UNIVERSITÀ DEGLI STUDI DI PADOVA

Facoltà di Ingegneria
Corso di Laurea Magistrale in Environmental Engineering
Dipartimento di Ingegneria Civile, Edile e Ambientale ICEA

MODELLING OF SOIL WATER DYNAMICS IN AN IRRIGATED CORN FIELD

Relatore:
Prof. Gianluca Botter

Correlatore:
Prof. Mario Putti

Laureando:
Gianandrea Lorenzin

A.A 2013-2014

Ai miei nonni

Contents

Chapter 1

Introduction

Irrigation and food production constitute one of the major uses of freshwater resources with about 3100 km^3 of annual water consumption. Agriculture accounts for around 70% of global freshwater withdrawals, reaching up to 90% in some fast-growing economies. About 40% of the total food production is relying on irrigated agriculture, which represents less than 20% of the total cultivated lands. Global population growth projections of 2 to 3 billion people over the next 40 years, combined with changing diets, result in a predicted increase in food demand of 70% by 2050 [*UN WATER, 2012*]. Responsible agriculture water management will make major contribution to future global environmental preservation and to securing human food needs.

Water management tightly depends on rainfall variability, which represents the primary source of uncertainty in quantifying the productivity and profitability of crop fields [*Vico and Porporato, 2011*]. When natural rainfall intermittency is too long, irrigation has the function of supplementing the soil water needs. Climatic conditions cannot be controlled or modified by humans in order to increase crop productivity, but a right water management may significantly increase the overall efficiency of irrigation and water productivity (crop yield per unit applied water). Micro-irrigation is one of the newest and most efficient irrigation scheme for water requirements minimization and water use efficiency but its installation and maintenance cost is very high compared to traditional irrigation schemes. Traditional irrigation schemes are the most diffuse worldwide and balance sustainability, yield and profitability with lower cost for farmers [*Vico and Porporato, 2011*].

Identifying the optimal irrigation strategies is not an easy task because of the multiplicity of variables involved: soil and vegetation features, climate characteristics, rainfall variability, water cost and crop sale price. Focusing on crop and soil properties, soil water content dynamics play a crucial role influencing most of relevant processes acting in the root zone, like partitioning of rainfall into infiltration and runoff as well as the partitioning of net radiation into sensible and latent heat [*Hupet and Vanclooster., 2002*]. In addition, soil moisture dynamics control the subsurface drainage of water and thereby losses by infiltration through deeper soil layers. In such environments rate of transpiration, carbon assimilation and biomass production are often limited by the soil water content during the plant growing season. In water-stressed conditions, plants undergo a state of limited transpiration which depends on the plant physiology and the local pedological and climate characteristics [*Porporato and D'Odorico, 2002*]. Water stress induces a negative impact on the plant's health and productivity.

Water management applied to agriculture activities, has the objective of minimize water losses through leaching and maximizing plant's carbon assimilation through an optimization of irrigation application. A proper knowledge of the processes which control soil water dynamics proves essential to achieve this target. Mathematical models can thus play a crucial role in the understanding of the dynamic interactions among climate, soil, water and vegetation [*Milly, 2001*]. In this study soil moisture dynamics in an irrigated maize field were monitored using six underground probes for the whole life of the plants. Probes were positioned at different depths into two separate sites: an Uninformed Site irrigated with traditional method and an Informed Site in which a water balance irrigation scheme was applied based on soil moisture measurements. A daily numerical model was implemented to quantify the different water balance terms (precipitations, evapotranspiration and leaching). The comparison between the two sites highlights soil moisture monitoring during agriculture activities leading to substantial savings in terms of water volumes requirements and money, without compromising the productivity of the crop field.

This thesis is organized as follows: soil moisture measurements method and TDR instruments functioning are described in the first chapter. Following chapters are dedicated to the model description and model results, water balance analysis and comparison. Finally some data on the water savings obtained and extrapolation to a larger regional scale is reported, in order to have a realistic projection of the benefits obtainable from large-scale soil water monitoring programs to support.

