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A GIS for irrigation management

Mladen Todorovic *, Pasquale Steduto [1]

Land and Water Management Research Group, Mediterranean Agronomic Institute of Bari, CIHEAM/IAMB, Via Ceglie 9, Valenzano (BA), Italy

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Abstract

This work describes the development, operational functionalities and spatial modeling applications of a Geographic Information Systems (GIS)-based irrigation management system, to be used by irrigation consortia and local governmental institutions. The system provides tools for the exploration of spatially-referenced databases relevant for irrigation and the evaluation of irrigation scenarios under different soil, climatic and management conditions. The irrigation water management system makes use of ArcView GIS and the Avenue programming language for customization of GIS applications and design of new tools for modeling irrigation water requirements and identifying of areas with water deficit. Irrigation requirements can be estimated taking into account different scenarios of cropping pattern, climatic conditions (from dry to wet year), applied irrigation method, volume of water available for irrigation and hydraulic characteristics of the water distribution system. The irrigation water management system runs on different scales of both irrigation (from irrigation field to irrigation consortia) and administrative (from municipality to region) units. The integration of spatial climatic and soil data is based on the "false-raster" format, a vector layer composed of regular square grid cells. The size of simulation units is a function of the surface area under consideration which means that the exploration of GIS database and development of irrigation scenarios provide more detailed data at field and municipality scale and less number of information at consortia and regional scales. An example of operational functionality of the GIS-based irrigation water management system is given for the Apulia region, in Southern Italy.

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Keywords: Geographic information systems (GIS); Crop water requirements; Irrigation water requirements; Irrigation planning and management

1. Introduction

Modern strategies for the management of natural resources promote sustainable land and water resource systems, designed and managed to "fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity" (ASCE, 1998). Among those systems, the improvement of irrigation management has become a priority due to obvious economic and environmental reasons arising especially in the regions where water is scarce and should be saved for other uses.

Efficient management of land and water resources in irrigated agriculture requires comprehensive knowledge on many variables including climate, soil, land use, crops, water availability, water distribution networks, management practices, etc. Most of these data are spatially distributed and their integration and use in irrigation planning and management has promoted the widespread utilization of Geographic Information Systems (GIS) and other modern information technologies (Su and Wen, 2001; Bioggio and Ding, 2001; Kjelds and Storm, 2001). In fact, the employment of geo-referenced databases enables faster exchange and aggregation of information coming from different sources, and easier interaction of those data with models and decision support tools (Maidment and Djokic, 2000). In turn, the development of GIS databases gives a great opportunity for better management of natural resources and implementation of many subsequent works and projects in different thematic areas, from risk analysis and measures to control and protect environment to the assessment of crop productivity under different soil, climatic and management conditions.

This work presents the development, operational functionalities and spatial modeling applications of a

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* Corresponding author. Tel.: +39-80-4606235; fax: +39-80-4606206.

E-mail addresses: mladen@iamb.it (M. Todorovic), steduto@iamb.it (P. Steduto).

[1] Tel.: +39-80-4606224; fax: +39-80-4606206.

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GIS-based irrigation water management system, to be used by irrigation consortia and local governmental institutions in the Apulia region. Furthermore, it describes applied modeling approaches and the customization of GIS applications for the creation of irrigation scenarios, with the aim of choosing the most appropriate cropping pattern for the area under investigation, estimating irrigation requirements and corresponding irrigation water deficit or surplus, and facilitating the exploration of the results of such analyses.

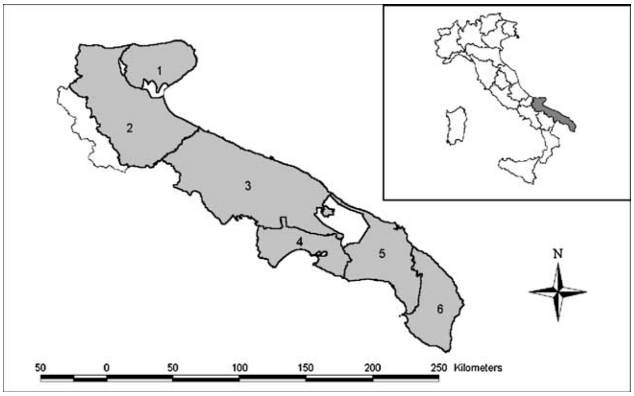

Fig. 1. Apulia region and administrative boundaries of irrigation consortia (1—Gargano, 2—Capitanata, 3—Terre d'Apulia, 4—Stornara e Tara, 5—Arneo, 6—Ugento e Li Foggi).

2. Description of the study area

The Apulia region, situated in the extreme south-east of the Italian "Boot", covers a surface area of approximately 19,500 km^2. Most of the region is flat to slightly sloping lowland except the Gargano massif situated in the North-East. The region borders on the Adriatic Sea on the East and the Ionian Sea on the South, while the Western and Northern part partially border with the uplands and hills of the Apennine massif.

The climate is predominantly of the semi-arid Mediterranean type with hot and dry summer and mild and rainy winter season. The annual precipitation ranges from 400 to 600 mm on most of the region, and it reaches up to 1000 mm only in the central part of Gargano. In the greatest part of the region, hydrological regimes are irregular, of torrential type with high flow rates during the rainy season and practically no water flow during summer.

Agricultural land covers about 72% of the Apulian territory. The greatest part of it is cultivated with cereals (about 27.4%) and olive-trees (about 23.9%), while the rest is dominated by vineyards and vegetable crops. Development, operation and maintenance of irrigation and drainage hydraulic structures (dams, water distribution networks, channels, etc.) are run by six reclamation consortia which cover an administrative area of 1,743,591 hectares, or about 90% of territory (Fig. 1). The area equipped with the consortia water distribution networks, and therefore, potentially irrigated extends over 236,012 hectares. However, in general, only one-third of it is effectively irrigated due to huge irrigation requirements and chronic shortage of water for irrigation and other uses (Table 1).

