

# Irr<sub>net</sub> estimation for maize and cotton in Piracicaba, São Paulo, Brazil

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**Abstract:** The aim of this work is to provide an easy methodology for the estimation of the Net Irrigation Water Requirements ( $I_{rnet}$ ) to be used in any developing country as first step in irrigation design. Two typical hot climate crops (maize - *Zea mays* - and cotton - *Gossypium hirsutum*), cultivated in the Piracicaba area, São Paulo (Brazil) have been studied. To estimate required data, different software were utilized. FAO software (*ET<sub>0</sub> Calculator 3.1* and *CROPWAT 8.0*) were adopted to compute Reference Evapotranspiration ( $ET_0$ ), Crop Water Requirements (CWR) and Net Irrigation Water Requirements ( $I_{rnet}$ ). RAINBOW (version 2.2) was used to examine the rainfall data from a statistical point of view in order to have a frequency analysis for the considered events. Daily climatic data for a twenty-year time period (January 1990 - December 2009) were analysed to calculate  $ET_0$ . These data were obtained from the Agro-meteorological Station of ESALQ (*Escola Superior de Agricultura "Luiz de Queiroz"*), USP (*Universidade de São Paulo*), Piracicaba. Three representative years for dry, normal and humid conditions were identified out of the twenty-year time period (1991-1992, 2000-2001, and 1996-1997 respectively) in order to reach a more complete level of analysis. For each of the three years and with reference to the two crops under analysis, CWR and  $I_{rnet}$  were computed.

Along the three representative years, effective rainfall proved to be always higher than CWR and well distributed during maize and cotton crop cycles. As a conclusion no relevant water stress (no yield reduction) have been noticed in the CROPWAT 8.0 outputs. It was then possible to affirm that no irrigation is needed for this kind of climate and soil conditions.

*Keywords: Net Irrigation Water Requirements; Zea mais; Gossypium hirsutum; Piracicaba.*

## Introduction

Water is fundamental in all human activities and agriculture represents one of the most important ones. The main source of food for the population of the world is

agriculture: about 90% of the present world population could not be sustained without agriculture (FAO, 2003). Agriculture is by far the largest consumer of water (FAO, 2007). It requires one thousand times more water than what we use to drink and one hundred times more than what we use to meet basic personal needs. Seventy percent of the water withdrawn from rivers and groundwater goes into irrigation (FAO, 2003).

Irrigation provides a powerful management tool against the vagaries of rainfall and makes it economically attractive to grow high-yield seed varieties and to apply adequate plant nutrition as well as pest control and other inputs, thus giving room for a boost in yields (FAO, 2003). Irrigation is fundamental in arid and semi-arid areas where, without artificial water application, it wouldn't be possible to sustain agricultural production. A sustainable water management contributes to guarantee a good quality production, both for direct consumption and market, generating economic surplus needed by the rural economies.

At present, around 20% of the world arable lands (277 million ha) are irrigated using about 2.000 to 2.500 km<sup>3</sup> per year, while rainfed agriculture is practiced on the remaining 80% of the world total cultivated land (1.260 million ha). Currently, almost 30 to 40% of the total amount of agricultural products comes from 20% irrigated lands; moreover, it has been predicted that, in the next 30 years, 80% of the total worldwide food availability will come from irrigated lands. These numbers demonstrate that irrigated agriculture has had, and will continue to have, an important role to play both in the provision of the world's food supply and beyond (FAO, 2007). The developed countries account for a quarter of the world's irrigated area (67 million ha). Their annual growth of irrigated area reached a peak of 3% in the 1970s and dropped to only 0.2% in the 1990s. The population of this group of countries is growing slowly and therefore a very slow growth in their demand and production of agricultural commodities is foreseen. The expansion of irrigation is projected to be strongest in South Asia, East Asia and Near East and North Africa (FAO, 2003). Even though it's a small growth race if compared with the one recorded in the 1990s, it's predictable that - especially at local and regional level - the water crisis will become serious, reducing agricultural productivity. Water withdrawals are predicted to increase by 50% by 2025 in developing countries, and 18% in developed countries (UNEP, 2007).

Especially due to insufficient and, sometimes, non-existent irrigation planning and scheduling, in the agricultural sector it is very common to have water wastes. A substantial change in the present water management is needed. Irrigation is a fundamental tool to improve agricultural production but, at the same time, it utilizes a great amount of fresh water. The volume of fresh water extracted is considerably greater than the consumptive use for irrigation because of conveyance losses from the withdrawal site to the plant root zone. Water use efficiency is an indicator often used

to express the level of performance of irrigation systems from the source to the crop (FAO, 2003). The improvement in agricultural water management will play a key role in the predictable fighting against water crisis. Improvement in water management or in water productivity means, frequently, to maximize the final production per unit of water consumed (“*more crop per drop*”). Farmers, being the ones paying more attention to profit, could aim for income maximization (“*more dollars per drop*”), and, however, local politicians could aim for more job opportunities and income due to agricultural sector (“*more jobs per drop*”) (FAO, 2003). Technology permits accurate water application in the optimum quantity and timing for crop development. Therefore, several economic benefits could be generated due to a growing agricultural productivity.

Speaking about improvements in water management and “water versus agriculture”, several topics could be discussed: 1. Developing of new approximations to the water consumption in the agricultural sector, trying to maximize water productivity, improve irrigation efficiency and utilize sustainable water sources; 2. developing of an economic water management, taking into consideration first of all less developed countries, often lacking in sustainable financial and economical strategies to prevent water shortages; 3. mitigation of the environmental impact of new systems and already existing ones (improvement of irrigation and drainage project management).

Even though developing countries use almost double quantity of water per ha if comparing with more developed countries, their agricultural production is low, due to high water losses and infrastructures lack. Moreover, it's important to focus on the basic problems of the stakeholders, trying to improve their knowledge and their capabilities, and involving all the community in the decision making phase. An increase in agricultural water use efficiency and a reduction in wastages represent a good strategy to prevent future water shortages; the introduction of more efficient technologies (such as, for example, new irrigation methods) it's an example even though, most of the times, due to financial and social problems, it is very hard to change production factors and techniques. At present time, most irrigation projects focus on the physical aspects of irrigated farming and are oblivious to the social context of the technology that they have introduced (Diemer, 1996).

Less efficient irrigation and drainage techniques could determine environmental problems (such as water pollution or desertification) and severe disadvantages to agriculture practice (such as waterlogging or salinization). Since rivers and lakes are polluted due to civil drains, ground water resources are especially polluted due to agricultural activities. Chemicals and fertilizers used by agricultures in their fields are responsible for this situation. Desertification and floods are two sides of the same medal<sup>1</sup>.

<sup>1</sup>According to the “*United Nation conference on Environment and Developing*” (Rio de Janeiro, 1992) desertification is “the arid, semi-arid and sub-humid lands degradation due to several causes, among which climate change and man's activities”.

The salinization of irrigation water leads up to a decrease in agricultural productivity especially in arid and semi-arid areas, both in qualitative and quantitative terms. According to a WWF dossier (“*Drought in the Mediterranean - WWF policy proposals*”), agriculture uses too much water. Drought phenomena in the Mediterranean area, WWF admits, “are going to be more and more frequent and serious: a lot of them, are going to worsen due to irrigation practice”.

