models is a runoff coefficient, which is usually estimated on the basis of vegetation cover and soil type.

Results obtained so far (Palero and Candia) indicate that relief does not affect reflectance to a great extent (see Fig. 8). This makes it feasible (see Fig. 9) to apply some vegetation index, e.g. the ratio of infrared to red reflectance, to estimate vegetation cover and next the required runoff coefficient.

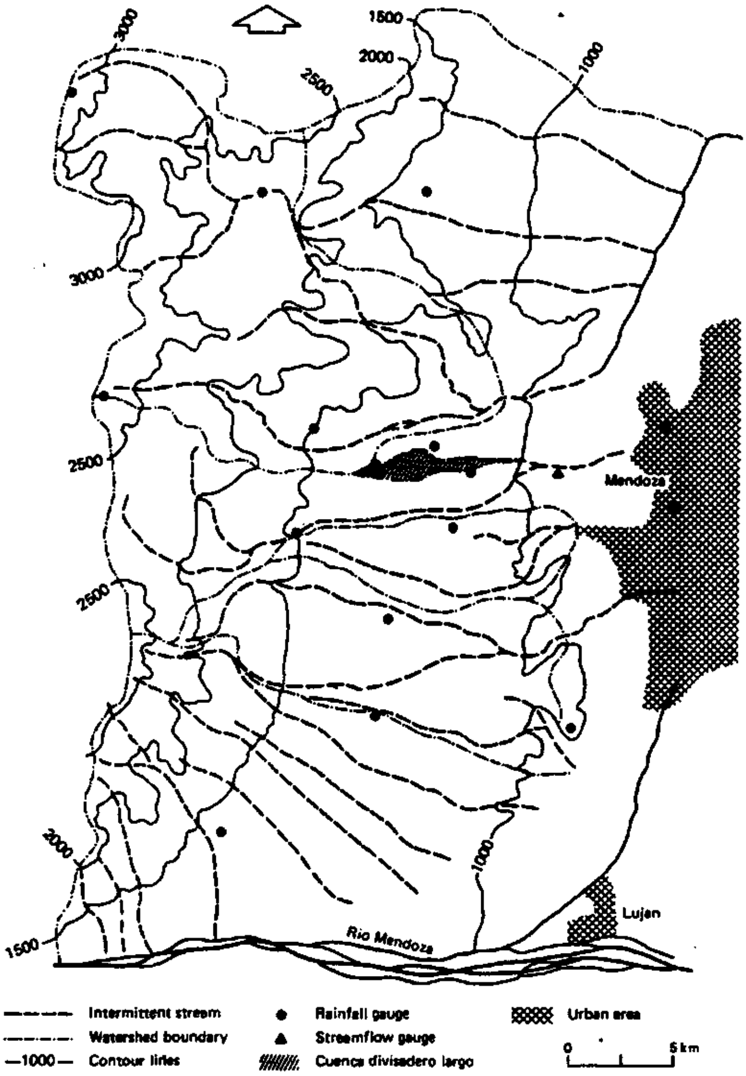


Fig. 7. Location map or real time hydrological network. Mendoza-Argentina (Roby et al)

Two approaches have been pursued to establish a relationship between vegetation cover and runoff coefficient, which is suitable for the characteristics of the catchments in the piedmont of Mendoza.
From one side the effect of vegetation and soil on interception, runoff and erosion is explicitly modelled (Vich). The processes indicated in Fig. 10A are explicitly described by means of equations, which are partly derived from theory and partly established by means of experiments, for each cell of a catchment, as sketched in Fig. 10B. The rainfall simulation experiments in the catchment of Divisadero Largo did prove that this approach is rather promising.

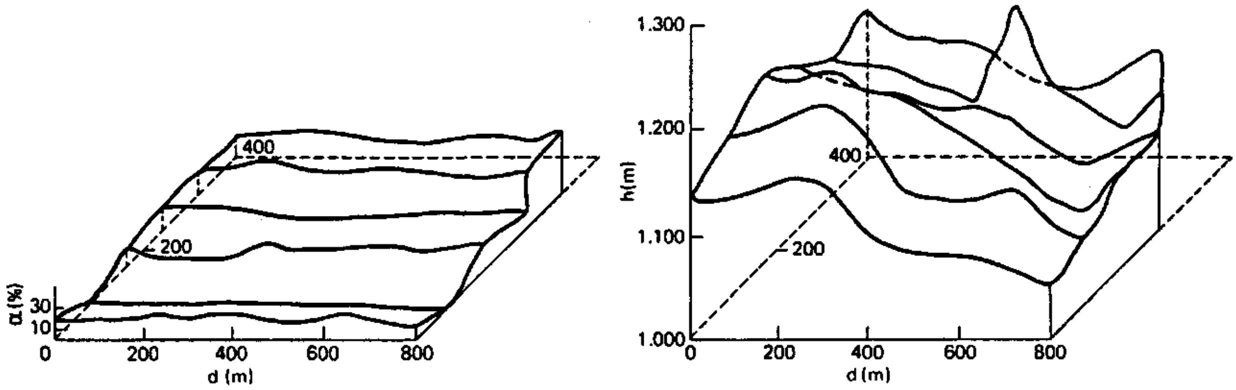


Fig. 8. Reflectance and relief in the catchment Divisadero Largo; reflectance data obtained with Landsat MSS data (Palero and Candia)