Water availability is one of the main factors limiting agricultural productivity in the region. In fact, the irrigation consortia usually supplies not more than one-third of the water used for irrigation (about 250 million m^3 per year) in the region, while the greatest part of water amounting to 550 million m^3 is withdrawn from private wells located mainly in the Central-Northern part of the region (Tavoliere di Foggia) and in the peninsula of Salento in the South. This allows the private sector to irrigate, independently, additional 182,500 hectares of agricultural land (Table 1). However, uncontrolled and excessive use of groundwater by farmers frequently causes lowering of groundwater table and intrusion of seawater which leads to serious salinization problems particularly in the coastal areas. In fact, in the last years, several initiatives have been promoted in order to make a census of the wells in the region and to create a comprehensive regional GIS database containing all required information for a better management of land and water resources (Vurro, 2002).

Table 1
Characteristics of irrigation consortia in the Apulia region (INEA, 1999)[a]

Consortia	Total surface area [ha]	Surface potentially irrigated by consortia [ha]	Surface effectively irrigated by consortia [ha]	Surface irrigated from private wells [ha]
Gargano	150,337	570	428	2,500
Capitanata	441,579	140,378	53,667	26,000
Terre D'Apulia	569,807	17,645	4,927	50,000
Stornara e Tara	142,949	43,705	13,203	41,000
Arneo	249,425	18,659	1,127	36,000
Ugento e Li Foggi	189,494	15,055	2,120	27,000
Total	1,743,591	236,012	75,517	182,500

[a] Note: data belong to observations and estimations from 1997.

3. GIS database development

GIS database of the Apulia region represents the combination of information coming from different thematic layers: administrative, soil, climatic, topographic and land-use and it has been developed mainly during the carrying out of the ACLA 2 project aimed at the agro-ecological characterization of the region (Todorovic et al., 1998; Steduto and Todorovic, 2001). Each thematic layer is composed of different sub-layers (coverages) and developed separately and therewith, according to the specific needs, the layers are integrated and used for the creation of thematic maps, the interaction with crop productivity models and the design of new tools like the creation of irrigation scenarios, the estimate of irrigation water requirements and consequent identification of water surplus/deficit zones. The development and integration of GIS database is performed in ARC/INFO, [2] while ArcView, [3] customized for specific purposes, is used for the evaluation of irrigation scenarios, links with crop productivity models and exploration of databases and presentation of the modeling results.

3.1. Climatic database

The National Hydrographic Institute provided the historical monthly values of minimum and maximum temperature and precipitation for a period of 42 years (1950–1992) at 162 meteorological stations, located not only in the Apulia region but also in its surroundings. These data are examined for error detection and spatial and temporal integrity (Todorovic et al., 1998), while the estimate of missing rainfall data is performed by using the double mass analysis (Steduto et al., 1999).

Monthly reference evapotranspiration is calculated for each location through minimum and maximum temperature and latitude of the meteorological stations using the Hargreaves method (Hargreaves and Samani, 1985). Then, the climatic water deficit is calculated as a difference between precipitation and reference evapotranspiration. Consequently, a point layer is created containing, for each month and on a yearly basis too, the on-site values of minimum and maximum temperature, average precipitation along with the precipitation values of different probabilities of occurrence (for description of dry and wet years), reference evapotranspiration and water deficit. This layer is used as an input for the spatial interpolation of weather variables over the whole region.

Spatial interpolation of weather variables is performed using the kriging interpolation method for both annual and monthly data. Several models are tested, for each weather variable and for each month, in order to identify the best-fitting theoretical function to the sample semi-variogram. In most cases, spherical function was the best matching for the modeling of semi-variance. Only in few cases, some other functions provided better results (e.g., linear function for minimum and maximum temperature in July, and circular function for precipitation in November and December). The nearest eight meteorological stations, within the maximum distance (radius) varying from 40 to 60 km, are used to interpolate weather variables at each mesh point. The results of interpolation are transformed into a vector layer where isolines are used to delineate the characteristic values of each climatic variable. In such a way, two layers are created for each climatic variable on monthly and annual basis, the first in the raster and the second in the vector data format as it is illustrated in Fig. 2.

In addition to the historical monthly weather data, a set of daily weather information available at 72 locations for a period of 10 years (1980–1990) is used for the calculation of the standard deviation of daily minimum and maximum temperature and frequency of precipitation for each month. Such information was necessary for the generation of daily climatic data to be used as an input for modeling crop productivity in the region. These data are interpolated by using the inverse distance weighing method since the type of variables and the number of point source information make the use of other methods inadequate.

3.2. Soil database

Soil database is realized using the results of analysis of several investigations and projects including in particular the ACLA 2 project (Steduto et al., 1999; Steduto and Todorovic, 2001).

Soil database includes a point layer specifying the location of about 5000 soil sampling sites and a polygonal layer where the basic soil mapping units are delineated. Soil sampling sites are characterized by a series of general attributes about the location (coordinates, elevation, slope, aspect, land use, morphology, vegetation type, stoniness, parent material, drainage, flooding risk, erosion, deposit material, groundwater table, soil color, permeability etc.) and a series of more specific attributes related to the results of physical and chemical analysis of soil samplings taken at different depths and corresponding to the observed soil layers.

Polygonal soil layer consists of 1048 basic soil mapping units and represents the regional soil map at a scale of 1:100,000. Each polygon is characterized by a series of general information (USDA and FAO soil classification), description of landscape (minimum and maximum elevation and slope, aspect, land use, morphology,

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[2] ARC/INFO is the trademark of ESRI, Redlands, CA.

[3] ArcView is the trademark of ESRI, Redlands, CA.

