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Applications of geographical information systems and remote sensing in agrometeorology

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Abstract

An eco-compatible and sustainable development requires integrated management of all available information and the extraction of analytical evaluation on the impact of human activities. Agrometeorology can be used to contribute to further understanding of the relative importance of each environmental component, organising the field activities and optimising the use of natural resources. This is especially true today, due to the availability of new tools, as geographic information systems (GIS), which allow the management of an incredible quantity of data, as traditional digital maps, database, models etc. The advantages are manifold and highly important, especially for the fast cross-sector interactions and the production of synthetic and lucid information for decision-makers. Remote sensing provides the most important informative contribution to GIS, which furnishes basic informative layers in optimal time and space resolutions.

This paper describes various recent applications of GIS and remote sensing in Agrometeorology, both in developed and developing countries. It illustrates the possible evolution of these systems and the expected future developments, which can be decisive for a re-launch of the role of this science in the environmental and land resource management.

Keywords: Agrometeorology; GIS; LIS; Remote sensing

1. Introduction

In the last 30 years, the role that agrometeorology could play both in developed and in developing countries has increased, because of the traditional objectives of agriculture, we should add the quality of products and the environmental role of agriculture, also in the context of global change. The 'rural development' concept launched by the Agenda 2000 of the European Union (E.U.) means an integrated management of land where the exploitation of natural resources, including climate, plays a central role. In this context, agrometeorology can help to reduce the inputs, while in the frame of the global change, allows the clarification of the contribution of ecosystems and agriculture to the carbon budget (Maracchi, 1991). Secondly, due to the dramatic increase in world population, which has grown from 3.5 billions of people in the 1960s to 6 billion in October 1999, there is a need to increase

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the total production under the constraints of a durable environment.

Nevertheless, the operational application of agrometeorology in the last 30 years has been slowed down due to several constraints, which can be summarised as follows.

1.1. *From a general point of view*

- The minor role that agrometeorology plays in the context of meteorological services with few personnel and scarce resources.
- A declining position of both national and international agricultural institutes of research, together with a very weak presence in the agriculture and physics departments.

1.2. *From a technical point of view*

- The need to diffuse agrometeorological information to users very accurately in time and space, because agricultural activities are related to the very local situation.

With regard to the last point, many new tools are at the disposal of agrometeorology to attain this goal. These include local area models, climatic models, satellite and radar measurements, together with the improvements in crop models. The outputs of all these tools, together with ancillary information on the land, should allow the downscaling up to a very detailed grid, consistent with the needs of the users. In order to combine all this information in a systematic way, the use of the GIS offers the scope to modernize agrometeorology.

2. GISs and LISs

A geographic information system (GIS) is a computer-assisted system for acquisition, storage, analysis and display of geographic data. GIS technology integrates common database operations such as query and statistical analysis with the unique visualisation and geographic analysis benefits offered by maps (Burrough, 1990).

Maps have traditionally been used to explore the earth and to exploit its resources. GIS technology is an expansion of Cartographic Science, which takes advantage of computer science technologies, enhancing the efficiency and analytic power of traditional methodologies (Coulson et al., 1991; Ballestra et al., 1996).

Nowadays, GIS is becoming an essential tool in the effort to understand complex processes at different scales: local, regional and global. In GIS, the information coming from different disciplines and sources, such as traditional or digital maps, databases and remote sensing, can be combined in models that simulate the behaviour of complex systems. Some common applications are relative to the control of industrial cycles, simulation of urban and natural systems, evaluation of specific procedures and analysis of environmental impact (Mueksch, 1996; Bouman et al., 1998; Taylor and Burger, 1998).

This can be represented schematically (Fig. 1) showing the main informative sources, the components and the results of the GIS's data processing. Data input can be obtained by means of direct digitalisation, scanning or acquisition from compatible sources.

The problem of the presentation of the geographic elements is solved in two ways: using *x*, *y* coordinates (vectors) or representing the object as variation of values in a geometric array (raster). The possibility to transform the data from one format to the other, allows fast interaction between different informative layers. Typical operations include overlaying different thematic maps, contributing areas and distances, acquiring statistical information about the attributes, changing the legend, scale and projection of maps, and making three-dimensional perspective view plots using elevation data.

The capability to manage this diverse information, analysing and processing together the informative layers, open new possibilities for the simulation of complex systems. A GIS can be used to produce images, not only maps, but the cartographic products, and drawings, animations or interactive instruments as well. These products allow researchers to analyse their data in new ways, predicting the natural behaviour, explaining events and planning strategies.

For the agronomic and natural components, in agrometeorology these tools have taken the name of land information systems (LIS).

In both GIS and LIS the key components are the same (hardware, software, data, techniques and tech-