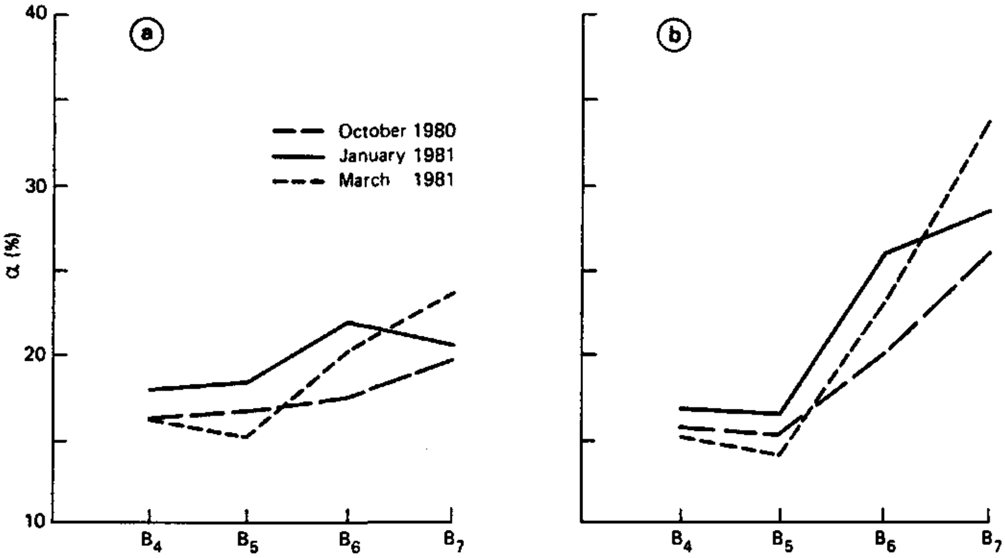


Fig. 9. Natural vegetation communities in the Divisadero Largo: Multitemporal pattern of spectral reflectance of: A) Larrea divaricata, 15%, vegetation cover; B) Zucagnia punctata, 5% vegetation cover (Palero and Candia)

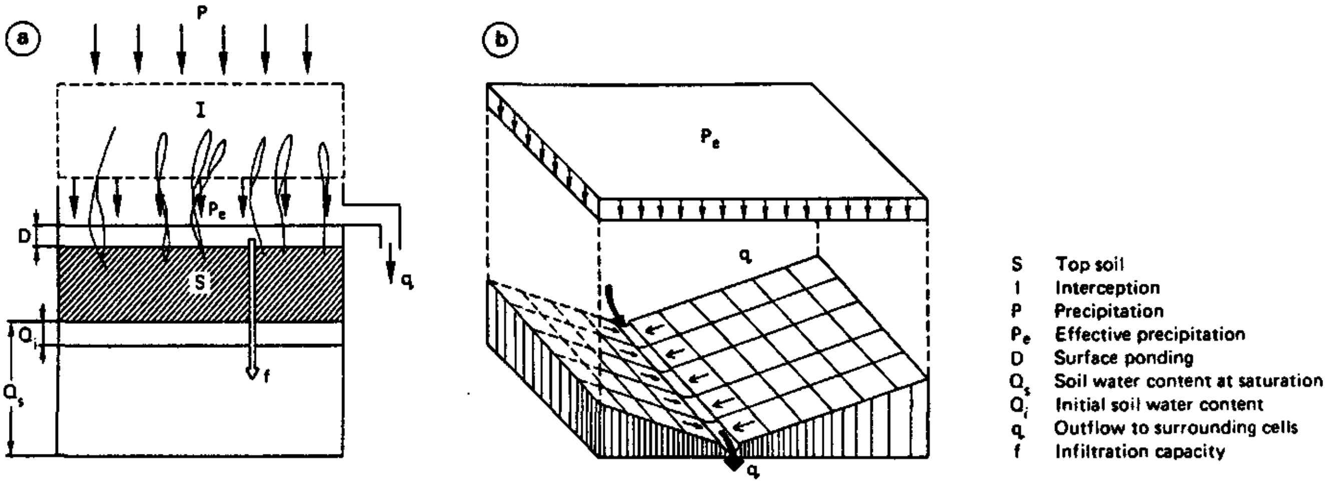


Fig. 10. Conceptual model of effect of vegetation on interception, run-off and erosion: A) sketch of relevant processes, B) conceptual scheme of a catchment (Vich)

The other approach is by rather empirically relating the run-off coefficient, via the curve-number CN (Roby et al), to vegetation cover or directly to a vegetation index obtained with satellite data. A map of CN-values is obtained (Fig. 11) and next streamflow is calculated and compared with measurements collected at the catchment closure. By trial and error a rainfall-run-off simulation model can be calibrated; this gives a pattern of CN/values which can be related to the distribution of a vegetation index in the catchment. This calibration effort is not always necessary, since the first-guess estimation of CN may give satisfactory results already (see Fig. 12). The challenge here is to establish an approach to apply the rainfall-run-off model to other catchments. To this end, explicit modelling of interception, run-off and erosion at the microscale, as done by Vich, can give an useful insight to improve the extrapolation procedure.