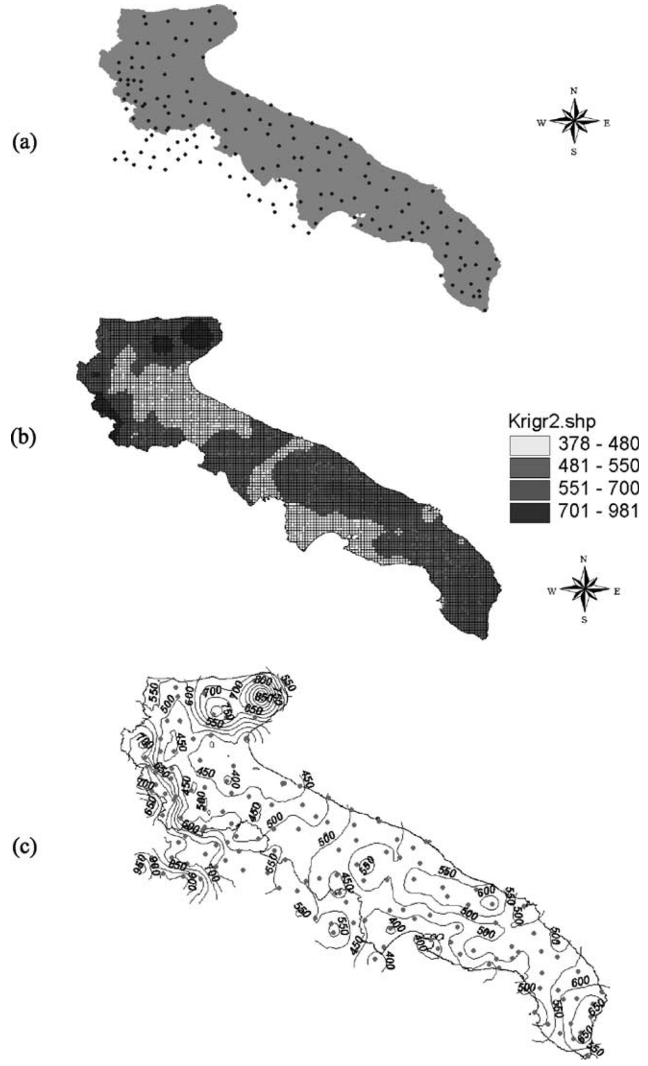

Fig. 2. Development of climate database: (a) point layer of meteorological stations source of data for spatial interpolation, (b) raster data-set representing the results of interpolation of precipitation (in mm) and (c) vector data-set representing the results of interpolation of precipitation (in mm) by means of isohyets.

vegetation type, stoniness, parent material, drainage, flooding risk, erosion, deposit material, groundwater table, soil color, permeability etc.), general description of basic soil mapping units (usable depth, texture, granulometric class, permeability, groundwater table, available water content, etc.) and description of functional horizons with depth and physical and chemical characteristics (pH, organic matter, available water content etc.) of each soil layer. Such "bottom-up" organization of soil database in GIS has allowed grouping the soil mapping units into eco-pedological units and, then, also into soil regions.

3.3. Other databases

Other GIS data concern administrative and irrigation boundaries, topographic database and land-use information. Administrative and irrigation databases are completed by digitizing the boundaries of irrigation units and integrating them with already existing administrative data. In addition, historical series of data related to irrigation water use, application of fertilizers and pesticides, cropping pattern and crop productivity, are collected to be used for reference years.

Topographic database is developed from already existing Digital Elevation Model of Italy with the grid cell size of 250×250 m, while land use database is developed at a scale of 1:100,000 mainly from the re-classified CORINE Land Cover data-catalog (CORINE, 1995). The main land use categories are: artificial surfaces (urban areas and infrastructures), agricultural areas, forests and semi-natural areas, wetland (salines, etc.) and water bodies (artificial and natural lakes, and coastal lagoons). The agricultural area is subdivided into arable non-irrigated and irrigated land, permanent crops (olive groves, vineyards and orchards), pastures and heterogeneous agricultural areas.

4. Database integration and GIS customization

The multi-objective purpose of GIS database called for the integration of different thematic layers at various complexity levels. For example, the basic level of information requires exploration of data by means of a single variable at different scales, from the area of municipality to province and whole region, or from agricultural fields to irrigation districts and consortia. However, for some more complex analyses, soil, climate (for each month and on annual basis too) and topographic databases need to be put together and evaluated at the same spatial unit. For running of the crop-productivity model, a geo-referenced database composed of basic simulation units characterized by soil and weather characteristics is needed. Moreover, the presentation of the same variable may be required in different data formats, depending on the purposes of data and their further evaluation. For example, on one side, the raster regular cell presentation of weather variables is more suited for modeling purposes, on the other, the same data give better insight with the printed maps when vector data model with isolines is used. Integration of data and consequent customization of GIS environment, presented in this work, are developed for the purpose of satisfying requirements of the final users of GIS database which are, in this case, the Apulia regional and consortia authorities.

4.1. Database integration

Three different spatial scales of integration are adopted and correspond to the administrative boundaries of region, provinces and municipalities on one side, and to the boundaries of farms, districts and consortia on the other. The overlay of thematic layers is based on the "false-raster" format, a vector layer composed of square grid cells like a raster. The cell dimensions vary in respect of the scale—level of integration, i.e. the size of the administrative unit under consideration. They are:

- 250 × 250 m, for the integration at municipality or district level,
- 500 × 500 m, for the integration at province or consortia scale, and
- 1 × 1 km, for the integration at regional scale.

Basically, it means that the exploration of GIS database is strictly related to the surface area under consideration providing less information at smaller scales and more detailed information at larger scales. This approach is adopted in order to maintain the volume of information and the resolution of displayed data at approximately the same level at different scales of investigation.

Data integration is performed in ARC/INFO by applying overlay functions on climatic, soil, topographic and land-use layers (Fig. 3). At the first step of integration, each thematic layer is elaborated separately bringing it to the desired cell size of the polygon layer. Then, data are integrated and clipped within the surface area of administrative unit.