Irrigation water management in an era of water scarcity will have to be carried out more efficiently, aiming at saving water and maximizing its productivity. Both implementation and development of new irrigation techniques and proper irrigation scheduling and management, represents a challenge for present and future irrigation engineers. Higher irrigation efficiency represents just one strategy to prevent water shortages. It's important to focus on:

- *Rainwater harvesting techniques*. Precipitation water is often lost and not utilized due to lack of harvesting and storage systems. Especially in humid and sub-humid countries, implementation of such systems could: prevent crop damage during dry periods, increase yields of rainfed farming, combat desertification by fruit tree planting or agro-forestry, supply domestic water and drinking water for animals.
- *Farm water conservation*. The utilization of proper agronomic techniques in order to prevent water scarcity is fundamental: soil and vegetation management to control surface run-off, conservation tillage practices, mulching to limit water losses from the soil surface.
- *Improving water-use productivity in agriculture*. Especially in arid areas where deficit irrigation represents the only way to carry out agriculture, the maximization of water productivity and water-use efficiency are fundamental. Improving efficiency can be a slow and laborious process that requires system modernization, therefore upgrading the technological environment and the knowledge and capacity of irrigation operators.
- *Using wastewater for irrigation*. Reducing the pollution loads of water used by farms, industries and urban areas would enable much more of it to be re-used in irrigation. There are enormous potential benefits to be had from the use of wastewater for irrigation (FAO, 2000).

The objective of a proper irrigation schedule is to supply the right amount of water before harmful stress occurs (optimum quantity and timing). It's very important to define a precise strategy when designing an irrigation system. Knowing the crop water requirements enables to determine the proper irrigation schedule at any given time; irrigation managers need to calculate the best time to irrigate, and how much water to use so that crops are produced economically, and water resources are managed in a sustainable manner. The calculation of seasonal and peak project supply required for a given cropping pattern and intensity includes the net irrigation requirements (I<sub>net</sub>) and other water needs including leaching of salts and efficiency of the

distribution system. Irrigation requirement is one of the principal parameters for the planning, design and operation of irrigation and water resources systems. Detailed knowledge of the  $Irr_{net}$  and its temporal and spatial variability is essential for assessing the adequacy of water resources, for evaluating the need of storage reservoirs and for the determining the capacity of irrigation systems. It is a parameter of prime importance in formulating the policy for optimal allocation of water resources as well as in decision-making in the day-to-day operation and management of irrigation systems (FAO, 2002). Simulation models, information systems and decision support systems can be relevant to support farmer's selection of water-use options, including crop patterns and irrigation systems, and to implement appropriate irrigation scheduling. FAO software, such as *CROPWAT*, *ETo Calculator* or *AquaCrop*, are nowadays widely used to calculate crop water requirements and irrigation requirements and to develop irrigation schedules for different management conditions (FAO, 1992).

## Materials and Methods

### Definitions

*Evapotranspiration* (ET, normally expressed in mm/day) is the combination of two separate processes: evaporation (water lost from the soil surface) and transpiration (water lost from the crop). Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. When the crop is small, water is predominately lost by soil evaporation (at sowing, nearly 100% of ET comes from evaporation), but once the crop is well developed and completely covers the soil, transpiration becomes the main process (FAO, 1998). Weather parameters, crop characteristics, management and environmental aspects are factors influencing evaporation and transpiration.

The evaporation power of the atmosphere is expressed by the reference crop evapotranspiration ( $ET_0$ ).  $ET_0$  (expressed in mm/day) is defined as “*the evapotranspiration rate from a reference surface, not short of water; the reference surface is a hypothetical grass reference crop with specific characteristics*”<sup>2</sup>. The principal weather parameters influencing evapotranspiration are radiation, air temperature, humidity and wind speed. A large number of empirical or semi-empirical equations have been developed for assessing reference crop evapotranspiration from meteorological data.

<sup>2</sup>The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as  $ET_0$ . The reference surface is a hypothetical grass with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m<sup>-1</sup> and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground (FAO, 1998).

Numerous researchers have analysed the performance of the various calculation methods for different locations. As a result of an Expert Consultation held in May 1990, the FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the  $ET_0$  (FAO, 1998). For daily, weekly, ten-day or monthly calculations, the FAO Penman-Monteith equation requires:

- *Site location*: altitude above sea level, latitude and longitude;
- *Air temperature* (°C): maximum and minimum temperatures or mean temperature;
- *Air humidity* (%): maximum and minimum or mean relative humidity;
- *Radiation* (MJ/m<sup>2</sup>/day or hours/day): net radiation or actual duration of bright sunshine;
- *Wind speed* (m/s): wind speed in metre per second.

All meteorological data can be estimated using agro-meteorological stations; these stations are commonly located in cropped areas where instruments are exposed to atmospheric conditions similar to those for the surrounding fields. In these stations, air temperature and humidity, wind speed and sunshine duration are typically measured at 2 m above an extensive surface of grass or short crop. Where needed and feasible, the cover of the station is irrigated (FAO, 1998). Calculations of  $ET_0$  are often computerized. Many software packages use the FAO Penman-Monteith equation to assess  $ET_0$ : nowadays, FAO *ET<sub>0</sub> Calculator* and *CROPWAT* are largely used. The selection of the time step with which  $ET_0$  is calculated depends on the purpose of the calculation, the accuracy required and the time step of the climatic data available. In this work, daily time step has been utilized.

Crop Water Requirements (CWR) are defined as “*the depth of water needed to meet the water loss through evapotranspiration of a crop, being disease-free, growing in large fields under non restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment*” (FAO, 1984). The water requirements of each crop are calculated taking into consideration the evapotranspiration rate; this depends mainly on climate, but also on growing season and crop development (FAO, 1977).  $ET_c$  is the sum of transpiration by the crop and evaporation from the soil surface. Prediction methods for CWR are used owing to the difficulty of obtaining accurate field measurements. The methods often need to be applied under climatic and agronomic conditions very different from those under which they were originally developed.

To estimate  $ET_c$  a three-stage procedure is recommended (FAO, 1977):

- Effect of climate on crop water requirements is given by  $ET_0$ ;
- Effect of the crop characteristics on CWR is given by the crop coefficient ( $K_c$ ), which represents the relationship between reference ( $ET_0$ ) and crop evapotranspiration under standard condition ( $ET_c$ ). Values of  $K_c$  vary with the crop; the main factors affecting its values are crop characteristics, crop planting or sowing date, rate of crop development and length of growing season;

- Effect of local conditions and agricultural practices on CWR includes the local effect of variations in climate over time, distance and altitude, size of fields, advection, soil water availability, salinity, irrigation and cultivation methods, for which local field data are required.

$ET_{cadj}$  represent the crop evapotranspiration under non-standard condition, and depends on weather parameters, crop characteristics, management and environmental factors. Also in this case, prediction methods have been developed for  $ET_{cadj}$  quantification, which can be calculated multiplying  $ET_c$  by  $K_s$  (water stress coefficient).  $K_s$  describes the effect of water stress on crop transpiration. According to FAO,  $p$  factor (critical depletion coefficient, due to water stress conditions) is the average fraction of Total Available Water (TAW; the amount of water that a crop can extract from its root zone, varying depending on soil moisture content) that can be depleted in order to have no crop water stress. By multiplying TAW by  $p$  factor, it is possible to obtain the readily available water (RAW; the fraction of TAW that a crop can extract from the root zone without suffering water stress).  $K_s$  is equal to 1 ( $ET_c = ET_{cadj}$ ) when the soil water content is within the RAW, while  $K_s$  is lower than 1 ( $ET_c > ET_{cadj}$ ) when the soil water content drops below the  $p$  fraction, reaching 0 when the soil water content is at Permanent Wilting Point.

