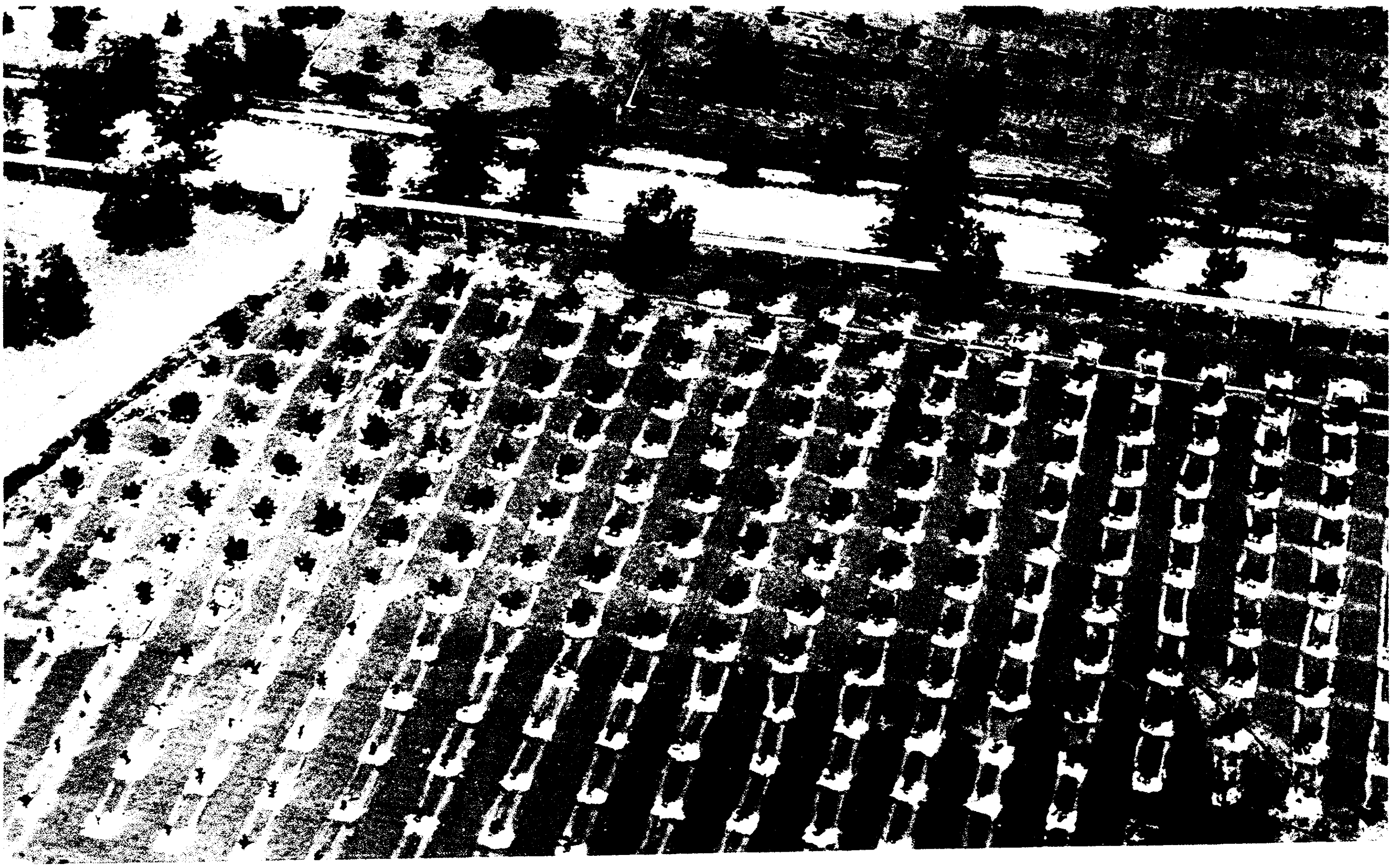
Angela M. S. Matarrese

EVALUATION OF CROP IRRIGATION WATER REQUIREMENTS IN THE APULIA REGION

(Calcolo del fabbisogno irriguo delle colture in Puglia)



UNIVERSITA' DEGLI STUDI BARI "ALDO MORO"
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<Tesi di Master of Science
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Evaluation of crop irrigation water requirements in the Apulia region.

Angela Maria Stella MATARRESE (Italy)

Abstract

This study has focussed on the assessment and quantification of crop irrigation water requirements (IWRs) in the Apulia region (Southern Italy) for the optimization of water use in agriculture. Regional climatic, pedologic and land use data have been applied to a computational model that has performed a monthly water balance for an average climatic year and has been implemented on a GIS platform with a view to estimate maximum IWRs and the requirements under regulated deficit irrigation (RDI). Estimates have been compared with the farmers' actual supplies, previously determined for some areas and then extended to the entire region. A distributed approach has been used to take into account the spatial variability of climate and landscape features, and depletion coefficients (Kd) have been utilised to take account of the applied deficit. Results show that maximum IWRs are reduced by 19.4% with RDI and by 25.9% with the actual supplies. In conclusion, the strategy of RDI allows optimizing water use with respect to maximum requirements and to farmers' actual supplies.

Key words: irrigation water requirements; water balance model; deficit irrigation; Geographical Information System (GIS); water use optimization; Apulia region.

Valutazione dei fabbisogni irrigui delle colture in Puglia.

Angela Maria Stella MATARRESE

Riassunto

Questo studio è focalizzato sulla valutazione e la quantificazione del fabbisogno irriguo nella regione Puglia per l’ottimizzazione dell’uso dell’acqua in agricoltura. Dati climatici, pedologici e di uso del suolo su scala regionale sono stati applicati a un modello computazionale che ha eseguito un bilancio irriguo mensile per un anno climatico medio e che è stato implementato su una piattaforma GIS, al fine di stimare i fabbisogni irrigui massimi ed i fabbisogni irrigui in condizioni di stress idrico controllato. Le stime sono state confrontate con i reali volumi irrigui forniti dagli agricoltori, determinati in precedenza per alcune zone e poi estesi a tutta la regione. Un approccio distribuito è stato utilizzato per tener conto della variabilità spaziale, del clima e delle caratteristiche del paesaggio, e coefficienti di riduzione (Kd) per tener conto del deficit idrico applicato. I risultati mostrano che i fabbisogni irrigui massimi delle colture sono ridotti del 19,4% con lo stress idrico controllato e del 25,9% nel caso degli effettivi volumi irrigui applicati. In conclusione, la strategia dello stress idrico controllato permette di ottimizzare l'uso dell’acqua di irrigazione rispetto ai fabbisogni massimi e ai volumi effettivamente forniti dagli agricoltori.

Parole chiave: fabbisogni irrigui; modello di bilancio idrico; irrigazione deficitaria; Geographic Information System (GIS); ottimizzazione dell’utilizzo idrico; regione Puglia.

Etude sur l'évaluation des besoins en eau d'irrigation des cultures dans la région des Pouilles.

Angela Maria Stella MATARRESE (Italie)

Résumé

Dans cette étude on a évalué et quantifié les besoins en eau d'irrigation des cultures (IWR) dans la région des Pouilles (Sud de l'Italie) en vue de l'optimisation de l'utilisation de l'eau en agriculture. La disponibilité des données climatiques, pédologiques et de l'occupation des sols au niveau régional a permis l'application d'un modèle de calcul, qui a dressé un bilan hydrique mensuel pour une année climatique moyenne et a été appliqué sur une plateforme SIG, dans le but d'estimer les IWR maximum et les besoins en cas d'irrigation déficitaire contrôlée (RDI). On a comparé les estimations avec les disponibilités réelles des agriculteurs, préalablement déterminées pour certaines aires et étendues à la région tout entière. On a utilisé une approche distribuée pour tenir compte de la variabilité spatiale des caractéristiques climatiques et paysagères, et les coefficients de tarissement (Kd) pour considérer le déficit appliqué. Les résultats démontrent que les IWR maximum se réduisent de 19,4% avec RDI et de 25,9% avec les disponibilités réelles. En conclusion, la stratégie de RDI permet l'optimisation de l'utilisation de l'eau par rapport aux besoins maximum et aux disponibilités réelles des agriculteurs.

Mots clés: besoins en eau d'irrigation des cultures; modèle du bilan hydrique; irrigation déficitaire; Système d'Information Géographique (SIG); optimisation de l'utilisation de l'eau; région des Pouilles.

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A_i	=	the surface area occupied by each crop *i* within the corresponding Province [ha];
AWC	=	available soil water content [%]
CDI	=	controlled deficit irrigation
CWR	=	crop water requirements [mm/d]
DI	=	deficit irrigation
E	=	actual evapotranspiration or evaporation from bare soil [mm/d]
ET_0	=	reference evapotranspiration [mm/d]
ET_c	=	maximum crop evapotranspiration [mm/d]
ET_e	=	actual crop evapotranspiration [mm/d]
FC	=	water content at field capacity [%]
GIS	=	Geographic Information System
GW	=	groundwater recharge [mm/d]
Inf	=	soil water infiltration [mm/d]
Irr	=	irrigation water [mm/d]
IWR	=	irrigation water requirements [mm/d]
$K_{c\ ini}$	=	initial crop coefficient
K_c	=	crop coefficient
K_{cb}	=	crop coefficient for bare soil
K_{ci}	=	the crop coefficient of the single crop i within the land cover unit j [m];
$\overline{Kc_j}$	=	the mean crop coefficient of the crops within the land cover unit j [m];
K_d	=	depletion coefficient
MAD	=	management allowable depletion [%]
N	=	natural inputs [mm/d]; number of different crops presented in the land cover unit *j*
p	=	% of available water that has to be reached
P	=	total rainfall [mm/d]
P_{eff}	=	effective rainfall [mm/d]
PR_i	=	the rooting depth of the single crop i within the land cover unit j [m];
$\overline{PR_j}$	=	the mean rooting depth of the crops within the land cover unit j [m];
Ra	=	extraterrestrial radiation [mm/d]
Rd	=	rooting depth [m]
RO	=	surface runoff [mm/d]
RO_{sub}	=	subsurface runoff [mm/d]
S	=	surface area [ha]
T_c	=	average monthly air temperature [°C]
WP	=	water content at wilting point [%]
$\delta w/\delta t$	=	variation in time of soil moisture content [mm/d]
ρ_{aps}	=	soil bulk density [t/m^3]

Chapter 1

Introduction

Water is one of the most important inputs required in agricultural production. Over 90% of fresh biomass is essentially water, which complements carbon dioxide as a major substrate in carbon fixation, photosynthesis, a process that is in the essence of life on earth. Water requirement for plant growth is granted by soil water stored within the plant root zone. In temperate and tropical regions of high rainfall, soil water is continuously replenished as is depleted by plant growth. In such regions, therefore, scarcity of water, limiting agricultural production, is a rare occurrence.
However, in arid and semi-arid regions, or in areas of low and erratic rainfall, which comprise one third of the global land area, available water resources must be sparingly and effectively used not only to ensure good crops but also to meet municipal and industrial water needs.
Therefore, under the conditions of highly variable climatological environment and chronically deficit rainfall of the arid zones, sustainable food security can not be obtained if the agricultural practices do not address to the effective usage of the most precious and yet uncertain resource, water (Kirda, 2000).

With respect to the need for irrigation water, a distinction can be made among three climatic situations:

1. Humid climates: more than 1200 mm of rain per year. The amount of rainfall is sufficient to cover the water needs of the various crops. Excess water may cause problems for plant growth and thus drainage is required.
2. Sub-humid and semi-arid climates: between 400 and 1200 mm of rain per year. The amount of rainfall is important but often not sufficient to cover the water needs of the crops. Crop production in the dry season is possible with irrigation only, while crop production in the rainy season may be possible but unreliable: yields will be less than optimal.
3. Semi-arid, arid and desert climates: less than 400 mm of rain per year. Reliable crop production based on rainfall is not possible; irrigation is thus essential (Brouwer and Heibloem, 1986).

The Apulia region is characterized by a typical Mediterranean climate with mild, rainy winters alternated by dry and very hot summers. Due to the influence of the Adriatic and Ionian Sea, coastal areas are less subject than the hinterland to large seasonal variations in temperature (Lamaddalena and Caliandro, 2008).
The climatic feature that most affects the development of vegetation in the region is the coincidence of the period of higher temperatures with the almost complete lack of rain (the name Apulia seems to come from Latin *a-pluvia* that means dry, without rain). This lack occurs in those months (from May to September) in which a higher activity of vegetation and a higher transpiration of plants occur, caused by high temperature. The phenomenon is highlighted in all the Southern regions, but in Apulia, it assumes greater importance

because it concerns almost the entire area and higher average temperatures are observed, corresponding to scarce or totally absent rainfall (INEA, 1999).

Thus, the availability of rain in the region hardly meets the demands of vegetation, and the region suffers for this deep gap between water demand and water supply. The water shortage, the periodic drought risk and the increasing evapotranspiration demand, due to the apparent climate changes that are occurring (overall increase of temperature and decrease of yearly precipitations) (Kapur, 2002) are the main reasons of this.
In addition, the decrease in surface and groundwater quality, due to the human activities, plays a role in the water availability for agriculture. In fact, the highest regional water demand is presented by the irrigated agriculture sector (about 70% according to ARPA Puglia, 2003) which, in order to deal with the insufficient water supply, causes groundwater exploitation (Azaña Labrador, 2007). This is a problem for the environmental sustainability, not only for the agriculture sector, that is the most sensitive, but also for the other social sectors (domestic and industrial). Following the traditional technique of increasing the supply is questionable; most of the available water resources have been mobilised.
Therefore, a solution should be searched in the improvement of water demand strategies and more efficient use of water resources (Vinterfeld, 2002), considering that in the irrigation sector, in particular, the difficulties of reaching satisfactory evaluations are linked to a water demand, that varies greatly in time and space, as it depends on both climate trends and farming systems, and these are difficult aspects to predict, since the first relates to laws of randomness and the second to market trends (Ciollaro *et al*., 1993).

In order to improve water use and move towards a sustainable development of the regional agriculture, the assessment and quantification, through the water balance, of crop irrigation water requirements (IWR) is needed, since it allows to draw conclusions on what may be the best strategy, at regional level, to make optimal use of water resources.

1.1 Study objectives

The main objectives of this work are:

- Setting an appropriate methodology to assess the maximum irrigation demand and the requirements under stress conditions, for a characteristic year of average, for the Apulia region;
- Providing informations about the estimation of regional crop IWR, through the use of data available from previous projects, properly developed, integrated and homogenized;
- Evaluating possible water saving strategies based on deficit irrigation, in order to ensure the optimal use of allocated water.

1.2 Study approach

A) The starting point of this work is the individuation of the most appropriate methodology to estimate crop irrigation water requirements: the different methodologies available in literature for the estimation of crop irrigation water requirements are examined, and identified those that best suit the environmental conditions of Apulia and environmental data available for the region. Among the available methodologies, particular attention is placed to those based on water balance in the different situations of soil.

B) The specification of the climatic, pedologic and cropping parameters needed for the application of the computational model. According to FAO n° 24 (1977) these parameters are:

- Climate:
    - a) Climatic data: historical series of climatic data (temperature and rainfall) for the whole region;
    - b) Identification of homogeneous climatic zones;
    - c) Computation of:
        1) effective rainfall;
        2) reference evapo-transpiration (ET_0), computed with the most indicated method, according to the available climatic data (FAO n° 56, 1998).
- Soil:
    - a) Cartographic units existing in each homogeneous climatic area;
    - b) Hydrological features and soil depth for each cartographic unit, previously identified, of the pedologic map available for the region.
- Land:
    - a) The most representative crops existing in every homogeneous climatic area, for each cartographic unit.
- Crops:
    - a) Crop coefficient (K_c) of the main herbaceous and tree crops in Apulia, for each phenological stage;
    - b) Mean rooting depth of the main herbaceous and tree crops in Apulia;
    - c) The maximum available water content (AWC) for the crops;
    - d) Depletion coefficient (K_d) of the water requirements.

The climatic and the pedologic data used for the computation of the water balance derive from various sources, including the ACLA 2 project (A.C.L.A. 2, 2001), the C.O.R.I.N.E. project (C.O.R.I.N.E., 2000) and the S.I.G.R.I.A. project (INEA, 1999).
In the evaluation of the irrigation requirements, the distribution efficiency is always assumed equal to 100%.

C) Once the regional areas affected by irrigated crops have been identified (according to the scheme of fig. 1.1), the maximum crop water demand and the requirements under controlled deficit irrigation can be estimated in each month of the irrigation season, by using a computational model with a distributed approach (Fig. 1.2) that performs a monthly water balance (Lamaddalena and Caliandro, 2008).

D) Finally, a Geographical Information System is used for spatial analysis and mapping of both the input and the output databases: GIS treats these databases as a set of layers and is able to identify, for each cropped field, the respective set of predominant characteristics. This allows the visualization of the spatial distribution of crop water requirements inside the case study region and comparison between the total actual crop water demand of the study area, the requirements under controlled deficit irrigation and the actual water volumes supplied by the farmers, according to the results obtained from the work of Lamaddalena and Caliandro (2008).

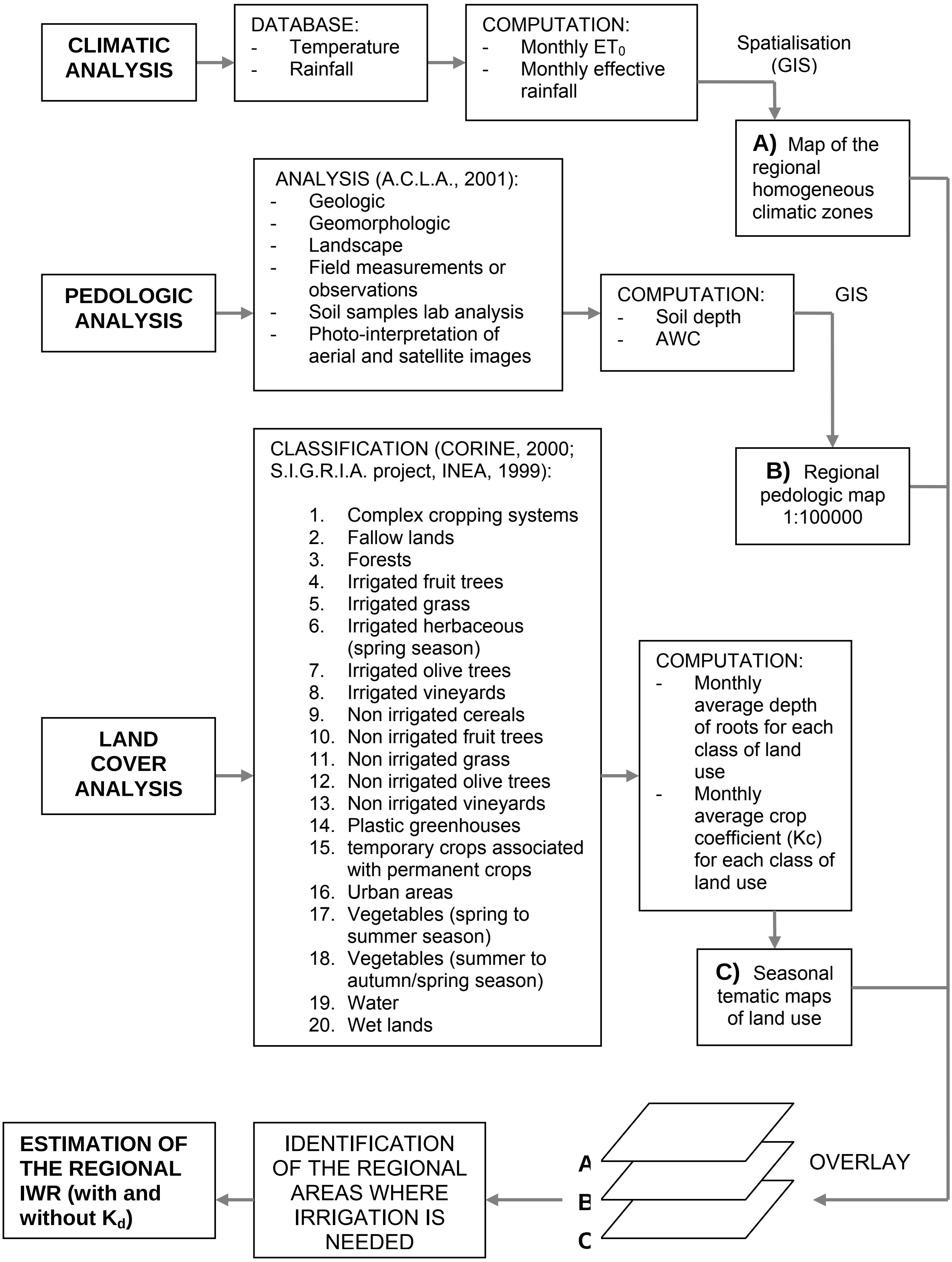

Figure 1.1: Outline showing the identification of the regional areas where irrigation is needed.