The procedure adopted for integration of climatic data, month by month, is schematically presented in Fig. 4. The basic information, presented in raster data model, is converted into the vector data model and subsequently overlapped to generate a vector data layer containing weather information for all months. In order to get information only over the specific area, this data layer is clipped with the polygon layer representing administrative boundaries. In such a way, as previously explained, a vector layer composed of regular cells with dimensions related to the size of administrative unit under consideration is produced.

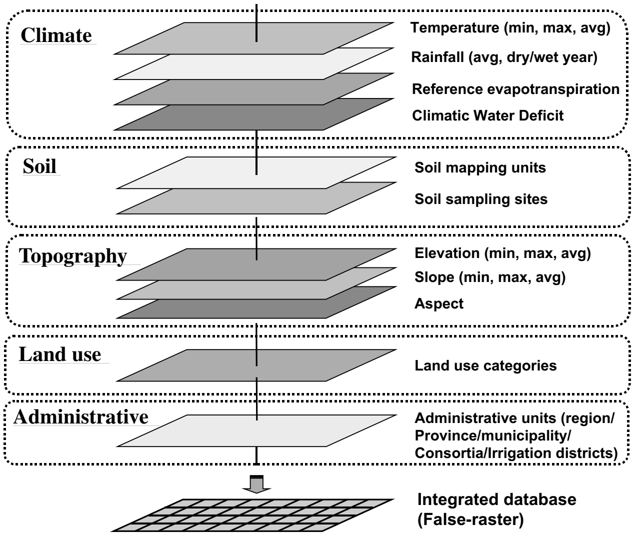

Fig. 3. Development of a GIS irrigation database: Integration of different thematic layers.

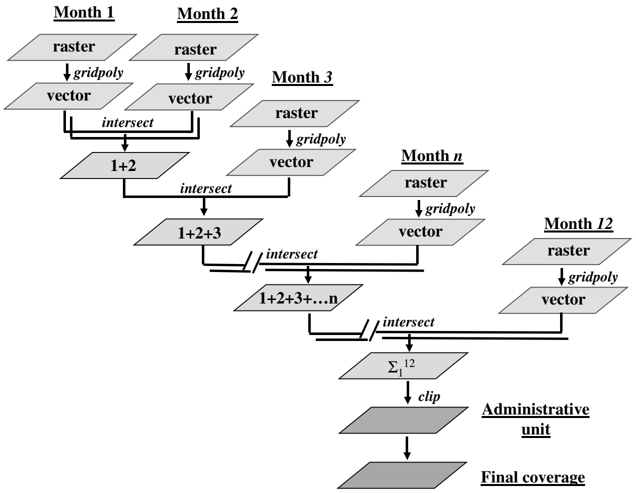

Fig. 4. Month-by-month integration of climatic data applied to all weather variables.

Upscaling of soil, topographic and land-use information into regular cells of larger size has inevitably provoked the loss of information. In fact, when soil polygons are converted into regular cells and more than one soil unit is presented in the cell, the attributes of the soil unit having the largest area in the cell are assigned. Then, the on-cell soil characteristics are compared and possibly modified in respect of the soil sampling site characteristics, point features belonging to the cells. When topographic data are transformed into cells of lower resolution, the output cells contain all, average, minimum and maximum values of the input cells that are encompassed by the output cell. Land-use database is following an approach similar to that of soil data, attributing to the output cells the features of the land-use class of the largest area.

4.2. GIS customization

The main users of the GIS database are regional authorities that should provide the characterization of the Apulia region by the suitability for agricultural production under both optimal and limited availability of resources. It means the preparation of an efficient GIS support able to assist regional institutions in storing, managing and exploring GIS database and providing spatially referenced answers to the questions of particular interest, as the following:

- Which area does satisfy the user-defined conditions regarding climate, soil, topography, etc.?

- Which area is most suitable for growing the user-specified crops and what are the plant species most appropriate for growing in a given administrative/irrigation unit?
- What are the irrigation requirements for growing specific crops in certain areas?
- What is the irrigation deficit with respect to the expected (programmed) irrigation water supply, the hydraulic characteristics of irrigation systems, etc.?

For the achievement of these objectives, two approaches are adopted. The first approach represents a simple irrigation module using a GIS-embedded procedure for the exploration of data, development of irrigation scenarios and identification of water deficit areas. The second approach applies a "stand-alone" crop productivity model for the estimation of crop suitability for being cultivated under specific climatic, soil and management conditions, and in this case, GIS is used as an interface for input–output data exchange and exploration of modeling results. Both approaches follow the same initial step that requires the identification of the scale, i.e. the area of interest for the analysis.

The customization of the software followed a general framework, presented in Table 2. It consists in the display of climatic, soil, land use and topographical data, the evaluation of irrigation scenarios for different crops, the link to mechanistic and statistical crop productivity models and the display of crop productivity according to different management practices. Basically, it is possible to distinguish between the items that provide only simple display of information about GIS database (*climate*, *soil*, *topology* and *land use*), and those within the *irrigation* and *model* menu which offer an opportunity

Table 2
General framework of the GIS applications customized for irrigation management