The Net Irrigation Requirements of the crop ( $Ir_{net}$ ), defined as “*the amount of irrigation water that needs to be supplied to the crop to compensate all evapotranspiration losses*” (FAO, 2002), are calculated using the soil water balance, which includes crop evapotranspiration, effective rainfall, groundwater contribution, stored soil water at the beginning of each period and leaching requirements:

$$Ir_{net} = ET_c - (Pe + Ge + Wb) + LR$$

where:  $Ir_{net}$  = Net irrigation requirement (mm);  $ET_c$  = Crop evapotranspiration (mm);  $Pe$  = Effective dependable rainfall (mm): not all dependable rainfall is effective and some may be lost through surface runoff, deep percolation or evaporation. Only a part of the rainfall can be effectively used by the crop, depending on its root zone depth and the soil storage capacity. Different methods exist to estimate the effective rainfall but, one of the most commonly used is the USDA Soil Conservation Service Method;  $Ge$  = Groundwater contribution from water table (mm): the contribution of the groundwater table to the soil water balance varies with the depth of the water table below the root zone, the soil type and the water content in the root zone (FAO, 2002);  $Wb$  = Water stored in the soil at the beginning of each period (mm): some water could be left in the soil from the previous irrigation or rainfall event, which can be used for the next crop. This amount can be deducted when determining the seasonal irrigation requirements;  $LR$  = Leaching requirement (mm): an excess amount of water is applied during the irrigation, where necessary, for the purposes of leaching.

If irrigation is the sole source of water supply for the plant, the gross irrigation

requirements will always be greater than the ET<sub>c</sub> to allow for inefficiencies in the irrigation system. If the crop receives some of its water from other sources (rainfall, water stored in the ground, underground seepage, etc.), then the irrigation requirement can be considerably less than the CWR (FAO, 2002).

### **Software**

*ET<sub>o</sub> Calculator* is a software developed by the Land and Water Division of FAO. Its main function is to calculate ET<sub>o</sub> according to FAO standards. ET<sub>o</sub> Calculator is meant as a practical tool to help agro-meteorologists, agronomists, and irrigation engineers to carry out standard calculations for ET<sub>o</sub>, to be later used in crop water use studies. ET<sub>o</sub> Calculator version 3.1, issued in January 2009, is written in Borland DELPHI and runs in the DOS environment. The ET<sub>o</sub> Calculator assesses ET<sub>o</sub> from meteorological data by means of the FAO Penman-Monteith equation. This method has been selected by FAO as the reference because it closely approximates grass ET<sub>o</sub> at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters. The program can handle daily, ten-day and monthly climatic data. When data for some weather variables are missing, procedures are used for estimating missing climatic data from temperature data or from specific climatic conditions according to methodologies outlined in the Irrigation and Drainage Paper No 56: “*Crop Evapotranspiration - Guidelines for computing crop water requirements*” (FAO, 1998). Even where the dataset contains only maximum and minimum air temperature, it is still possible to obtain reasonable estimates for ten-day or monthly ET<sub>o</sub>. By selecting appropriate lower and upper limits for meteorological data, the program applies a quality check when specifying or importing data.

*RAINBOW 2.2* (released in March 2006) is a simple software package elaborated by the Interuniversity programme in Water Resources Engineering (K. U. Leuven University, Iupware, Belgium), designed for analysing climate and hydrological data and, for analysing their frequency and testing their homogeneity. The software can estimate the magnitude and the return period of each selected hydrological or meteorological event. Such estimates are obtained by means of a frequency analysis on historical data. For hydrologic purposes, typically historical time series of meteorological and hydrological data are analysed to determine design rainfall depths, evapotranspiration levels, floods, etc that can occur with a selected probability. The total rainfall received in a given period at a particular location is highly variable from one year to another. The variability depends on the type of climate and the length of the considered period. In a frequency analysis estimates of the probability of occurrence of future rainfall events are based on the analysis of historical rainfall records. Frequency analysis of data requires that the data be homogeneous and independent. By assuming that the past and future data sets are stationary and have

no apparent trend one may expect that future time series will reveal frequency distributions similar to the observed one. It is obvious that the longer the data series the more similar the frequency distribution will be to the probability distribution. After the creation of a data set, an analysis on the data is performed. When opting for a frequency analysis, a menu is opened. It contains various folders where a probability distribution can be selected, the data transformed, and results can be viewed or saved on disk. Apart from graphical methods for evaluating the goodness of fit, RAINBOW offers also statistical tests for investigating whether data follow a certain distribution.

CROPWAT 8.0 for Windows is a decision support tool developed by the Land and Water Development Division of FAO for the calculation of CWR and Ir<sub>net</sub> based on soil, climate and crop data. The computer program allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying crop patterns. All calculation procedures used in CROPWAT 8.0 are based on two FAO publications of the Irrigation and Drainage Series, namely, No. 33 titled “Yield response to water” (FAO, 1979) and No. 56 “Crop Evapotranspiration - Guidelines for computing crop water requirements” (FAO, 1998). The development of irrigation schedules in CROPWAT 8.0 is based on a daily soil-water balance using various user-defined options for water supply and irrigation management conditions. In order to run properly, CROPWAT 8.0 need some data inputs, namely: climatic and rainfall data, crop characteristics and soil features. As a starting point, and only to be used when local data are not available, CROPWAT 8.0 includes standard crop and soil data. When local data are available, these data files can be easily modified or new ones can be created. Likewise, if local climatic data are not available, these can be obtained for over 5,000 stations worldwide from CLIMWAT, the associated climatic database. After all inputs have been correctly introduced, the software gives some important outputs, such as reference evapotranspiration, effective rainfall, net and gross irrigation requirements<sup>3</sup>. After CRW has been calculated, CROPWAT 8.0 can simulate different types of irrigation scheduling, mainly depending on the user desired option: by changing the *Irrigation timing* (irrigate at critical depletion, irrigate at user defined intervals, irrigate at given yield reduction, etc..) and *Irrigation application* (fixed application depth, refill soil to

<sup>3</sup>Apart from a completely redesigned user interface, CROPWAT 8.0 for Windows includes a host of updated and new features, including: monthly, decade and daily input of climatic data for calculation of ET<sub>0</sub>; decade and daily calculation of crop water requirements based on updated calculation algorithms including adjustment of crop-coefficient values; interactive user adjustable irrigation schedules; daily soil water balance output tables; easy saving and retrieval of sessions and of user-defined irrigation schedules; graphical presentations of input data, crop water requirements and irrigation schedules; easy import/export of data and graphics through clipboard or ASCII text files; extensive printing routines, supporting all windows-based printers; multilingual interface and help system: English, Spanish, French and Russian.

field capacity, etc..) the user can find the more suitable irrigation scheduling for the specific situation.

### ***Meteorological station***

The ESALQ (*Escola Superior de Agricultura “Luiz de Queiros”; Universidade de São Paulo*) meteorological station is located in Piracicaba, São Paulo State, Federative Republic of Brazil. Geographical coordinates are: Latitude 22°42’30” S, Longitude 47°38’30” W, Altitude 546m.

The geographic profile of the State of São Paulo can be divided in three zones: a narrow coastal zone, an abrupt mountain chain (*Serra do Mar*) and the interior plateau. At *Serra do Mar*, altitudes vary between 800 and 1.100 m. The plateau has three distinct sections: the area surrounding *Serra do Mar* has a basement of granitic rocks, a profound valley (about 200 m deep) called *Depressão Interior* (separating two neighbors plateaus) and the occidental plateau (*Planalto Ocidental*), which covers about half of the State. The Tropic of Capricorn passes right over the city of São Paulo; climate of the State is tropical, with some variations caused by altitude. Along the coastline, average temperature is 20°C, and precipitations are over 2.000 mm, with rains well distributed along the year. The western plateau has the same average temperature, but precipitations are between 1.000 and 1.250 mm. In the areas of higher altitude (*Serra do Mar* and surroundings, which includes the city of São Paulo), temperature is slightly lower (yearly average of 18°C), and precipitation are between 1.250 and 2.000 mm.