Furthermore, mapping of landscape units (González Loyarte) can also be a rather useful guide to mapping CN-values, since each unit basically relates to an association of a dominant vegetation community, a dominant soil type and morphology, with special emphasis on drainage pattern. A clear example are the results obtained in the watershed of Rio Las Tunas where digital enhancement of TM image composition does already highlights individual units (González Loyarte).

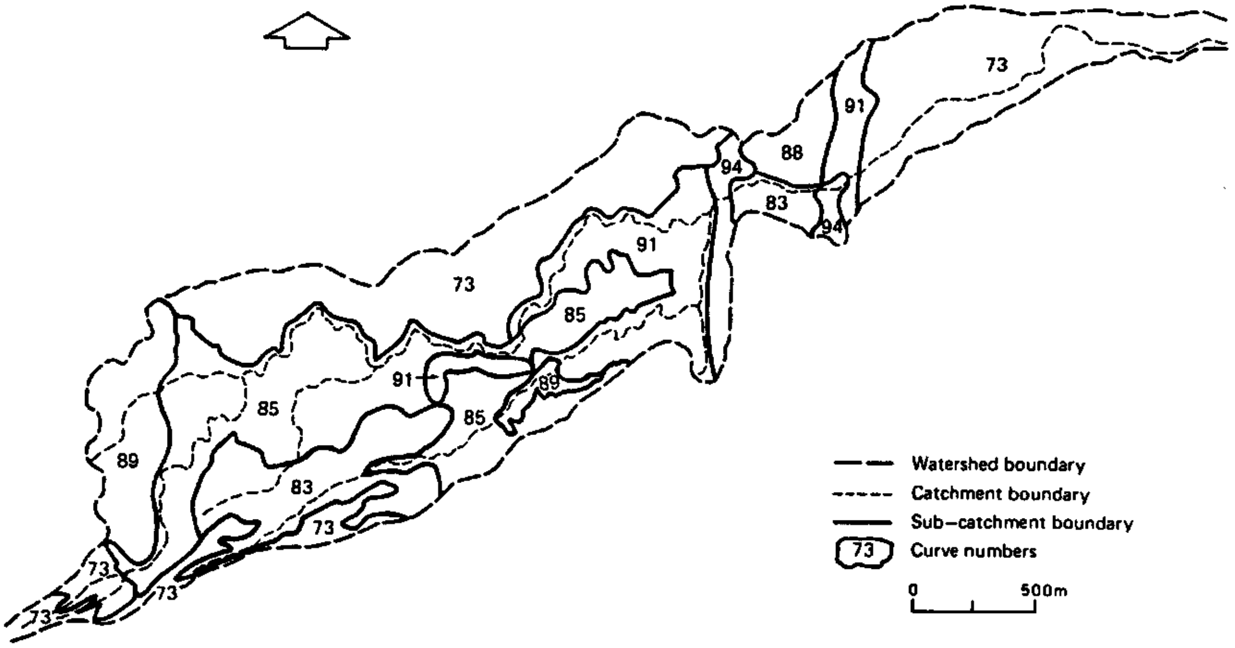


Fig. 11. Map of curve numbers, catchment of Divisadero Largo (Roby et al)

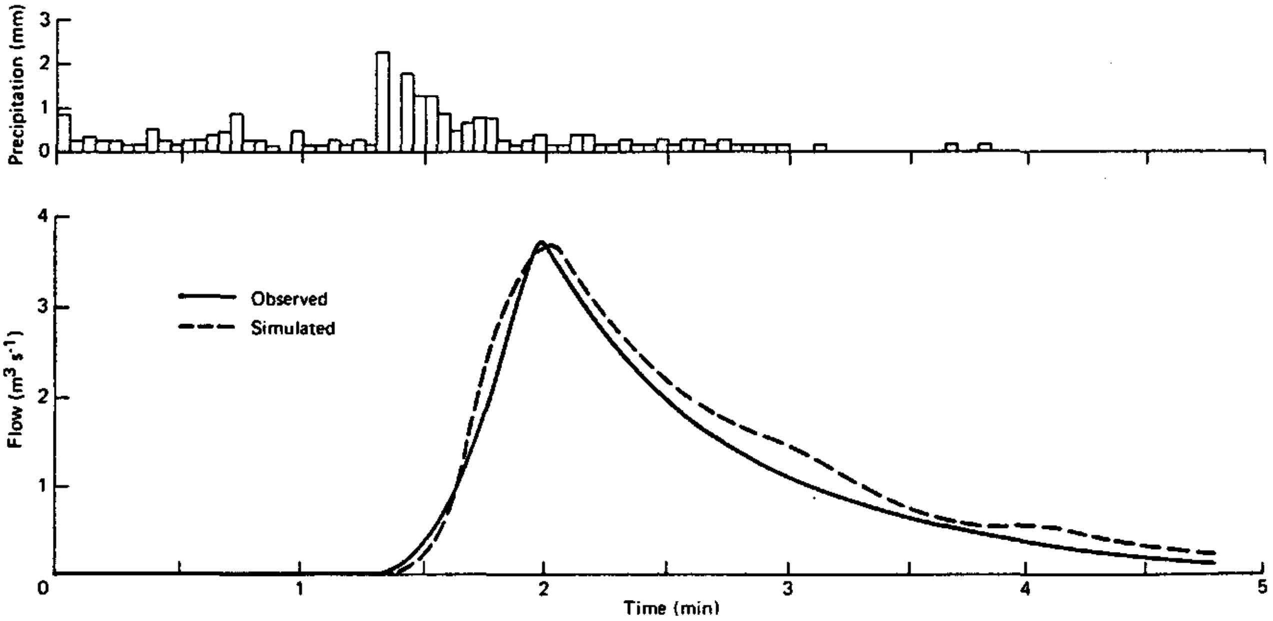


Fig. 12. Simulated and measured hydrograph at the closure of Divisadero Largo catchment (Roby et al)