Menu	Item	Action
Climate	Temperature	Display of average, minimum and maximum temperature on monthly and annual basis
	Precipitation	Display of average precipitation and precipitation of different probabilities of occurrence on monthly and annual basis
	Reference ET	Display of reference evapotranspiration (ETo) on monthly and annual basis
	Water deficit	Display of water deficit as a difference between ETo and precipitation
Soil	USDA class	Display of great soil groups according to the USDA soil classification
	FAO class	Display of major soil groups according to the FAO 1990 soil classification
	Soil units	Display of the basic soil mapping units
	Soil properties	Display of principal soil properties (texture classes, soil water content, useful depth, pH, organic matter)
Topography	Elevation	Display of average, minimum and maximum elevation values
	Slope	Display of average, minimum and maximum slope
	Aspect	Display of aspect values
Land use	Main	Display of main land use categories
	Agriculture	Display of arable irrigated and non-irrigated areas, permanent crops, pastures and heterogeneous agricultural areas.
Irrigation	Effective rainfall	Estimate and display of effective rainfall (according to user defined rainfall coefficient)
	ETc	Estimate and display of crop evapotranspiration (user defined cropping pattern)
	NIR	Estimate and display of net irrigation requirements
	GIR	Estimate and display of gross irrigation requirements (user defined irrigation method and efficiency)
	Irrigation water deficient	Estimate of irrigation water deficit by means of total available water and hydraulic characteristics of the water distribution system (defined by user)
	New scenario	Run new scenario
	Compare	Compare different scenarios
Model	Mechanistic	Link to mechanistic crop growth and productivity model
	Crop rank	Display of the best ranking crops for the whole area
	Crop yield	Display of the crop productivity according to the different management conditions, by means of potential productivity and capability to reach such productivity
	Statistic	Link to statistical values of crop productivity

to estimate irrigation requirements and irrigation water deficit and provide a link to the crop productivity models and display of modeling results. The latter two are described here after.

5. Irrigation module

The irrigation module provides comparison of different irrigation scenarios by means of the user-defined cropping pattern and climatic conditions (average, dry and wet year), applied irrigation method, total volume of water available for irrigation and hydraulic characteristics of the water distribution system. Furthermore, comparing water demand and supply, the irrigation module allows the identification and display of water deficit and surplus zones over the area under consideration.

The calculation of crop irrigation requirements is based on the standard procedure, as it is proposed in the FAO CROPWAT software for irrigation planning and management (FAO, 1992). The basic difference is in the development of the calculation procedures within a GIS environment which permits spatial distribution of results on square grid cells covering the whole territory under consideration.

At the beginning of the session, the area under investigation concerning municipality, province, irrigation district or consortia, should be indicated by the user. Also, the user should choose among the total (administrative) area, agricultural area and potentially irrigated area (to which water delivery is supplied by consortia). Moreover, it is possible to distinguish between the land grown with perennial crops (olive groves, vineyards, orchards) and other agricultural land. The irrigation module works on monthly time scale and may be run partially or for the whole season. The flowchart of the calculation procedure is given in Fig. 5. All calculations are done on cell-basis and the results are expressed in mm of water. Exceptionally, irrigation demand (gross irrigation requirements), irrigation supply and irrigation water deficit are expressed also as volume of water in m^3. Display of the results of calculation is provided for each month and on seasonal (yearly) basis.

The calculation of effective rainfall (P_{eff}) takes into consideration the runoff and percolation losses which may be adopted as a fixed fraction of rainfall over the whole area or as a value which varies from cell to cell depending on the monthly amount of rainfall and/or land cover, i.e. actual cropping pattern. Effective rainfall is calculated cell-by-cell as:

$$P_{\mathrm{eff}} = P_{\mathrm{coeff}}P \qquad (1)$$

where P_{coeff} is the rainfall coefficient, fixed to 0.8 as a default value, and P is the monthly amount of rainfall taken out from the GIS database. Two different options are proposed for the input rainfall data: an average value or a value corresponding to a given probability of occurrence of the rainfall event (ranging from wet to dry year). After the calculation of effective rainfall, GIS environment allows the display of both, effective rainfall and interception losses. The display of the results of effective rainfall estimate over the whole Apulian territory is presented in Fig. 6.

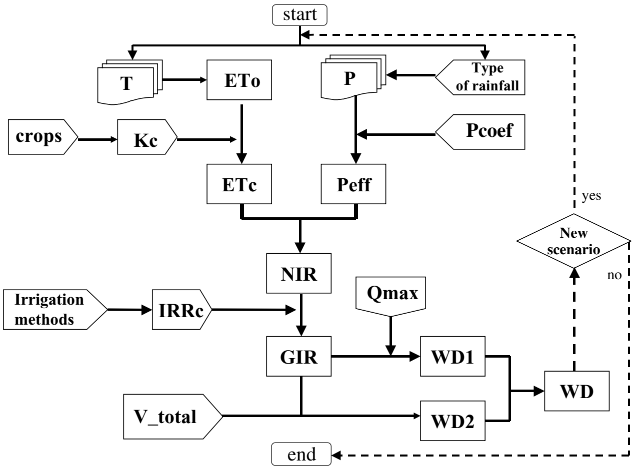

Fig. 5. Flowchart of the calculation procedure for the estimation of irrigation requirements and identification of water deficit areas.

Crop evapotranspiration ($\mathrm{ET_c}$) is calculated as:

$$\mathrm{ET_c} = K_{\mathrm{c}}\mathrm{ET_o} \qquad (2)$$

where K_{c} is the crop coefficient that varies with the crop and its growing stage. $\mathrm{ET_o}$ is the reference evapotranspiration calculated by Hargreaves method, interpolated over the whole area and integrated in the GIS database as previously explained. The $\mathrm{ET_c}$ calculation starts with a dialog box which gives the user the possibility to choose between the crops existing in the database with pre-determined K_{c} values and new crops with the K_{c} values defined and inserted directly by the user. The results of calculation may be displayed on monthly and seasonal basis at the user's request. An example of the seasonal crop evapotranspiration calculated for tomato crop is given in Fig. 7.

Net irrigation requirement (NIR) is calculated as a difference between crop evapotranspiration and effective rainfall, both have to be calculated in advances for defined cropping pattern. Exceptionally, if necessary, the user of the system can also take into account the amount of water required for leaching. Net irrigation requirements may be displayed on monthly and seasonal basis in mm of water and also as the volume of water in m^3 needed for the area under consideration.