Most rivers of São Paulo are tributaries of the *Paraná* river. Two important rivers flow to the ocean. The *Ribeira do Iguape*, in the south, brings fertility to an otherwise very poor area. The *Paraíba do Sul* flows into Rio de Janeiro before reaching the sea; the areas around this river were the first to receive coffee, because of the combination of: proximity with Rio, fertile soils and navigability of the river. *Tietê* and *Paraíba do*



Figure 1 - São Paulo State and Piracicaba.

*Sul*, the two rivers with more cities on their banks, are highly polluted.

Piracicaba (“*place where the fish stops*”, according to the traditional *Tupi* language) is a city located in the State of São Paulo, in the *Planalto Ocidental* area. The population in 2008 was 365.440 in an area of 1.371km<sup>2</sup>, that makes it the 19<sup>th</sup> city in the State of São Paulo. The city elevation is 547 m above sea level. The city houses the oldest agricultural faculty in Brazil, the *Escola Superior de Agricultura Luiz de Queiroz* (ESALQ) of the University of São Paulo.

The conventional station was built in 1917. Measurements (rainfall and air temperature) started in the same year. In 1926, sunshine started to be measured and, from 1943, also wind speed, air relative humidity and atmospheric pressure. Global solar radiation and liquid radiation started to be measured in 1929, while evaporation and evapotranspiration in 1943. The automatic station (CR10X and 21X models) was built later. Measurements started in 1997. The station is constituted by sensors linked to a datalogger, registering the different agro-meteorological variables. Currently, the station is provided with sensors measuring: precipitation, temperature, relative humidity, solar radiation, evapotranspiration, wind speed and direction. The measurements are stored in a memory card and then transferred to a personal computer using a serial cable.

### **Representative soil characteristics**

Utilizing the *Mapa dos Solos do Brasil* (2001), elaborated by IBGE (*Instituto Brasileiro de Geografia e Estatística*) and EMBRAPA (*Empresa Brasileira de Pesquisa Agropecuária*), it has been noticed that the most representative soils of the studied area are *Latossolos Vermelhos* - according to the “Brazilian Soil Classification” (EMBRAPA) - or *Ferralsols* - according to the FAO World reference base for soil resources 2006. Ferralsols represent the classical, deeply weathered, red or yellow soils of the humid tropics (FAO, 2006).

The soils have diffuse horizon boundaries, a clay assemblage dominated by low-activity clays (mainly kaolinite) and a high content of sesquioxides. Since clay is the dominant component, the available water holding capacity (AWHC) is high (between 150 mm/m for a clay loam soil up to 210 mm/m for a clay soil)<sup>4</sup>. On the other hand,

<sup>4</sup> When a soil has been wetted, then allowed draining by gravity for a specified period of time (usually one or two days depending on soil structure) the soil is said to be at field capacity (FC). When plants can no longer extract water from the soil profile, the permanent wilting point (PWP) has been reached. The available water holding capacity (AWHC) of a soil is the amount of moisture a soil stores between field capacity (FC) and permanent wilting point (PWP). The total available water (TAW) is the amount of soil moisture from FC to oven dried and includes the soil moisture that is not available to plants. In order to improve water use efficiency, it is important to consider the readily available water (RAW) i.e. water that can be readily removed from the soil by the plants. RAW is expressed in mm/m and indicates the depth of water (mm) held in every metre (m) of soil depth that can be readily removed by the plants. For practical purposes, RAW is commonly 2/3 TAW.

the infiltration rate is quite low if compared with loam or sandy soils (2.5 mm/h for a clay soil and 7.6 mm/h for a light clay)<sup>5</sup>.

The worldwide extent of Ferralsols is estimated at some 750 million ha, almost exclusively in the humid tropics on the continental shields of South America (Brazil) and Africa (Democratic Republic of Congo, southern Central African Republic, Angola, Guinea and eastern Madagascar) (FAO, 2006). Most Ferralsols have good physical properties. Great soil depth, good permeability and stable microstructure make Ferralsols less susceptible to erosion than most other intensely weathered tropical soils. Moist Ferralsols are friable and easy to work.

The chemical fertility is poor; weatherable minerals are scarce and cation retention by the mineral soil fraction is weak. Maintaining soil fertility by manuring, mulching and/or adequate agroforestry practices, and prevention of soil erosion are important management requirements (FAO, 2006). Fixation of P is a characteristic problem of Ferralsols that are normally low in N, K, secondary nutrients such as Ca and Mg, and some 20 micronutrients. Liming is a means of raising the pH value of the rooted surface soil; it also combats Al toxicity and raises the ECEC (FAO, 2006).

### **Crops**

Maize and cotton are two of the most important cash crops worldwide cultivated. They represent an important source of income both for substantial farming and big agricultural enterprises. In Brazil, both crops are widely cultivated in almost every region, even though, due to more favourable environmental conditions, the most important areas for cultivation are situated in the southern part of the country (São Paulo and Paraná states have the biggest maize production). Within the Brazilian economy, in 2007 maize reached the 3<sup>rd</sup> place while cotton (cottonseed) reached the 15<sup>th</sup>. In Brazil, irrigated cotton recently started to gain importance, especially in those areas in which rainfall is not enough to satisfy crop water requirements; the main used irrigation methods are surface and sprinkler but, drip irrigation is in expansion phase (Embrapa). In Brazil, the total harvested irrigated area in 1998 was 2.224.000 ha (Aquastat data).

Maize (*Zea mais* L.) originates in the Andean region of Central America. Present world production is about 822 million tons grain from about 162 million ha. In 2007, the maize cultivated area in Brazil reached 13 million ha. The estimated yield was 4 ton/ha (FAOSTAT, 2007). Widely cultivated in all Brazilian states, maize is utilized both for human (15%) and animal consumption (between 70 and 80%) (Embrapa data).

<sup>5</sup> The rate that water can enter the soil is called the infiltration rate of a soil. This parameter is influenced both by soil texture and soil structure. In order to avoid water losses, with pressurized irrigation systems, the rate water is applied must not exceed the soil's infiltration rate.

Generally speaking, maize is grown in climates ranging from temperate to tropic. When mean daily temperatures during the growing season are greater than 20°C, early grain varieties take 80 to 110 days and medium varieties 110 to 140 days to mature. In the present work, a medium grain variety with a 140 days cycle has been considered since, according to Embrapa, the *Grupo II* (in the classification of maize conventional cultivars), i.e. the ones with a crop cycle between 110 and 145 days, is the most cultivated one. The crop is very sensitive to frost, particularly in the seedling stage but it tolerates hot and dry atmospheric conditions so long as sufficient water is available to the plant and temperatures are below 45°C. In respect of day-length, maize is considered to be either a day-neutral or a short-day plant. Plant population varies from 20.000 to 30.000 plants per ha for the large late varieties to 50.000 to 80.000 for small early varieties. Spacing between rows varies between 0.6 and 1 m. Sowing depth is 5 to 7 cm with one or more seeds per sowing point.