Chapter 2

Soil Moisture Measurements in an Irrigated Crop Field

Soil moisture measurements can provide important information about the proper amount of water to be provided at each irrigation application and the suitable timing at each application. Monitoring the soil water content dynamics of a crop field during the entire life of the plant from the sowing to the harvest can help the farmer to provide water to the field at the best moment and in right amount, in order to avoid water stress conditions and water losses. The soil moisture measurements were obtained using a Time Domain Reflectometry (TDR) which is described in the following sections.

2.1 Time Domain Reflectometry (TDR)

Time Domain Reflectometry is used in telecommunications to identify locations of discontinuities in cables, but it can be also applied for measuring soil moisture. TDR instrument is able to measure electrical conductivity. Soil moisture can be indirectly inferred from through the application of empirical relationships. The main advantage of TDR instrument over other measurement methods are the superior accuracy (1-2% in terms of volumetric water content), the minimal calibration requirements and the lack of radiation hazard associated to other techniques. The instrument is composed by a TDR electromagnetic wave-generator and six probes. Probes were assembled in the laboratory using PVC blocks, stainless steel rods, coaxial cable and epoxy resin. The chosen configuration of the utilized probes consists of with a single central conductor and two lateral conducting rods. The PVC block has been drilled in order to let the central part of the cable be in contact with the central rod and the two outer rods to be in contact with the outer part of the cable. Once the cable is inserted into the PVC block, the steel rods are placed in the correspondent holes. The central bar has a larger diameter (8mm versus 6mm). Since the bars will be positioned within a soil, all the holes were filled with epoxy resin. The correct functioning of the instrument was verified in laboratory before the positioning the probes in the field. One of the six resulting probes is reported in *Figure 2.1*:

Figure 2.1 Final probe configuration

The physical principle on which TDR techniques are based is the comparison between the reflection from the unknown transmission environment, obtained with an impulse sent from TDR through the probe's rods, and those produced by a standard impedance. Using probes of known length (L) embedded into the soil, the travel time for a TDR-generated electromagnetic wave to travel across the probe length can be determined. From the travel time analysis the bulk dielectric constant of soil is computed, and from it the volumetric water content is estimated. The bulk dielectric constant of soil (ε_b) is a function of the propagation velocity according to the following equation:

$$\varepsilon_b = \left(\frac{ct}{2L} \right)^2 \qquad (2.1)$$

Where *c* is the velocity of the electromagnetic waves in vacuum ($2 \cdot 10^8$ m/s) and *t* is the travel time for the pulse to travel the length of the embedded probe. The travel time is evaluated on the base of the apparent or electromagnetic length of the probe, which is characterized on the TDR output screen by diagnostic changes in the waveform. The dielectric constant simply stated that it is the ratio squared propagation velocity in vacuum relative to that observed in the medium. The soil bulk dielectric constant is governed by the dielectric constant of liquid water (ε_w = 81 at 20°C), as the dielectric constants of other soil constituents are typically much smaller (soil mineral ε_s= 3-5, frozen water ε_i=4, air ε_a=1). This large disparity of the dielectric constants makes the method relatively insensitive to soil composition and texture. [*Topp et al., 1980*] empirical relationship, was used to link the measured bulk dielectric constant of soil (ε_b) to volumetric water content (ϑ_v).

$$\vartheta_v = -5,31 \cdot 10^{-2} + 2,92 \cdot 10^{-2} \cdot \varepsilon_b - 5,51 \cdot 10^{-4} \cdot \varepsilon_b{}^2 + 4,31 \cdot 10^{-6} \cdot \varepsilon_b{}^3 \qquad (2.2)$$

This equation provides an adequate description for water content lower than 0,5, which covers the entire range of interest in most mineral soils. This because Topp obtained the third order polynomial relationship from experimental results on mineral soils with water content concentrated in range lower than 0,5. The estimation error is of about 0,013 for ϑ_v. Measurements of the dielectric constant and then of the volumetric water content can be influenced by several factors: soil porosity, bulk density, measurements frequencies, temperature and water status but they are negligible compared to the possible intrinsic errors due to calibration [*Quinones et al., 2003*].