Gross irrigation requirement (GIR) depends on the efficiency of the applied irrigation method ($\mathrm{IRR_{eff}}$) and is calculated as:

$$\mathrm{GIR} = \frac{\mathrm{NIR}}{\mathrm{IRR_{eff}}} \qquad (3)$$

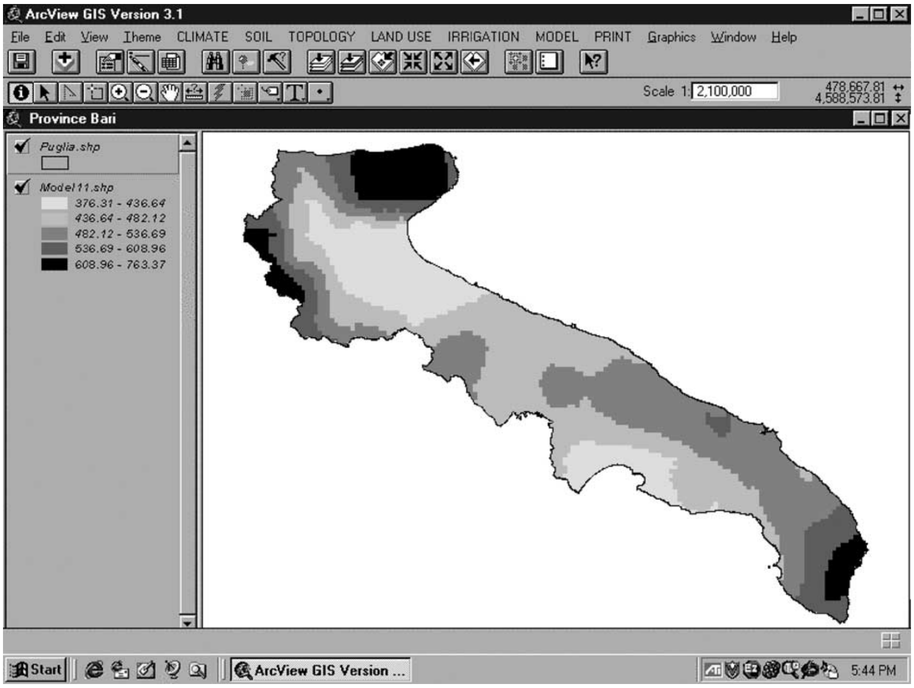

Fig. 6. Effective rainfall (in mm), based on average precipitation data, in the Apulia region.

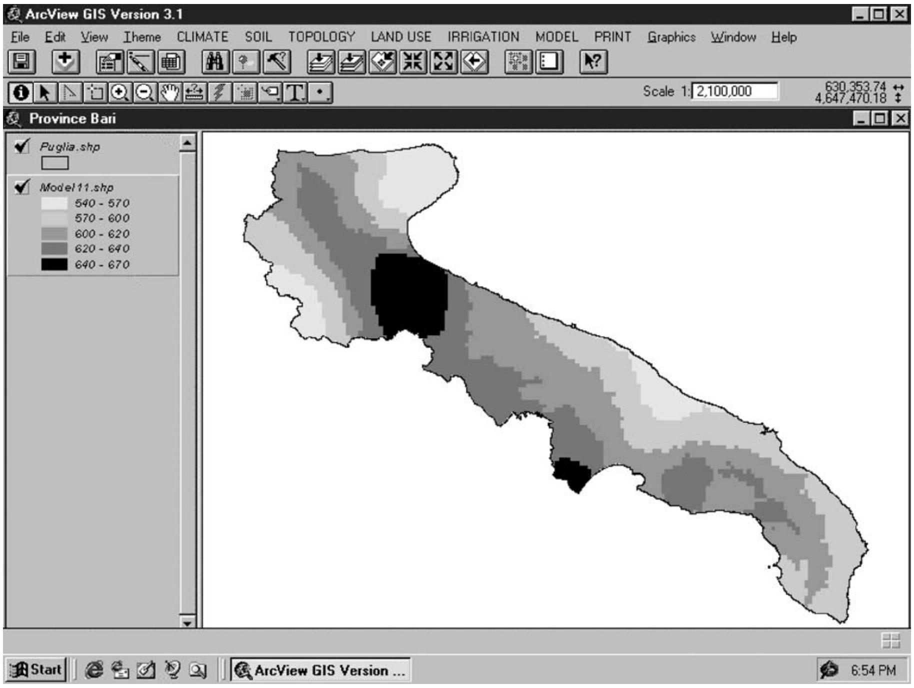

Fig. 7. Seasonal evapotranspiration (in mm), estimated for tomato crop, in the Apulia region.

A dialog box allows the user of the system to select the irrigation method and eventually insert the user-defined irrigation efficiency to be used in calculation. The distribution of gross irrigation requirements in the area of interest may be displayed on monthly and seasonal basis as it is illustrated in Fig. 8. Also, the total amount of water necessary for irrigating the area under consideration may be calculated and displayed at the user's request.

The irrigation module provides the calculation of irrigation water deficit as a difference between irrigation demand (gross irrigation requirements) and irrigation