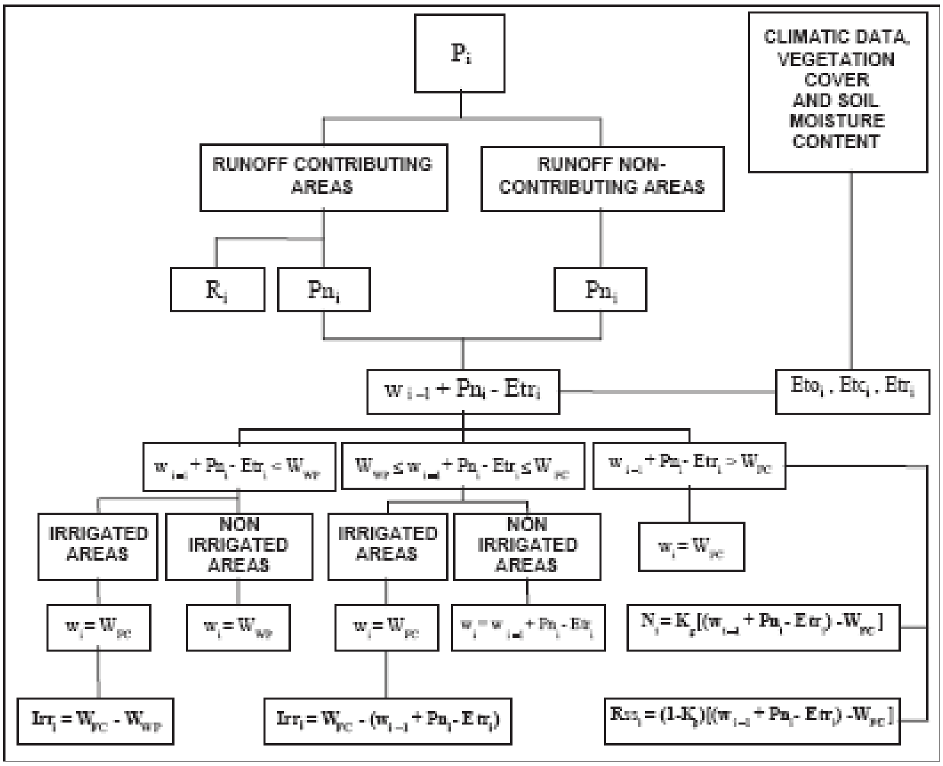

Figure 1.2: Flow chart of soil water balance and natural recharge evaluation procedure using a distributed approach (source: Portoghese *et a*l, 2005). P_i is the monthly total rainfall, R_i is the surface monthly runoff, Pn_i is the net monthly rainfall, ET_{0i} is the monthly reference evapotranspiration (referred to reference crop), ET_{ci} is the monthly maximum evapotranspiration (referred to actual crop), ET_{ri} is the monthly actual evapotranspiration, w_i is the soil moisture, W_{WP} is the soil moisture content at the wilting point, W_{WC} is the soil moisture content at the field capacity, Irr_i is the monthly actual irrigation amount, K_g is the geologic permeability coefficient, Rss_i is the sub-surface monthly runoff, N_i is the monthly natural recharge amount, *i* is the current time step (month) and *i-1* is the previous time step.

Chapter 2

Literature review

2.1 Crop water requirements

About 99% of the water uptake by the plants from the soil is lost as evapotranspiration (ET). For this reason, it can be stated that the measurement of a crop's ET on a daily scale, and for the whole vegetative cycle, is equal to the water requirement of the given crop (Katerji and Rana, 2008).

Crop water requirements (CWR) are defined as the amount of water [mm] needed by the crop from the beginning to the end of its cycle, which is equal to the sum of all the millimeters of evapotranspired water during the whole cropping cycle (FAO, 1998):

$$CWR = \sum_{1}^{x} \left(ET_o \cdot K_c \right) = \sum_{1}^{x} ET_c \qquad [1]$$

where:

ET_0 is the reference evapotranspiration, K_c is the crop coefficient, ET_c is the maximum evapotranspiration of the crop and x is the unit of time, which refers to the cropping cycle.

For irrigated crops, irrigation water requirements (IWR) are defined as the net depth of water [mm] that is required to be applied to a crop to fully satisfy its specific crop water requirement (CWR). The IWR is the fraction of CWR not satisfied by rainfall, soil water storage and groundwater contribution (Vinterfeld, 2002):

$$IWR = \sum_{1}^{x} \left(ET_c - N \right) \qquad [2]$$

where N are the natural inputs (rainfall, soil water storage and groundwater contribution).

If irrigation water needs are not properly determined, water wastes are inevitable: in case of underestimation, in short time the amount of water supplied completely evaporates from soil and leaf surface, whereas in case of overestimation water percolates down and can not be further absorbed by plant roots (Mannini and Genovesi, 2004).
In order to avoid the underestimation or overestimation of crop water consumption, knowledge of the exact water loss through evapotranspiration is

necessary for sustainable development and environmentally sound water management in the Mediterranean region (Katerji and Rana, 2008).

2.2 Evapotranspiration (ET)

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration.

The evapotranspiration process involves a phase change of water from liquid to gaseous state, with latent heat requirements of about 2.47 MJ per kg of water evaporated, and is one of the major components of the hydrological cycle (Steduto, 2000).

The process of evapotranspiration plays an important role in water balance of crops. Evaporation and transpiration occur simultaneously and it is very difficult to separate these two processes in the nature (Fig. 2.1). They are considered as evapotranspiration and we refer to both: evaporation from all freely wet surfaces, including free-water surfaces (oceans, lakes, water streams), soil and man-made surfaces and transpiration from plants (FAO, 1998).

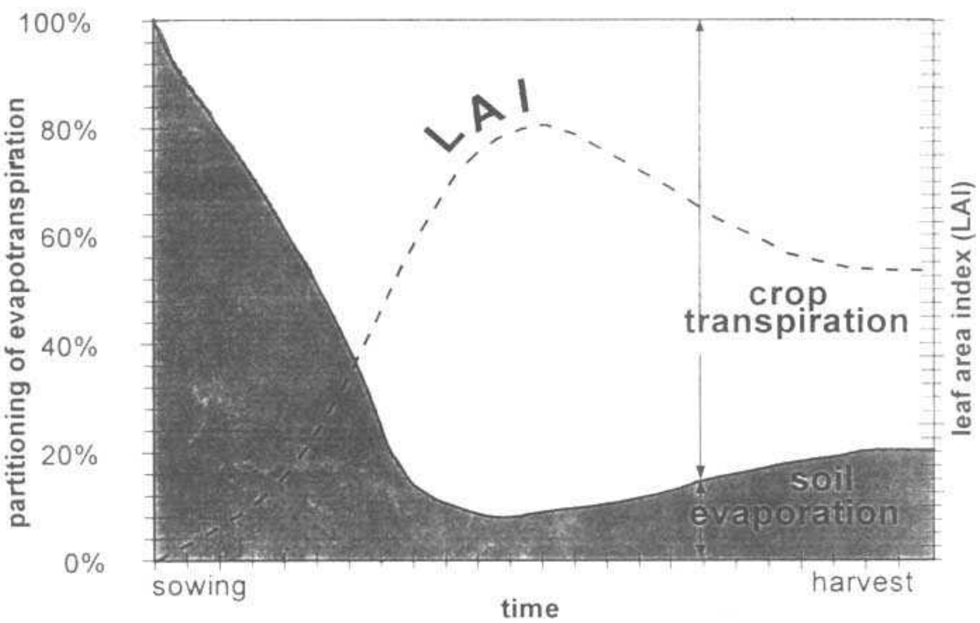

Figure 2.1: trend of the processes of soil evaporation and crop transpiration during the whole cropping cycle (source: FAO, 1998).

2.2.1 Evaporation

Evaporation is a physical process whereby water is converted from liquid to vapour (vaporization) and removed from the evaporating surface (vapour removal). Water evaporates from different surfaces, such as lakes, rivers, pavements, soils and wet vegetation.
Energy is required to change the state of the molecules of water from liquid to vapour. Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide this energy. The driving force to remove water vapour from the evaporating surface is the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere.
As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity and wind speed are climatological parameters to consider when assessing the evaporation process.
Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other factors that affect the evaporation process. Frequent rains, irrigation and water transported upwards in a soil from a shallow water table wet the soil surface. Where the soil is able to supply water fast enough to satisfy the evaporation demand, the evaporation from the soil is determined only by the meteorological conditions.
However, where the interval between rains and irrigation becomes large and the ability of the soil to conduct moisture to the surface is small, the water content in the topsoil drops and the soil surface dries out. Under these circumstances the limited availability of water exerts a controlling influence on soil evaporation. In the absence of any supply of water to the soil surface, evaporation decreases rapidly and may cease almost completely within a few days (FAO, 1998).

Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominantly lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process.

2.2.2 Transpiration

Transpiration consists of the vaporization of liquid water contained in the cells which cover the internal walls of the surface openings, or stomata, on the leaves of the plant, and the vapour removal to the atmosphere.
Although the driving climatic forces that determine the two processes (evaporation and transpiration) are the same, the process of transpiration is more complex, because it requires, beside the climatic factors, the consideration of the geometry and roughness of the plant canopy, of its

physiological stage and of the availability of water in the soil. Moreover, transpiration is very important for the plant, since it induces a movement of water and nutrients through the plant and is also an important mechanism through which the plant can dissipate the heat gained, mostly, through the solar radiation.
Transpiration, like direct evaporation, depends on the energy supply, vapour pressure gradient and wind. Hence, radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate, as do water logging and soil water salinity. Crop characteristics, environmental aspects and cultivation practices also influence the transpiration rate. Different kind of plants may have different transpiration rates. Not only the type of crop, but also the crop development, environment and management should be considered when assessing transpiration (FAO, 1998).

2.2.3 Units

The evapotranspiration rate is normally expressed in millimetres (mm) per unit time. The rate expresses the amount of water lost from a cropped surface in units of water depth. The time unit can be an hour, day, decade, month or even an entire growing period or year. Water depths can also be expressed in terms of energy received per unit area. The energy refers to the energy or heat required to vaporize free water. This energy, known as the latent heat of vaporization (λ), is a function of the water temperature. The evapotranspiration rate expressed in units of MJ m^{-2} day^{-1} is represented by λ ET, the latent heat flux (FAO, 1998).

2.2.4 Factors affecting evapotranspiration

The main factors affecting the evapotranspiration (ET) are the climatic parameters, crop characteristics, management and environmental conditions.

2.2.4.1 Weather parameters

The principal weather parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed. Several procedures have been developed to assess the evaporation rate from these parameters. The evaporation power of the atmosphere is expressed by the reference crop evapotranspiration (ET_o). The reference crop evapotranspiration represents the evapotranspiration from a standardized vegetated surface and it will be analysed later.

2.2.4.2 Crop factors

The crop type, variety and development stage should be considered when assessing the evapotranspiration from crops grown in large, well-managed fields. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different ET levels in different types of crops under identical environmental conditions. Crop evapotranspiration under standard conditions (ET_c) refers to the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions, and achieve full production under the given climatic conditions.

2.2.4.3 Management and environmental conditions

Factors such as soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration. Other factors to be considered when assessing ET are ground cover, plant density and the soil water content. The effect of soil water content on ET is conditioned primarily by the magnitude of the water deficit (the less the amount of water in the soil, the less the water evapotranspired, the more the water deficit) and by the type of soil (water holding capacity in sandy soils is lower than in clay soils).
When assessing the ET rate, additional consideration should be given to the range of management practices that act on the climatic and crop factors affecting the ET process. Cultivation practices and the type of irrigation method can alter the microclimate, affect the crop characteristics or affect the wetting of the soil and crop surface (FAO, 1998).

2.2.5 Evapotranspiration concepts

Distinctions are made between reference crop evapotranspiration (ET_o), crop evapotranspiration under standard conditions (ET_c) and crop evapotranspiration under non-standard conditions or crop effective evapotranspiration (ET_e).

2.2.5.1 Reference evapotranspiration (ET_o)

The evapotranspiration of a surface covered by a hypothetical reference crop, with an uniform average height between 0.08 and 0.16 meters, a surface resistance of 70 s m^{-1} and an albedo of 0.23, well-irrigated, which covers the ground, is called reference evapotranspiration (ET_o). The ET_o depends only on climatic factors, expresses the evaporating power of the atmosphere at a specific location and time of the year (FAO, 1998) and is not dependent on either the crop, because it is kept at constant height, or by land, because the water supply is optimum (Lamaddalena and Caliandro, 2008).
The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the reference evapotranspiring surface, soil factors do not affect ET_o. Relating ET to a specific surface provides a reference to which ET from other surfaces can be related. It obviates the need to define a separate ET level for each crop and stage of growth. ET_o values measured or calculated at different locations or in different seasons are comparable, since they refer to the ET from the same reference surface (FAO, 1998).

2.2.5.2 Crop evapotranspiration under standard conditions (ET_c)

ET_c refers to the evapotranspiration from excellently managed, large, well-watered fields that achieve full production under the given climatic conditions. This represents conditions where no limitations are placed on crop growth or evapotranspiration due to water shortage, crop density, or disease, weed, insect or salinity pressures.
ET_c differs distinctly from the ET_o as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass.
The effects of characteristics that distinguish field crops from grass, are integrated in the crop coefficient (K_c), that is the ratio between ET_c and ET_o.
In the crop coefficient approach, ET_c is calculated by multiplying ET_o by K_c (FAO, 1998):

$$ET_c = ET_o \times K_c \qquad [3]$$

where:

ET_c is the maximum crop evapotranspiration [mm/d]
ET_o is the reference evapotranspiration [mm/d]
K_c is the crop coefficient [dimensionless]

Most of the effects of the various weather conditions are incorporated into the ET_o estimate. Therefore, as ET_o represents an index of climatic demand, K_c varies predominantly with the specific crop characteristics (crop type, crop height, soil evaporation and crop growth stages) and only to a limited extent with climate. This enables the transfer of standard values for K_c between locations and between climates (FAO, 1998).

2.2.5.3 Crop evapotranspiration under non standard conditions or crop effective evapotranspiration (ET_e).

The ET_c predicted by K_c is adjusted if necessary to non standard conditions (ET_e) whenever any environmental condition or characteristic is known to have an impact on or to limit ET_c, so whenever sub - optimal crop management and environmental constraints affect crop growth and limit evapotranspiration.
Low soil fertility, salt toxicity, soil waterlogging, pests, diseases and the presence of hard or impenetrable soil horizons in the root zone may result in scanty plant growth and lower evapotranspiration. Soil water shortage and soil salinity may reduce soil water uptake and limit crop evapotranspiration. The evapotranspiration from small isolated stands of plants or from fields where two different crops are grown together or where mulches are used to reduce evaporation may also deviate from the crop evapotranspiration under standard conditions (FAO, 1998).

2.3 ET measurement and estimation

There is a great variety of methods for measuring ET; some methods are more suitable then others because of their accuracy or cost, or because they are particularly suitable for given space and time scales. Often it is necessary to predict ET, so a model needs to be estimated.
It is convenient to discuss the methods of determining ET by considering the measurement and modelling aspects separately (Katerji and Rana, 2008).

2.3.1 ET measurement

In general, the *measurement* of a physical parameter is the quantification of an attribute of the material under investigation. The methods of measuring ET should be divided into different categories, since they have been developed to fulfil very different objectives.
One set of methods is primarily intended to quantify ET over a long period of time, from weeks to months and to growth seasons. Another set of methods has been developed to understand the process governing the transfer of energy and matter between the surface and the atmosphere. The last set of methods is used to study the water relations of individual plants or parts of plants.

So that, in discussing the measurement of ET it is convenient to cluster into groups, where the main method depends on concepts from hydrology and micrometeorology:

A) ET measurement at the plot scale:
- Direct measurement
  1. weighing lysimeter
- Indirect measurement
  I. Micrometeorological measurement
  2. Bowen ratio
  3. Eddy covariance
  4. Aerodynamic method
  5. Radiation temperature method
  II. Measurement at soil level
  6. Soil water balance

B) ET measurement at the plant scale:
  7. Sap flow method
  8. Chamber system

The different methods for directly or indirectly measuring ET are based on the determination of two classes of factors:

a) The soil water content and the physical and biological properties of the evapotranspirative surface (height, plant density, canopy roughness, leaf area, stomatal conductance, albedo and so on);
b) The climatic variables: solar radiation, wind speed and thermodynamic characteristics of the atmosphere above the canopy (air temperature and humidity) (Katerji and Rana, 2008).

2.3.2 ET estimation

A physical parameter can be considered as *estimable* if it can be expressed by a model. The objective of an ET model can vary from the provision of a management tool for irrigation design, to the provision of a framework for the detailed understanding of a system, or as means to interpret experimental results. To meet these requirements, it is more appropriate to use methods with a sound physical basis, but often the available data only allow for the use of empirical or statistical approaches.
Therefore, to discuss ET modelling it is better to divide the ET models as follows:

C) ET estimation at the plot scale:
- Direct estimation
    9. Penman- Monteith model
- Indirect estimation
    I. Starting from ET measured on a reference surface:
        10. Using watered grass
        11. Using water pan
    II. Starting from ET calculated for a reference surface:
        12. Using Penman analytical formulas and their by-products
        13. Using the FAO-56 analytical formula method
        14. Using empirical formulas
- Estimation by simulating the soil water balance
    15. Soil water balance modelling

This categorisation is, of course, far from complete, but it can be considered a good outline in a review of ET determination (Katerji and Rana, 2008).

2.3.3 The estimation of ET with a soil water balance model

Evapotranspiration can also be obtained through simulation, instead of measurement, of the soil water balance. This kind of model is a simple representation of different complex processes, like root absorption, drainage, runoff, capillary rising and the variation of the water stock in the root system layer (Fig. 2.2). Its validity depends, above all, on the hypothesis made for analysing the phenomenon concerned. These hypotheses link different elements, each one dependent on the other.

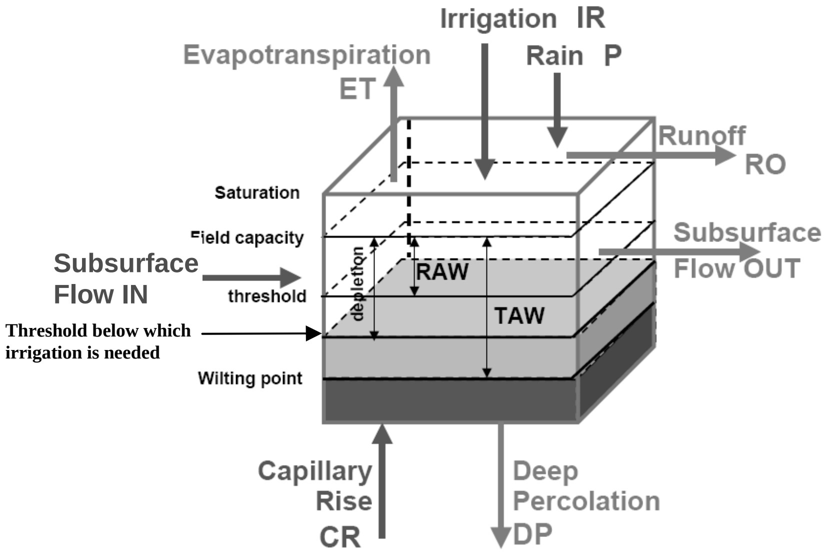

Figure 2.2: schematic representation of the water balance (modified from Todorovic *et al*., 2007). *RAW* is the readily available water and *TAW* is the total available water.

The model can address soil water balance only, or also its different components. Nevertheless, it can be part of sub-modules included in more general models (for example, a productivity model), for the simulation of evapotranspiration. It can also be part of a model including growth/ development, yield and the development of crops as related to environmental balances (water and/or nitrogen balances).
According to Xu and Singh, (1998), present applications of water balance models are directed along three main lines: reconstruction of the hydrology of catchments, assessment of climatic impact changes and evaluation of the seasonal and geographical patterns of water supply and irrigation demand.

Two classes of models are generally used for the simulation of soil water balance:
I) mechanistic models;
II) analogue (or water reservoir) models.

In the mechanistic approach, the water flux in the soil is verified by the existence of soil water potential gradients, by means of Darcy's Law and the continuity principle. The equations are usually solved with different methods, all involving the discretisation of the soil in more or less small layers.
Several difficulties can be encountered in the application of these models. The most important are:
1) absence of required soil, weather and crop data to operate these models;
2) insufficient awareness of technical capabilities of numerical tools;
3) absence of validation opportunities.
These models can be considered as useful tools able to analytically reproduce the hydrological functioning of crops in a given time step.

In the analogue approach, the soil is treated as a collection of water reservoirs, filled by rainfall or irrigation and emptied by evapotranspiration and drainage. They can be based on the two following principles:

1) determination of soil water storage (ΔS) as a function of the depth of the soil and roots;
2) the division of soil water in Readily Transpirable Soil Water (RTSW) and Total TSW (Katerji and Rana, 2008).

The unit of measure used for all calculations are the millimetres of water:
1 mm = 1 l/m^2 = 10,000 l/ha = 10 m^3/ha.
The average moisture content in the layer of soil colonized by the roots is estimated on a monthly basis, using the water balance equation (Portoghese et al, 2005; Lamaddalena and Caliandro, 2008):

$$\delta w/\delta t = P - E - RO - RO_{sub} - Inf - GW + Irr \qquad [4]$$

where:

P	is the total rainfall [mm/δt]
E	is the actual evapotranspiration or evaporation from bare soil [mm/δt]
RO	is the surface runoff [mm/δt]
RO_{sub}	is the sub-surface runoff [mm/δt]
Inf	is the water infiltration through the root zone to the groundwater [mm/δt]
GW	is the groundwater recharge given by the vertical infiltration below the root zone [mm/δt]
Irr	is the irrigation water [mm/δt]
$\delta w/\delta t$	is the variation over time (usually on a monthly basis) in soil moisture content [mm/δt]

The quantity of water available to plants is greatly influenced by soil type and its depth, i.e. the ability of soil to store water and the strength with which it is retained by the particles constituting the soil. The depth, density and efficiency of plant roots interact with soil and then determine the fraction of water actually used by plants, characteristic of each species and generally increasing gradually over time with the development and deepening of the roots (Mannini and Genovesi, 2004).