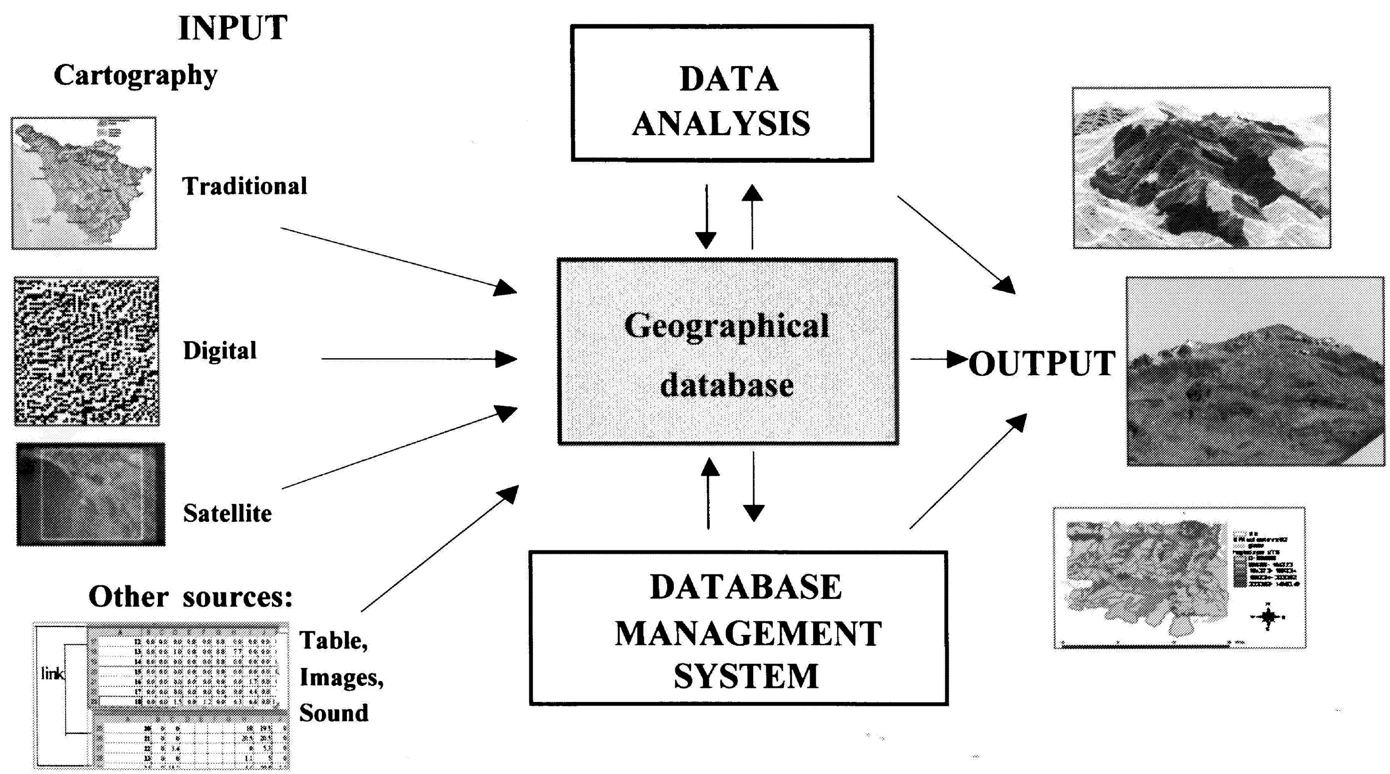

Fig. 1. General structure of a GIS.

nicians), but in relationship to the information that is required, their relative importance varies.

In particular, LISs requires a series of very detailed information on the environmental elements, such as meteorological parameters, vegetation, soil and water. The final product of a LIS, is often the result of a combination of numerous complex informative layers, whose precision is fundamental for the reliability of the whole system. An example of the main information is schematically shown in Fig. 2.

The importance of each informative layer provides various examples of applications in developed countries are outlined below.

2.1. The informative layers

In a GIS all the information can be linked and processed simultaneously, obtaining a syntactical expression of the changes induced in the system by the variation of a parameter. In this way, we have two types of archives: static and dynamic. This technology allows the contemporary updating of geographical data and their relative attributes, producing a fast adaptation to the real conditions and obtaining answers in near real-time. The system requires preliminary basic information that, in the agrometeorological sector, is often furnished by the historical archives of different disciplines: geography, meteorology, climatology, agronomy, etc. The importation of data requires time and attention, mainly because this information will provide the basic knowledge of the territory and on the individual parameters, and it is difficult to modify in a second time. A recent important improvement is relative to the realisation of high resolution digital elevation models (DEMs) (Moore et al., 1991), which are three-dimensional representations of the land, realised starting from quoted contour lines (Fig. 3). A realistic reproduction of the morphology, allows a series of considerations on many other parameters, like hydrology, sunshine duration, etc. (Bruneau et al., 1995; Mitasova et al., 1995). Nowadays, we can say that this layer is basic to all the others, especially for the agrometeorologist.

Other elements can be introduced, such as text, photographs, film, etc, to complete the informative layer. For example, an area characterised by a typical agronomic technique can be linked to an image that explains this technique. This is important not only for educational purpose, but also for enlarging information in particular aspects.

In agrometeorological applications, data collected directly in the field are the most important, because they present the ground truth. Meteorological stations, field data collection (eco-physiological observations, agronomic practices, insect attacks, diseases, soil, etc.) and direct territorial observations are fundamental to all the possible agrometeorological GIS applications.

All these sources produce the reality of the territory and the condition of the elements that it is composed of. These data are used directly or after further treatment. After the preliminary considerations, only the availability of real time field data may allow simulations and evaluation of the actual and future scenario.

When there is a lack of information, the models can help the users to complete the information and understand the real situation (Rijks et al., 1998). For instance, it is possible to estimate the soil water deficit of a given area in two ways: direct measurements (very expensive process) or using the estimated values of a model.

Programme such as EvapoTraspirazione Reale Ottimizzata (ETRO), compute daily water requirements for crops, taking into account the different components of water balance (evapotranspiration, rainfall, irrigation and cultural coefficient) and the initial condition of soil water condition (Battista et al., 1996). ETRO calculates daily values of different parameters: root development, maximum water supply, easily extractable water supply, effective rainfall and true EvapoTranspiration (ETr), etc. The software uses three different methods (Integrated model micrometeorological, Penman_FAO and Hargreaves) for the estimation of true evapotranspiration, according to the available measurements and the accuracy required by the user. Fig. 4 shows the spatialisation of the water deficit estimated by the model with Hargreaves method, in the lowland of Grosseto, using the data of the available agrometeorological stations. The simulation was made for the culture of maize in the month of June 1997. The chart in the picture shows the trend of water balance and minimal reserve, for one point, suggesting the best moment for the irrigation and the volume of water necessary to restore the water reserve.