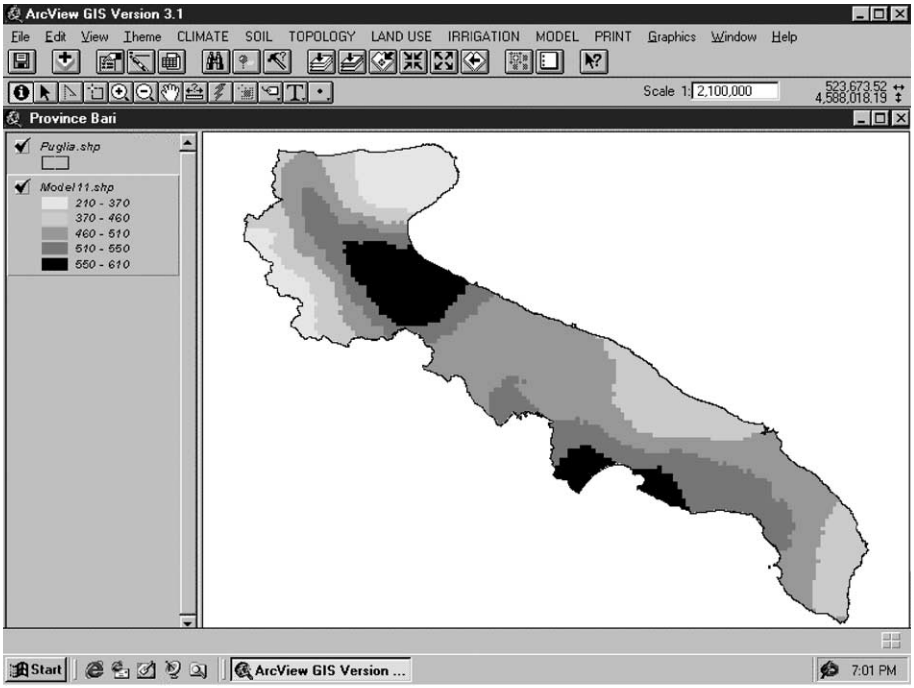

Fig. 8. Seasonal gross irrigation requirements (in mm) for tomato crop in the Apulia region.

supply (amount of water available for irrigation). Two criteria (constraints) may be used for water supply:

- Limited total amount of water available for irrigation of an area (WD1) and
- Limited amount of water for each cell (WD2), as a function of maximum flow rate of the water distribution system.

When the first criteria is chosen, the user of the system inserts the total volume of water available for irrigation and chooses the mode of distribution: uniform over the whole area or irregular depending upon the user-defined management criteria (more water to one irrigation district in respect to others etc.). The result of this calculation identifies the areas of water deficit and surplus (Fig. 9) as a function of user-defined criteria regarding cropping pattern, rainfall input, irrigation method and distribution of total volume of water available for irrigation.

When the second criteria is chosen, water deficit zones are identified by comparing irrigation requirements for each month through the total amount of water available on monthly basis and determined from designed maximum flow rate of water distribution network. Then, if both criteria for water supply are used, the areas that satisfy both may be determined in GIS by using simple logical operators and map algebra functions, as in the case of raster data model.

Lastly, the irrigation module offers the possibility to introduce new scenarios by changing the whole set of input data or modifying only some input parameters. This allows comparing different irrigation scenarios and identifying the irrigation practices most appropriate for the imposed climatic conditions, irrigation methods and availability of water in volume and flow rate.

6. Crop productivity modeling

Two approaches, mechanistic and statistical, are adopted for crop productivity modeling. At this stage of development, the customized GIS provides the link (input–output) to the mechanistic model and the tools for the exploration of the results from the statistical approach.

6.1. Mechanistic approach

The mechanistic model amalgamates knowledge of CROPSYST (Stockle and Roger, 1992; Stockle et al., 1994) and EPIC (Williams et al., 1989) and it is explained in detail in Steduto and Todorovic (2001). The model integrates crop growth and soil–water-balance modules, runs on different time-steps (daily, 10-days and monthly) and provides quantitative prediction of crop growth and yield only for field crops. Three major peculiarities distinguish this model from the others. They are: (i) spatial scale of adaptation; (ii) combination of both the "solar-driven" and the "water-driven" "growth-engines" at the heart of the model (Azam-Ali

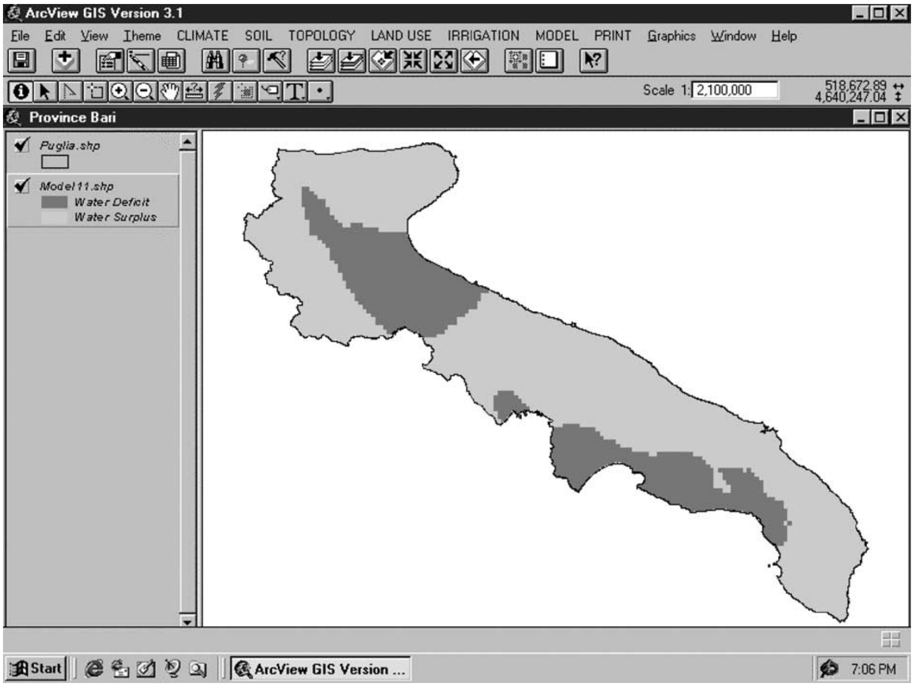

Fig. 9. Irrigation water deficit (dark color) and surplus areas for the case of tomato crop with limited total amount of water available for irrigation and uniform water distribution throughout the region.

et al., 1994) and (iii) the algorithms implementation in both a stand-alone and a GIS-linked software format.