2.4 Water use in agriculture

How to reduce agricultural water use and make water resources more sustainable is an increasingly urgent question. It is a question that requires combined agronomic, physiological, biotechnological/genetic and engineering approaches, which may be collectively described as ‘water saving agriculture’ (Morison *et al*., 2008).
Water balance of crops represents a good starting point to establish the proper supplies of irrigation water in agriculture. The target of water supplies

should not be the sole maximization of the crop yields and quality, but also proper water use.
The application of water saving irrigation techniques involves limiting application depths, such that a portion of the field is under-irrigated, and controlling irrigation timing and frequency to optimize water use in agriculture (English et al., 1990); so, it implies three main choices: when, how much and how to provide water.
The first one, often influenced by the other two, concerns the optimal irrigation period so that maximum production yields can be achieved.
The second choice concerns the optimal water supply at each irrigation operation. In this case, too, the choice is affected by many factors but, above all, by soil capacity to retain water, root depth and irrigation method adopted (the latter is the third choice). If irrigation water needs are not properly determined, water wastes are inevitable: in case of underestimation, in short time the amount of water supplied completely evaporates from soil and leaf surface, whereas in case of overestimation water percolates down and can not be further absorbed by plant roots (Mannini and Genovesi, 2004).

2.4.1 The optimal irrigation volume

The water holding capacity of soils is known to depend on soil hydraulic characteristics and on plant root depth and density (Milly, 1994).
The hydrological characteristics of each soil are described by the Field Capacity (FC) and the Wilting Point (WP). The FC expresses the percentage of moisture present in a saturated soil after all the water more subject to gravity is deeply percolated, while the WP expresses the percentage of moisture that the plant is no longer able to absorb from the soil, so the permanent wilting occurs.
The fraction of water contained between the FC and the WP is the maximum available water content (AWC - or TAW in Fig. 2.2) and represents the ability of soil to store water, and hence to allow the crops to resist to more or less prolonged drought.
Despite this amount of water is available for the plant, the force with which it is retained by the soil increases when this water decreases. This happens because, moving from FC to WP, the force that keeps the water increases (the matricial potential of the soil is changed from -33 kPa to -1500 kPa) to reach a threshold beyond which the plant has difficulties in absorbing water from the soil, so that it can not fully meet the evapotranspiration demand of the atmosphere.
The plant, therefore, with the gradual drying of the soil, even if does not show obvious symptoms of water scarcity, is going to a progressive water stress, reaching levels that would affect negatively production (Caliandro, pers. Comm.).
Moving from sandy soils to medium and finishing to clay soils, the value of WP, FC and the volume of AWC increase, with greater accumulation and subsequent utilization of rain or irrigation water (Table 2.1, page 18).

Table 2.1: hydrological characteristics of soils with different texture (modified from Mannini and Genovesi, 2004).

Soil texture	FC (volume %)	WP (volume %)	AWC (volume %)	Available water in 100 cm of depth (mm)	Available water in 50 cm of depth (mm)	RAW* (mm)
Sandy	15	7	8	80	40	20
Sandy-loam	21	9	12	120	60	30
Loam	31	14	17	170	85	43
Clay-loam	36	17	19	190	96	48
Silty-loam	40	19	21	210	105	53
Clay	44	21	23	230	115	58

* *RAW = Readily Available Water = 50% of AWC in 50 cm of depth*.

Waiting for the crops to use the whole AWC, in order to restore the soil to the FC, is a mistake because crops will be exposed to periods of water stress, above all if the soil water content is near to WP, and brings to the waste of huge volumes of water for each kind of irrigation system.
At the same time, if the plants can use the amount of water corresponding to the RAW, too much water will be available, creating an exagerated consumption that does not lead to increases in production.
The solution to this problem is to restore the soil moisture to a previously determined value of available water, according to the following equation (modified from Giardini, 2002):

$$Irr = S \times h \times \rho_{aps} \times [(FC - WP) / 100] \times p \qquad [5]$$

where:

Irr is the volume of irrigation water needed to restore the soil moisture to a previously determined value of available water
S is the surface area equal to 1 ha
h is the rooting depth [m]
ρ_{aps} is the bulk density of soil [t/m^3]
FC is the water content at field capacity [%]
WP is the water content at wilting point [%]
p is the RAW expressed as % of the TAW [%]

2.4.2 The optimal irrigation timing

The volume of irrigation affects the irrigation timing, defined as the period of time that passes between one irrigation and the subsequent, for the same plot. The irrigation schedule is also strictly linked to the rooting depth of the crop, meaning the volume of soil explored by the crop roots, the soil texture and the efficiency of the method of irrigation.

A sandy soil with a limited volume explored by the crop roots is characterized by low water storage because of its porosity, so the irrigation water volumes will be reduced in comparison to a clay soil, which can store higher amounts of water for the same depth. Indeed, the crop water requirements in a sandy soil determine a rapid consumption of irrigation volumes provided, so a frequent water supply is necessary. On the other hand, in case of clay soils occupied, in a deep layer, by the roots of drought resistant crops or crops that are in sufficient resistant physiological stages to water stress, higher irrigation volumes can be supplied, with a longer irrigation turn (Mannini and Genovesi, 2004).

2.5 Deficit irrigation

At present and more so in the future, irrigated agriculture will take place under water scarcity. Insufficient water supply for irrigation will be the norm rather than the exception, and irrigation management will shift from emphasizing production per unit area towards maximizing the production per unit of water consumed (the water productivity) (Fereres and Soriano, 2007). A rational irrigation management assumes, therefore, a strategic importance for water saving by ensuring greater availability for other uses (Bortolini, 2008).

For water saving, there is no single solution, but there is a set of strategies that, if integrated, can achieve good results. The main strategies for saving water may fall into four categories (Mannini, 2007):

- choice of systems and dry farming cultivation techniques;
- choice of timing and volume of irrigation;
- choice of type and the proper use of irrigation;
- recovery and reuse of water.

2.5.1 The concept of Deficit Irrigation

One management option with great promise is deficit irrigation (the application of only a predetermined percentage of calculated potential plant water use), and in particular, controlled deficit irrigation (CDI) (Morison *et al.*, 2008). It represents an optimizing strategy under which water supply occurs only when plants most need it, so they are deliberately allowed to sustain some degree of water deficit and yield reduction in order to optimize the water use, either by reducing irrigation adequacy or by eliminating the least productive irrigations (English *et al.*, 1990; Fereres and Soriano, 2007).

Irrigation supply under DI is reduced relative to that needed to meet maximum ET (English, 1990). Therefore, water demand for irrigation can be reduced and the water saved can be diverted for alternative uses. Even though DI is simply a technique aimed at the optimization of economic output when water is limited, the reduction in the supply for irrigation to an area imposes many adjustments in the agricultural system.

Each DI situation should be defined in terms of the level of water supply in relation to maximum crop ET. So, to quantify the level of DI, it is first necessary to define the full crop ET requirements.
When irrigation is applied at rates below the ET, the crop extracts water from the soil reservoir to compensate for the deficit.
Two situations may then develop. In one case, if sufficient water is stored in the soil and transpiration is not limited by soil water, even though the volume of irrigation water is reduced, the consumptive use (ET) is unaffected. However, if the soil water supply is insufficient to meet the crop demand, growth and transpiration are reduced, and DI induces an ET reduction below its maximum potential.
The difference between the two situations has important implications at the basin scale. In the first case, DI does not induce net water savings and yields should not be affected. If the stored soil water that was extracted is replenished by seasonal rainfall, the DI practice is sustainable and has the advantage of reducing irrigation water use. In the second case, both water use and consumption (ET) are reduced by DI but yields may be negatively affected (Fereres and Soriano, 2007).

Although deficit irrigation is widely practised over millions of hectares for a number of reasons — from inadequate network design to excessive irrigation expansion relative to catchment supplies — it did not received sufficient attention in research at the beginning. In fact, in the academic world, deficit irrigation was not usually treated as a practical alternative to full irrigation (English and Raja, 1996). Recently the consideration for this technique as a good alternative to full crop irrigation has led to further research and some results show that deficit irrigation treatments promote an optimization of water use as compared to full irrigation, either in the short-term or in the long-term (Chaves *et al*., 2007). Moreover, moderate plant water deficits enhance flowering in some horticultural and forestry species (Sharp *et al*., 2009). Deficit irrigation technique can also affect seasonal changes in leaf physiology and oil quality of *Olea europaea* (Tognetti *et al*., 2007), as well as a reduction in vegetative growth greater than the reduction of oil content (Iniesta *et al.*, 2009), and seems to be useful for improving the final fruit quality in oranges (Pérez Pérez *et al*., 2009).
Deficit irrigation techniques have demonstrated a high validity for water saving in the case of various tree crops without particular negative effects on crop production and farmer's income in both Southern and Northern Italy. However the technique of regulated deficit irrigation can be applied on the already grown trees since the deficit irrigation can provoke negative impacts (later start of production and overall decrease of productivity) if applied during the first three – four years since plantation.
The results of numerous deficit irrigation experiments carried out in Northern Italy on peach tree (Fig. 2.3) indicate that the regulated deficit irrigation technique has increased crop production in respect to traditional irrigation, has maintained the average weight of fruits, has improved the flowering in the successive years and has reduced the necessity for pruning. Similar results have been obtained also in the experiments on peach and nectarine trees carried out under Southern Italy climatic conditions (Mannini and

Genovesi, 2004; Xiloyannis et al., 2003). With regulated deficit irrigation (RDI), trees are kept short of water when fruit growth is slow or after harvest but ample amount of water is given during the time of rapid growth of fruit. If RDI is properly managed, there is no reduction in the size of fruit or yield, because water stress will reduce the growth of shoots without markedly affecting the growth of fruit (Goodwin, 2000). The study of regulated deficit irrigation has been done also on herbaceous crops in Southern Italy giving different results in respect to those obtained with orchards. In fact, serious drops of production can be observed even in the cases of limited water reduction during the non-critical phenological stages (Mannini and Genovesi, 2004; Todorovic et al., 2007).

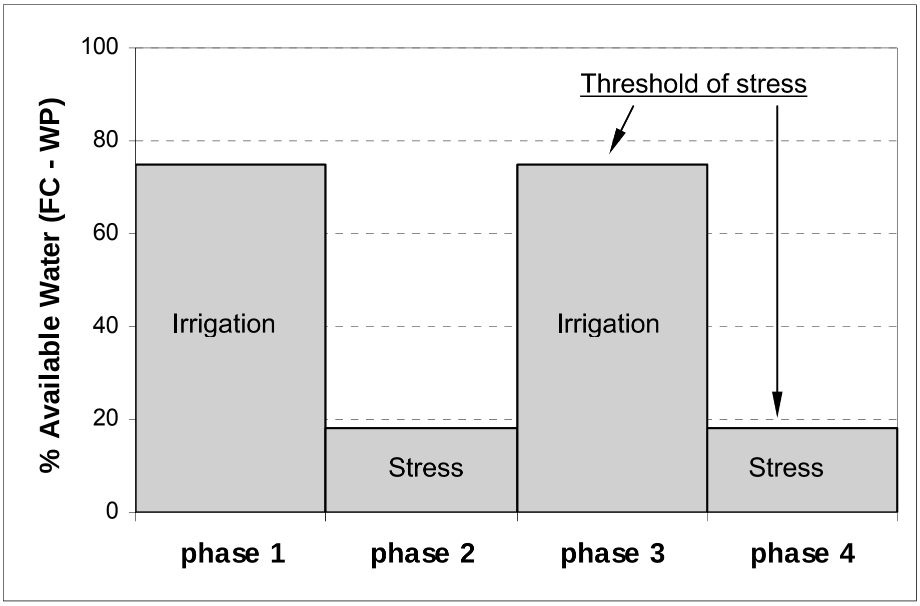

Figure 2.3: simplified graphical representation of the stress thresholds to apply on the peach tree under regulated deficit irrigation treatments. Phase 1 goes from the beginning of flowering to the formation of small fruits; Phase 2 concerns the hardening of the seed; Step 3 arrives at harvest; Phase 4 is the post-harvest (modified from Mannini and Genovesi, 2004).

Management of deficit irrigation is fundamentally very different from conventional irrigation management. Rather than working to minimize crop water deficits, the irrigation manager must decide what level of deficit to allow and must recognize when that level has been reached. The choice may be made to allow deficits to occur at some times and not others, and/or to apply water at a lower level of adequacy in order to achieve the higher efficiencies and lower costs that are possible under deficit irrigation (English *et al.*, 1990).

Moreover, management of deficit irrigation can vary considering annual crops or orchards. Annual crops generally require irrigation only during stages of maximum sensitivity to water stress and are able to increase the crop yield

more than when irrigation occurs during resistant stages. The target of limitation of irrigations is to increase the optimization in agricultural water use, eliminating irrigations that have a low impact on crop yields. The possible yield reduction appears not relevant if compared to the benefits obtained by the water saving (optimization of water use and better water allocation in agriculture).
The potential benefits of deficit irrigation derive from three factors linked to economic concepts (English *et al.*, 1990):

- Reduced costs of production: DI will generally result in reduced yields. However, near the full irrigation level, yield reductions will usually be proportionately less than reductions in applied water. Moreover, reductions in water applications may have a favourable effect on yields by reducing the incidence of disease, improving the storage and handling properties of a crop, minimizing the leaching of fertilizers from the root zone and improving aeration of the soil. This brings to reducing the use of fertilizers, pesticides and water, so a general reduction in production costs.

- Greater optimization of irrigation water use: full irrigation is usually planned to meet crop water requirements for short periods of peak demand during drier than average years; for example, a system might be configured to satisfy the peak two-week demand that will occur in four years out of five. Such systems will be operating at less than full capacity much of the time and, in favourable weather years, a significant fraction of the available water or delivery capacity may go unused or be used ineffectively. By planning for a more favourable weather year, anticipated water requirements will be reduced. Yields will be reduced to some extent in dry years and will tend to be more variable because of this strategy, but long term average income can be increased.
  As said before, some results show that deficit irrigation treatments promote an optimization of water use as compared to full irrigation, either in the short-term or in the long-term.

- The opportunity costs of water: when water is the limiting resource, water saved by deficit irrigation might be used to irrigate additional land. The potential increase in farm income that would result is an opportunity cost associated with the water. Where water supplies are limited, opportunity costs may be the most important consideration in irrigation management.

2.6 Geographic Information System (GIS)

The management of huge amounts of data (soil, climate, biodiversity, productivity, hydrological issues, etc.) at a variety of scales (from specific local to national, regional, continental and global level) requires the development of large, interactive databases. This necessity has promoted the widespread application of Geographic Information System (GIS) technology to gather, assimilate, analyze and display multi-thematic information (Todorovic and Steduto, 2000).
GIS is a system that provides tools for the exploration of spatially-referenced databases, whose exploitation enables faster exchange and aggregation of information coming from different sources, and easier interaction of those informations with models and decision support tools.
This tool allows the integration of different thematic layers at various complexity levels; data integration is performed by applying overlay functions on the different layers. 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 (Fig. 2.4).
The presentation of the same variable may be required in different data formats, depending on the purposes of data and their further evaluation.
Moreover, 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 (Todorovic and Steduto, 2003).

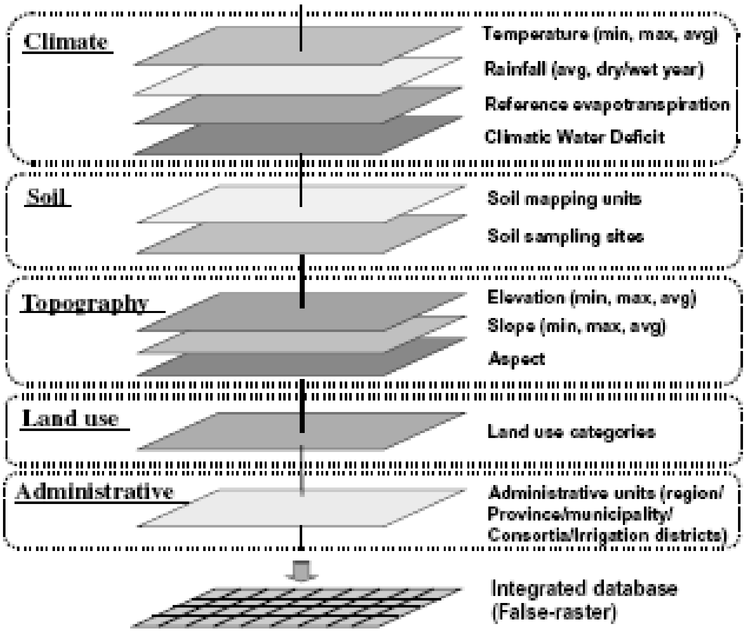

Figure 2.4: development of a GIS irrigation database: integration of different thematic layers (modified from Todorovic and Steduto, 2000).

GIS offers an effective support for hydrogeological water balance modelling and allows the identification of areas with water deficit. Such a tool is capable of archiving, analysing and handling the large amounts of data required to describe hydrological processes on different scales (Portoghese *et al*., 2005).

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

Figure 2.5: general framework of the GIS applications customized for irrigation management (modified from Todorovic and Steduto, 2000).

Chapter 3

Materials and Methods

3.1 Introduction

In this work, a computational model performing a monthly water balance has been applied to the Apulia region for an average climatic year to compute the maximum irrigation water requirements and the irrigation water requirements under controlled deficit irrigation (CDI). Then, these results have been compared with the actual water volumes supplied by farmers, previously determined for the Consortium of Reclamation of Capitanata, and then extended to the entire region (Lamaddalena and Caliandro, 2008). The comparison has allowed to draw some considerations about the most effective strategy for water saving in the region.

3.2 Presentation of the study area

Apulia, with a total regional area of 19,357.90 km^2, equal to 8.4% of the total national surface area, represents the largest region in Italy in length with more linear extension of the coasts. The 53.3% of the region is flat area, the 45.2% is hilly land and the remaining 1.4% is mountainous (Annuario statistico regionale Puglia 2004) (Figure 3.1).

The land extension is a peculiarity of Apulia compared to other regions of the peninsula: the region is relatively long (350 km) and narrow (60 km), extended from NW to SE. The Apulia region borders with the Adriatic Sea on the East and the Ionian Sea on the South, while the western and the northern parts partially border with the uplands and hills of the Appenine massif. From a morphological point of view, most of the land is flat and the hilly or undulating morphology are generally limited and attributable mainly to the territories of the Gargano and the Appenine Dauno (A.C.L.A. 2, 2001; Caliandro *et al*., 2005; Kapur, 2002).

A relevant component of the territory is agriculture; indeed, agricultural land covers about 70% of the total surface area of the region (INEA, 2008; Steduto and Todorovic, 2001). Large part of it is cultivated with cereals and olive trees (about 27.4% and 23.9% respectively), while the rest is covered by vineyards and vegetable crops (Kapur, 2002; Todorovic and Steduto, 2003).
Agriculture represents an important sector whose function is not only productivity, but also and above all multifunctionality, in particular the environmental protection (Caliandro, 2005). Apulia has always been characterized by a vocation for agriculture and production activity carried on in the region has diversified over time, giving space to agricultural industry, which today constitutes an increased demand for use of water resources

(Figure 3.2), despite water availability is one of the main factors limiting agricultural productivity in the region (ARPA Puglia, 2003).

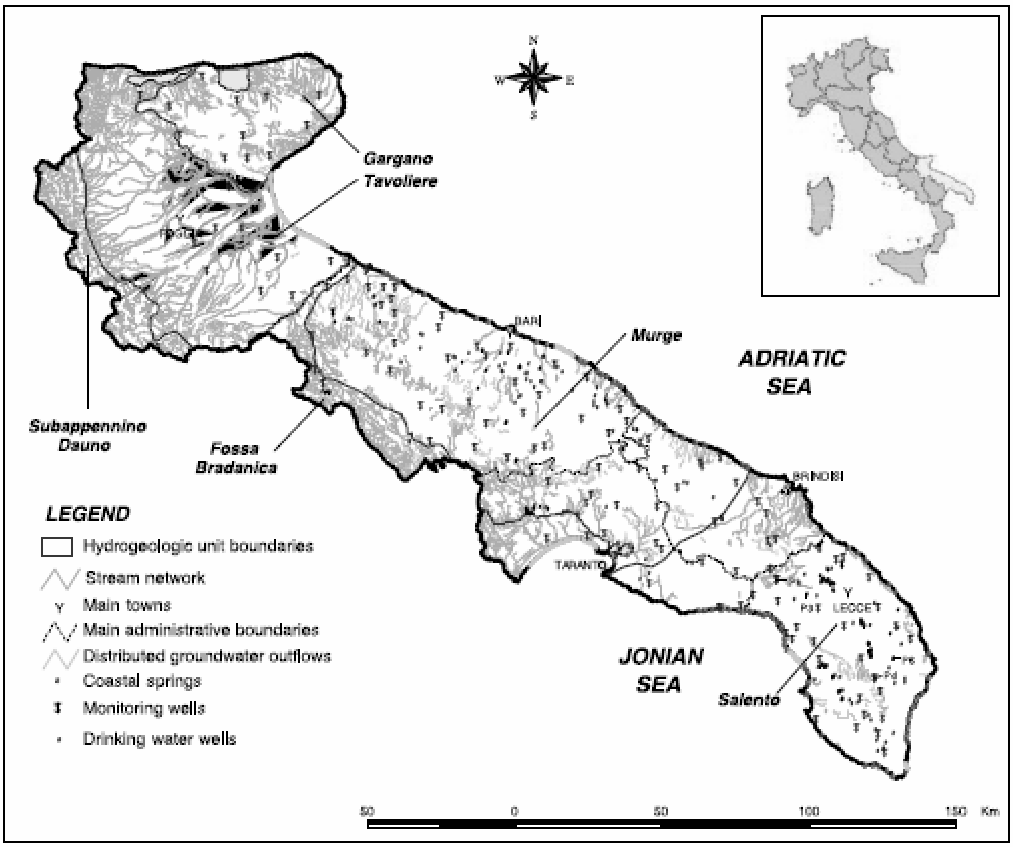

Figure 3.1: the study region: Apulia, Southern Italy (Portoghese *et al*, 2005).