The plant does well on most soils but less so on very heavy dense clay and very sandy soils. The soil should preferably be well-aerated and well-drained as the crop is susceptible to waterlogging. Maize is moderately sensitive to salinity. Yield decrease under increasing soil salinity is: 0% at ECe 1.7 mmhos/cm, 10% at 2.5, 25% at 3.8, 50% at 5.9 and 100% at ECe 10 mmhos/cm. The crop coefficient (Kc) is for the initial stage 0.30, mid-season stage 1.20 and at harvest 0.50 (Table 1). Yield response factor (Ky)<sup>6</sup> is for the initial stage 0.40, mid-season stage 1.30 and at harvest 0.50.

Being an indigenous crop to tropical environments, maize requires hot-humid climates; as a result, together with both heat and nitrogen, the third fundamental production factor is water (Tassinari, 1976). For maximum production, a medium maturity grain crop requires between 500 and 800 mm of water depending on climate. Maize appears relatively tolerant to water deficits during the vegetative and ripening periods. Greatest decrease in grain yields is caused by water deficits during the flowering period (Table 1). The effect of limited water on maize grain yield is

Table 1 - Maize main crop coefficients used for water management.

|                            | INITIAL | CROP DEVELOPMENT | MID-SEASON | LATE | TOTAL |
|----------------------------|---------|------------------|------------|------|-------|
| Stage Length (days)        | 25      | 40               | 40         | 35   | 140   |
| Depletion Coefficient (p)  | 0.50    | 0.50             | 0.50       | 0.80 | -     |
| Root Depth (m)             | 0.30    | >>               | >>         | 1.00 | -     |
| Crop Coefficient (Kc)      | 0.30    | >>               | 1.20       | 0.50 | -     |
| Yield Response Factor (Ky) | 0.40    | 0.40             | 1.30       | 0.50 | 1.25  |

(Source: FAO, 1998)

<sup>6</sup> Ky is a factor that describes the reduction in relative yield according to the reduction in ET<sub>c</sub> caused by soil water shortage. Ky are crop specific and may vary over the growing season. In general, the decrease in yield due to water deficit during the vegetative and ripening period is relative small if compared with the one during flowering and yield formation periods (FAO, 1998).

considerable and careful control of frequency and depth of irrigation is required to optimize yields under conditions of water shortage.

When evaporative conditions correspond to ET<sub>c</sub> of 5 to 6 mm/day, soil water depletion up to about 55% of available soil water has a small effect on yield ( $p = 0.55$ ). To enhance rapid and deep root growth a somewhat greater depletion during early growth periods can be advantageous. Depletion of 80% or more may be allowed during the late season (Table 1). Where rainfall is low and irrigation water supply is restricted, irrigation scheduling should be based on avoiding water deficits during the flowering period followed by yield formation period. Under conditions of marginal rainfall and limited irrigation water supply, the number of possible irrigation applications may vary between 2 and 5.

Cotton (*Gossypium hirsutum*) is the most important plant fibre and is grown both for fibre and seed. Present world production is about 65 million tons seed from about 32 million ha (FAOSTAT, 2008); Brazilian cottonseed production in 2008 has been 3.9 million tons, with a total cultivated area of 1 million ha and an estimated yield of 3.7 ton/ha. Since cotton is used especially for clothing, plantations require greater attention than some other traditional crops: cotton lint has to comply with certain quantity and especially quality standards in order to gain importance on the domestic and international markets; cotton cultivation is labour-intensive and the grower must have the necessary equipment and supplies in order to obtain a good quality product (Sément, 1988).

The development of the crop is sensitive to temperature. The crop is very sensitive to frost and a minimum of 200 frost-free days is required. The length of the total growing period is about 195 days (Table 2). In relation to reference evapotranspiration (ET<sub>0</sub>) K<sub>c</sub> for cotton is: for the initial stage 0.35, for the mid-season stage 1.20, and at harvest 0.7 (Table 2).

Cotton is a short-day plant but day-neutral varieties exist. However, the effect of day-length on flowering is influenced by temperature. Germination is optimum at temperatures of 18 to 30°C, with minimum of 14°C and maximum of 40°C. For early vegetative growth, temperature must exceed 20°C with 30°C as desirable. Cotton is extensively grown under rainfed conditions. Continuous rain during flowering and

Table 2 - Cotton main crop coefficients used for water management.

|   | INITIAL | CROP DEVELOPMENT | MID-SEASON | LATE | TOTAL |
|---|---------|------------------|------------|------|-------|
| Stage Length (days)                     | 30      | 50               | 60         | 55   | 195   |
| Depletion Coefficient (p)               | 0.60    | >>               | 0.60       | 0.90 | 0.65  |
| Root Depth (m)                          | 0.30    | >>               | >>         | 1.40 | -     |
| Crop Coefficient (K <sub>c</sub> )      | 0.35    | >>               | 1.20       | 0.70 | -     |
| Yield Response Factor (K <sub>y</sub> ) | 0.20    | 0.50             | -          | 0.25 | 0.85  |

(Source: FAO, 1998)

boll opening will impair pollination and reduce fibre quality. Heavy rainfall during flowering causes flower buds and young bolls to fall.

Cotton is grown on a wide range of soils but medium and heavy textured, deep soils with good water holding characteristics are preferred. Acid or dense sub-soils limit root penetration. The pH range is 5.5 to 8 with 7 to 8 regarded as optimum. Depending on climate and length of the total growing period, cotton needs some 700 to 1300 mm to meet its crop water requirements. In the early vegetative period, crop water requirements are low, or some 10% of total. They are high during the flowering period when leaf area is at its maximum, or some 50 to 60% of total. Later in the growing period the requirements decline.

Excess water early in the growing period will restrict root and crop development. Cotton requires adequate water supply particularly just prior and during bud formation. Continued water supply during flower opening and yield formation periods results in prolonged and excessive growth and yield. Abrupt changes in water supply will adversely affect growth and cause flower and boll shedding. Severe water deficits during flowering may fully halt growth, but with subsequent water supply crop growth recovers and flower formation is resumed.

Water supply for high production must be adjusted to the specific requirements of each growth period. Optimum use of available water supply can be made by fully wetting the entire root zone up to 1.40 m at sowing and with subsequent wetting of the upper part (0.50 to 1 m) of the root zone only. At sowing, adequate soil water should be available for germination and establishment. During the vegetative period, soil water content over the root depth of some 0.75 m should not fall below 60% depletion (Table 2); greater depletion of available soil water will restrict vegetative growth but when followed by ample supply, vegetative growth will be somewhat excessive, which may cause late flowering, boll shedding and reduced yield when the growing season is short. Cotton is grown under a great variety of irrigation methods of which furrow irrigation is the most common surface method.

## Results

### *Reference Evapotranspiration (ET<sub>0</sub>) estimation using available climatic data*

The first objective of this work is to estimate ET<sub>0</sub> in Piracicaba (State of São Paulo, Brazil). Daily climatic data for a twenty-year time period (January 1990 - December 2009) have been analysed<sup>7</sup>. All meteorological data have been obtained from the Agrometeorological Station of the ESALQ (*Escola Superior de Agricultura "Luiz de*

<sup>7</sup> Due to space constraints, it has not been possible to include all initial climatic data for the considered twenty-year time period.

Queiroz”). In order to estimate the ET<sub>0</sub> values over the twenty-year time period, FAO ET<sub>0</sub> Calculator version 3.1 has been utilized.

First, climatic data - namely: maximum and minimum air temperature (°C), wind speed (m/s), mean relative humidity (%) and hours of sunshine (h/d) - have been transferred from a Microsoft Excel sheet to a text file (\*.CXT extension); then, they have been stored in the “EToCalc/import” sub directory, in order to be read by the software. Once the file (PIRACICABA.CXT) has been selected, “Climatic station”, “Meteorological data” and “Climatic parameters” options have been filled in and the file has been imported, utilizing the “import” button. Finally, selecting the file from the database and running the model, it has been possible to estimate the daily ET<sub>0</sub> over the entire time period.