6.1.3. Irrigation water use

Accurate and up-to-date mapping of irrigated land, as done with Landsat MSS y TM data (see Paragraph 6.1.1.) does allow for an approximate quantitative analysis of water use in the irrigation districts of Mendoza (see also Fig. 2). More accurate calculations do however, require mapping of individual crops and determination of the pattern of irrigation efficiencies.

At first one would assess the cropping pattern in Mendoza as being rather simple, because of the overriding dominance of vineyard. This may be rather misleading, however, as shown (Fig. 13) by the results of Chambouleyron et al (1982), which underscore the large variability of water requirements within the broad class 'vineyard', because of variety and set-up. Moreover, the difference between net and gross water requirements is large, since the overall irrigation efficiency is about 40%. To properly take the variability of irrigation efficiency into account, a numerical model can be applied as done for the río Tunuyán district (CHAMBOULEYRON et al, 1982; MENENTI et al, 1985). By means of such model the functioning of the irrigation infrastructure can be mimicked to obtain, for example, the pattern of the actual contribution of surface water, i.e. delivered by thye canal system, to water use by crops (Fig. 14).

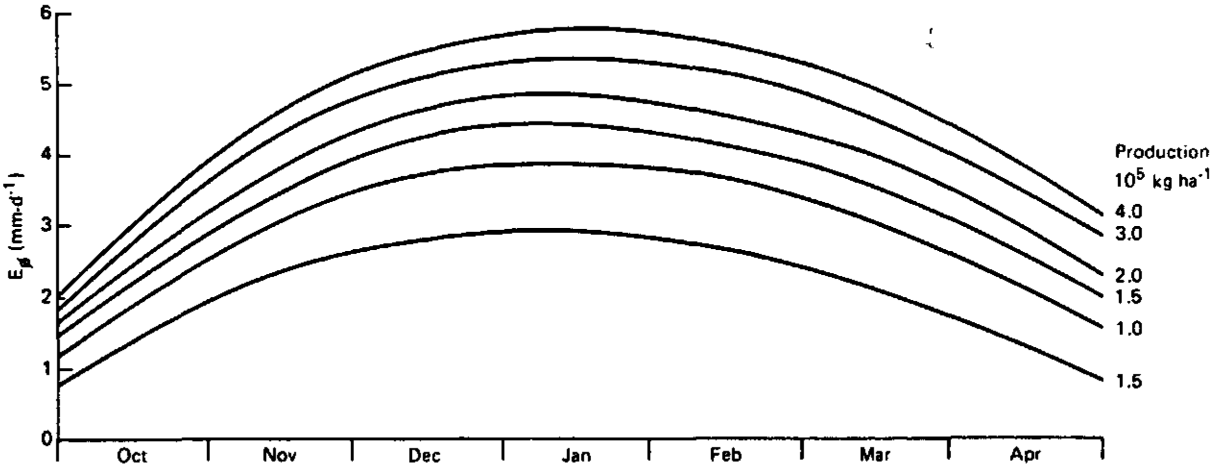


Fig. 13. Water requirements of different vine varieties (after CHAMBOULEYRON et al, 1982)

Especially because of a rapidly changing economical situation, the cropping pattern in Mendoza does change from year to year. Multitemporal analysis of MSS data has been applied to discriminate crops in the irrigation districts in the North of Mendoza (MENENTI et al, 1986). To gather a data base of crop signatures, a large number of agricultural fields have been located. Precise co-location of map and images is currently a major bottleneck of sub-obtimal performance of the geometric correction package available and of out-dated topographic maps.