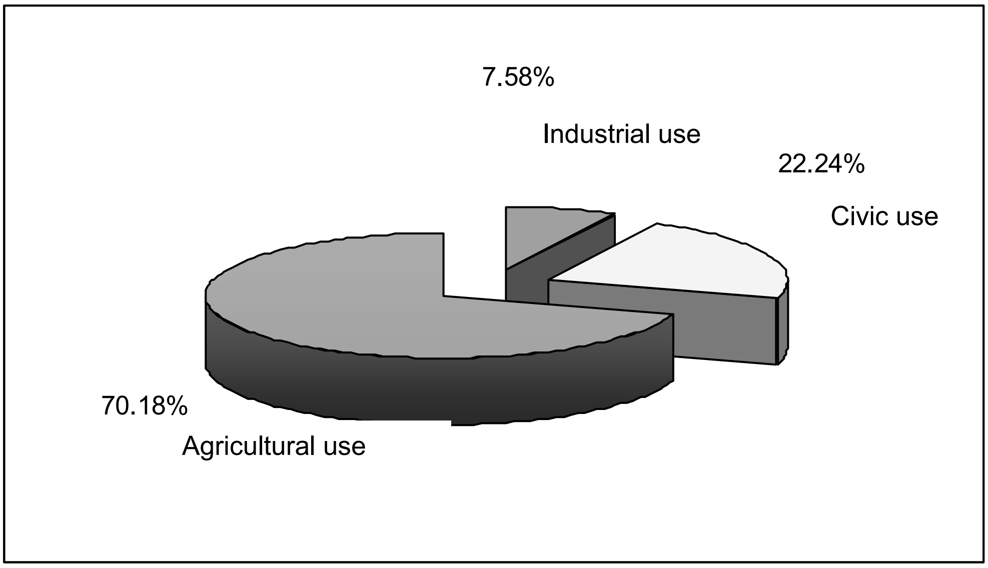

Figure 3.2: available amount of water for the different uses in the inter – regional hydrographic watersheds (ARPA Puglia, 2003).

Apulia is generally characterized by a typical Mediterranean climate with mild winters and hot, long and, in most of the region, dry summers. The coastal stretches, thanks to the mitigating action of the Adriatic and Ionian seas, are characterized by a typically maritime climate with seasonal temperature ranges less remarkable. The hinterland presents a continental climate, with more fluctuations in seasonal temperatures (INEA, 1999)
Most of the regional areas present annual average temperature values between 16 °C and 17 °C. The coldest month is apparently everywhere January, with temperatures generally in the range of 6 °C and 10 °C, with lower peaks, even below 0 °C (Lamaddalena and Caliandro, 2008); in the mountainous areas and higher peaks in the Salento. The hottest month is July, with average temperature values between 24 °C and 26 °C, peaks of 40 °C and lower values in mountainous areas and in the Murge.

The annual precipitation is between 300 and 1200 mm / year. In most of the region, it ranges between 500 and 700 mm. The rain is concentrated in the autumn - winter period, while in summer the number of rainy days is very low, with an absolute minimum between July and August. Not infrequently, there are periods of persistent rainfall deficiency of two or three months and even more. In the most 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 (INEA, 1999; Kapur, 2002).
The hydrograph of the regional precipitations (Figure 3.3) has two peaks corresponding to the months of November and January. The average annual total precipitation, obtained from the analysis of time series available on 162 weather stations spread over the whole of Puglia, is 650 mm. The minimum value is 447 mm, recorded in the station of Manfredonia, and the maximum is 1137 mm, in the station of Foresta Umbra (Gargano) (Lamaddalena and Caliandro, 2008).

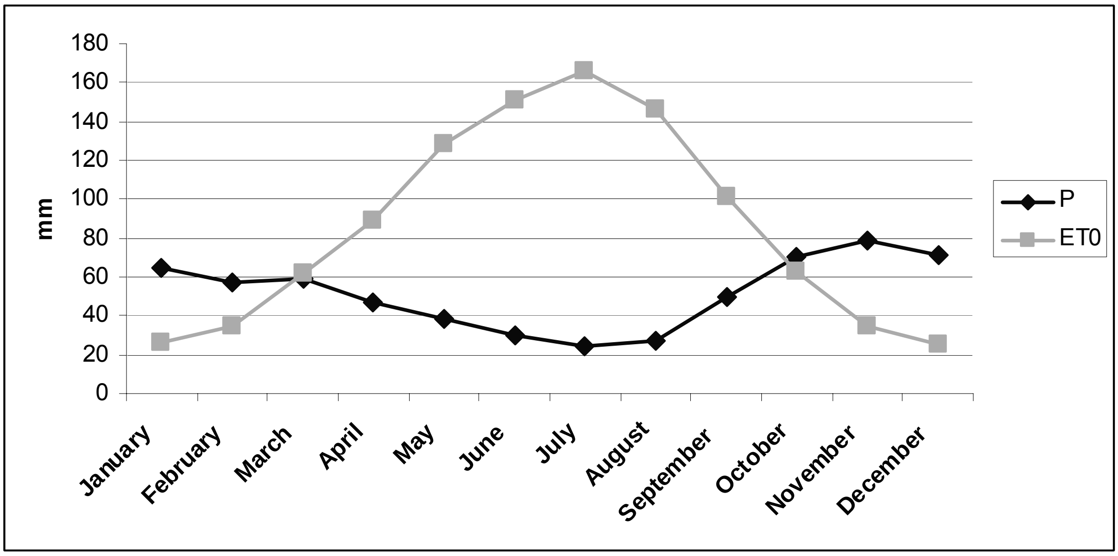

Figure 3.3: mean regional hydrograph of the regional precipitations P and reference evapotranspiration ET_0 (Lamaddalena and Caliandro, 2008).

Recent analysis of the trend of the mean temporal variation of weather variables in the Apulia region throughout four decades, from 1951 – 1960 to 1981 – 1990, has demonstrated a significant decrease of annual precipitation, in the range of 22.5%, which corresponds to an average yearly amount of about 167 mm. The analysis of temperature data indicate a slight decrease in maximum air temperature and a minor increase in minimum air temperature, both in the range of 0.5 °C over four decades. Such a variation of air temperature has provoked, in average, a decrease in evapotranspiration of about 57 mm/year, which is equivalent to 5.4%. The overall results of this analysis have shown that water deficit in the region has increased over four decades, on annual basis, in average, by 110 mm (Todorovic, 2007; Todorovic *et al.*, 2008).

3.3 Description of the data used

This paragraph describes the basic data used to determine the crop irrigation water requirements and for the computation of the water balance.

3.3.1 Climatic data

The meteorological data used in calculations result from the ACLA 2 project. Data relating to the key climatic variables – precipitation and minimum and maximum temperature – have been collected from the National Hydrographic Institute for a period of 41 years, from 1951 to 1992. These data have been examined for error detection and spatial and temporal integrity, while the estimate of missing rainfall data is performed by using the double mass analysis (Todorovic and Steduto, 2003).
This work was done for 162 meteorological stations located in the region and its surroundings (Figure 3.4) that have a time series long enough to characterize a representative state of the regional climate (A.C.L.A. 2, 2001; Caliandro, 2005).

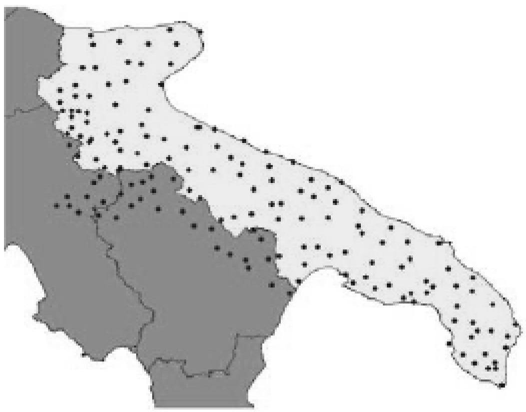

Figure 3.4: Localization of the termo – pluviometric stations considered in the climatic analysis of the ACLA 2 project (2001).

All the calculations refer to an “average climatic year”, defined as a year during which the values of the climatic variables have a probability of occurrence that equals 50%.
ACLA 2 project shows, for the average year, the monthly values of maximum, average and minimum temperature and precipitation, reference evapotranspiration (ET_0) and total annual climatic water deficit (that is the summation of the negative values deriving from the difference between the monthly values of reference evapotranspiration and total rainfall), properly spatialised on the region on homogeneous areas (homogeneous temperature and precipitation surfaces) of 2 km x 2 km (Figure 3.5).

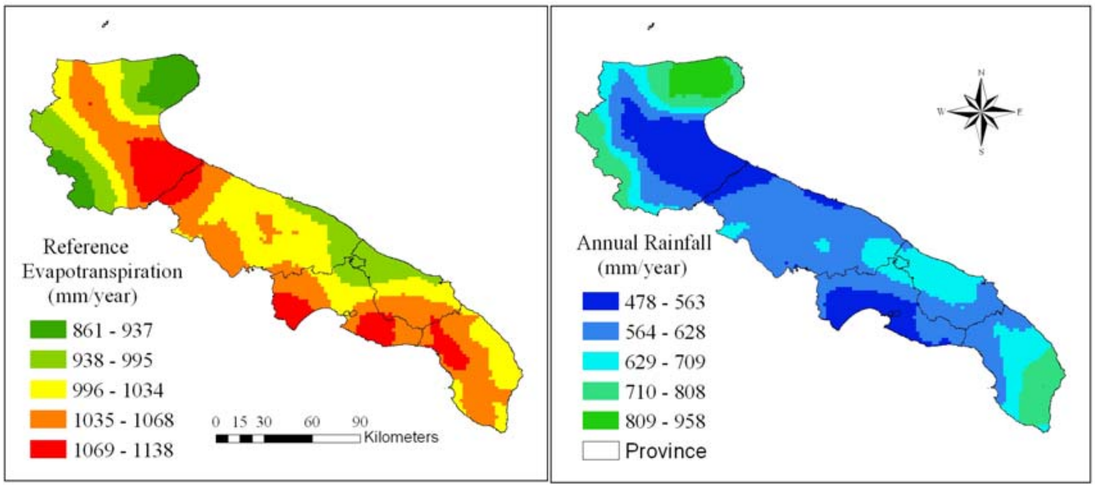

Figure 3.5: graphic representation of the spatialisated mean annual ET_0 and rainfall (Lamaddalena and Caliandro, 2008).

On the basis of the available data on a regional level, the ET_0 has been calculated using the Hargreaves-Samani equation, which requires only the maximum and minimum temperature and solar terrestrial radiation. This equation is not recommended for the calculation of ET_0 on a daily basis, because variations in wind and humidity are not taken into account, but it gives values not very different from those obtained with the equation of Penman-Monteith at monthly time intervals and adapts well to Mediterranean climates (Steduto *et al.*, 2003). In addition, this empirical method gave satisfactory results in studies comparing the values of estimated ET_0 and those measured in a southern environment with a weighing lysimeter on a lawn of *Festuca arundinacea*, (Caliandro *et al.*, 1990).

According to Hargreaves and Samani (Hargreaves and Samani, 1982, 1985), reference evapotranspiration (ET_0) is calculated as:

$$ET_0 = 0.0023 \cdot (Tc + 17.8) \cdot Ra \cdot (Td)^{½} \qquad [6]$$

where:

ET_0 is the reference evapotranspiration [mm/d]
Tc is the mean monthly air temperature [°C]
Ra is the extraterrestrial radiation [mm/d]
Td is the difference between maximum and minimum mean monthly air temperature [°C]

The spatial interpolation of weather variables have been performed using the kriging method for both monthly and annual data sets. The results of interpolation are integrated into a cell-based (raster) GIS format, where isolines are used to delineate the characteristic values of each climatic variable. In this way, three different maps showing, for each pixel (of 2km x 2km resolution), respectively the average monthly precipitation, temperature and ET were generated. This process produced reliable data sets, which were suitable for the application of a distributed model (Portoghese *et al.*, 2005; Lamaddalena and Caliandro, 2008).

3.3.2 Pedologic data

The pedologic map of the region (Figure 3.6) comes from ACLA 2 project. Starting from the regional base MSO map (Military Survey Office), scale 1: 50000, through several soil analyses, the base pedologic map was realised, scale 1: 100000, according to the Soil Taxonomy method (USDA, 1998) and to the FAO World Reference Base for Soil Resources (FAO - ISSDS1998).
The soil analyses took into consideration various aspects such as local geology, geomorphology, landscape, field measurements or observations etc, supplemented with laboratory analysis of soil samples as well as from studies of photo interpretation of aerial and satellite images.
Soil database was 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). Within the ACLA project, 4109 soil samples distributed across the region were collected for the classification of the Apulian soils. Laboratory analysis was conducted on a limited number of these soil samples in order to identify their hydraulic characteristics. For the remaining samples, field capacity and wilting point were estimated from the soil texture using several pedotransfer functions (Cainarca, 1998) previously validated on the Apulian soils, that take into consideration as database the pedologic characteristics and especially the texture of each layer of soil (Lamaddalena and Caliandro, 2008).
To map the hydraulic characteristics from the soil samples, a statistical analysis has been conducted by overlapping soil samples and soil type classification defined by the ACLA 2 project.
Given the extreme variability of the database, it was considered advisable not to interpolate the values using geostatistical functions, but to use the polygons of the soil map deriving from the ACLA 2 project and representing homogeneous soils. Consequently, to each soil type has been assigned a unique value of soil depth, wilting point and field capacity that correspond to the average value of all the samples corresponding to that type of soil (Figure 3.7).

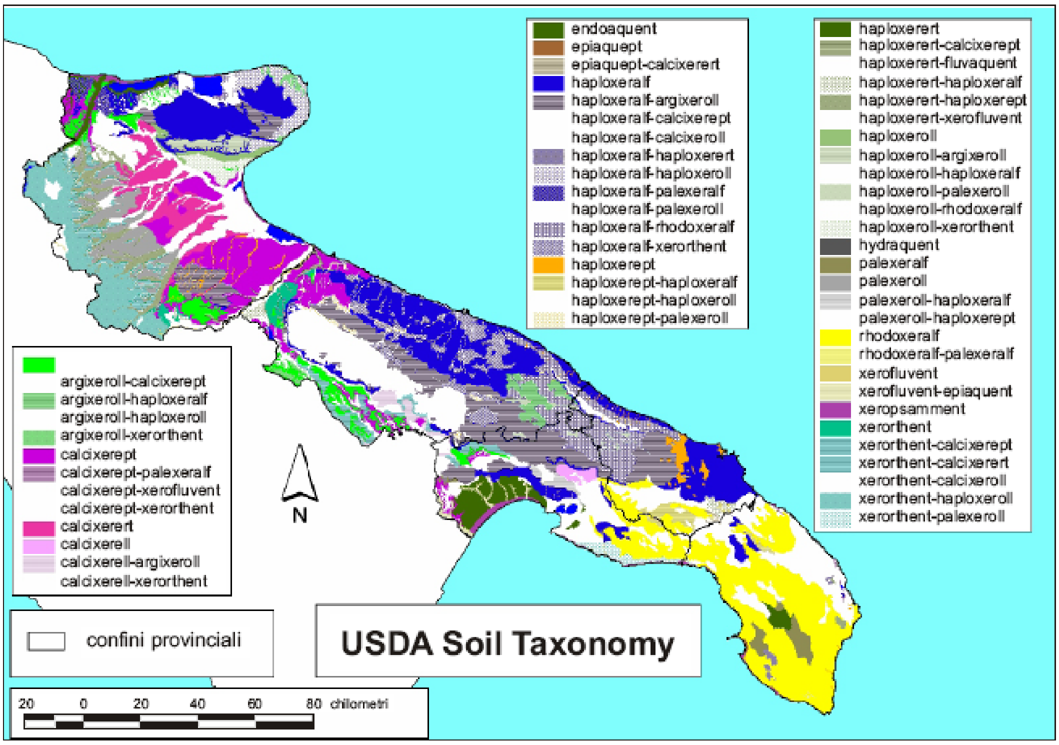

Figure 3.6: distribution of the different regional types of soil classified according to the USDA Soil Taxonomy (1998).

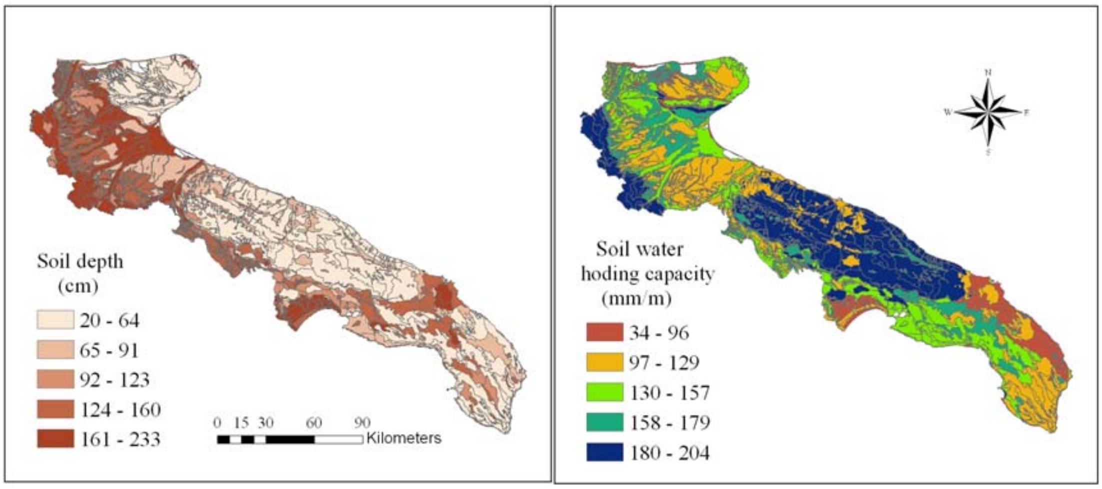

Figure 3.7: Soil depth (cm) and water holding capacity of the Apulia region (modified from Lamaddalena and Caliandro, 2008).

The realization of the pedologic map resulted in a first division of the regional area in landscape systems and subsystems, representing homogeneous areas for geological, morphological and climatic conditions. Within the previous groupings, mapping units were obtained; these units represent the polygon of greater detail of the map and enclose homogeneous areas according to type of soil. Soils were classified and described in the Taxonomic Units of soil, which are reference soils representative of all the soils in the region (A.C.L.A. 2, 2001; Caliandro et al., 2005).

3.3.3 Land use data

Land use database is developed at a scale of 1:100000 mainly from the re–classified C.O.R.I.N.E. Land Cover data–catalog (C.O.R.I.N.E., 2000).
Existing informations on a regional scale were significantly uneven and often not enough to make a reliable water balance. The C.O.R.I.N.E. project of the Apulia region provided a very detailed plan for both the wooded and for urban areas, but less precise for farmland.
S.I.G.R.I.A. project (INEA, 1999) has conducted a more detailed classification on the agricultural land of the region. Consequently, three thematic maps corresponding to spring, summer and fall land cover were produced and presented the possible seasonal change in land cover as well as the spatial distribution of the irrigated fields. Their final result is summarized in table 3.1, page 33, which shows the land cover, expressed in hectares, in the different seasons of the year.

The relevant data for this work are the irrigated crops, which include irrigated fruit trees, irrigated olive trees, vegetables, irrigated grass and irrigated vineyards.
"Vegetables" includes all the different horticultural crops present on the region during the year ("spring to summer season" and "summer to autumn/spring season" vegetables), while "Orchards" includes all the main tree crops of the region and "Vineyards" includes both the table and wine grapes.
"Irrigated grass" covers an irrelevant area of the region (0.007%), so it has been excluded from the calculations.

Table 3.1: Land cover of the Apulia region as identified by S.I.G.R.I.A. project (INEA, 1999).

Land use	Spring	Summer	Autumn
Water	847.11	847.11	847.11
Temporary crops associated with permanent crops	24564.03	24564.03	24564.03
Forests	249135.91	249135.91	249135.91
Complex cropping systems	45432.4	45432.4	45432.4
Herbaceous crops (Spring season)	50349.96	58688.24	9778.98
Irrigated fruit trees	25532.55	25532.55	25532.55
Non irrigated fruit trees	11317.89	11317.89	11317.89
Irrigated Olive trees	110902.03	110902.03	110902.03
Non-Irrigated Olive trees	371257.83	371257.83	371257.83
Vegetables (spring to summer season)	54583.78	31335.45	39490.19
Vegetables (summer to autumn/spring season)	5781.43	34843.7	2407.89
Non-Irrigated grass	96816.98	96816.98	96816.98
Irrigated Grass	137.18	137.18	137.18
Non irrigated cereals	639131.22	624979	698169.33
Plastic Greenhouses	61.17	61.17	61.17
Fallow lands	5620.89	5620.89	5620.89
Wet lands	1920.18	1920.18	1920.18
Urban areas	86804.24	86804.24	86804.24
Non irrigated vineyards	26518.5	26518.5	26518.5
Irrigated vineyards	100176.79	100176.79	100176.79
Total	**1,906,892.07**	**1,906,892.07**	**1,906,892.07**

Taking as a reference the classes of land use from SIGRA, a thorough analysis of the crops has been carried out.