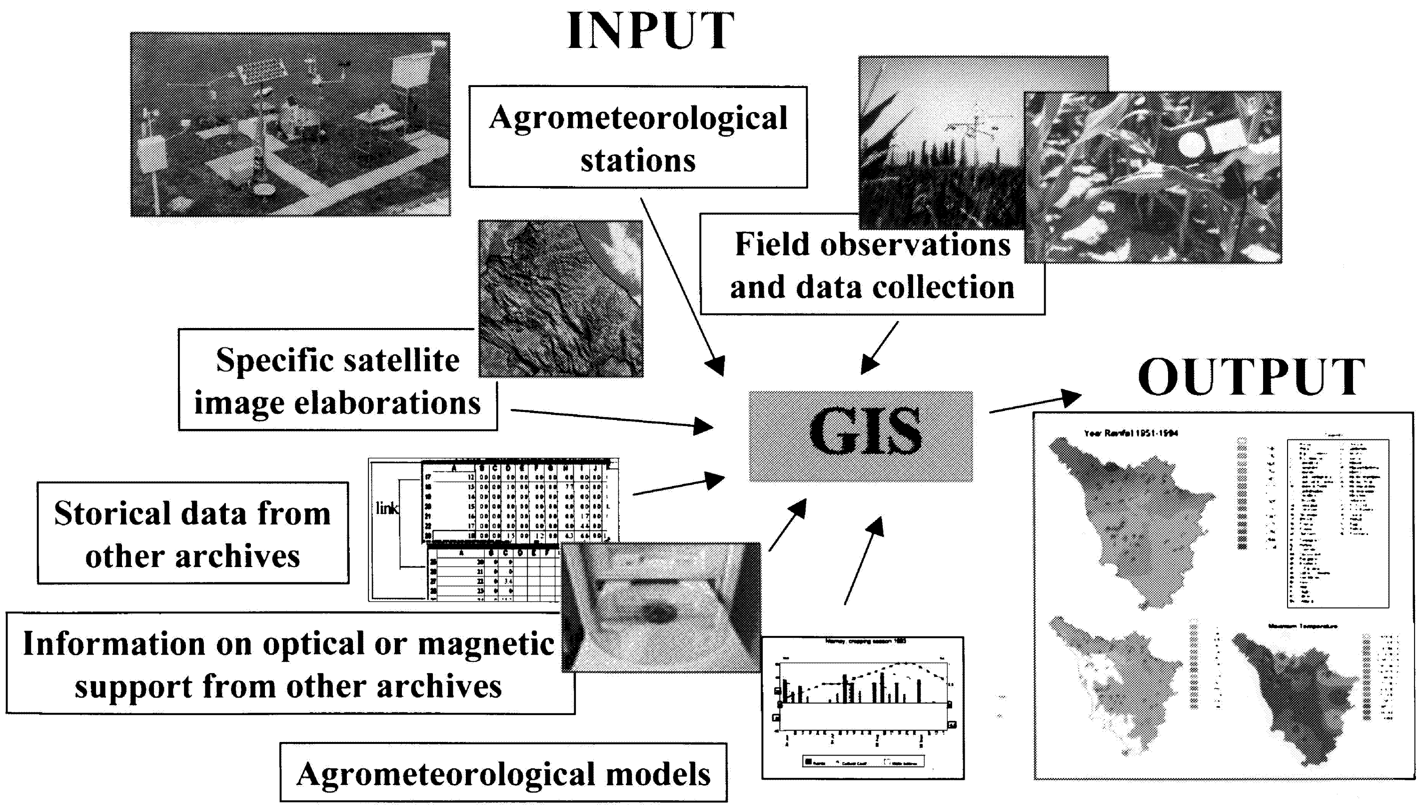

Fig. 2. Schematic representation of a land information system in Agrometeorology.

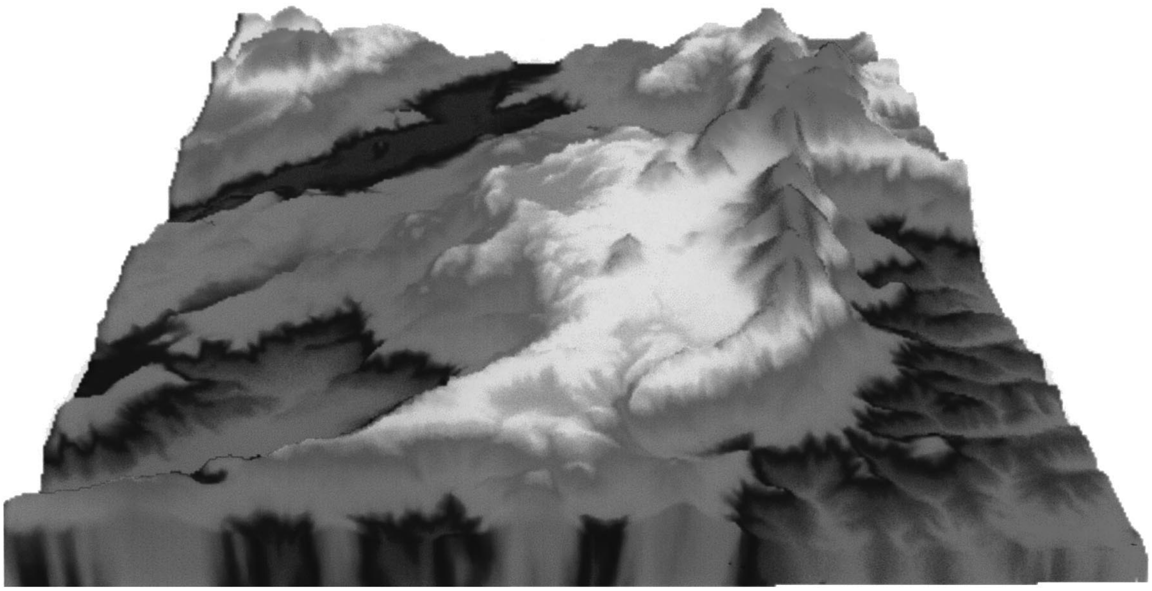

Fig. 3. Digital evaluation model (DEM) of a part of Gran Sasso National Park. Quotes are represented in false colour.

In many cases the outputs of the models are introduced as inputs in the GIS, but it is also possible to introduce the models directly. In this way, all the informations could be used for news interactions with other informative layers.

2.2. The role of remote sensing

Remote sensing provides spatial coverage by measurement of reflected and emitted electromagnetic radiation, across a wide range of wavebands, from the

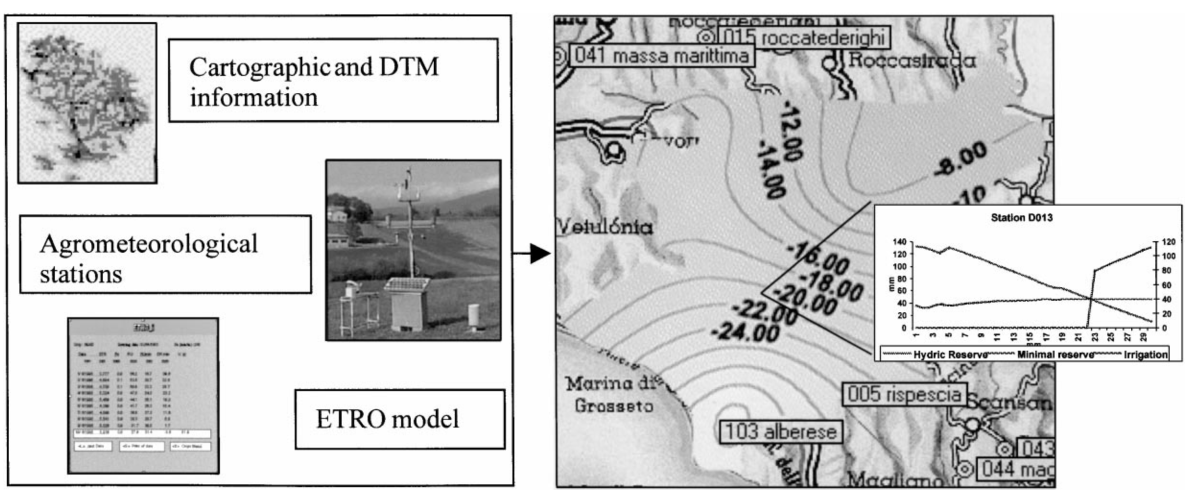

Fig. 4. Water deficit of the Grosseto lowland (26 June 1997) as estimated by ETRO. In input the different informative layers and in output the cartographic representation.

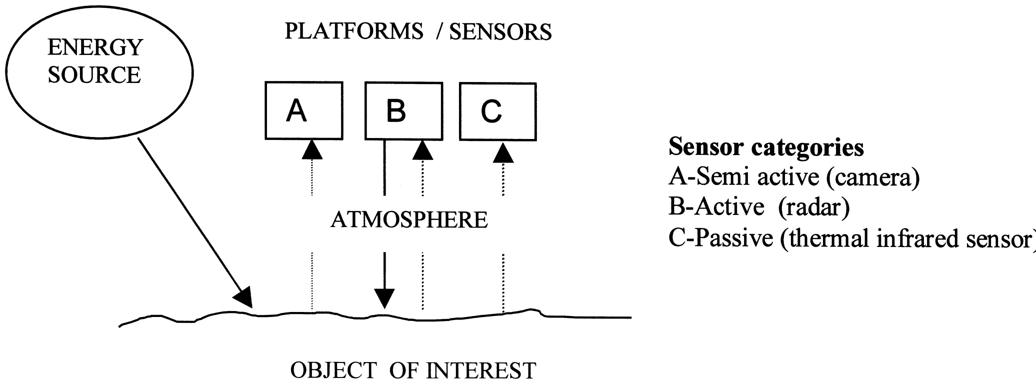

Fig. 5. Main types of remote sensing techniques.

earth's surface and surrounding atmosphere. Without entering into a detailed description of remote sensing instruments and techniques, Fig. 5 shows the main elements of these systems (Cochran, 1986).