In general, according to obtained data analysis, the lowest ET<sub>0</sub> values are recorded between the 120<sup>th</sup> and 240<sup>th</sup> day of the year, corresponding to the winter period in the southern hemisphere. During that specific period of the year (approximately going from the end of April till the beginning of September), lowest air temperatures (minimum and maximum temperatures), global radiation and hours of sunshine values are reported. During the remaining months of the year, ET<sub>0</sub> is usually higher than 4 mm/day, mainly due to the effect of raising air temperatures and radiation.

Table 3 - ET<sub>0</sub> data analysis (1990-1999).

|                    | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 |
|--------------------|------|------|------|------|------|------|------|------|------|------|
| Max. value         | 7.7  | 8.0  | 6.9  | 7.3  | 7.4  | 7.3  | 7.2  | 7.1  | 7.2  | 7.4  |
| Min. value         | 1.2  | 0.9  | 0.9  | 0.9  | 1.0  | 0.9  | 0.8  | 0.9  | 1.0  | 0.9  |
| Mean value         | 4.2  | 4.0  | 3.7  | 3.7  | 4.1  | 3.8  | 3.8  | 3.7  | 3.5  | 3.8  |
| No. values > mean  | 171  | 164  | 165  | 160  | 165  | 164  | 161  | 177  | 179  | 171  |
| No. values < mean  | 189  | 196  | 194  | 190  | 187  | 191  | 195  | 180  | 183  | 185  |
| Standard deviation | 1.51 | 1.45 | 1.35 | 1.37 | 1.34 | 1.42 | 1.26 | 1.34 | 1.37 | 1.38 |
| Variance           | 2.28 | 2.11 | 1.81 | 1.88 | 1.79 | 2.02 | 1.60 | 1.80 | 1.87 | 1.91 |
| Mode               | 3.0  | 3.3  | 2.7  | 3.7  | 3.6  | 3.3  | 3.5  | 4.1  | 2.0  | 3.9  |

Table 4 - ET<sub>0</sub> data analysis (2000-2009).

|                    | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|--------------------|------|------|------|------|------|------|------|------|------|------|
| Max. value         | 7.3  | 8.0  | 7.4  | 7.8  | 8.3  | 6.5  | 7.3  | 7.0  | 7.0  | 6.9  |
| Min. value         | 1.0  | 1.0  | 1.0  | 0.9  | 0.7  | 1.1  | 0.9  | 0.8  | 0.9  | 1.0  |
| Mean value         | 3.8  | 3.9  | 3.9  | 3.6  | 3.5  | 3.5  | 3.6  | 3.7  | 3.7  | 3.6  |
| No. values > mean  | 174  | 180  | 179  | 169  | 175  | 166  | 171  | 179  | 175  | 172  |
| No. values < mean  | 183  | 181  | 173  | 191  | 186  | 187  | 187  | 179  | 185  | 185  |
| Standard deviation | 1.29 | 1.42 | 1.34 | 1.38 | 1.42 | 1.15 | 1.27 | 1.43 | 1.33 | 1.32 |
| Variance           | 1.66 | 2.02 | 1.80 | 1.91 | 2.02 | 1.33 | 1.60 | 2.05 | 1.77 | 1.74 |
| Mode               | 4.7  | 4.9  | 2.7  | 2.5  | 2.1  | 3.1  | 2.4  | 2.5  | 2.7  | 3.8  |

In tables 3 and 4,  $ET_o$  values along the twenty year period are summarized, taking into consideration specific statistical operations: maximum, minimum and mean values along the year, number of values over or under mean value, standard deviation and variance and, finally, mode.

### ***Crop Water Requirements (CWR) and Net Irrigation Water Requirements ( $Ir_{net}$ )***

In order to estimate the net irrigation requirements of a crop, all parameters for the field balance equation must be estimated. Using computer techniques, all variables can be combined in a water balance model. In this work, CROPWAT 8.0 has been used in order to estimate CWR and  $Ir_{net}$  of maize and cotton.

A frequency analysis of the precipitation data using the software package *RAINBOW* has been first performed. Rainfall values have been analysed starting from September, 1<sup>st</sup> of one year till August, 31<sup>st</sup> of subsequent year, in order to cover the entire crop cycle assumed to start on October, 1<sup>st</sup> for both maize and cotton (as discussed later). The Piracicaba.DAT file has been created, introducing the annual precipitation data relative to the analysed time period. Then, by clicking on the “*Frequency analysis*” button, it has been possible to observe the data relative frequency, the data probably of exceedance and the return period. Three representative years for dry (80% probability of exceedance), normal (50% probability of exceedance) and humid (less than 30% probability of exceedance) condition have been selected in order to achieve a more precise irrigation design along the entire twenty-year time period. Namely: 1991-1992 has been considered to be the representative dry year (997 mm total rainfall), 2000-2001 the representative normal year (1303.3 mm total rainfall) and 1996-1997 the representative humid year (1519.2 mm total rainfall) (Table 5).

Once selected the reference years and inputted all general required data, it has been possible to run CROPWAT 8.0 in order to calculate CWR and  $Ir_{net}$ . In the “*Climate/ETo*” window, 1991-1992, 2000-2001 and 1996-1997 daily climatic data (minimum and maximum temperature, humidity, wind speed and hours of sunshine) have been introduced. In the second window (“*Rain*”), total effective rain for the chosen representative years (884.5 mm in 1996-1997, 871.3 mm in 2000-2001 and 732.3 mm in 1991-1992) have been calculated using the USDA S.C. Method. In the

*Table 5 - Total amount of rain per year (mm).*

|    |         |         |         |         |         |         |         |         |         |         |
|----|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|    | 1990-91 | 1991-92 | 1992-93 | 1993-94 | 1994-95 | 1995-96 | 1996-97 | 1997-98 | 1998-99 | 1999-00 |
| mm | 1514.70 | 997.00  | 1561.90 | 1210.20 | 1678.50 | 1423.50 | 1519.20 | 1451.70 | 1595.10 | 1137.70 |
|    | 2000-01 | 2001-02 | 2002-03 | 2003-04 | 2004-05 | 2005-06 | 2006-07 | 2007-08 | 2008-09 | 2000-01 |
| mm | 1303.30 | 1601.40 | 1131.30 | 1205.00 | 1057.50 | 1078.50 | 1463.40 | 1467.20 | 973.20  | 1303.30 |

“Soil” window, soil type and characteristics have been selected: a heavy-clay soil from the FAO database (taking into consideration previous information about soil features), with different initial soil moisture depletion (depending on the analysed year) has been chosen for each simulation.

Since (as discussed later) October 1<sup>st</sup> has been chosen as planting date for both crops, it’s important to take into consideration soil moisture content and all hydrological parameters during that period of the respective year. In the last two weeks of September 1991, several rain events were recorder. As a result, soil moisture content at planting date can be reasonably assumed equal to FC and, for that reason, the initial soil moisture depletion has been set equal to 0% of TAW depletion. In 2000-2001, a different situation occurred: during the last two weeks of September, no strong rains were recorded (the last significant rain was recorded on September, 15<sup>th</sup> with 24.6 mm). As a result, 35% of TAW depletion was assumed. Finally, in 1996-1997, when rainfall in late September was higher than in September 2000 but lower than in September 1991, 15% of TAW depletion was selected.