For each class of land use *j* it has been possible to identify:

1) the percentages of the different *i* crops for each class of land use, according to data supplied by other sources (ISTAT and consortia);
2) the crop coefficients (K_c) of the different crops, listed in FAO Irrigation and Drainage Paper No. 24 (1977) and properly integrated with those determined, confirmed or modified for the Apulia region with weighing lysimeters by the Department of Plant Production – University of Bari (Table 3.2, page 34,and tables 3.3.a and 3.3.b, pages 35 - 36);
3) the root depth of each crop, derived from data available in literature, including those obtained for Apulia by the Department of Plant Production - University of Bari. Table 3.4 (page 37) and table 3.5 (page 38) show for the crops of each land use class, month by month, the rooting depth from the beginning to the end of the cropping cycle.

Table 3.2: monthly values of crop coefficients (K_c) of irrigated orchards, irrigated olive trees, irrigated vineyards and irrigated grass, for each province of the Apulia region. “Altri” is referred to three areas (Nord Fortore, Sud Fortore and Sinistra Ofanto), in the province of Foggia, which have different values of K_c (Lamaddalena and Caliandro, 2008).

Province	***Crop***	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
ALTRI	Orchards	0.25	0.25	0.26	0.55	0.9	1.2	1.14	0.73	0.25	0.25	0.24	0.24
ALTRI	Olive trees	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
ALTRI	Irrigated grass	1.09	1.15	1.3	1.12	0.65	0.25	0	0	0	0.94	1.01	1.05
ALTRI	Vineyards	0	0	0	0.45	0.6	0.6	0.75	0.75	0.7	0	0	0
BARI	Orchards	0.2	0.2	0.34	0.59	0.79	0.81	0.81	0.79	0.77	0.21	0.2	0.2
BARI	Olive trees	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
BARI	Vineyards	0	0	0	0.45	0.6	0.6	0.75	0.75	0.5	0	0	0
BRINDISI	Orchards	0.21	0.21	0.45	0.51	0.73	0.74	0.74	0.73	0.72	0.31	0.21	0.21
BRINDISI	Olive trees	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
BRINDISI	Vineyards	0	0	0	0.45	0.6	0.6	0.75	0.75	0.38	0	0	0
FOGGIA	Orchards	0.28	0.28	0.48	0.61	0.75	0.77	0.77	0.76	0.73	0.51	0.27	0.27
FOGGIA	Olive trees	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
FOGGIA	Vineyards	0	0	0	0.45	0.6	0.6	0.75	0.75	0.42	0	0	0
LECCE	Orchards	0.53	0.53	0.58	0.66	0.73	0.71	0.71	0.7	0.69	0.58	0.5	0.5
LECCE	Olive trees	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
LECCE	Irrigated grass	1.09	1.15	1.3	1.12	0.65	0.25	0	0	0	0.94	1.01	1.05
LECCE	Vineyards	0	0	0	0.45	0.6	0.6	0.75	0.75	0.36	0	0	0
TARANTO	Orchards	0.68	0.68	0.66	0.68	0.71	0.67	0.67	0.66	0.66	0.61	0.63	0.63
TARANTO	Olive trees	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
TARANTO	Vineyards	0	0	0	0.45	0.6	0.6	0.75	0.75	0.52	0	0	0

Table 3.3.a: monthly values of crop coefficients (K_c) of vegetables, for each province of the Apulia region. “Altri” is referred to three areas (Nord Fortore, Sud Fortore and Sinistra Ofanto), in the province of Foggia, which have different values of K_c. “N. I. cereals” are not irrigated cereals cultivated, during the year, before or after the vegetables in the same areas (Lamaddalena and Caliandro, 2008).

Province	***Area***	***Spring***	***Summer***	***Autumn***	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
ALTRI	Fortore	Vegetables	Vegetables	Vegetables	0.38	0.38	0.38	0.7	1.07	1.28	1.25	0.46	0.2	0.21	0.32	0.32
ALTRI	interm_alto	Vegetables	Vegetables	Vegetables	0.25	0.25	0.26	0.55	0.9	1.2	1.14	0.73	0.25	0.25	0.24	0.24
ALTRI	interm_basso	Vegetables	Vegetables	Vegetables	0.38	0.43	0.46	0.67	0.77	0.94	0.78	0.49	0.23	0.23	0.26	0.29
ALTRI	Fortore	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.38	0.7	1.07	1.28	1.25	0.46	0.2	0.94	1.01	1.05
ALTRI	Gargano	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.26	0.55	0.9	1.2	1.14	0.73	0.25	0.94	1.01	1.05
ALTRI	interm_basso	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.46	0.67	0.77	0.94	0.78	0.49	0.23	0.94	1.01	1.05
ALTRI	Tav_alto	N.I. cereals	Vegetables	Vegetables	0.38	0.38	1.3	1.12	0.65	0.25	1.25	0.46	0.2	0.21	0.32	0.32
ALTRI	interm_alto	N.I. cereals	Vegetables	Vegetables	0.25	0.25	1.3	1.12	0.65	0.25	1.14	0.73	0.25	0.25	0.24	0.24
ALTRI	Ofanto	N.I. cereals	Vegetables	Vegetables	0.38	0.43	1.3	1.12	0.65	0.25	0.78	0.49	0.23	0.23	0.26	0.29
ALTRI	Fortore	N.I. cereals	Vegetables	N.I. cereals	1.09	1.15	1.3	1.12	0.65	0.25	1.25	0.46	0.2	0.94	1.01	1.05
ALTRI	Gargano	N.I. cereals	Vegetables	N.I. cereals	1.09	1.15	1.3	1.12	0.65	0.25	1.14	0.73	0.25	0.94	1.01	1.05
ALTRI	interm_basso	N.I. cereals	Vegetables	N.I. cereals	1.09	1.15	1.3	1.12	0.65	0.25	0.78	0.49	0.23	0.94	1.01	1.05
TARANTO	Alta_Murgia	Vegetables	Vegetables	Vegetables	0.53	0.55	0.55	0.38	0.47	0.52	0.5	0.48	0.41	0.49	0.56	0.61
TARANTO	Alta_Murgia	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.55	0.38	0.47	0.52	0.5	0.48	0.41	0.94	1.01	1.05
TARANTO	Murgia_sud	Vegetables	N.I. cereals	Vegetables	0.53	0.55	0.55	0.38	0.47	0.52	0	0	0	0.49	0.56	0.61
TARANTO	Alta_Murgia	Vegetables	N.I. cereals	N.I. cereals	1.09	1.15	0.55	0.38	0.47	0.52	0	0	0	0.94	1.01	1.05
TARANTO	Arco_ionico	N.I. cereals	Vegetables	Vegetables	0.53	0.55	1.3	1.12	0.65	0.25	0.5	0.48	0.41	0.49	0.56	0.61
TARANTO	Alta_Murgia	N.I. cereals	Vegetables	N.I. cereals	1.09	1.15	1.3	1.12	0.65	0.25	0.5	0.48	0.41	0.94	1.01	1.05
LECCE	Salento_wfd	Vegetables	Vegetables	Vegetables	0.38	0.39	0.48	0.5	0.69	0.84	0.55	0.4	0.27	0.32	0.36	0.39
LECCE	Salento_wfd	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.48	0.5	0.69	0.84	0.55	0.4	0.27	0.94	1.01	1.05
LECCE	Salento_wfd	Vegetables	N.I. cereals	Vegetables	0.38	0.39	0.48	0.5	0.69	0.84	0	0	0	0.32	0.36	0.39
LECCE	Salento_wfd	Vegetables	N.I. cereals	N.I. cereals	1.09	1.15	0.48	0.5	0.69	0.84	0	0	0	0.94	1.01	1.05
LECCE	Salento_wfd	N.I. cereals	Vegetables	Vegetables	0.38	0.39	1.3	1.12	0.65	0.25	0.55	0.4	0.27	0.32	0.36	0.39
LECCE	Salento_wfd	N.I. cereals	Vegetables	N.I. cereals	1.09	1.15	1.3	1.12	0.65	0.25	0.55	0.4	0.27	0.94	1.01	1.05

Table 3.3.b: monthly values of crop coefficients (K_c) of vegetables, for each province of the Apulia region*.

FOGGIA	Fortore	Vegetables	Vegetables	Vegetables	0.51	0.48	0.43	0.39	0.58	0.75	0.73	0.61	0.4	0.55	0.6	0.61
FOGGIA	Ofanto	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.43	0.39	0.58	0.75	0.73	0.61	0.4	0.94	1.01	1.05
FOGGIA	Ofanto	N.I. cereals	Vegetables	Vegetables	0.51	0.48	1.3	1.12	0.65	0.25	0.73	0.61	0.4	0.55	0.6	0.61
BRINDISI	Brindisi	N.I. cereals	Vegetables	N.I. cereals	1.09	1.15	1.3	1.12	0.65	0.25	0.68	0.59	0.48	0.94	1.01	1.05
BRINDISI	Brindisi	Vegetables	Vegetables	Vegetables	0.74	0.72	0.65	0.36	0.48	0.57	0.68	0.59	0.48	0.63	0.72	0.77
BRINDISI	Brindisi	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.65	0.36	0.48	0.57	0.68	0.59	0.48	0.94	1.01	1.05
BRINDISI	Brindisi	N.I. cereals	Vegetables	Vegetables	0.74	0.72	1.3	1.12	0.65	0.25	0.68	0.59	0.48	0.63	0.72	0.77
BARI	Alta_Murgia	N.I. cereals	Vegetables	N.I. cereals	1.09	1.15	1.3	1.12	0.65	0.25	0.49	0.49	0.54	0.94	1.01	1.05
BARI	Alta_Murgia	Vegetables	Vegetables	Vegetables	0.63	0.66	0.68	0.54	0.59	0.54	0.49	0.49	0.54	0.61	0.59	0.64
BARI	Alta_Murgia	Vegetables	Vegetables	N.I. cereals	1.09	1.15	0.68	0.54	0.59	0.54	0.49	0.49	0.54	0.94	1.01	1.05
BARI	F_bradanica	Vegetables	N.I. cereals	Vegetables	0.63	0.66	0.68	0.54	0.59	0.54	0	0	0	0.61	0.59	0.64
BARI	Alta_Murgia	Vegetables	N.I. cereals	N.I. cereals	1.09	1.15	0.68	0.54	0.59	0.54	0	0	0	0.94	1.01	1.05
BARI	Alta_Murgia	N.I. cereals	Vegetables	Vegetables	0.63	0.66	1.3	1.12	0.65	0.25	0.49	0.49	0.54	0.61	0.59	0.64

* Table 3.3.b follows table 3.3.a

Table 3.4: monthly values of rooting depth of irrigated orchards, irrigated olives, irrigated vineyards and irrigated grass, in each province of the Apulia region (Lamaddalena and Caliandro, 2008).

Province	***Crop***	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
BARI	Orchards	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
BARI	Olive trees	1	1	1	1	1	1	1	1	1	1	1	1
BARI	Vineyards	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
BRINDISI	Orchards	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
BRINDISI	Olive trees	1	1	1	1	1	1	1	1	1	1	1	1
BRINDISI	Vineyards	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
FOGGIA	Orchards	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
FOGGIA	Irrigated Grass	0.5	0.7	0.8	0.8	0.8	0	0	0	0	0.1	0.25	0.3
FOGGIA	Olive trees	1	1	1	1	1	1	1	1	1	1	1	1
FOGGIA	Vineyards	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
LECCE	Orchards	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
LECCE	Olive trees	1	1	1	1	1	1	1	1	1	1	1	1
LECCE	Irrigated Grass	0.5	0.7	0.8	0.8	0.8	0	0	0	0	0.1	0.25	0.3
LECCE	Vineyards	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
TARANTO	Orchards	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
TARANTO	Olive trees	1	1	1	1	1	1	1	1	1	1	1	1
TARANTO	Vineyards	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Table 3.5: monthly values of rooting depth of vegetables, in each province of the Apulia region. "Altri" is referred to three areas (Nord Fortore, Sud Fortore and Sinistra Ofanto), in the province of Foggia, which have different values of rooting depth. "N. I. cereals" are not irrigated cereals cultivated, during the year, before or after the vegetables in the same areas (Lamaddalena and Caliandro, 2008).

Province	***Area***	***Spring***	***Summer***	***Autumn***	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
ALTRI	Gargano	Vegetables	Vegetables	Vegetables	0.18	0.2	0.23	0.36	0.46	0.6	0.7	0.26	0	0	0.14	0.17
ALTRI	Gargano	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.23	0.36	0.46	0.6	0.7	0.26	0	0.1	0.25	0.3
ALTRI	Interm alto	Vegetables	Vegetables	Vegetables	0.05	0.05	0.07	0.24	0.34	0.51	0.62	0.51	0.03	0.03	0.04	0.05
ALTRI	Gargano	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.07	0.24	0.34	0.51	0.62	0.51	0.03	0.1	0.25	0.3
ALTRI	Ofanto	Vegetables	Vegetables	Vegetables	0.11	0.14	0.2	0.32	0.27	0.38	0.39	0.28	0.02	0.02	0.06	0.11
ALTRI	Ofanto	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.2	0.32	0.27	0.38	0.39	0.28	0.02	0.1	0.25	0.3
BARI	Ofanto	Vegetables	Vegetables	Vegetables	0.23	0.25	0.3	0.19	0.18	0.18	0.2	0.22	0.19	0.18	0.18	0.22
BARI	F_bradanica	Vegetables	N.I. cereals	Vegetables	0.23	0.25	0.3	0.19	0.18	0.18	0	0	0	0.18	0.18	0.22
BARI	F_bradanica	Vegetables	N.I. cereals	N.I. cereals	0.5	0.7	0.3	0.19	0.18	0.18	0	0	0	0.1	0.25	0.3
BARI	Alta_Murgia	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.3	0.19	0.18	0.18	0.2	0.22	0.19	0.1	0.25	0.3
BRINDISI	Brindisi	Vegetables	Vegetables	Vegetables	0.29	0.3	0.31	0.12	0.15	0.19	0.46	0.42	0.26	0.26	0.28	0.3
BRINDISI	Brindisi	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.31	0.12	0.15	0.19	0.46	0.42	0.26	0.1	0.25	0.3
FOGGIA	Gargano	Vegetables	Vegetables	Vegetables	0.16	0.17	0.16	0.13	0.18	0.28	0.42	0.41	0.14	0.17	0.2	0.21
LECCE	Salento_wfd	Vegetables	Vegetables	Vegetables	0.1	0.11	0.18	0.19	0.25	0.33	0.26	0.21	0.04	0.06	0.08	0.1
LECCE	Salento_wfd	Vegetables	N.I. cereals	Vegetables	0.1	0.11	0.18	0.19	0.25	0.33	0	0	0	0.06	0.08	0.1
LECCE	Salento_wfd	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.18	0.19	0.25	0.33	0.26	0.21	0.04	0.1	0.25	0.3
LECCE	Salento_wfd	Vegetables	N.I. cereals	N.I. cereals	0.5	0.7	0.18	0.19	0.25	0.33	0	0	0	0.1	0.25	0.3
LECCE	Salento_wfd	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.18	0.19	0.25	0.33	0.26	0.21	0.04	0.1	0.25	0.3
TARANTO	Murgia_sud	Vegetables	Vegetables	Vegetables	0.2	0.21	0.23	0.15	0.16	0.19	0.21	0.24	0.12	0.14	0.2	0.23
TARANTO	Murgia_sud	Vegetables	N.I. cereals	Vegetables	0.2	0.21	0.23	0.15	0.16	0.19	0	0	0	0.14	0.2	0.23
TARANTO	Murgia_tar	Vegetables	N.I. cereals	N.I. cereals	0.5	0.7	0.23	0.15	0.16	0.19	0	0	0	0.1	0.25	0.3
TARANTO	Salento_wfd	Vegetables	Vegetables	N.I. cereals	0.5	0.7	0.23	0.15	0.16	0.19	0.21	0.24	0.12	0.1	0.25	0.3
TARANTO	Salento_wfd	Vegetables	N.I. cereals	N.I. cereals	0.5	0.7	0.23	0.15	0.16	0.19	0	0	0	0.1	0.25	0.3

For vegetables, the rooting depth increases from the beginning to the end of the crop cycle, while for the tree crops, as they have been considered adult, the rooting depth is constant during the entire year.
Moreover, for tree crops, in case of shallow soils, the depth of the roots has not been considered equal to the depth of the soil, but equal to that shown in the table. It is known, in fact, that in most pedologic situations of Apulia, with shallow soils where tree crops are present, the depth of the soil is limited by cracked limestone that allows the roots to go deeper penetrating cracks in the limestone often full of soil.
Therefore, in these pedologic situations, in order to consider the possibility that roots go deeper than the thickness of the soil, it has been considered a depth equal to the maximum reachable in soils without limitation of depth.

In this way, for each class of land use *j*, it has been possible to calculate the monthly mean crop coefficients ($\overline{Kc}_j$) and rooting depth ($\overline{PR}_j$) using the weighted average method (Lamaddalena and Caliandro, 2008):

$$\overline{Kc_j} = \frac{\sum_{i=1}^{N} Kc_i \cdot A_i}{\sum A_i} \qquad [7]$$

$$\overline{PR}_j = \frac{\sum_{i=1}^{N} PR_i \cdot A_i}{\sum A_i} \qquad [8]$$

where:

$\overline{Kc_j}$ is the mean crop coefficient of the crops within the land cover unit *j*;
Kc_i is the crop coefficient of the single crop *i* within the land cover unit *j*;
$\overline{PR}_j$ is the mean rooting depth of the crops within the land cover unit *j* [m];
PR_i is the rooting depth of the single crop *i* within the land cover unit *j* [m];
A_i is the surface area occupied by each crop *i* within the corresponding Province [ha];
N is the number of different crops presented in the land cover unit *j*.

In order to identify the initial K_c, essential for the estimation of the evapotranspiration during the initial phase of the crops, the methodology proposed by FAO No. 56 (1998) has been taken into consideration. According to this methodology, the initial K_c depends on the frequency of rainfall, the reference evapotranspiration, the amount of rainfall per event and the soil texture (Figures 3.7, 3.8 and 3.9).

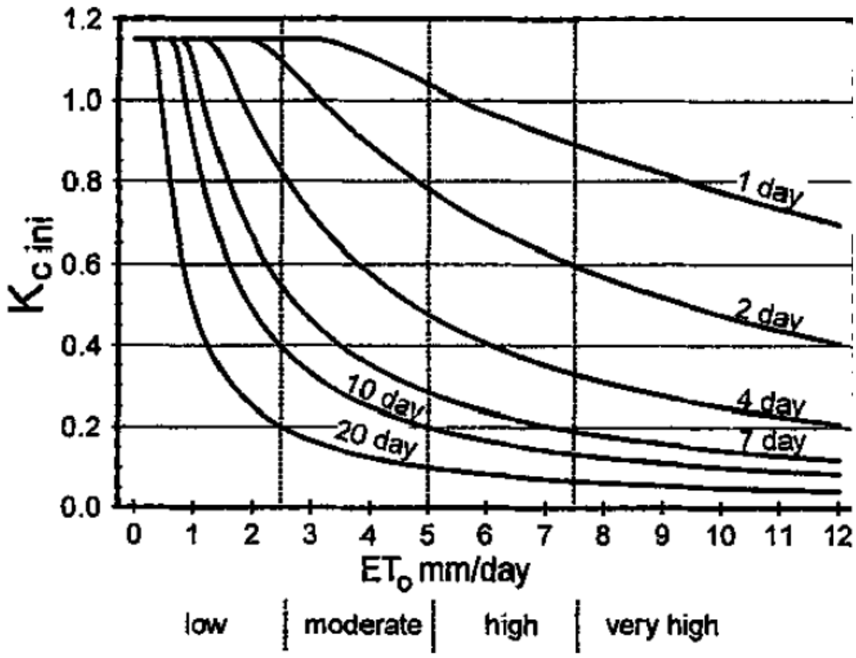

Figure 3.7: trend of the values of the initial crop coefficient (Kc_{ini}) in relation to frequency of rainfall and the daily ET_0, with rainfall below 10 mm per event, for all soil types (source: FAO, 1998).

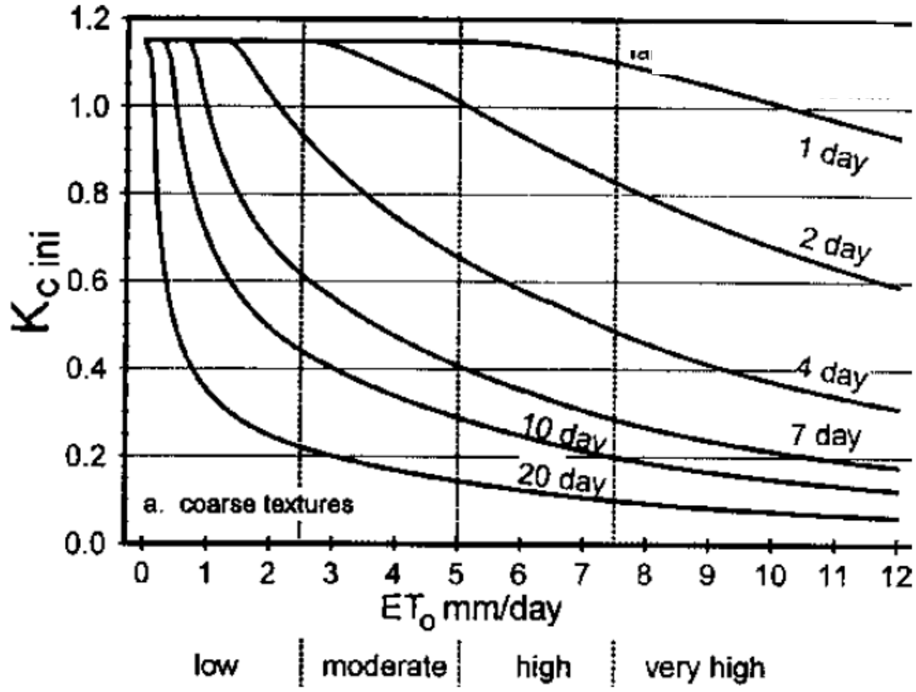

Figure 3.8: trend of the values of the initial crop coefficient (Kc_{ini}), in relation to frequency of rainfall and the daily ET_0, with rainfall exceeding 40 mm per event, for coarse soils (source: FAO, 1998).