Remote sensing provides a series of information, continually improved, which become very reliable and practically irreplaceable (Rijks, 1995).

A modern and effective agrometeorological weather service, using advanced data collection methods such as remote sensing, must be equipped with sophisticated devices, but above all must have efficient and trained staff.

The improvement in technical tools of meteorological observation, during the last 20 years, has created a favourable substratum for research and monitoring in many applications of sciences of great economic relevance, such as agriculture and forestry. Each waveband provides different information about the atmosphere and land surface: surface temperature, clouds, solar radiation, processes of photosynthesis and evaporation, which can affect the reflected and emitted radiation, detected by satellites. The challenge research, therefore, is to develop new systems extracting this information from remotely sensed data, giving to the final users, near-real-time information.

The platform for remote sensing can be either fixed or moving, terrestrial or operating from different altitudes, and be either manned or unmanned. Considering the operating time, the platform can be classified as temporary, semipermanent or virtually permanent. These aspects are important in order to understand the quality and quantity of the information available to the agrometeorological service. The distance of the instruments affects directly the resolution and the precision of the information. The scale of observation can vary from a few square meters, with a scanner mounted on a vehicle, to continental scale, using a meteorological satellite.

The sensors most widely used by environmental scientists are:

- cameras with quartz lenses for use with ultraviolet film;
- cameras for use in the visible and photo infrared spectral region;
- multiband cameras (VIS, NIR, SWIR);
- optical mechanical scanners and radiometers for thermal infrared and passive microwave regions;
- active microwave sensors such as side-looking airborne radar (SLAR) and synthetic aperture radar (SAR) which are not dependent on daylight and possess a near all-weather capability.

Each instrument furnishes different information and a station of detection is generally multipurpose, because it is equipped with different sensors. The most common remote sensing products and applications are reported in the Table 1 (Maracchi et al., 1998).

All informations produced by the satellite is elaborated for the extraction of the desired information. There are many methods, algorithms and procedures to derive fundamental data for agrometeorological application from remote sensing. Among the existing indices, the most extensively used are:

Table 1
Main products of the operating satellites

Field	Parameters/products	Applications
SPOT		
Lands	Vegetation index maps Land cover and land use classification maps Digital Elevation Model Orthophotomap	High resolution land use analysis, biomass and vegetation hydrological conditions Agricultural and natural resources planning and managing Cartography
LANDSAT TM		
Atmosphere	Cloud cover maps Albedo maps Aerosol maps	Meteorological forecasts, numerical models, climatology, floods forecasting Energetic assessment, general climatology
Inland and coastal waters	Water quality monitoring Sea surface temperature maps (SST)	Pollution monitoring, environmental impact assessment Coastal zones monitoring, coastal streams dynamics, sediments mapping
Lands	Land surface temperature maps (LST) Normalized difference vegetation index maps (NDVI) Land cover and land use classification maps	Temperature distribution maps for urban areas, high resolution land use analysis, biomass and vegetation, hydrological conditions, fire risk maps and damage assessment Agricultural and natural resources planning and managing
AVHRR-NOAA		
Atmosphere	Temperature and humidity profiles Precipitation maps Cloud cover maps Cloud top height and temperature	Meteorological forecasts, numerical models, climatology, floods forecasting Energetic assessment, global climatology, support to air traffic control
Inland and coastal waters	Oil slick maps and monitoring Sea surface temperature maps (SST)	Pollution monitoring, environmental impact assessment Coastal zones monitoring, coastal streams dynamics, sediments mapping
Lands	Land surface temperature maps (LST) Normalized difference vegetation index maps (NDVI) Land cover classification maps	Temperature distribution maps for urban areas, high resolution land use analysis, biomass and vegetation hydrological conditions, fire risk maps and damages assessment Monitoring of the temporal variations of the coverage
ERS-1 SAR		
Inland and coastal waters	Oil slick maps and monitoring Ship tracking	Monitoring and evaluation of accidental oil slicks, area assessment Temporal evolution forecasting of oil slicks and identification of coastal areas at risk in case of accidental oil slicks Coordination support for anti-pollution actions Ship identification in case of illegal polluting slicks Maritime traffic control also in fishing areas
Lands	Flooded areas maps	Emergency actions support in flooded areas Area and damage assessment for flooded areas Strong temporal soil moisture variation evaluation

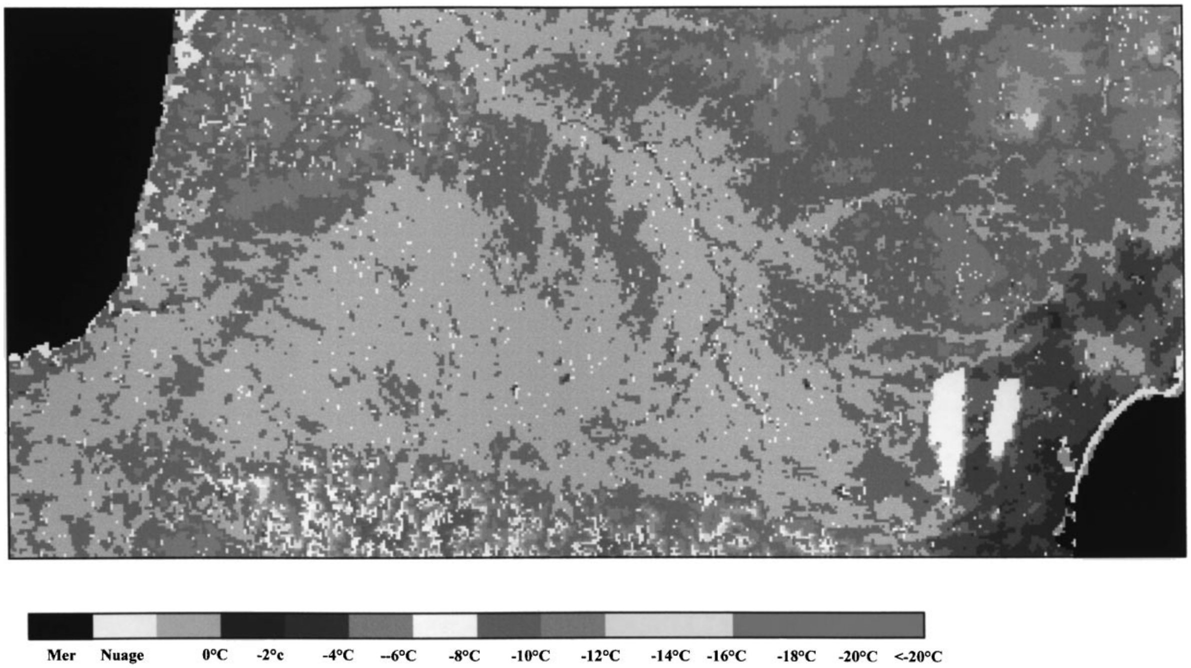

Fig. 6. Surface temperature on 25th February 1993 in the south-west of France. The algorithm used in the calculation is a linear combination of the satellite's AVHRR channels (split-window technique) that enables most atmospheric effects to be eliminated.