Once climate/ET<sub>o</sub> data, rainfall data and soil data have been introduced into the CROPWAT 8.0 model, crop data are required to calculate crop water requirements (CWR) and net irrigation water requirements (Irr<sub>net</sub>).

## Maize

In the “Crop” window, “Maize” from FAO database has been selected. Characteristics of the variety in the local conditions have been described using values reported in Table 2. October, 1<sup>st</sup> has been selected as planting date, according to Embrapa information about maize cultivation in Brazil. Three CRW and Irr<sub>net</sub> simulations have been performed, selecting each of the three previously analysed dry (1991-1992), normal (2000-2001) and humid (1996-1997) years. After all input data have been introduced into the model, it has been possible to estimate CRW and Irr<sub>net</sub> values by clicking on “CWR” button.

It has been calculated that maize CWR for the specified time period was: 554.4 mm (in 1991-1992), 526.2 mm (in 2000-2001) and 476.7 mm (in 1996-1997). The Irr<sub>net</sub> was: 252.2 mm in 1991-1992 (332.6 mm effective rain), 96.7 mm in 2000-2001 (521.8 mm effective rain) and 98.6 mm in 1996-1997 (558 mm effective rain) (Table 6).

Table 6 - Maize crop water requirements and net irrigation requirements.

|                         | 1991-1992 | 2000-2001   | 1996-1997  |
|-------------------------|-----------|-------------|------------|
|                         | Dry year  | Normal year | Humid year |
| CWR (mm)                | 554.4     | 526.2       | 476.7      |
| Irr <sub>net</sub> (mm) | 252.2     | 96.7        | 98.6       |

Then, clicking on the “*Schedule*” button, a soil water balance under rainfed conditions was performed.

### ***1991-1992 (Representative dry year)***

During a representative dry year (997 mm of total rain and 732.3 mm of total effective rain, using the USDA S. C. Method), in rainfed condition, due to soil moisture depletion during two periods of the entire crop cycle (going from 55 to 75 and 100 to 125 days after planting) a yield reduction of 2.5% was simulated. The black line represents field capacity while green and brown lines represent soil total available moisture content (TAW) and readily available moisture content (RAW), respectively. Depletion bars (indicating the soil water deficit along the whole analysed crop cycle) were always far from permanent wilting point, and usually above the brown line representing RAW. Just during two periods of the whole crop cycle (from 55 to 75 and 100 to 125 days after planting), due to a lower precipitations rate, the depletion bars went under the readily available water line causing some limited water stress to the crop. In this situation, knowing the CROPWAT approximation level, a very small yield reduction was estimated; it means that this value could be neglected, and practically maize plantation still produces its maximum. The observed water stress during the crop cycle was practically absent and so, no irrigation (rainfed condition) is needed for this specific situation.

### ***2000-2001 (Representative normal year)***

During a representative normal year (1303.3 mm of total rain and 871.3 mm of total effective rain, using the USDA S. C. Method), effective rainfalls are enough to cover maize CWR during the entire 140 days crop cycle. In this specific climate and soil situation, depletion bars are always above the readily available moisture content line and, in some cases, very close to field capacity, indicating a high and constant soil moisture content during certain periods of the crop cycle (from 23 to 65, 76 to 90 and 120 to 140 days after planting almost no depletion is recorded). As a result of this non-limiting water condition, a yield reduction of 0% was estimated by the software. As a result, irrigation is not needed during the whole crop cycle.

### ***1996-1997 (Representative humid year)***

As for the previous case, during a humid year (1519.2 mm total rainfall while 884.5 mm effective rainfall) there is no need to irrigate maize plantation, since total effective rain is sufficient to cover the maize CWR during the whole cycle. During the entire growing period, depletion bars are always far above the brown line of RAW. It's then

clear that, during the first 35 days and from 110 to 125 days after planting, due to high precipitations, soil moisture content is always very high being very close to its maximum (field capacity). As a result, a yield reduction of 0% was estimated by the software.

Looking at the model simulation outputs, since no water stress (no yield reduction) was recorder in both three analysed situations, there is no need to design an irrigation system. From a statistical point of view, the design of an irrigation scheme in this climatic situation wouldn't be a good strategic and economical choice for farmers since, as it has been previously discussed, rainfall events entirely cover the maize CWR during the whole crop cycle.

### **Cotton**

The same procedure and steps used for maize have been followed in the case of cotton. As in the previous case, the first step consists of the introduction of all general input data into the model; then, in the "Crop" window, "Cotton" from FAO database has been selected. Crop characteristics and parameters in the local conditions have been described using values reported in Table 3.

As in the case of maize, October, 1<sup>st</sup> was selected as planting date. Then, by clicking on "CWR" button, CWR and  $Irr_{net}$  for representative dry, normal and humid conditions were estimated. Cotton CWR for the specified time period (going from planting date - October, 1<sup>st</sup> - till harvest - April, 13<sup>rd</sup>) were: 779 mm (1991-1992), 771.7 (2000-2001) and 739.8 (1996-1997);  $Irr_{net}$  was: 329.3mm in 1991-1992 (528.7 mm eff. rain), 207.9 mm in 2000-2001 (665.5 mm eff. rain) and 246.4 mm in 1996-1997 (647.7mm eff. rain).

The crop irrigation schedule for cotton has been arranged utilizing the "Schedule" button. As in the case of maize, a soil water balance under no irrigation (rainfed condition) has been simulated.

### **1991-1992 (Representative dry year)**

During a representative dry year (997 mm of total rain and 732.3 mm of total effective rain, using the USDA S. C. Method), in rainfed conditions, due to some soil

Table 7 - Cotton crop water requirements and net irrigation requirements.

|                  | 1991-1992 | 2000-2001   | 1996-1997  |
|------------------|-----------|-------------|------------|
|                  | Dry year  | Normal year | Humid year |
| CWR (mm)         | 779       | 771.7       | 739.8      |
| $Irr_{net}$ (mm) | 329.3     | 207.9       | 246.4      |

moisture depletion taking place during crop cycle (roughly from 140 to 150 days after planting) a yield reduction of 0.4% was simulated. Along the above mentioned deficit period, depletion bars went below the RAW brown line, determining (as in the case of maize) some yield reduction (due to a little water stress situation). As previously described for maize, such a small yield reduction could be easily neglected since, practically, cotton still produces at its maximum level. As a result, no irrigation is needed in this particular situation.

### ***2000-2001 (Representative normal year)***

As in the case of maize, during a representative normal year (1303.3 mm of total rain and 871.3 mm of total effective rain), since effective rainfall is enough to cover the cotton CWR during the entire crop cycle (665.5 mm effective rainfall during crop cycle), irrigation is not needed. It's clear that no water stress is recorded during the entire crop cycle, from planting date till harvest. Depletion bars are always far from readily available water line being, in some cases, very close to field capacity. Rains are well distributed along the crop cycle, ensuring high and almost constant soil moisture content and so, a perfect development of the crop. As a result, by selecting "No irrigation (*rainfed*)" as irrigation timing, a yield reduction of 0% is noticed.

### ***1996-1997 (Representative humid year)***

As expected, during a representative humid year (1519.2 mm total rainfall along the year and 647.7 mm effective rainfall during cotton crop cycle) irrigation is not needed. Along the entire crop cycle no soil moisture depletion is noticed; soil moisture content is nearly always close to field capacity, with the exception of the last part of the season (roughly from day 140 after planting till harvest) where water depletion is higher due to a lower precipitation rate.