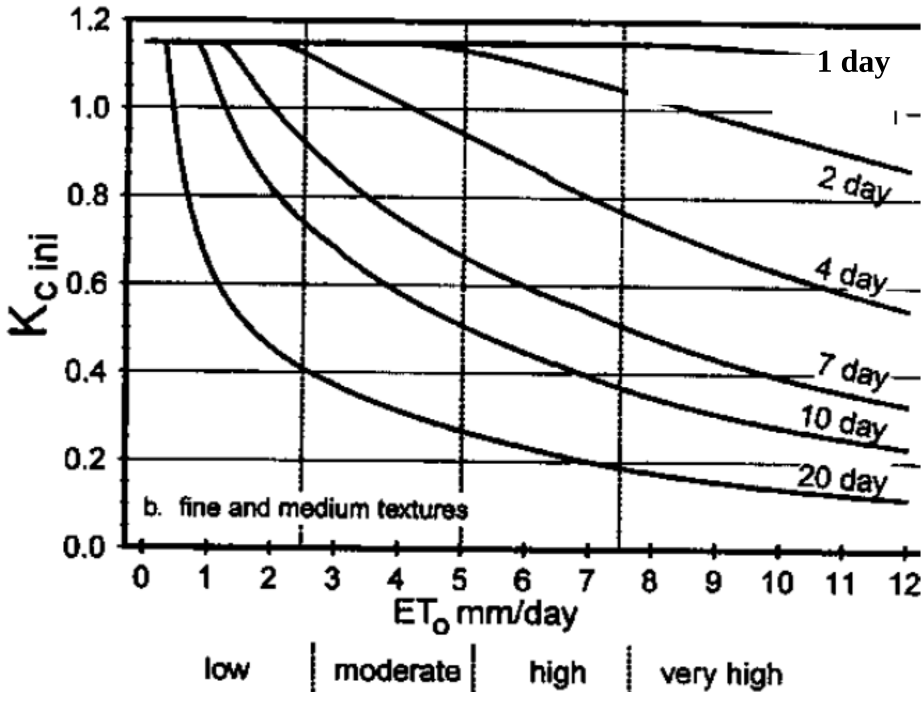

Figure 3.9: trend of the values of the initial crop coefficient (Kc_{ini}), in relation to frequency of rainfall and the daily ET_0, with rainfall exceeding 40 mm per event, for medium and fine-grained soils (source: FAO, 1998).

3.4 Regional crop irrigation water requirements

3.4.1 Determination of IWR by means of a model

Once the regional areas affected by irrigated crops have been identified, the maximum crop water demand have been estimated, crop by crop, for each month of the irrigation season, as the quantity of water necessary to reach the field capacity, by using a computational model, developed on Fortran language, with a distributed approach that performs a monthly water balance. The first operation performed by the model is the calculation of the maximum available water content (AWC), as shown in figure 3.10, according to the following equation (Giardini, 2002; Mannini and Genovesi, 2004):

$$AWC = FC - WP \qquad [9]$$

where:

AWC is the maximum available water content [%]
FC is the soil water content at field capacity [%]
WP is the soil water content at wilting point [%]

Subsequently, the AWC has been related, month by month, to the depth of the roots and thickness of all the soil horizons affected by the roots at that point.
As previously mentioned, if the thickness of the soil results greater than the depth of the root system, the AWC will be determined on the radical depth, otherwise (thickness of soil below the root depth) the AWC is calculated on the thickness of the soil, since it is not possible for the root system to extend beyond.

The second step concerns the calculation, crop by crop, of monthly ET_c, starting from the monthly values of ET_0 obtained with Hargreaves – Samani equation and K_c values of table 3.2, through the single crop coefficient approach (FAO, 1998):

$$ET_{c\,(i,j)} = ET_{0\,(j)} \times K_{c\,(i,j)} \qquad [10]$$

where:

$ET_{c\,(i,j)}$ is the maximum evapotranspiration of the crop *i* in the month *j*
$ET_{0\,(j)}$ is the reference evapotranspiration in the month *j*
$K_{c\,(i,j)}$ is the crop coefficient of the crop *i* in the month *j*

In case of irrigated crops, the program gives to the land use polygon a value of management allowable deficit (MAD) between 0 and 100%.
MAD is the desired soil moisture deficit at the time of irrigation. It is the value, selected by irrigation management, which relates to the optimum allowable soil moisture stress for the crop-soil-water-weather system.

It is first expressed as the management allowable percent deficient of the available soil water in the root zone with its corresponding stress, and then as the resultant depth deficit to be replaced for a specific soil and root zone. For not irrigated crops, a value of MAD equal to 100% is considered.

This first part of the computational model allows to obtain, for each cell and month, the root depth, ET_c and MAD.

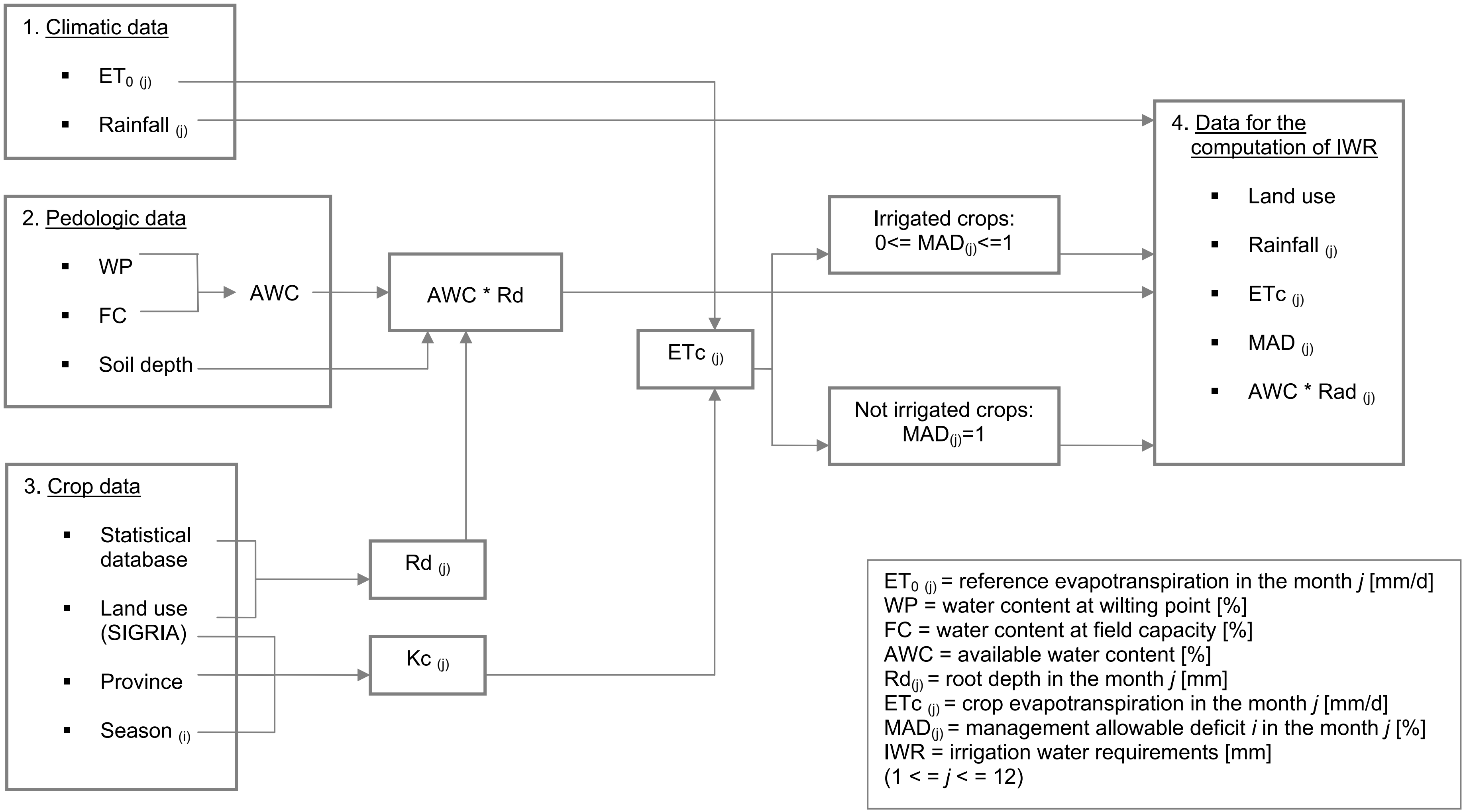

Figure 3.10: diagram of the conceptual model for the calculation of crops monthly irrigation water requirements.

The second part of the model allows the computation of the water balance, month by month, according to equation [4] of page 16.
The methodology used considers the whole surface-subsurface system as two connected subsystems. The first represents the water dynamics in the root zone, while the second represents the phenomenon of the natural groundwater recharge (De Girolamo *et al*., 2001).
The output obtained is a map that includes the monthly irrigation, runoff and infiltration (groundwater recharge) values.

For the purpose of this work, the water dynamics in the root zone represent the most important aspects of the computational model.
Surface subsystem can be summarized by the following equation (De Girolamo *et al*., 2001):

$$\delta w/\delta t = P - E - RO - Per + Irr \qquad [11]$$

where:

δw/δt is the monthly variation in soil moisture content [mm/δt]
P is the total rainfall [mm/δt]
E is the actual evapotranspiration or evaporation from bare soil [mm/δt]
RO is the surface runoff [mm/δt]
Per is the deep percolation from the root zone to the growndwater [mm/δt]
Irr is the irrigation water [mm/δt]

The difference between *P* and *Per* is the part of the total rainfall that infiltrates the soil and reaches the water table, and is called effective rainfall. This amount of water is retained in the soil layer occupied by the rooting systems, so it becomes available for plants.
The difficulty in estimating the effective rainfall is due to the temporal variation of the water infiltration capacity into the soil, the state of soil moisture, and finally the spatial and temporal variation of rain.
In this work, since the monthly average amount of rainfall does not exceed 250 mm, the monthly effective rainfall *Peff* has been computed according to the following equation (Lamaddalena and Caliandro, 2008):

$$Peff_{(j)} = (P_{(j)} / 125) \times (125 - 0.2\, P_{(j)}) \qquad [12]$$

where $Peff_{(j)}$ and $P_{(j)}$ are, respectively, the effective rainfall and the total amount of rainfall in the month *j* of the average climatic year.
Once computed the effective rainfall, the monthly surface runoff $RO_{(j)}$ has been determined according to the following equation (Lamaddalena and Caliandro, 2008):

$$RO_{(j)} = (0.2 / 125) \times (P_{(j)}) \qquad [13]$$

with an obvious meaning of the symbols.

For the computation of the water balance, several conditions have been considered:

- At the beginning of the year, the available water content in the soil is considered to be maximum;
- Deep percolation occurs only when the water infiltrated into the soil exceeds the water holding capacity throughout the depth of soil occupied by the roots;
- The amount of water for irrigation is determined only in areas where cultivation has been identified as irrigated, and only when the soil water content falls below the value of MAD of the crop considered. In this case, irrigation prevents that plants reach levels of water stress incompatible with the optimal production;
- Areas where cultivation has been identified as not irrigated, do not require irrigation, so if the soil water content is not sufficient to satisfy the crop water requirements, crops may suffer severe water stress;
- At the end of the crop cycle, so during some months only, some soils are left fallow. In this case, instead of K_c utilized for the computation of ET_c, the crop coefficient for bare soil (K_{cb}) is utilized (K_{cb} corresponds to the initial K_c, $K_{c\ ini}$, previously described).

A GIS tool has been finally used for mapping the output database obtained from the model.
GIS treats the database as a set of layers and the overlay of input and output layers enables to identify, for each cropped field, the respective set of predominant characteristics.

3.4.2 Determination of IWR step by step

The determination of regional IWR has also been developed on an Excel sheet in order to verify the reliability of the results obtained from the model and to insert in the computations the depletion coefficient K_d, in order to obtain the regional IWR under controlled deficit irrigation (CDI).

K_d is a coefficient that considers the effects of the water depletion on the quality of the yield, the crop's capacity to withstand temporary periods of drought and the cost of irrigation. It varies from zero (whenever irrigation is missing) to one (whenever the depletion is missing, so full IWR are satisfied) and changes according to the crop type and the phenological stage.

The values of K_d utilized in this work (table 3.6, page 47) derive from previous regional projects realised for the Department of Plant Production - University of Bari - and have been corrected, according to the distribution of crops in land use classes for each of the 5 provinces of the Apulia region, through the calculation of average values. This involves an approximation in the computation of the IWR under CDI.

Table 3.6: monthly values of the depletion coefficient (K_d) utilized for each land use class (Department of Plant Production - University of Bari).

Crop	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Vegetables	0.86	0.84	0.87	0.93	0.93	0.95	0.88	0.88	0.9	0.98	0.94	0.88
Olive trees					0.8	0.5	0.6	0.8	0.5			
Vineyards				0.5	0.6	0.78	0.85	0.9	0.6			
Orchards	1	1	0.65	0.8	0.93	0.93	0.93	0.85	0.7	1	1	1

3.4.3 The actual irrigation water requirements

In addition to the IWR estimated as previously reported, the actual irrigation volumes supplied by farmers have been taken into consideration. These values derive from the results of a study conducted from 1991 to 1999 on some irrigation systems managed by the Consortium of Reclamation of Capitanata, and then have been extended to the entire region, assuming that the management conditions of the irrigation schemes in the region are comparable (Lamaddalena and Caliandro, 2008).

Chapter 4

Results and discussion

4.1 Introduction

The results of the estimation of the irrigation water requirements for the Apulia region are represented in three thematic maps. The GIS map in figure 4.1 shows the maximum crop IWR of the region, figure 4.2 shows the GIS map with the IWR under controlled deficit irrigation (CDI), while figure 4.3 is the GIS map with the effective irrigation water volumes provided by farmers. All values are expressed in mm per year and are referred to an average climatic year.
Tables 4.1, 4.2, 4.3, 4.4 and 4.5 show, for each province of the Apulia region and for the different irrigated crops, the comparison between total actual crop water demand, requirements under controlled deficit irrigation and effective water volumes provided by farmers. In this case, requirements are expressed in millions of m^3 per year.
Tables 4.6, 4.7, 4.8, 4.9 and 4.10 include, for each province, the average values of total IWR, total IWR under CDI and total actual irrigation volumes provided by farmers, expressed in m^3 per ha.
Moreover, figures 4.4, 4.5, 4.6, 4.7 and 4.8 show the monthly distribution, for each province, of maximum and actual irrigation water requirements, and the demand under CDI, all expressed in Mm^3, for the average climatic year previously defined.
Table 4.11 includes the surfaces occupied by the different irrigated crops, expressed in ha, for each province of the region.

4.2 Spatial distribution of regional crop irrigation water requirements

Figure 4.1 (page 49) shows the regional distribution of annual irrigation water requirements in case of optimal water supply (maximum IWR), expressed in mm per year. The darker areas are occupied by crops that need higher irrigation volumes respect to yellow areas, while white areas include all the other land use classes. The highest irrigation water demands are concentrated in the province of Foggia, followed by more distributed areas in the province of Lecce, the Ionian arc near Taranto, some areas in the province of Brindisi and few areas near Bari.

Figure 4.2 (page 50) shows the regional distribution of annual IWR under CDI, expressed in mm per year. A visible reduction of darker areas is shown, because controlled water deficit has been applied to the main irrigated crops, so the millimetres of water applied are less. The strongest reductions concern the provinces of Lecce and Bari, followed by Brindisi, Taranto and some areas of Foggia.

Figure 4.3 (page 50) shows the regional distribution of actual IWR provided by farmers. In general, yellow areas are spread on the regional territory more than in the other two maps, showing that irrigation volumes provided by farmers are further lower than the supplies under CDI and, of course, of maximum IWR, but there are some exceptions for vegetables. In this case, farmers prefer to supply higher irrigation volumes because these crops are more sensitive to water stress and because they are high-income crops.

In general, in the region, the crop whose irrigation supplies are drastically reduced, both through the CDI strategy and by farmers, is the olive, because this crop can better withstand water stress.
The other crop unable to cope well water scarcity is vineyard. In this case, the justification for reducing the consumption of water is quantitative. Indeed, in this work, "Vineyards" include both table and wine grapes, and the reductions are attributable to the fact that the wine grape undergoing a water stress, will give a higher quality product because of increased sugar concentration.

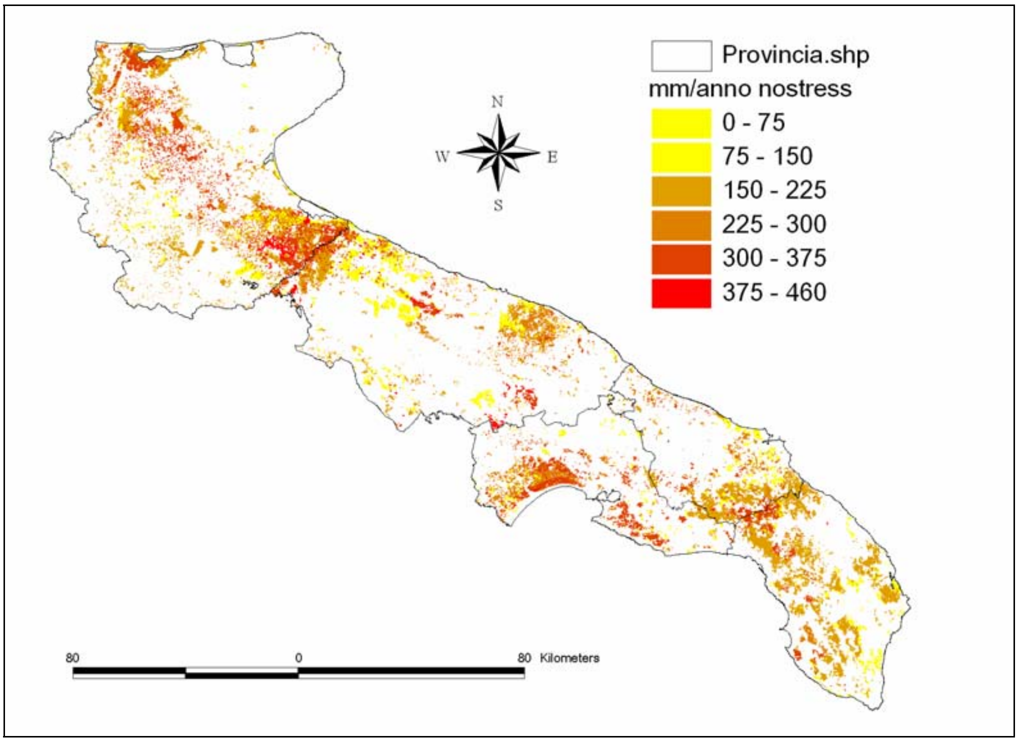

Figure 4.1: spatial distribution of maximum regional crop irrigation water requirements (mm/year).

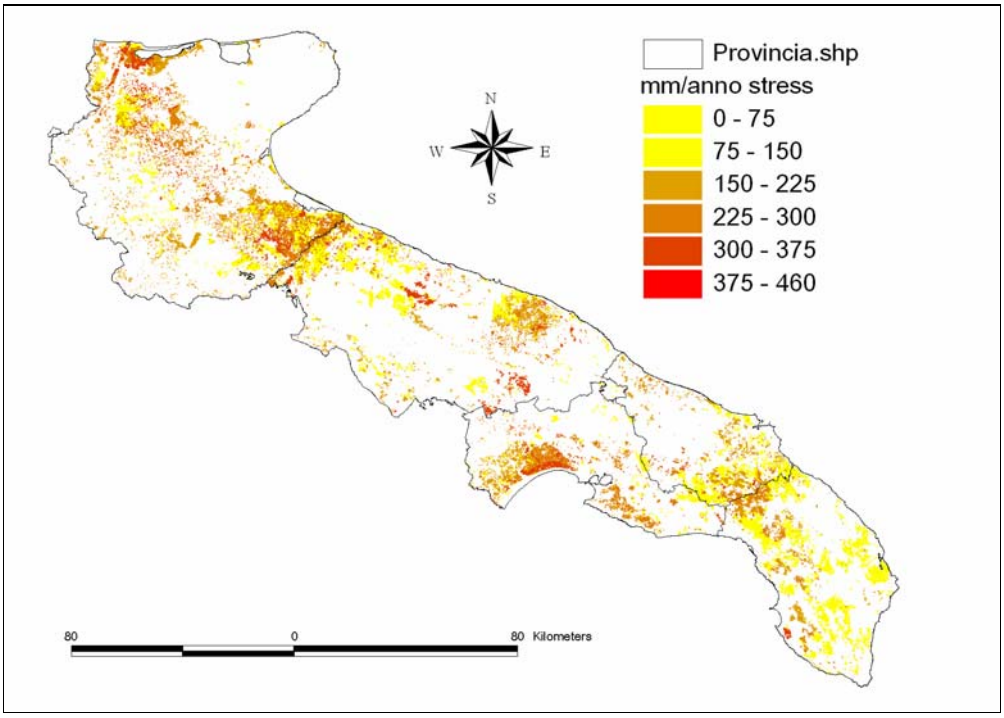

Figure 4.2: spatial distribution of regional crop irrigation water requirements under controlled deficit irrigation (mm/year).