- The sea surface temperature (SST) — index used for meteorological and climatological study and observations
- The land surface temperature (LST) — good indicator of climatic and microclimatic conditions prevailing close to the surface, as well as the frost or the moisture soil (Fig. 6).
- The normalised difference vegetation index (NDVI) — optimal index of current plant cover and its variation with time.

The images can be subsequently used as informative layers in the GIS, entering in a quantity of analysis or evaluation procedures. One of the simplest methods is the overlapping of these images with a digital elevation model (DEM), for a realistic representation of the observed phenomenon.

It is sufficient to remember that remote sensing outputs are the bases for principal strategic decisions systems (e.g. Early Warning System — FAO, FAS — USA, EXTEC — Russia, and meteorological archive and retrieval system (MARS — EU)), to understand the relevance of these contributions.

The transfer of the new techniques of processing and interpreting remote sensing data from developed to developing countries is limited by many factors, such as the cost of receiving equipment, the restrictive or very difficult access to the archives of satellite images and data, the shortage of qualified staff, etc. The situation has changed to better in recent years, thanks to the availability of long series of satellite data; for example the data archives from NOAA (USA) and Meteor (Russia), contain information for more than 15 years. In this way, the researcher and user, have the possibility to apply the traditional techniques, approaches and procedures and to local studies. The access to the archives and the transfer of information, software and so on is becoming simpler, especially with the use of INTERNET tools.

International organisations and in particular the WMO also play an active role in coordinating efforts connected with receiving, processing, disseminating and using remote sensing data. WMO's Commission on Basic Systems (CBS) has recently established a Working Group on SATellites

(WGSAT) that can be the place designed for such activity.

The main goal is the development of common working strategies and the improvement of regional and global management capability of satellite data. For this reason, particular emphasis is placed on data compatibility and integration between different sources of data. WGSAT has supported a project aimed at developing the receiving stations (both hardware and software) at a reasonable cost to be available for developing countries. The WGSAT has discussed a possible process to improve the use of satellite data from the present global satellite observing system, and has proposed a set of recommended actions.

Table 2 shows the requirements for agrometeorological parameters, outlined by the Working Group.

The WMO strategy to improve satellite system utilisation is made up by four components:

- the strategic vision;
- the long-term strategic goal;
- the major objectives;
- the methodology to meet the objectives.

The strategic vision, to improve satellite system utilisation, is the prospect of substantially improved transfer to communities around the world of the benefit of meteorological science and technology, via rapidly evolving global and regional communications networks. This will allow improved access to satellite data and services and the interactions between developed and developing countries.

The long-term strategic goal for the next 15 years is to improve systematically the utilisation of satellite systems by National Meteorological and Hydrometeorological Services with emphasis on improving utilisation in the developing countries.

The major strategic objectives are:

- to focus on the needs of the developing countries;
- to improve access to satellite data through increased effectiveness in the distribution of satellite system data and products at major hubs, in particular those maintained by the satellite operators, WMO WMC's, RSMCs and other entities as appropriate;
- to improve the use of satellite data through increased capabilities in its applications by direct involvement of existing WMO Member expertise.

The methodology to improve satellite system utilisation is based on an iterative process to assess continuously the status of the use of satellite data and services and their impact on the various applications and, therefore, to identify limitations and deficiencies. The necessary steps to improve the utilisation will be developed and implemented through the use of specific projects.

The overall strategy is summarised in Table 3.

3. GISs and remote sensing applications in Agrometeorology

Nowadays, public agencies, research laboratories, academic institutions, private and public services, have established their own information system such as GIS. Due to increasing pressure on land and water resources, land use management and forecasting (crop, weather, fire, etc.) become more essentials every day. GIS is, therefore, an irreplaceable powerful tool at the disposal of decision-makers.

As discussed earlier the term GIS is currently applied to computerised storage, processing and retrieval systems that have hardware and software specially designed to cope with geographically referenced spatial data and corresponding informative attribute. Spatial data is commonly in the form of layers that may depict topography or environmental elements.

In Agrometeorology, to describe a specific situation, we use all the informations available on the territory: water availability, soil types, forest and grasslands, climatic data, geology, population, land-use, administrative boundaries and infrastructure (highways, railroads, electricity or communications systems). Each informative layer provides to the operator the possibility to consider its influence to the final result. However, more than the overlap of the different themes, the relationship of the numerous layers is reproduced with simple formulas or with complex models. The final information is extracted using graphical representation or precise descriptive indexes.

Developed countries use agricultural and environmental GIS to plan the times and types of agricultural practices, territorial management activities, population security, to monitor devastating events and to evaluate damages, etc.

More than the classical applications, such as crop yield forecasting, uses such as those of the environmental and human security are becoming more and more important. For instance, an effective forest fires

Table 2
Requirements for agrometeorological parameters

Requirement	Application													Remarks
	Horizontal Res.		Vertical Res.		Obs. cycle		Delay avail.		Accuracy RMS		Accurracy bias		Confidential	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min		
Fires (extent and temperature)	0.01 km	10 km			0.25 day	1 day	1 h	6 h	5.0 K	20.0 K			2	Recommendation on putting out the fire
Land cover	100 m	1000 m			1 year	1 year	10 day	30 day	10 cl.	4 cl.			2	Composing of land utilisation maps
Land surface temperature by frost; drought evaluation	0.1 km	10 km			1 h	72 h	3 h	1 day	0.3 K	2.0 K			2	Detection of areas affected
Leaf area index (LAI)	0.01 km	1 km			5 day	7 day	1 day	5 day	5%	10%			2	Evapotranspiration estimation; crop productivity evaluation
Norm.Dif.Veg.Index (NDVI)	1 km	10 km			1 day	7 day	1 day	5 day	5%	10%			2	Phenological events detection; crop state estimation
Photosyn.Active Radiat.(PAR)	5 km	100 km			1 h	7 day	1 day	5 day	10 W m^{-2}	50Wm^{-2}			2	Photosynthesis estimation; crop productivity evaluation
Precipitation index(daily cummul)	10 km	50 km			24 h	72 h	24 h	48 h	2mm/day	10mm/day			2	Evaluation of soil moisture and its availability to plants
Snow cover	1 km	10 km			5 day	7 day	1 day	5 day	2%	10%			2	Evaluation of crop wintering
Snow depth	1 km	10 km			5 day	15 day	1 day	5 day	0.1 m	1 m			2	Evaluation of crop wintering
Snow water equivalent	1 km	10 km			7 day	30 day	1 day	7 day	5 mm	50 mm			2	Evaluation of soil water storage in spring
Soil composition	0.1 km	10 km			1 year	2 year	10 day	30 day	15 cl.	5 cl.			2	Crop state estimation, soil moisture evaluation
Soil moisture	0.1 km	1 km			1 day	7 day	1 day	5 day	10 g/kg	50 g/kg			2	Crop state and productivity estimation
Vegetation type	50 m	500 m			30 day	60 day	1 day	7 day	30 cl.	5 cl.			2	Composing of land utilisation maps; evaluation of crop development