2.2 Crop Field Description and Probes Positioning

The instruments has been installed in a maize field in Albettone, Vicenza, North-East Italy (11° 35' East – 45° 21' North). On 17 April 2013 the crop field was sowed with an hybrid corn sown (P1758) which is delivered by the brand Pioneer. Such maize belongs to class 700, according to a classification proposed by the FAO. This classification divides the different maize hybrids on the basis of their maturation period by assigning a label ranging from 100 (the most early) to 800 (the most late). Hence the value 700 stands for a late corn with a maturation period from 130 to 140 days (Nelly et al, 2013). P1758, in particular has an estimated maturation period of 132 days and it is considered to be one of the most productive corn (Pioneer Hi-Bred Italia). Moreover, Pioneer suggest a plant density of about 7-7,8 plants/m^2 to ensure the best productivity for grain maize. Therefore, in the corn field used in this study, plants are sown at a distance of 75cm in the longitudinal direction and 18cm in the transversal direction like shown in Figure *2.2*.

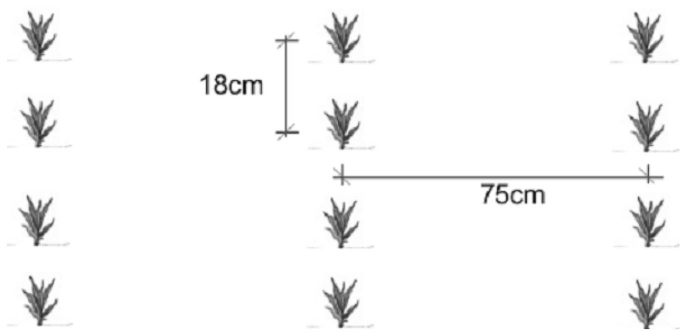


Figure 2.2 Plant disposition on field

The soil of the considered crop field has been analyzed by the Pioneer laboratory in autumn 2010 and the results in terms of grain size percentages show that it has a clay loam texture, as derived from the soil texture diagram based on USDA classification. Others soil properties will be discussed in *Chapter 3*.

Table 2.1 Soil granulometry

Soil Composition	Grain Size	Percentage (%)
Skeleton	ϕ > 2mm	Absent
Sand	2 mm < ϕ < 0,05 mm	24,7
Silt	0,05 mm < ϕ < 0,002 mm	44,5
Clay	ϕ < 0,002 mm	30,7

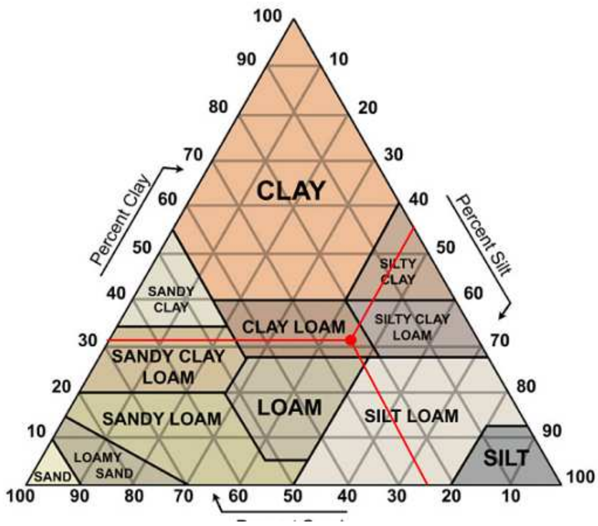


Figure 2.3 USDA soil classification diagram

On June 10 2013 the TDR instrument was placed in the maize filed. TDR instruments is provided with six probes that are subdivided into two groups: three of them (probes 4, 5 and 6) are placed in a field area in which traditional sprinkler irrigation is applied relying o the farmer experience (Uninformed Irrigation), while the other three probes (probes 1, 2 and 3) were positioned in a part of the field in which an informed water balance irrigation, which account for the available hydrologic measurements, is performed. In both sites the probes are positioned horizontally at three different depths (10cm, 20cm and 35cm) and in different planar locations to reduce mutual interferences as shown in *Figure 2.4* and *Figure 2.5*:

Figure 2.4 Position of probes in Informed Site (green spot) and Uninformed Site (yellow spot), TDR instrument (blue spot) and rain gauge (red spot)

Figure 2.5 Probes positioning operations

Probes 1 and 4 are the nearest to the ground surface, 2 and 5 are located at an intermediate depth while probes 3 and 6 are the deepest. The holes made to place the probes are progressively filled with the soil removed to drill the holes. Each probe is connected to the TDR with a 15m long cable, thus allowing the positioning of the two distinct groups at distance of about 30m from each other, hopefully enough to reduce the interferences between the two sites during irrigation operations. Between two sites there is a small altitude difference due to the crop field morphology which has a light curvature in order to facilitate the water flow to the side areas of he field, where ditches are located (*Figure 2.4*).

TDR instrument has a timer which was been set to acquire one measure every 2 hour and, during the irrigation applications, one measure every 15 minutes to better observe the soil water content response. The instrument output is, for each acquisition and each probe, a curve made by 255 points for a total of 8592 points during the whole acquisition period. The obtained curves were elaborated via a suitable Fortran code which calculates the electric conductivity, the bulk dielectric constant and the volumetric water content through equation (*2.2*).

2.3 Irrigation Technique Adopted

To irrigate the maize field a sprinkler irrigation technique was used. The sprinkler irrigation method consists in delivering water as an “artificial rainfall” over the crop. Water is applied through sprinklers that can be fixed, moving or distributed along moving bars. This kind of irrigation is suitable for many types of crops such as row, field and tree, but large sprinkler cannot be used for irrigate delicate crops. Each sprinkler distributes water through circular patterns in a non-uniform way, because rates decrease with the distances from the sprinkler. Today the sprinkler irrigation represents the most diffuse irrigation technique in Italy.

The major part of the maize field (Uninformed Site) was irrigated using a hose reel. This mobile machine has a large diffusion in irrigation application since the seventies and actually it is the main irrigation system used in Italy as it is used on about 80% of the 1 million hectares of sprinkler irrigated field in Italy [*Bertocco, 2012*]. Irrigation timing is typically decided by farmer basing on his experience. Farmers decide the time to irrigate observing the leaves of the maize plants and taking also into account the air temperature. Some farmers may also take into account quantitatively the amount of water coming form rainfalls. In other cases, the shift of crops implied by use of consortium water represents a big constraint.

The major advantages of using the hose reel are the following:

- Pipe diameter of 150mm allows a reduction of the head losses and energy consumption
- The amount of water released is automatically measured by an internal computer and visualized on a display.

The major disadvantages of using hose reel are:

- In most cases the corners of the field are not properly irrigated (non uniformity of application). This is the reason why usually corners are irrigated using fixed sprinklers.
- Irrigation applications cannot be suspended during the hottest hours of the day, implying higher water losses through evaporation.

Fixed sprinkler has been employed to irrigate only the part of the maize field where probes 1, 2 and 3 were located. The instrument used is a quite old machinery fixed on a pump which is directly connected to a tractor. Sprinkler irrigation coupled with a water balance scheme results to be the combination which ensures the best ratio efficiency/costs in most cases and it is the reason why sprinkler irrigation is the most used all over the world.