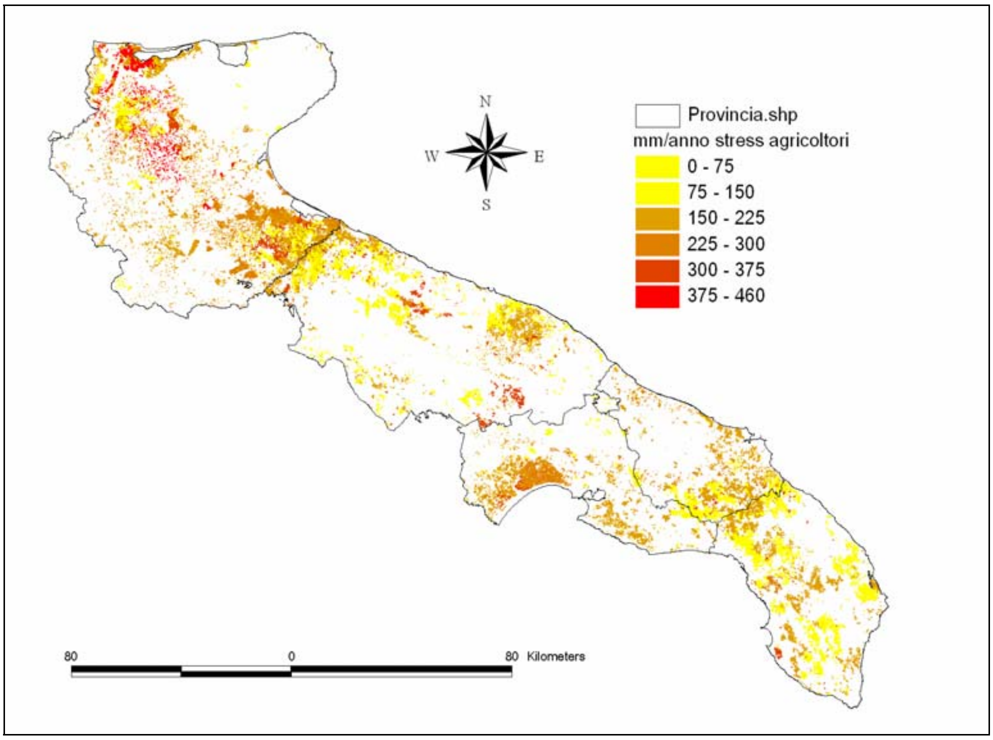

Figure 4.3: spatial distribution of regional crop irrigation water requirements actually provided by farmers (mm/year).

4.3 Irrigation water requirements for each province of Apulia

The estimation of the irrigation volumes needed to cover the requirements of the main classes of irrigated crops, for each province of Apulia, has led to the following results, expressed in millions of m^3.

4.3.1 Irrigation water requirements for the province of Bari

The province of Bari has an irrigated area equal to 91349 ha and it is occupied by olive trees with 35682.2 ha, irrigated vineyards with 25752.37 ha, vegetables with 17900.67 ha, and orchards with 12013.73 ha.

In order to cover the maximum IWR of the province, 198.87 Mm^3 of water are needed (table 4.1, page 53). The application of CDI leads to a partial reduction of the total demand, equal to 20.69% and corresponding to 157.72 Mm^3, while the farmers provide 122.91 Mm^3, which corresponds to a reduction of 38.19% respect to the maximum demand. This means that farmers provide less water than the volumes expected from the strategy of CDI.

This behaviour is found for all crops of the province: orchards need 45.12 Mm^3 of water to fully cover the IWR, and with CDI this volume decreases up to 40.18 Mm^3, which represents a reduction of 10.95%, but farmers supply 37.07 Mm^3 (17.84% less than maximum IWR).

Maximum IWR of olive trees are 51.66 Mm^3, which become 31.69 Mm^3 in case of controlled deficit irrigation, with a reduction of 38.64%. Farmers provide only 21.34 Mm^3, which corresponds to a reduction of 58.68% respect to the maximum demand, which is the largest percentage reduction in water volume required by different crops in the province.

Vegetables need 28.89 Mm^3 of water to satisfy the full IWR. This volume becomes 26.18 Mm^3 (a reduction of 9.36%) with deficit irrigation, but farmers provide only 22.66 Mm^3 (a reduction of 21.56% respect to the maximum requirements).

Although olive trees occupy a wider surface, vineyards need the highest irrigation volumes in the province (73.19 Mm^3) in order to satisfy the maximum IWR and receive 59.65 Mm^3 in case of CDI (18.5% reduction). Farmers provide 41.83 Mm^3 only (requirements are reduced by 42.85% respect to the maximum demand), which means that the amount of water which satisfy the maximum requirements is almost halved. This low percentage can be justified by the fact that the voice “vineyards” includes both table grapes and wine grapes. Farmers allocate less water to vine grapes than table grapes and the surfaces in the province occupied by table grapes are less than vine grapes.

4.3.2 Irrigation water requirements for the province of Brindisi

The irrigated area in the province of Brindisi covers 41532.17 ha, divided as follows: 16637.25 ha of vegetables, 12529.43 ha of olive trees, 7039.23 ha of vineyards and 5326.25 ha of orchards.

Table 4.2 (page 53) shows that maximum IWR of the province are equal to 88.37 Mm^3, reduced to 71.41 Mm^3 (19.19% reduction) in case of CDI and 66.09 Mm^3 (25.21% reduction) supplied by farmers.

Orchards require maximum 17.29 Mm^3; with CDI, water supply decreases to 15.43 Mm^3, which means that there is a reduction of 10.76%, and farmers supply 14.77 Mm^3 (maximum water supply is reduced by 14.6%).

Maximum IWR of olive trees are 24.82 Mm^3, but the crop will receive 16.14 Mm^3 (34.97% of reduction) in case of CDI. The reduction of inputs by farmers is consistent, because they provide only 9.59 Mm^3, with a reduction of 61.36% respect to the maximum requirements.

Vegetables cover the widest surface in the province and require the highest irrigation volume (26.95 Mm^3) to fully satisfy the IWR of the province, but with CDI, this volume decreases to 24.15 Mm^3 (with a reduction of 10.37%). In this case, farmers supply a higher volume of water, equal to 29.88 Mm^3, with a surplus of 10.9% of the maximum IWR. Reasons for this behaviour may be sought in the fact that farmers provide a greater quantity of water for vegetables such as tomato and artichoke, very common in this province, rather than other crops such as orchards.

Vineyards need 19.3 Mm^3 of water to satisfy the maximum IWR. This volume is reduced by 18.74%, becoming 15.68 Mm^3 with CDI, but farmers further reduce it, up to 11.84 Mm^3 (38.64% less than maximum IWR).

4.3.3 Irrigation water requirements for the province of Foggia

The irrigated surface of the province of Foggia equals 139145 ha, of which more than half are vegetables (74460.95 ha), 36665.43 ha are vineyards, 21402.81 ha are olive trees, 6607.61 ha are orchards, and the remaining 8.212 ha are grass. Since irrigated grass covers an irrelevant surface in the region, it was not considered in the calculations, and tables just contain the main irrigated crops. This is why in table 4.3, the total irrigated surface for the province of Foggia is different.

As for the other provinces, considerable reductions occur in the actual water supplies if compared to the maximum requirements, as shown in table 4.3 (page 53). In order to cover the maximum IWR, 340.02 Mm^3 of water are required. This volume is partially reduced by 16.4% if CDI is applied, reaching 284.25 Mm^3. The actual total volume provided by farmers to all crops is slightly higher than the latter: 291.36 Mm^3 (14.31% less than the maximum IWR).

Table 4.1: maximum crop irrigation water requirements, IWR under controlled deficit irrigation and effective IWR provided by farmers, all expressed in Mm^3 per year, for the province of Bari.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%	TOT	%
Full IWR	45.12	100.00	51.66	100.00	28.89	100.00	73.19	100.00	198.87	100.00
IWR with Kd	40.18	89.05	31.69	61.36	26.18	90.64	59.65	81.50	157.72	79.31
Actual IWR	37.07	82.16	21.34	41.32	22.66	78.44	41.83	57.15	122.91	61.81

Table 4.2: maximum crop irrigation water requirements, IWR under controlled deficit irrigation and effective IWR provided by farmers, all expressed in Mm^3 per year, for the province of Brindisi.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%	TOT	%
Full IWR	17.29	100.00	24.82	100.00	26.95	100.00	19.30	100.00	88.37	100.00
IWR with Kd	15.43	89.24	16.14	65.03	24.15	89.63	15.68	81.26	71.41	80.81
Actual IWR	14.77	85.40	9.59	38.64	29.88	110.90	11.84	61.36	66.09	74.79

Table 4.3: maximum crop irrigation water requirements, IWR under controlled deficit irrigation and effective IWR provided by farmers, all expressed in Mm^3 per year, for the province of Foggia.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%	TOT	%
Full IWR	24.11	100.00	39.94	100.00	164.97	100.00	110.98	100.00	340.02	100.00
IWR with Kd	21.46	89.00	24.87	62.28	148.83	90.22	89.07	80.26	284.25	83.60
Actual IWR	20.71	85.89	12.51	31.33	193.83	117.49	64.30	57.93	291.36	85.69

Maximum requirements for orchards equal 24.11 Mm^3, but the application of controlled deficit irrigation determines a reduction of 11%, equal to 21.46 Mm^3. Farmers provide less water, reaching 20.71 Mm^3 (14.11% reduction respect to the maximum demand).

Olive trees need 39.94 Mm^3 to cover their maximum IWR; in case of controlled deficit irrigation, there is a supply reduction of 37.72%, which low irrigation volumes to 24.87 Mm^3. As for the other provinces, the actual quantity of water supplied to this crop by farmers is much lower than maximum IWR, reaching 12.51 Mm^3 (maximum water supply is reduced by 68.67%).

As for the other provinces (excluding Bari), the crop with highest IWR is vegetables: 164.97 Mm^3 in order to satisfy their maximum IWR. When CDI is applied, this value reaches 148.83 Mm^3 (9.78% less). As for the province of Brindisi, farmers in this case provide more water than the maximum requirements, reaching 193.8 Mm^3 (equal to a surplus of 17.49%). These high volumes are justified by the surfaces occupied, that for this crop are the highest of the province.

Vineyards also require high irrigation volumes, in relation to the surfaces occupied. Maximum IWR equal 110.98 Mm^3 of water and, if controlled deficit irrigation is applied, water supplies are reduced to 89.07 Mm^3 (19.74% less), but farmers only satisfy a little more than half of the maximum requirements (42.07% of reduction), equal to 64.3 Mm^3.

4.3.4 Irrigation water requirements for the province of Lecce

The province of Lecce has an irrigated surface equal to 76161.98 ha and the most relevant crop is olive with 41698.95 ha, followed by vegetables with 20363.54 ha, vineyards with 12377.58 ha, orchards with 1684.53 ha and the remaining 37.35 ha are grass. As for the province of Foggia, irrigated grass has not been included in the calculations because of the low impact of this crop on the final estimation, and his is why in table 4.4 it does not appear among the irrigated crops.

In order to cover the maximum IWR of the province, 153.61 Mm^3 of water are needed (table 4.4, page 56). With the application of controlled deficit irrigation practice, volumes are reduced by 25.97%, reaching 113.57 Mm^3, but the actual supplies equal 101.49 Mm^3, which means a reduction of 34.37% respect to the maximum IWR.

The full IWR of the orchards are 5.68 Mm^3 and the application of controlled deficit irrigation leads to a reduction of the volumes of 10.61%, reaching 5.07 Mm^3, while farmers supply 5.31 Mm^3 (6.51% less than the total).

Olive trees require the highest amount of water among the crops of the province (80.97 Mm^3), because of the surfaces covered by this crop. With controlled deficit irrigation, volumes decrease up to 51.01 Mm^3 (36.89% of reduction), but farmers supply an amount of water equal to 33.71 Mm^3, which is 58.37% less than the maximum IWR.

Vegetables require 31.01 Mm^3 of water and the controlled deficit irrigation provokes a slight reduction of the volumes (8.87%), reaching 28.26 Mm^3. As for other provinces, farmers in this case provide more water than the maximum requirements, reaching 40.65 Mm^3, with a surplus of 31.08%.

Maximum IWR of vineyards equal 36.86 Mm^3. With controlled deficit irrigation, there is a reduction of the maximum requirements of 18.74%, with 29.95 Mm^3 of water. The actual water supply equals 21.74 Mm^3, which means that maximum water supply is reduced by 41.02%.

4.3.5 Irrigation water requirements for the province of Taranto

The irrigated surface of the province of Taranto equals 45998.54 ha, of which 20168.98 ha are covered by vineyards, 13238.314 ha by orchards, 7884.8 ha by vegetables and 4706.44 ha by olive trees.

Table 4.5 (page 56) shows that, in order to satisfy the maximum IWR of the province, 123.26 Mm^3 of water are needed. The application of controlled deficit irrigation leads to a reduction of the maximum demand equal to 17.54% and corresponding to 101.63 Mm^3, while the farmers provide 88.58 Mm^3, which represents a reduction of 28.13% respect to the maximum IWR.

Maximum IWR for orchards are 43.42 Mm^3 and are reduced to 38.5 Mm^3 (11.32% less) in case of CDI. Farmers apply a further reduction, equal to 13.83% of maximum demand, reaching 37.41 Mm^3.

Olive trees require 8.89 Mm^3 to fully satisfy the IWR of the province, but with CDI this volume decreases to 5.67 Mm^3 (36.24% less). As for the other provinces, farmers apply to the olive trees a strong reduction (60.16% less than the maximum requirements) in the water supplies, reaching 3.54 Mm^3.

Vegetables require maximum 9.15 Mm^3 of water; with CDI, water supply decreases to 8.3 Mm^3, which represents a reduction of 9.38%, but farmers in this case provide more water than the maximum requirements, reaching 11.82 Mm^3, equal to a surplus of 29.1%. This occurs because, as for Brindisi and Foggia, farmers allocate a greater quantity of water for vegetables such as tomato and melon, very common in this province, rather than other crops.

Since vineyards cover a high percentage of the irrigated land, they require the highest amount of water among the crops of the province: 61.78 Mm^3. CDI strategy leads to supply 49.15 Mm^3 (20.43% less), but the actual supplies reach 35.79 Mm^3, which represents a reduction of 42.06% respect to the maximum irrigation volume required.

Table 4.4: maximum crop irrigation water requirements, IWR under controlled deficit irrigation and effective IWR provided by farmers, all expressed in Mm^3 per year, for the province of Lecce.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%	TOT	%
Full IWR	5.68	100.00	80.97	100.00	31.01	100.00	36.86	100.00	153.61	100.00
IWR with Kd	5.07	89.39	51.01	63.11	28.26	91.13	29.95	81.26	113.57	73.03
Effective IWR	5.31	93.49	33.71	41.63	40.65	131.08	21.74	58.98	101.49	65.63

Table 4.5: maximum crop irrigation water requirements, IWR under controlled deficit irrigation and effective IWR provided by farmers, all expressed in Mm^3 per year, for the province of Taranto.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%	TOT	%
Full IWR	43.42	100.00	8.89	100.00	9.15	100.00	61.78	100.00	123.26	100.00
IWR with Kd	38.50	88.68	5.67	63.76	8.29	90.62	49.15	79.57	101.63	82.46
Actual IWR	37.41	86.17	3.54	39.84	11.82	129.10	35.79	57.94	88.58	71.87

4.4 Average irrigation volumes (m^3/ha) for the different classes of crops, for each province of the region.

Tables 4.6, 4.7, 4.8, 4.9 and 4.10 of page 59 and 61 include, for each province, the average values of total IWR, total IWR under CDI and total actual irrigation volumes provided by farmers, expressed in m^3 per ha.
These tables allow understanding how the percentages of the different classes of crops influence the irrigation volumes needed, regardless the hectares occupied by the single crops.
The application of CDI and the farmers' supplies determine different reduction percentages (from a minimum of 6.51% for orchards, up to 68.68% for olive), but also surplus percentages (for vegetables, up to 31.09%), according to the different percentages of the single crops that are in each crop class (e.g., the crop class "vineyards" includes both table and wine grapes).
The crops that require the highest irrigation volumes are orchards and vineyards for all the provinces. Olives require the lowest volumes, because this crop can withstand periods of stress, while vegetables receive from farmers more water than the needs, for all the provinces except Bari, because these are high-income crops very sensitive to water stress.

4.4.1 Average irrigation volumes (m^3/ha) for the different classes of crops in the province of Bari.

In table 4.6 (page 59) there are the average values of total annual IWR, total requirements under CDI and total effective irrigation volumes provided for the province of Bari, all expressed in m^3 per ha.
The crop with the highest requirements is orchards, with 3755.7 m^3/ha as maximum requirements, reduced by 10.95% in case of CDI (3344.51 m^3/ha) and by 17.84% in case of actual supplies (3085.64 m^3/ha). The crop with the lowest requirements is olive, with 1447.79 m^3/ha as maximum requirements, reduced by 38.66% in case of CDI (888.12 m^3/ha) and halved in case of actual supplies (58.69% of reduction, equal to 598.06 m^3/ha). A strong reduction (42.85%) is also applied by farmers to vineyards, which require maximum 2842.11 m^3/ha, 2316.32 m^3/ha in case of CDI, but receive 1624.34 m^3/ha. Vegetables do not suffer for very strong reductions: maximum IWR equal 1613.91 m^3/ha, with a reduction by 9.38% in case of CDI (1462.52 m^3/ha) and by 21.56% in case of actual supplies.

4.4.2 Average irrigation volumes (m^3/ha) for the different classes of crops in the province of Brindisi.

Table 4.7 of page 59 includes the average values of annual IWR, requirements under CDI and effective volumes supplied, all expressed in m^3 per ha, for the province of Brindisi. As for Bari, orchards need the highest volumes, with 3246.19 m^3/ha as maximum IWR, 2896.97 m^3/ha in case of CDI (10.76% of reduction) and 2773.06 m^3/ha actually supplied by farmers (14.57% of reduction). The crop with the lowest requirements is olive, with 1980.94 m^3/ha as maximum needs. In case of CDI, the supply is reduced by

34.97%, reaching 1288.17 m^3/ha, but farmers supply only 765.4 m^3/ha, with a reduction equal to 61.36%. Vineyards' maximum IWR equal 2741.78 m^3/ha, reduced by 18.76% (so reaching 2227.52 m^3/ha) in case of CDI and by 38.65% (equal to 1682 m^3/ha) in case of actual supplies. Vegetables' maximum requirements equal 1619.86 m^3/ha, and in case of CDI this value is reduced in some extent (10.39%), reaching 1451.56 m^3/ha, but farmers supply 1795.97 m^3/ha, with a surplus of 10.87%, for the reasons already explained.

4.4.3 Average irrigation volumes (m^3/ha) for the different classes of crops in the province of Foggia.

Table 4.8 (page 59) shows that, also for the province of Foggia, orchard is the crop with the highest IWR, with maximum 3648.82 m^3/ha, 3247.77 m^3/ha in case of CDI (10.99 % of reduction) and 3134.26 m^3/ha as actual water supplies (14.10% of reduction). Vineyards need maximum 3026.83 m^3/ha, while in case of CDI there is a reduction of 19.74%, corresponding to 2429.26 m^3/ha, but farmers supply only 1753.7 m^3/ha (with a reduction of 42.06%), probably because there is a higher percentage of wine grapes than table grapes, and water stress provoke in some extent the increase of quality. Olives' maximum IWR equal 1866.11 m^3/ha, reduced by 37.73% in case of CDI. Also in this case, farmers supply a lower volume: 584.5 m^3/ha, corresponding to a reduction of 68.68%. Vegetables need 2215.52 m^3/ha to cover the maximum requirements, while with CDI strategy the water volume decreases by 9.78%, reaching 1998.77 m^3/ha. Farmers exceed in supplies, providing 2603.11 m^3/ha with a surplus of 17.49%.

4.4.4 Average irrigation volumes (m^3/ha) for the different classes of crops in the province of Lecce.

The water requirements for Lecce are included in table 4.9, page 61. Orchards need the highest volumes, with 3371.86 m^3/ha as maximum IWR, 3009.74 m^3/ha in case of CDI (10.74% of reduction) and 3152.21 m^3/ha actually supplied by farmers (6.51% of reduction, slightly higher than CDI). The crop with the lowest requirements is olive, with 1941.78 m^3/ha as maximum needs. In case of CDI, the supply is reduced by 37%, reaching 1223.29 m^3/ha, but farmers supply only 808.41 m^3/ha, with a reduction equal to 58.37%. Vineyards' maximum IWR equal 2977.96 m^3/ha, reduced by 18.75% (so reaching 2419.7 m^3/ha) in case of CDI and by 41.02% (equal to 1756.4 m^3/ha) in case of actual supplies. Vegetables' maximum requirements equal 1522.82 m^3/ha, and in case of CDI this value is reduced in some extent (8.87%), reaching 1387.77 m^3/ha, but farmers supply 1996.21 m^3/ha, with a surplus of 31.09%, for the reasons already explained.