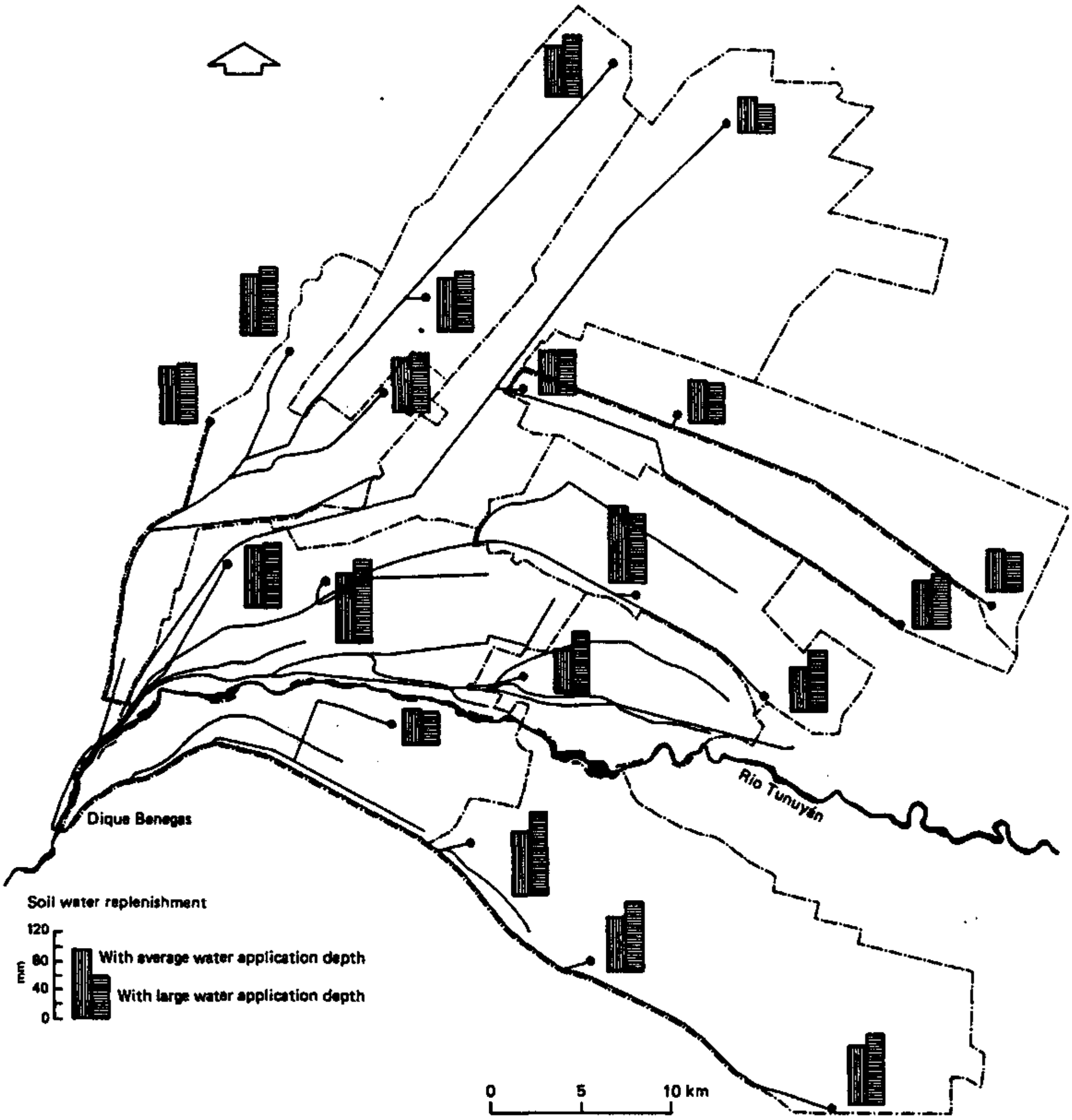


Fig. 14. Actual contribution of water delivered through the irrigation infrastructure to replenishment of soil water reservoir, as obtained by means of a simulation model; río Tunuyán district (CHAMBOULEYRON et al, 1982; MENENTI et al, 1985)

The results presented in Table 2 do confirm that total water allocation is in excess of actual requirements, because of a shrinking cultivated area. This implies a potential waterlogging and salinization hazard (see Fig. 15). MSS and TM data are being applied to detect areas affected by high salt concentration. While saline soils show up clearly in enhanced images, salinity assessment through crop conditions is made rather complicated by the composite pattern.

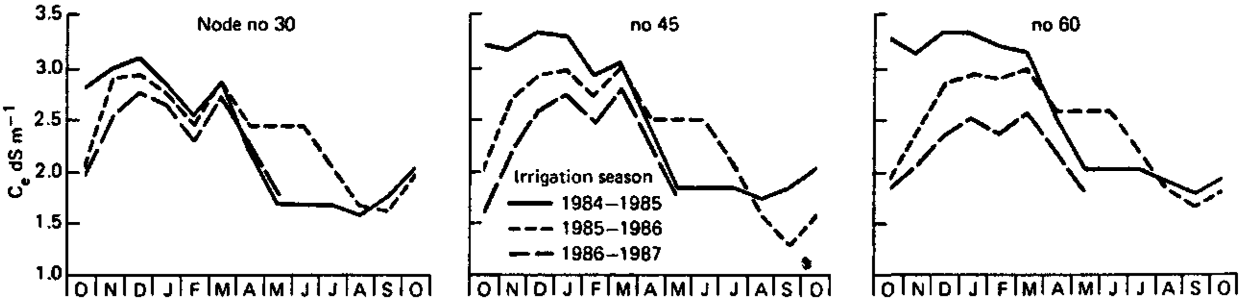


Fig. 15. Electrical conductivity of the soil layer between 0 and 50 cm, as calculated by means of the simulation model of the río Tunuyán district (Mirábile).

6.1.4. Vegetation and hydrology of the arid lands of Mendoza

The hydrological interrelation between return flow from the irrigated land and growth conditions in the neighbouring arid lands is somewhat selfspeaking. Analysis of MSS images has, however, brought about a strikingly real picture of this interrelation.