Table 3
Strategy to improve satellite system utilisation

Strategic goal	Major objectives	Implementation plan
To improve systematically the utilisation of satellite systems with emphasis on improving utilisation in developing countries	To focus on the needs of developing countries	Critical review process linking monitoring to action plans
		CEOS help for better Indian Ocean/RA II satellite coverage
		Links to WMO satellite education and training strategy
		Major WMO project on low-cost satellite workstation
		Expand European METeorological SATellite (EUMETSAT) MDD system use in RA I & II
		Focus on effective use of LRIT in RA II & V (with MTSAT-1)
		Expand US-based virtual lab network in RA III & IV
		Satellite utilisation hubs/networks for developing countries
		Initial funding focus on work station and networking
		Expand use of DCP/DRS for agriculture and Hydrology
		Focus on better use of polar–orbiting data and products
		Strategies for system utilisation in early/mid 2000
		Improved promotion of system, use at User Forum
		Multi agency strategy promoting satellite system benefits
	To improve the access to satellite data through increased effectiveness in the distribution of satellite system data and products at major hubs. In particular those of satellite operators, WMO WMC's RSMC and other entities as appropriate.	Upgrade MTN and GTS performance
		Implement operational distributed database system
		Better use of Internet and systems such as VSAT
		Specialised WMO centres for satellite data into NWP
		Specifications for improved WMC/RSMC satellite products
	To improve the use of satellite data trough increased capabilities in their applications by direct involvement of existing WMO Member expertise.	Review WMO requirements for new Earth Observ. Satellite data
		Better research/operational applications system transfer
		Focus in high identified priority user requirements for satellite applications
		Focus on improved applications for environmental hazards such as volcanic ash, earthquakes, air and ocean pollution etc.
		Closer operational development links with Pis

prevention needs a series of information very detailed on an enormous scale. The analysis of data, such as the vegetation coverage with different levels of inflammability, the presence of urban agglomeration, the presence of roads and many other aspects, allows the mapping of the areas where risk is greater. The use of other informative layers, such as the position of the control points and resource availability (staff, cars,

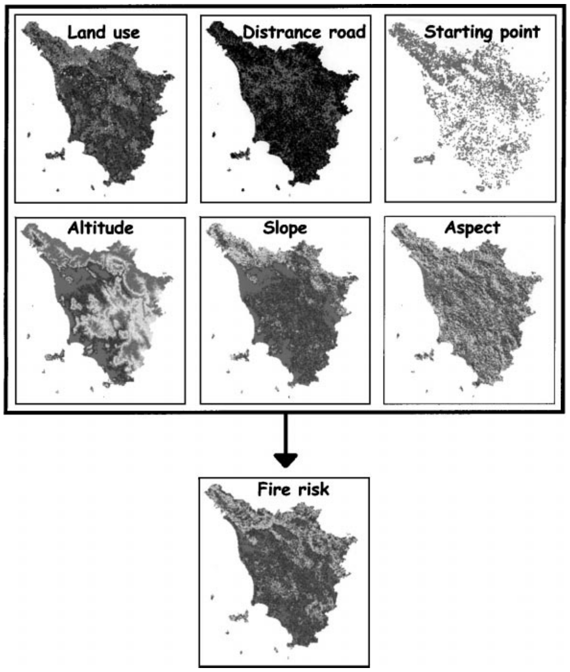

Fig. 7. Informative layers for the evaluation of fire risk index.

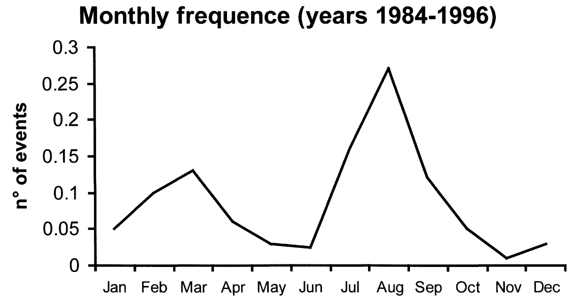

Fig. 8. The monthly distribution of fire frequency in Tuscany region (1984–1996).

helicopters, aeroplanes, fire fighting equipment, etc.), can help the decision-makers in the management of the territorial systems.

Monitoring the resources and the meteorological conditions, therefore, allows, the consideration of the dynamics of the system, with more adherence to reality.

For instance, Fig. 7 shows the informative layers used for the evaluation of fire risk in Tuscany (Italy). The final map is the result of the integration of satellite data with territorial data, through the use of implemented GIS technologies (Romanelli et al., 1998).

The input data required are:

- Multitemporal satellite images (Landsat TM);
- Colour Aerial photographs;
- High resolution digital elevation model of region;
- Vectorial map of roads;
- Vectorial map of municipality boundary;
- Informative technical schedule of the Tuscany Region on fire events (period 1984–1996);
- Direct measurements.

A preliminary analysis of the data has allowed the realisation of the following informative layers: land use; starting point of fire; distance road; elevation; slope; aspect.

The ground truth for the supervised classification of the Landsat Tm images and auxiliaries data has been done by means of direct measurements and aerial photographs.

The classification, according to a modified maximum likelihood model, has produced a thematic fuzzy representation, to which has been assigned the relative levels of risk. Since the risk of fire changes during the year, the monthly distributions of the fire frequencies in the period 1984–1996 were observed (Fig. 8). The figure shows two different periods of fire risk: winter-spring with its maximum in March, and summer–autumn with its maximum in August.

The methodology foresees the extraction of the fire frequencies for each class of land use. These values were normalised for the area of each class and give values of probability, according to the number of starting points of fire.

A comparative analysis of the winter map with the summer one, shows a sharp difference in the spatial distribution of the risk of fire in the two seasons (Fig. 9). In summer the risk is generally higher, with extreme values in hilly zones. Instead in winter the risk is mostly definite, located mainly to the more elevated elevations.