Flowchart of data exchange between GIS and mechanistic crop productivity model is presented in Fig. 10. The mechanistic model runs on the basic simulation unit, describing homogeneous soil and climate conditions. The main input information about weather and soil characteristics is extracted directly from GIS database, while the crop-related parameters are imported from an external crop database, built for the majority of field crops growing in the region. The model output is geo-referenced to the same basic simulation unit and provides quantitative prediction of crop yield under three different management practices: potential production with no water and nutrient deficit, rainfed agriculture with water restriction but with no nutrient deficit, and poor practices, with water and nutrient constraints. Moreover, the model measures the amount of resource (water and nutrient) necessary for crop to achieve potential productivity under optimal management practices.

The model has been calibrated for wheat, sugar beet, tomato, green pepper, lettuce, sunflower, artichoke and potato. The running of the model for different crops over the whole area permits ranking the crops according to three levels of productivity corresponding to different management practices (potential productivity, rainfed agriculture and poor management). These results may be displayed by means of the best ranking crops for each cell over the area of interest (*Crop rank* item) and the productivity of specific crop under different management practices and capability to reach the potential productivity level (*Crop yield* item).

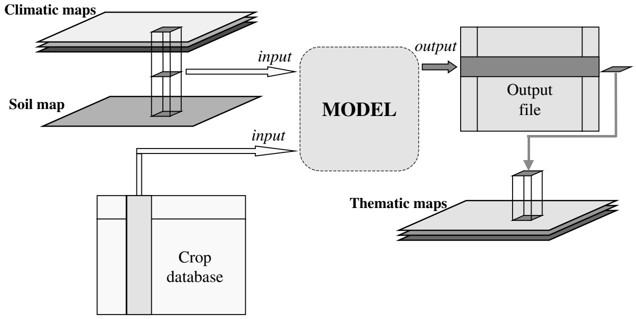

Fig. 10. Flowchart of data exchange between GIS and the mechanistic model.

6.2. Statistical approach

The statistical model uses historical information about crop productivity in different areas of the region. It provides an estimate of productivity for the whole season and is particularly useful for tree crops (olive trees and orchards) and vineyards which are not considered in the mechanistic modeling approach. The statistical model is completely based on GIS applications (Fig. 11) since statistical records are spatially referenced to the agricultural land of basic administrative units (municipalities). The model puts together admini-

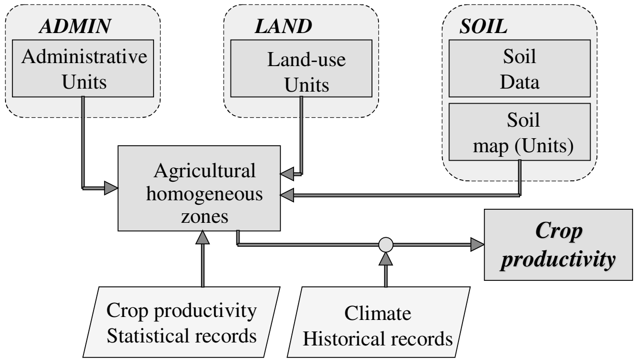

Fig. 11. Flowchart applied for the investigation of crop productivity by means of statistical modeling approach.

strative, land use and soil layers to draw the relationship between crop productivity and soil characteristics. Then, it associates the historical weather data for the area under consideration. It permits to derive the relationship between local soil characteristics, weather conditions and crop productivity. In many cases, it was difficult to develop a straightforward relationship due to the difficulties of taking into consideration also the local irrigation and fertilizer applications and management practices.

7. Conclusions

This work covers two topics relevant for the improvement of irrigation management in the Apulia region: the development of the regional GIS irrigation database and its further evaluation through the creation of irrigation scenarios and the estimate of irrigation requirements and irrigation water deficit. They are both necessary to improve the strategies in the choice of agricultural crops and to schedule irrigation accordingly, deciding which fields (or crops) to irrigate, when and how much.

This paper illustrates one of the numerous opportunities offered by GIS once the necessary information is collected and GIS database is developed. Moreover, it underlines the importance of the spatial evaluation of irrigation scenarios within a GIS which promotes the user's interaction with the system, easy modification and comparison of scenarios and clear insight with visualization and interpretation of spatially-referenced results.

The presented approach of GIS customization offers different scales of investigation, from municipality and irrigation district to province, irrigation consortia and region, increasing the size of the basic simulation unit as the area under investigation increases. Therefore, the lower the surface area under investigation, the higher the resolution of spatial data, and thus the better the quality of available information and the possibility of creating more detailed, reliable and complex irrigation scenarios.

The basic irrigation module presented in this work runs on PC, is very simple and may be applied without modification at different scales and also at different locations since most of the required input GIS data are available at national and continental scale. Moreover, the use of the irrigation module at a time scale shorter than monthly may be easily implemented, but could significantly increase its running time and decrease the overall versatility of the system.

Furthermore, an added value could be attributed to the system, especially when smaller areas are considered (municipalities and irrigation districts), by transforming the regular cells into irrigation fields. It will allow the application of more complex irrigation modules that takes into consideration the site specific soil characteristics and local management practices. In fact, the development of a soil water balance module is one of the primary tasks to be accomplished. This could be particularly important when the irrigation module has to be extended to on-farm irrigation scheduling applications.

Finally, it is worthwhile emphasizing the necessity to integrate information about the wells (their locations, volumes of water extracted and water use) into existing GIS database because the wells provide most of the irrigation water supply in the region and they are also responsible for groundwater draw-down and subsequent environmental issues. In fact, these data, along with a comprehensive monitoring system, are indispensable not only for better planning and management of irrigation activities in the region but also for risk analysis related to the variation of groundwater level, recharge of aquifers, possible intrusion of seawater and degradation of groundwater quality. It is thus in the interest of the region to support an integrated research effort to address these continuing and rising water and environmental problems.

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