Table 4.6: average values of annual IWR, requirements under CDI and actual volumes supplied, all expressed in m^3 per ha, for the province of Bari.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%
Full IWR	3755.70	100.00	1447.79	100.00	1613.91	100.00	2842.11	100.00
IWR with Kd	3344.51	89.05	888.12	61.34	1462.52	90.62	2316.32	81.50
Actual IWR	3085.64	82.16	598.06	41.31	1265.87	78.44	1624.34	57.15

Table 4.7: average values of annual IWR, requirements under CDI and actual volumes supplied, all expressed in m^3 per ha, for the province of Brindisi.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%
Full IWR	3246.19	100.00	1980.94	100.00	1619.86	100.00	2741.78	100.00
IWR with Kd	2896.97	89.24	1288.17	65.03	1451.56	89.61	2227.52	81.24
Actual IWR	2773.06	85.43	765.40	38.64	1795.97	110.87	1682.00	61.35

Table 4.8: average values of annual IWR, requirements under CDI and actual volumes supplied, all expressed in m^3 per ha, for the province of Foggia.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%
Full IWR	3648.82	100.00	1866.11	100.00	2215.52	100.00	3026.83	100.00
IWR with Kd	3247.77	89.01	1162.00	62.27	1998.77	90.22	2429.26	80.26
Actual IWR	3134.26	85.90	584.50	31.32	2603.11	117.49	1753.70	57.94

4.4.5 Average irrigation volumes (m^3/ha) for the different classes of crops in the province of Taranto.

Average values of annual IWR, requirements under CDI and effective volumes supplied, all expressed in m^3 per ha, for the province of Taranto are in table 4.10, page 61. The crop with the highest requirements is orchards, with 3279.87 m^3/ha as maximum requirements, reduced by 11.33% in case of CDI (2908.23 m^3/ha) and by 13.84% in case of actual supplies (2825.89 m^3/ha). The crop with the lowest requirements is olive, with 1888.9 m^3/ha as maximum requirements, reduced by 36.22% in case of CDI (1204.73 m^3/ha) and more than halved in case of actual supplies (60.18% of reduction, equal to 752.16 m^3/ha). A strong reduction (42.07%) is also applied by farmers to vineyards, which require maximum 3063.12 m^3/ha, 2436.91 m^3/ha in case of CDI, but receive 1774.51 m^3/ha. Vegetables do not suffer for very strong reductions: maximum IWR equal 1160.46 m^3/ha, with a reduction by 9.4% in case of CDI (1051.39 m^3/ha), while in case of actual supplies there is a surplus of 29.18% (1499.09 m^3/ha).

Table 4.9: average values of annual IWR, requirements under CDI and actual volumes supplied, all expressed in m^3 per ha, for the province of Lecce.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%
Full IWR	3371.86	100.00	1941.78	100.00	1522.82	100.00	2977.96	100.00
IWR with Kd	3009.74	89.26	1223.29	63.00	1387.77	91.13	2419.70	81.25
Actual IWR	3152.21	93.49	808.41	41.63	1996.21	131.09	1756.40	58.98

Table 4.10: average values of annual IWR, requirements under CDI and actual volumes supplied, all expressed in m^3 per ha, for the province of Taranto.

Crop	Orchards	%	Olives	%	Vegetables	%	Vineyards	%
Full IWR	3279.87	100.00	1888.90	100.00	1160.46	100.00	3063.12	100.00
IWR with Kd	2908.23	88.67	1204.73	63.78	1051.39	90.60	2436.91	79.56
Actual IWR	2825.89	86.16	752.16	39.82	1499.09	129.18	1774.51	57.93

Table 4.11: hectares occupied by the irrigated crops for each province of the Apulia region.

	Orchards	%	Olives	%	Vegetables	%	Vineyards	%	TOT	%
BARI	12013.73	13.15	35682.20	39.06	17900.67	19.60	25752.37	28.19	91348.97	100.00
BRINDISI	5326.25	12.82	12529.43	30.17	16637.25	40.06	7039.23	16.95	41532.16	100.00
FOGGIA	6607.61	4.75	21402.81	15.38	74460.95	53.52	36665.43	26.35	139136.80	100.00
LECCE	1684.53	2.21	41698.95	54.78	20363.54	26.75	12377.58	16.26	76124.60	100.00
TARANTO	13238.31	28.78	4706.44	10.23	7884.80	17.14	20168.98	43.85	45998.53	100.00
TOT	38870.43	9.86	116019.83	29.44	137247.21	34.82	102003.59	25.88	394141.06	100.00

4.5 Monthly distribution of crop irrigation water requirements for each province

The regional irrigation requirements have been also estimated month by month for each province of Apulia and have been expressed in Mm^3.
For all the provinces, the relevant irrigation demand starts in April to end in October, with more or less defined peaks during July – August.

Figure 4.4 (page 63) shows that, for the province of Bari, during the whole irrigation season, maximum needs stand always above requirements with controlled deficit irrigation and actual supplies. Peaks of requirements occur in July, with 76.94 Mm^3 for maximum IWR, 59.27 Mm^3 for IWR under CDI and 48.51 Mm^3 for actual supplies.

The province of Brindisi (figure 4.5, page 63) needs the lowest irrigation volumes among the provinces of the Region. From the beginning of the irrigation season up to May, requirements with CDI are less than maximum IWR and more than actual supplies. In June, farmers' supplies increase and stand over requirements with controlled water deficit, up to July, when actual supplies reach the peak of 24.72 Mm^3. Maximum IWR and requirements under CDI reach the peak in August, respectively of 28.28 Mm^3 and of 24.11 Mm^3, while actual supplies drop to 17.91 Mm^3.

Foggia is the province with the highest requirements of the Region, as shown in figure 4.6 (page 64). From the April to July, the trend shows a general increase in the requirements. From April to May, requirements under CDI are higher than the actual supplies, but less than maximum requirements. Between May and June, actual irrigation volumes exceed both those with deficits and the maximum IWR, but in July, they stand under the maximum IWR and reach the peak of 108.32 Mm^3, while maximum IWR reach the peak of 114.14 Mm^3 and demand under CDI reach the peak of 94.68 Mm^3. In August, trends decrease and farmers supply the lower irrigation volumes.

Figure 4.7 (page 64) shows the monthly trend of the IWR for the province of Lecce. Maximum IWR are never exceeded and reach a peak of 44.07 Mm^3 in July, that lasts till August. From April to May, farmers supply lower irrigation volumes than the requirements under CDI, but from June farmers increase the supplies up to reach a peak of 34.5 Mm^3 in July and then decrease. Irrigation water requirements under CDI increase of irrigation volumes from April and a peak of 36.62 Mm^3 in August.

The trends for the province of Taranto (figure 4.8, page 65) show that maximum IWR are never exceeded and reach the peak of 32.85 Mm^3 in July, coincident with the one of the actual supplies. From April to June, farmers supply lower irrigation volumes than IWR under CDI, then both increase up to July, when requirements under CDI reach the peak of 28.38 Mm^3.

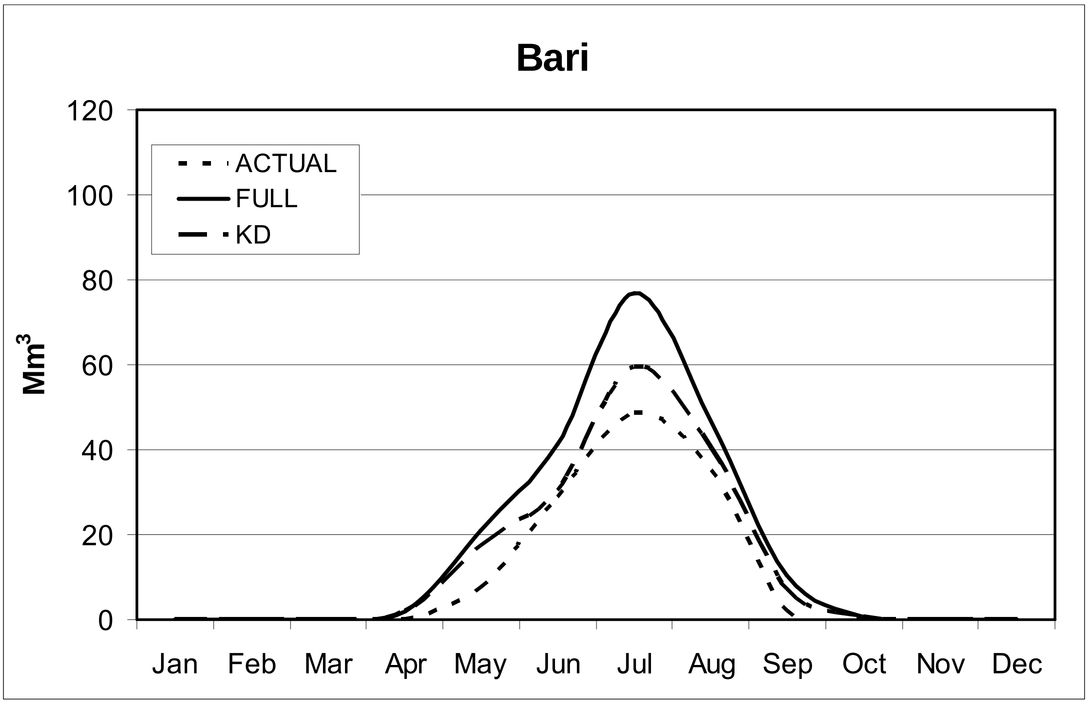

Fig. 4.4: monthly distribution of total maximum irrigation water requirements (“Full”), total requirements under controlled deficit irrigation (“Kd”) and total actual supply (“Actual”) for the province of Bari.

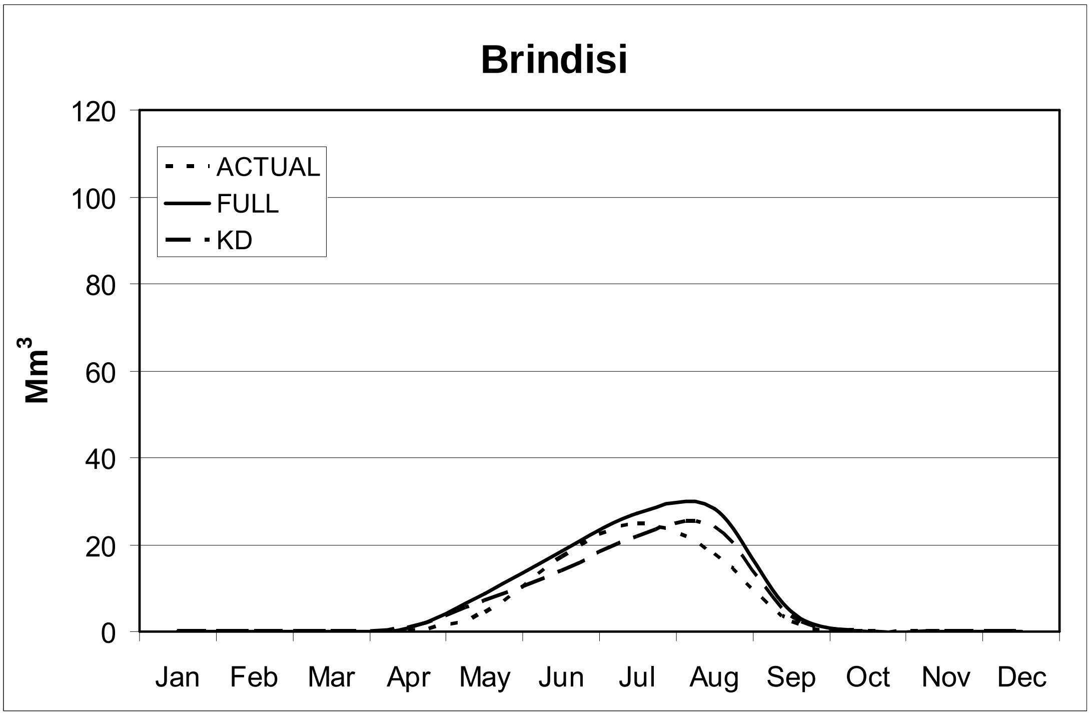

Fig. 4.5: monthly distribution of total maximum irrigation water requirements (“Full”), total requirements under controlled deficit irrigation (“Kd”) and total actual supply (“Actual”) for the province of Brindisi.

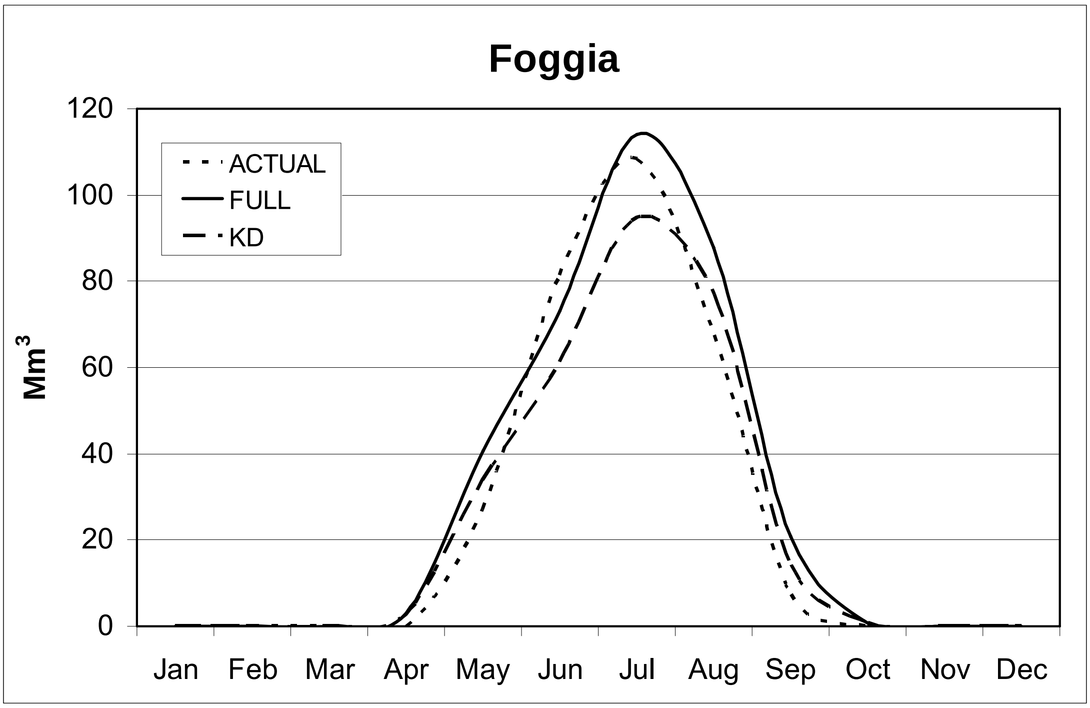

Fig. 4.6: monthly distribution of total maximum irrigation water requirements ("Full"), total requirements under controlled deficit irrigation ("Kd") and total actual supply ("Actual") for the province of Foggia.

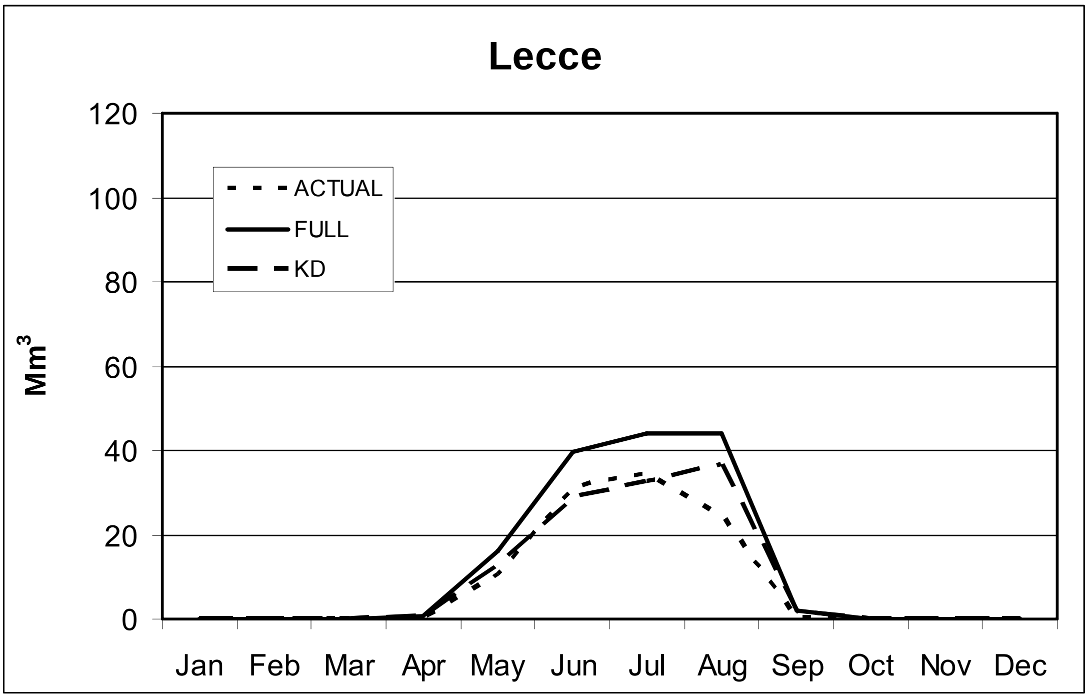

Fig. 4.7: monthly distribution of total maximum irrigation water requirements ("Full"), total requirements under controlled deficit irrigation ("Kd") and total actual supply ("Actual") for the province of Lecce.

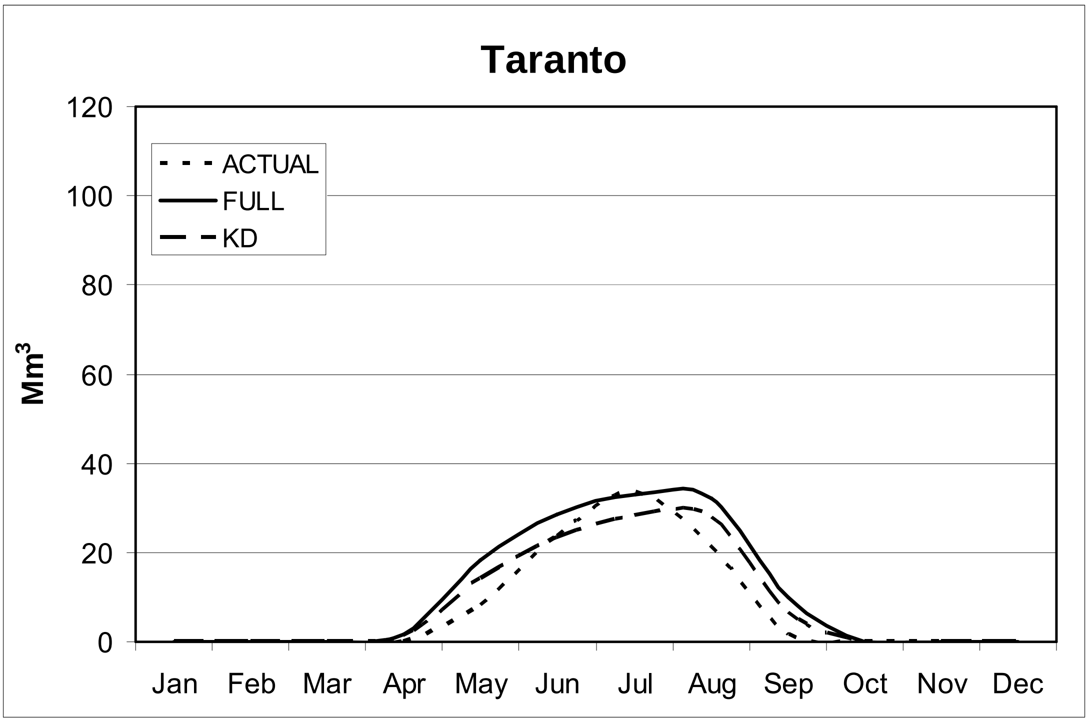

Fig. 4.8: monthly distribution of total maximum irrigation water requirements (“Full”), total requirements under controlled deficit irrigation (“Kd”) and total actual supply (“Actual”) for the province of Taranto.

Conclusions

The overview on the region through an analysis of the morphological, hydrographical, geological, climatic and land use features, provides a real and detailed vision of significant importance for any intervention on the territory. In particular, the assessment and quantification of crop irrigation water requirements in Apulia allow drawing conclusions on the water use in the regional agriculture.

Controlled deficit irrigation appears to be an effective strategy for water saving, despite the reductions applied by farmers on water volumes are more substantial. This occurs at the level of the whole region and for almost all the crops, except for some vegetables in some areas.
Farmers supply the irrigation volumes according to empirical considerations about the type of crops, physiological needs of crops, yield quality and economic aspects related to the maximization of profit and irrigation costs They prefer to give more water to spring – summer vegetables in most of the region, because they are more sensitive to water stress and are high-income crops (e.g. tomato and artichoke), to the detriment of other crops such as olives, which are less affected by periodic water stress.

The strategy of CDI allows the development of new irrigation scheduling, designed to ensure an optimal use of allocated water, taking into account economical and quality aspects of the yields.
The depletion coefficient K_d inserted in the calculations often influences more yield quality, but less yield quantity (stress in some crops promotes quality but reduces quantity, e.g. for wine grape and olive trees): this means that yield reduction may be small if compared with the benefits gained through diverting the saved water to irrigate other crops.

The results presented in this work demonstrate a static view, because an average year among an historical series of 41 years was considered, and the available data needed to carry on the work relate to this historical series, which stops at 1992. On the other hand, the regional context is rapidly changing, due to several reasons such as the apparent climate changes that are occurring, so it would be an update of data for calculating more accurate irrigation water requirements.

Moreover, this work does not allow a detailed analysis because the assessment of crop irrigation water requirements involves many variables, especially if it has been developed on a regional level, so approximations are needed in order to simplify the calculations.
This means also that some differences in the results and comparisons are attributable to the approximations in the calculation of ET_0, to the extension of management conditions of the irrigation schemes of the Reclamation Consortium of Capitanata to the entire region, and to the recruitment of

average values for the rooting depth, the crop coefficients and the depletion coefficients adopted.

The possibilities of optimize irrigation water use are influenced by what is technically possible and by the general rule of the economic feasibility. This study provides a generic idea of what are the irrigation needs and the effects of a reduction in the irrigation volumes supplied on a regional level, but it needs to be deepened and refined for a more complete and realistic evaluation, in order to provide useful informations that can be the basis for identifying the best response to any practical intervention for the optimization of regional water use.

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