In paragraph 6.1.1. it has been pointed out already that vegetation in the surroundings of the irrigation districts of San Rafael y General Alvear owes its existence to return flow. The intricated paleohydrography of the northern part of the Province shows up rather clearly in a MSS composition, obtained by applying a bi-dimensional filter to each band. Although a continuing effort will be needed to draw in detail a picture of this interrelation for the entire region, several interesting cases have been studied, already. In the north-eastern part of the Province the potential use of phreatophytic vegetation is being assessed. The enhanced TM composition in Photo 8 does clearly

indicate to which extent these natural vegetation communities depend on water left over after irrigation water consumption.
The productivity of natural vegetation is currently being assessed by means of field experiments and numerical models to simulate water limited accumulation of biomass. Regional extrapolation of such local results is, however, rather difficult as can be aptly pointed out by means of a MSS composition showing one of the test-sites (Ñacuñan) where the experiments on vegetation productivity are being carried out in the northern (upper) portion. As clearly appears, biomass accumulation is much larger in the southern (lower) part, because of more favourable hydrological conditions (drainage in-flow).

6.2. Appraisal

Few of the results presented above are conclusive or of immediate practical application. The determination of irrigated land is, in this respect, a remarkable exception. Because of the urgent need of monitoring irrigated land, this result alone would justify the efforts spent so far. There is, however, much more in the set of preliminary results presented. First of all a number of pieces of the intricated piecework described in Chapter 1 and 2 begin to match with each other.
Second the regional view taken on hydrological conditions, as implied by the analysis of satellite images, is somehow forcing the involved scientists to make a more efficient use of the wealth of field hydrological data being collected. Third, the introduction of numerical models makes the synthesis of available information easier and, therefore, it becomes easier to establish how on-going hydrological investigations have to be redirected.
This nothwithstanding, the progress of the research and development program could be improved, e.g. and by formally establishing a committment of the involved parties to a work-and reporting schedule.
Moreover, the time seems to be ripe now, after the first training phase, to specify in detail individual tasks and responsibilities.
In addition to the above there are a few improvements of the hardware and software of the image processing systems which would rather improve its performance at a stage when large areas have to be dealt with during any processing session:

- increase the video-memory of the COMTAL with planes of 4096 x 4096 elements;
- add a suitable hard copy unit or interface the COMTAL with the graphic system under development at INCYTH;
- develop a suitable geometric correction package and routines to perform basic operations on data with a vector structure.

At last, the analysis of investments and running costs of the program, see Table 3, does pin-point a structural problem, i.e. the badly undersized resources available for operational costs in comparison with investments.

Table 3. Synopsis of project outlays (US $); 1984 through 1987

Institution	Investments	Satellite images	Services
IIACE CRICYT	280 000	5 200	42 900
INCYTH		4 800	35 000
DGI		2 500	4 250
INTA		1 000	250
INV		600	250
DPA		600	
ICW			18 200
Projects			750
Total	280 000	14 700	101 600

Out of total outlays for services, only 2 000 US $ have been available for actually operational costs, such as data processing, field work, etc. This implies that the output of the entire program is limited by the severely restricted operational funds.

APPENDIX I

List of participants 'Introductory short course on quantitative analysis of satellite images'
November 26 to December 12, 1984
Mendoza-Argentina

Working Group	Participants	Affiliation
1	ing. Collado	IIACE
	ing. Thomé	DGI
	sr. Cejas	IIACE
2	ing. Bro	DGI
	sr. Yañez	INCYTH
	agr. Casas	DGI
3	ing. Martínez Carretero	IADIZA
	ing. González Loyarte	IADIZA
	lic. Cobos	IANIGLA
	ing. Maza	INCYTH
	ing. Abraham de Vazquez	IADIZA
4	ing. Barrero Oro	INV
	ing. Basile	INV
	ing. Zuluaga	INCYTH
5	ing. Mirábile	INCYTH
	ing. Pippi	DPA
	ing. Roatta	DPA
	ing. Gaviola	UNC-FCA
	ing. Hudson	INTA

APPENDIX II

List of participants; workshop on 'Application of satellite data to hydrology and water management'
28 October to 15 November, 1985
Mendoza-Argentina

Working Group	Participants	Affiliation
1	ing. Collado	IIACE
	ing. Zuluaga	INCYTH-CRA
	ing. Thomé	DGI
	ing. Barrera Oro	INV
2	agr. Rosas	DPC
	agr. Rodríguez	DPC
	sr. Varone	Undergraduate student
	ing. Luraschi	DGI
	sr. Yañez	INCYTH-CRA
	agr. Casas	DGI
3	ing. Ibánez	CIDEM/IIACE
	ing. Hudson	INTA
	ing. Gaviola	FCA
	ing. Roatta	DPA
	ing. Pippi	DPA
	ing. Mirábile	INCYTH-CRA
4	ing. Torres	IADIZA
	ing. Barbeito	INCYTH-CIHRSA
	ing. Roby	INCYTH-CRA
	ing. Candia	IADIZA
	sr. Cejas	IIACE

APPENDIX III

Program: 1st. Symposium 'The Hydrology of Mendoza: Satellite Images
and Simulation Models'
5 November 1986
Mendoza, Argentina