These maps of fire risk, constitute a valid tool for foresters and for organisation of the public services. At the same time, this new informative layer may be used as the base for other evaluations and simulations. Using meteorological data and satellite real-time information, it is possible to diversify the single situations, advising the competent authorities

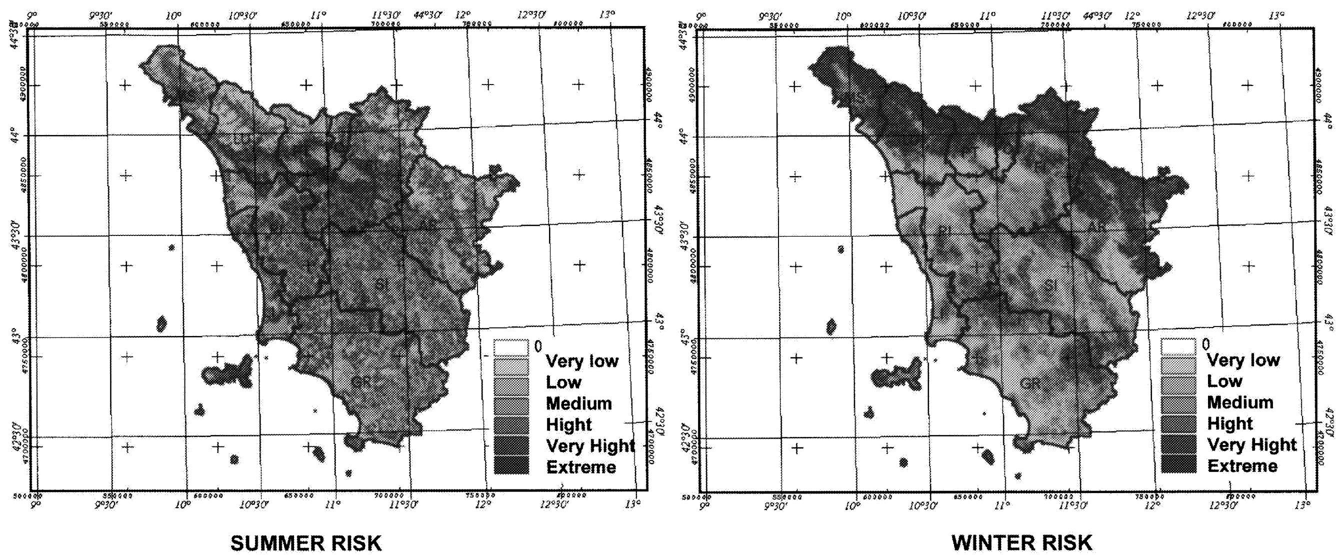

Fig. 9. Risk of fire in Tuscany in summer and winter.

when the situation moves to hazard risks. Modelling the ground wind profile and taking into account the meteorological conditions, it is possible to advise the operators of the change in the conditions that can directly influence the fire, allowing the modification of the intervention strategies.

In developing countries, GIS use can be promoted through transfer of technologies and an information from the developed ones. This requires generalisation of the knowledge and studies carried out elsewhere. Moreover, frequently in developing countries, data used for the production of the informative layers are often unreliable or even lacking. Besides, the models used in these systems are the results of studies and projects, realised at different scales.

Implementation of a GIS requires a great effort to collect and organise the available information on the territory. This important activity requires a period of validation for the operational use of the system.

In any case, many projects have started to implement GIS in a number of different environmental and economical systems, mainly using information derived from remote sensing to complete the direct observations. The common advantage is the definition of the state of the art and a first study of the particular problems, with the suggestion of innovative specific solutions. At this level, the products often are already used for practical applications and the operators find it sufficiently powerful and reliable.

The general philosophy of the projects, finalised to produce GIS, is to realise more and more complex and integrated systems, to satisfy the needs of users. In developing countries, the approach has to be quite different, realising in a first phase sufficiently simple systems, which answer specific problems, arriving gradually complete the different informative layers and to create a fully operative GIS.

An example of preliminary information system to country scale is given by the SISP (Integrated information system for monitoring cropping season by meteorological and satellite data), developed to allow the monitoring of the cropping season and to provide an early warning system with useful information about evolution of crop conditions (Di Chiara and Maracchi, 1994).

The SISP uses:

- Statistical analysis procedures on historical series of rainfall data to produce agroclimatic classification;
- A crop (millet) simulation model to estimate millet sowing date and to evaluate the effect of the rainfall distribution on crop growth and yield;
- NOAA-NDVI image analysis procedures in order to monitor vegetation condition;
- Analysis procedures of Meteosat images of estimated rainfall for early prediction of sowing date and risk areas.

The results of SISP application shown for Niger (Fig. 10) are charts and maps, which give indications to the expert of the millet conditions during the season in Niger, with the possibility to estimate the moment of the harvest and final production.

SISP is based on the simulation of the millet growth and it gives an index of annual productivity (range 0–1) by administrative units. These values, compared to the historical crop yields of the single administrative unit, allow the estimation of the expected productivity.

By means of systems like this, based on modelling and remote sensing, it is possible to extract indices relative to the main characteristics of the agricultural season and conditions of natural systems. This system is less expensive, easily transferable and requires minor informative layers, adapting it to the specific requirements of the users.

When the information available on the territory is sufficient, the passage of all this information to GIS is immediate. An example in this regard is the environmental information system (EIS) realised by the PEICRE project for the department of Keita (Niger), starting from a large data set collected on this area (2.500 km^2).

The data collected and the different information layers are organised in a database and all the information about the territory is integrated in a GIS. Each layer is composed of different archives (numeric data, text and images), which were preliminary controlled and evaluated. The archives are completed with graphical representations of the main data trends and synthetic information, obtained by means of spreadsheet and statistical software (Genesio and Di Vecchia, 1998).

The most important information is extracted to describe the territory and then combined for understanding the possible relationships between the different factors. The representation of these data can be made for discrete or continuous values, to obtain thematic maps or territorial representation of the spatially distributed parameters. The combination of all the

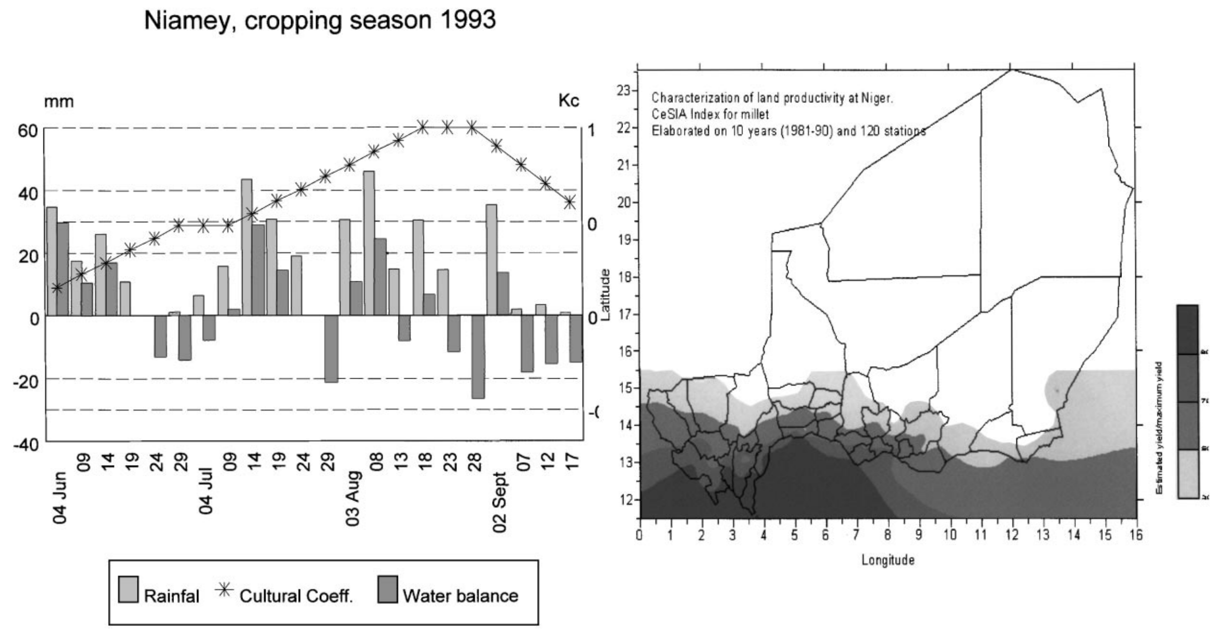

Fig. 10. Examples of outputs of SISP.

informations can give a synthetic representation of the reality.