## **Discussion and conclusions**

Water represents life. All human economic activities depend on this more and more scarce natural resource. Agriculture is the sector where water represents the main production factor. Agriculture is fundamental for life since is the main source of food for the world population; at the same time, is the largest consumer of water. Almost 70% of the water withdrawn from rivers and groundwater is used for irrigation. In a period where saving water represents a fundamental factor in order to maintain a proper level of population well being, the controlled water application in the agricultural sector plays a key part towards the growth and stabilization of agricultural productivity along the years. A sustainable water management contributes to

guarantee a good and more stable quality production. Improving irrigation efficiency is very important for farmers in order to have a more correct water use and, for that reason, before thinking about irrigation as alternative water source, they have to establish if irrigation is really needed or not in their specific environmental conditions. For this purpose, a preliminary analysis is very useful.

The planning stage of an irrigation project design actually implies a survey of all factors which could influence CWR (climate, soil and crop itself). Then CWR need to be compared with available water coming from the rain (effective rainfall) and from the soil (initial soil water available). In case of a water deficit, the technician can evaluate the possibility of introducing irrigation, assessing if the water source will be able to cope with all aspects of demand. This survey is of paramount importance in order to establish if irrigation is effectively needed or not. The first three parameters that have to be considered during a so described survey are: climate, soil and crop. If effective rainfall during the considered time period is enough to cover the entire crop cycle, soil infiltration rate and permeability are low and soil water holding capacity is high, irrigation system construction wouldn't be a necessary choice. This kind of situation is perfectly normal in the case of a tropical humid or sub-humid climate with a heavy soil, where both relative humidity and precipitation rate are high and often constant along the year. Frequently, where precipitations are high but not well distributed and therefore concentrated just in certain months of the year, farmers use to plant or transplant their crops in the period coinciding with the beginning of the rainy season. By doing so, they avoid using irrigation as alternative water source during the crop cycle, since all the amount of water they need for the proper cultivation of their crops comes from the rainfall events. That is the situation simulated and presented in this work.

The objective of the study was to assess the potential need of irrigation to achieve maximum production of maize and cotton in the Piracicaba area, State of São Paulo, Federal Republic of Brazil. The first step was to create a climate database allowing a good level of statistical accuracy; for this purpose, a twenty-year time period (January 1990 - December 2009) with daily data has been selected. During the considered twenty-year time period, in almost all cases, total rainfall is over 1.000 mm per year. It means that effective rainfall (computed utilizing the USDA S.C. Method) is around 800 mm. In order to better understand the local situation, three representative years (for dry, normal and humid conditions, according to the frequency statistics carried out with RAINBOW), have been selected from the twenty-year time database. The same three years have been utilized both for maize and cotton simulations in order that a more clear view about the specific water requirements was possible. During normal and humid representative years, effective rainfall was 871.3 mm and 884.5 mm respectively; in these situations, due to the great amount of water coming from rainfall events, was already clear at the beginning of the simulation that no irrigation

schedule could be planned. During dry representative year (year 1991-1992, more than 80% of exceedance according to RAINBOW frequency analysis) effective rainfall was less than in the previous cases, arousing a somehow different situation. In both maize and cotton cases, during the net irrigation requirements calculation in rainfed conditions, just a very small yield reduction has been simulated (0.4% in the case of cotton, while 2.5% in the case of maize). Knowing the CROPWAT approximation level, for practical purposes those values can be neglected and both crops can be assumed to produce at their maximum. Given that in rainfed conditions no water stress is practically observed along the entire crop cycle, we can affirm that no irrigation system is needed to be designed in such a specific climate and soil conditions.

In conclusion, since a successful design is a design which represents the future use that farmers will make of the scheme, if designing an irrigation system taking into consideration climatic data of a rare dry year, no use of the scheme will be done in the others, more common, normal or humid years. It would be of paramount importance both for technicians and farmers to carry out this kind of analysis before thinking about the possibility or not to design an irrigation system. This quite easy methodology gives the chance of knowing the real water needs of the chosen crops. In fact, if there's no need for irrigation and so the crops produce their maximum without using any other water source, the design of an irrigation scheme wouldn't give any benefit to the farmer. This analysis would be very important in developing countries where irrigation efficiency is still quite low. Moreover, in dry areas where saving water is fundamental for well being and life itself, it would represent a real benefit. This work proves that just utilizing simple user-friendly software is possible to access very important analysis, useful in order to improve irrigation efficiency and so to have a more correct agricultural water use.

## References

- ACIAR 2004. Water in Agriculture. Edited by: V. Seng, E. Craswell, S. Fukai and K. Fischer. Proceeding 116e. Canberra, Australia.
- Diemer G. and Huibers F.P. (ed.), 1996. Crop, people and irrigation, Intermediate Technology Publications, London, UK.
- FAO 1971. Water and the environment. By: M. Holý FAO Irrigation and Drainage Paper 8. Rome, Italy.
- FAO 1973. Man's influence on the hydrological cycle. By: UNESCO/FAO working group on the International Hydrological Decade Unesco. FAO Irrigation and Drainage Paper 17. Rome, Italy.
- FAO 1979. Yield Response to Water. By: J. Doorenbos and A.H. Kassam. FAO Irrigation and Drainage Paper 33. Rome, Italy.

- FAO 1984. Crop Water Requirements. By: J. Doorenbos and W.O. Pruitt. FAO Irrigation and Drainage Paper 24. Rome, Italy.
- FAO 1988. Irrigation methods. By: C. Brouwer. Irrigation Water Management - Training Manual 5. Rome, Italy.
- FAO 1992. CROPWAT - A computer program for irrigation planning and management. Developed by: M. Smith. FAO Irrigation and Drainage Paper 46. Rome, Italy.
- FAO 1998a. Crop evapotranspiration: Guidelines for computing crop water requirements. By: R. Allen, L. Pereira, D. Raes and M. Smith. FAO Irrigation and Drainage Paper 56. Rome, Italy.
- FAO 2000. Crops and Drops. Making the best use of water for agriculture. Land and Water Development Division. Rome.
- FAO 2002. Crop Water Requirements and Irrigation Scheduling. Developed by: A.P. Savva and K. Frenken. FAO Irrigation Manual Module 4. Harare, Zimbabwe.
- FAO 2006. World reference base for soil resources 2006. By: IUSS working group. World Soil Resources Reports 103. Rome, Italy.
- FAO 2007. Irrigation management transfer. Worldwide efforts and results. By C. Garces-Restrepo and D. Vermillion. FAO Technical Papers - Water Reports 32. Rome, Italy.
- FAO 2009. Aquacrop - The FAO crop model to simulate yield response to water. Developed by: D. Raes, P. Steduto, T. C. Hsiao and E. Fereres. Ag. Journal (in press).
- FAO 2009. ETo Calculator - Version 3.1. By: D. Raes. Rome, Italy.
- FAO 2010. AquaCrop - Version 3.1 Reference Manual – Chapter 2. By: D. Raes. Rome, Italy.
- Isendahl N. and Schmidt G., 2006. Drought in the Mediterranean: WWF policy proposal, WWF REPORT. Madrid, Spain.
- Sément G., 1988. Cotton. The Tropical Agriculturalist. Edited by: CTA Macmillan Publishers Ltd. London, UK.
- Tassinari G., 1976. Manuale dell'agronomo - V Edizione. Ed. REDA, edizioni per l'agricoltura. Torino, Italia.
- UNDP 2001. Poverty and the drylands. By: P. Dobie. Drylands Development Center. Nairobi, Kenya.
- UNEP 2007. Global Environment Outlook GEO4 environment for development. Edited by M. Schomaker, M. Keating and M. Chenje. Valletta, Malta.