INTRODUCTION

El área regada de la Provincia de Mendoza
R. Thomé - DGI

WATER SUPPLY

Neoglaciación en la Sierra de Catantil-Neuquén
D. Cobos - IANIGLA

Análisis de la sensibilidad de modelos de lluvia-escorrentía a la determinación de cobertura vegetal
H. Roby - INCYTH

EL HUIGC y el análisis morfométrico del sistema de drenaje; evaluación del uso de imágenes Landsat MSS.
M. Palero - INCYTH

Modelo de simulación del balance de agua y sedimentos a nivel de parcela
A. Vich - IADIZA

Relieve, cobertura vegetal y reflectancia en la cuenca del Divisadero Largo
M. Palero - INCYTH

IRRIGATION WATER USE

Simulación del funcionamiento de la red de riego y cálculo del balance salino en el distrito del Tunuyán Medio
C. Mirábile - INCYTH

Cultivos afectados por salinidad
G. Ibañez - IIACE

Censo de cultivos y precisión de los mapas catastrales
J.C. Basile - INV

Información proporcionada por las bandas Landsat MSS 4, 5, 6 y 7
S. Leguizamón - IIACE

Análisis de observaciones fenológicas para identificar cultivos por comparación multitemporal de imágenes Landsat MSS.
M. Menenti - ICW

VEGETATION AND HYDROLOGY OF ARID LANDS

Las regiones fitogeográficas de Argentina en las imágenes de índice de vegetación NOAA/AVHRR
C. Labianca - CIDEM

Paleocauces y posibles conecciones entre los ríos Mendoza y Tunuyán por filtrado bidimensional de imágenes Landsat
E. Abraham - IADIZA

Relación entre el balance hídrico del suelo y el crecimiento de especies herbáceas
M. Horno - IADIZA

Delimitación de campos en la región Centro Este de Mendoza
R. Llorens - UNC

Análisis de correlación entre producción vegetal e índice de vegetación en el campo del Divisadero

R. Candia - IADIZA

PROGRESS REPORT OF JOINT PROJECT

M. Menenti - ICW

REFERENCES

CHAMBOULEYRON, J., M. MENENTI, L. FORNERO, J. MORABITO and L. STEFANINI, 1983. Evaluación y optimización del uso del agua en grandes redes de riego. Instituto Italo-lationo Americano (IILA), Roma: 176 p.

MENENTI, M., J. CHAMBOULEYRON, L. STEFANINI, J. MORABITO and L. FORNERO, 1985. Agricultural water use in large irrigation schemes. In: A. Perrier and C. Riou (Eds): Crop water requirements. Proceedings of the ICID Conference held at UNESCO, Paris 11-14 Sept. 1984: 597-610.

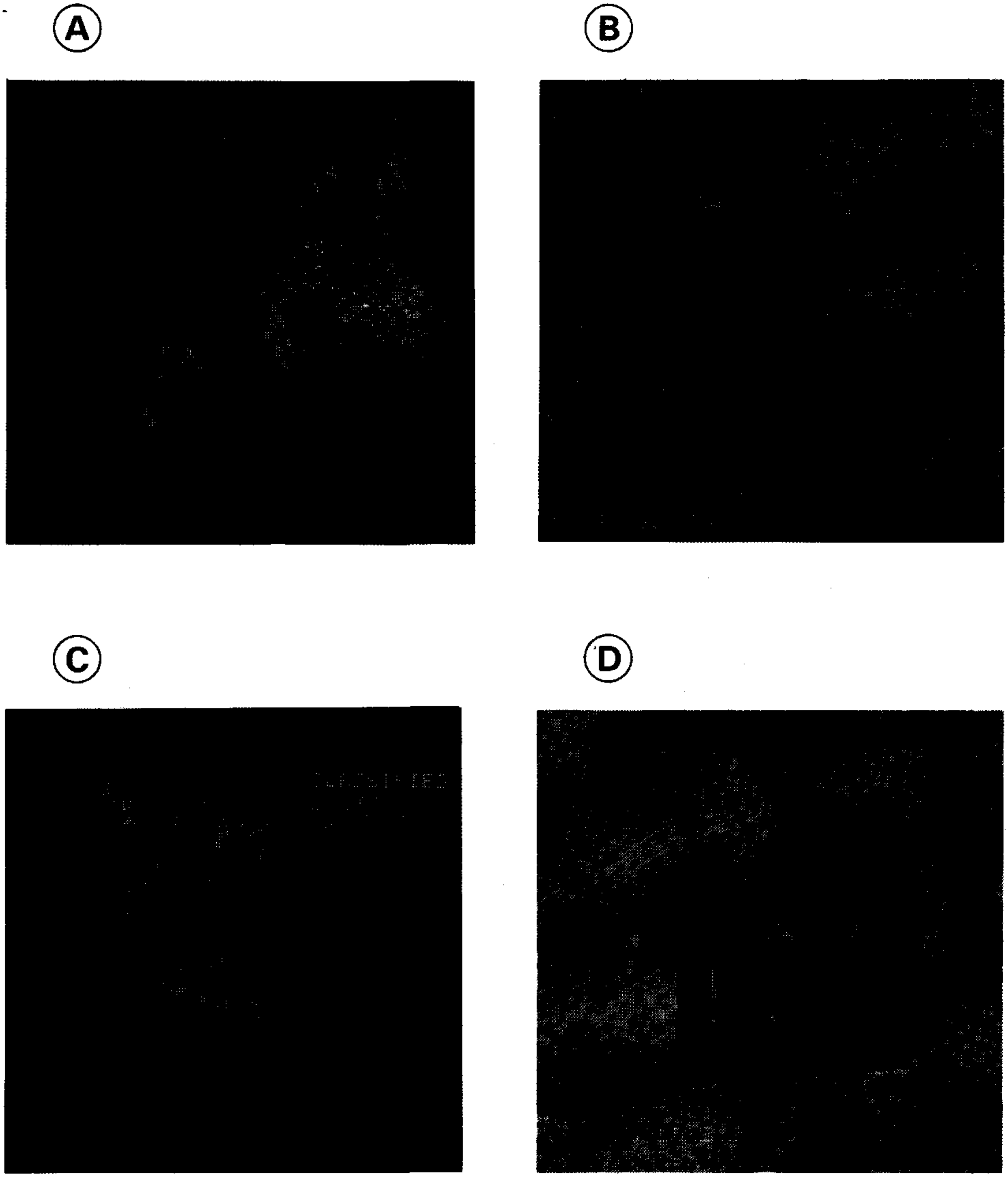
——— S. AZZALI, D.A. COLLADO and S. LEGUIZAMON, 1986. Multitemporal analysis of Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) data in the Po Valley (Italy) and in Mendoza (Argentina). 7th Symposium - Comm. VII-ISPRS; Enschede 25-28 August 1986 (Proceedings), A.A. Balkema, Rotterdam: 293-299.