An analysis of Landsat TM, MSS and SPOT multispectral images has been used to update the available maps and to obtain territorial classifications. The classification procedure is based on the integration of the different information layers (digital cartography, on-field observation, multispectral satellite images, aerial photographs etc.).

In the EIS–PEICRE some models are also introduced, which are able to simulate the behaviour of different parameters or show possible scenarios. In particular, great importance is given to water and to the soil degradation. For instance, the evaluation of the erosion hazard requires many different layers for the application of the RUSLE model (Renard et al., 1994), derived from the USLE equation:

$$A = R\,K\,L\,S\,C\,P$$

where A is the soil loss (t/ha/year); R represent rainfall and runoff erosivity; K is the soil erodibility; L represent slope length; S is the slope steepness; C represent cover management and P denotes supporting practices.

Fig. 11 shows the images of different layers of the RUSLE model. The erosivity (R factor) is calculated using rain data; the K values, given to each class of soil, are evaluated using all the available informations and indications derived from ground observations. Cover management and supporting practices have been introduced by means of combinations of different information: digital cartography, on-field observation, aerial and satellite photographs. The heart of the model is a DEM of the land, which allows the evaluation of the morphological factors (L and S of the USLE) for each point of the territory and the estimation of the water flow direction.

These new powerful tools give the possibility to introduce a new coefficient for the USLE, that was called transport capacity factor (T) and represents the soil transport capacity of the water flow in each element (pixel).

The simple multiplication of the resulting layers, each with its own series of values for each territorial unity, allows the evaluation of the erosion hazard in the considered time period.

In comparison between the erosion in 1984, before the intervention of land recovery, and 1995, after the realisation of the agronomic works by the environmen-

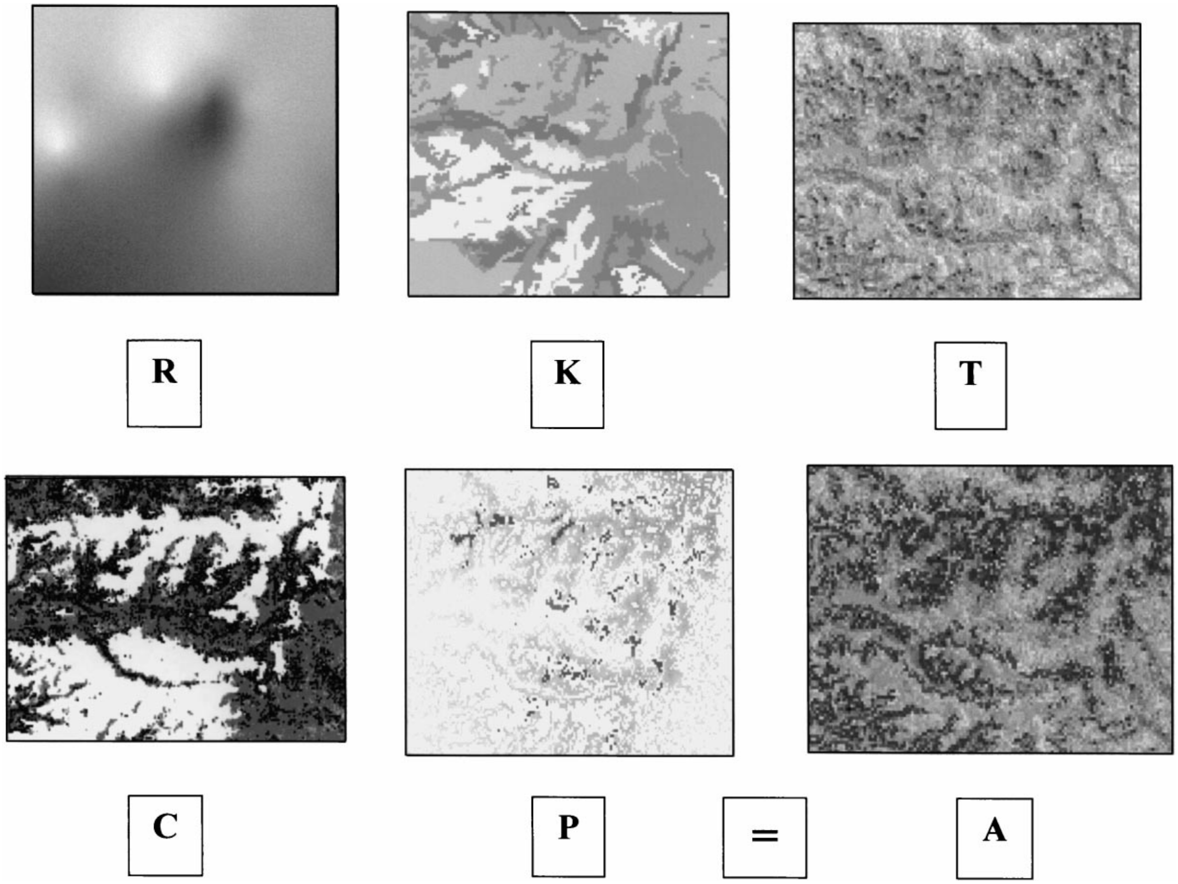

Fig. 11. Information layers for RUSLE model ($T=L\times S$).

tal recovery and preservation project PIK (Integrated Project Keita), the positive effect of the agronomic works in the reduction of erosion has been evaluated. This effect is due to the increase of the vegetation coverage and to a better water management (Rapi et al., 1996).

4. Conclusions

The existence of new tools is based to reinforce the use of agrometeorology and to increase its applications both in developed and developing countries, is based on the strengthening of this use of GIS and remote sensing in the national services, research and training.

To reach this objective there are several initiatives that should be undertaken:

- a greater visibility of the agrometeorology at both national and international level;
- a larger participation to the international programmes;
- better integration with meteorology and climatology.

All these activities are based on the development of new competencies as in the case of GIS utilisation. To prepare this new type of agrometeorologist we can identify three possible ways:

- the reinforcement of training in these new fields;
- the promotion of specialised software;
- the preparation of multimedia training tools to make learning and the updating of the competencies easier.

The promotion of new specialised software should make the applications of the various devices easier, bearing in mind the possible combination of several types of inputs such as data coming from standard networks, radar and satellites, meteorological and climatological models, digital cartography and crop models based on the scientific acquisition of the last 20 years.

In this perspective, the activity of International Agencies such as the WMO and the FAO, in cooperation with the national services and the scientific institutions, is the only way to guarantee the strengthening of the role of agrometeorology for the service of agriculture and of environment in the world.

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