ENCLOSURE 1

IRRIGATED LAND

To map irrigated land in the state of Mendoza, two full Landsat scenes are needed. In the northern part of the province (A) the discrimination between irrigated land (yellow) is quite clear. To apply this information to irrigation water management, the pattern of irrigated land must be related to the irrigation infrastructure, as for example the district irrigated by the Rio Mendoza (B). Irrigated land is here green; the discrimination between bare soil (yellow) and urban areas is clear. The overlayed irrigation infrastructure is black. To map irrigated land of individual tertiary units, Thematic Mapper data are needed (C). A land use map, as obtained through classification of the TM image, can be superimposed onto a map of the boundaries of individual tertiary units (green). Land use within each unit can thus be obtained. The accuracy of available topographic maps is essential for the results to be meaningful. Sometimes not even large scale maps (1:10 000) of individual large farms (D) are accurate.

Irrigated land



RAINFALL, RUNOFF AND EROSION

Understanding the regional hydrology of Mendoza requires that hydrological interrelations between portions of the region are established, by mapping both pales - and present drainage.

Rio Tunuyán and Rio Mendoza, for example, were one river in the past, so the gradual displacement of the two rivers (A: Rio Mendoza, upper left, Rio Tunuyán, lower left) left behind an intricated pattern of drainage lines and soil types, which can be seen in Landsat images (MSS in this case).

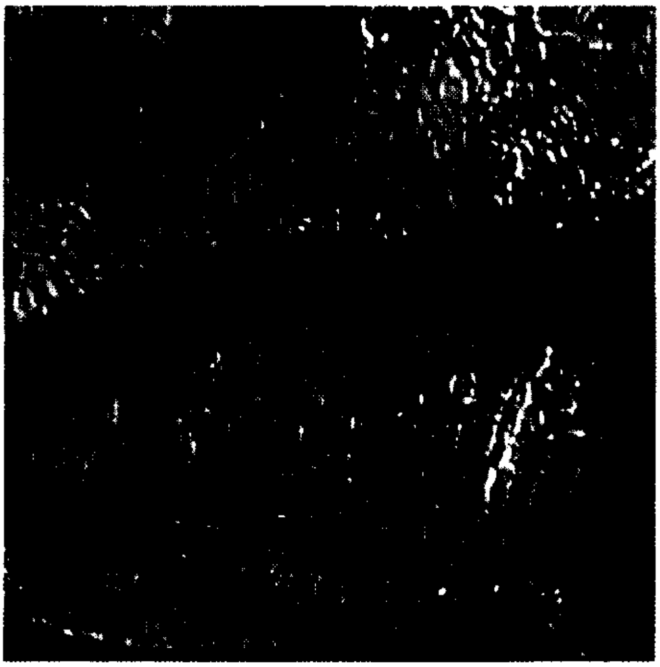
All along the Andean piedmont of Mendoza, many small catchments (B: Divisadero Largo, bottom left) contribute to water supply and call for proper control of flash floods in the urban area (B: Mendoza, right).

As mentioned, not only natural drainage, but also soil types and vegetation communities must be mapped to apply hydrological models. Application of bi-dimensional filters and contrast-enhancement of Thematic Mapper images gives a fairly consistent and detailed mapping of landscape units (C: watershed of Rio Las Tunas).

The rainfall - runoff process in combination with human impact on vegetation cover has made of erosion a major environmental issue in Mendoza. Analysis of TM images does clearly indicates sites where erosion takes place (D: bright spots, bottom right).

A

B



C

D