The major advantages of fixed sprinklers are:

- Can be used to irrigate small part of the field
- Can be easily stopped or used in the early hours of the day minimizing water evaporation

The major disadvantages on using fixed sprinkler, instead, are the following:

- It is not provided with a computer, so the amount of water provided to the field in this case was measured using a rain gauge (*Figure 1.5*)

Figure 2.6 Fixed sprinkler irrigation on Informed Site, hose reel irrigation on Uninformed Site and the rain gauge instrument

2.4 Hydrologic Data

Water content measurement started on 10 June and ended on 18 September 2013, just before the maize harvesting. In the whole acquisitions period of 101 days there have been three irrigation (on June 25, July 23 and August 3) and several rainfall events. Uninformed Site and Informed Site irrigations were performed at slightly different times with significantly different amounts of water. The water delivered in the Uninformed Site by the hose reel was 40 mm for every application, while the amount of water delivered in the Informed Site determined at each instance by the underlying soil moisture. The measured data of the Informed Site are reported in *Figure 2.8* while measures referred to Uninformed Site are shown in *Figure 2.9*. In graphs are reported separately the soil moisture dynamic of each probes. Probes 6, at 67th days of acquisition start to malfunctioning giving no-acceptable values. The water content measured by the six probes shows marked hourly fluctuation (*Figure 2.7*). In particular, the soil moisture is maximum during the night time when evapotranspiration is null and minimum at noon, when evapotranspiration is maximum. Sub-daily fluctuations highlight the strong influence of temperature on the evaporation rate and soil moisture dynamics, especially during dry days.

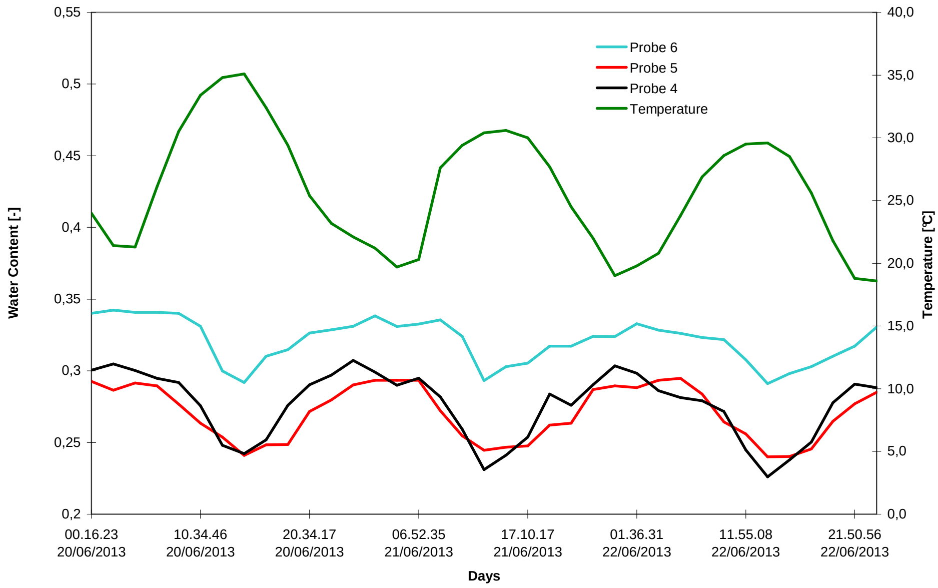


Figure 2.7 Water content daily fluctuation in Uninformed Site

Temperature variation during the whole period is reported in the upper part of the graph (*Figure 2.7*). To eliminate the fluctuations due to the daily cycle of evapotranspiration processes and been able to focus on the water balance and seasonal soil water dynamics, daily mean values were considered from point measurements. Daily mean value of soil moisture is obtained calculating the mean water content value for each day (*Figure 2.10 and 2.11*). TDR instrument provided 12 measures per day in non-irrigated days, while the number of acquisitions increases during the irrigation days. During the acquisition period (August 2-3) fractures appeared into the soil, in particular in the Informed site. Fractures, probably formed by drought, can strongly impact connectivity of the field through macro pores and small channels, giving rise to soil water redistribution in all the space direction. To take in consideration the non-negligible influence of fractures on soil water processes the hydrological data were subdivided into two separate periods: a first period in which fractures were neglected (June 10 to August 3) and a second period strongly influenced by fractures (August 3 to September 18).

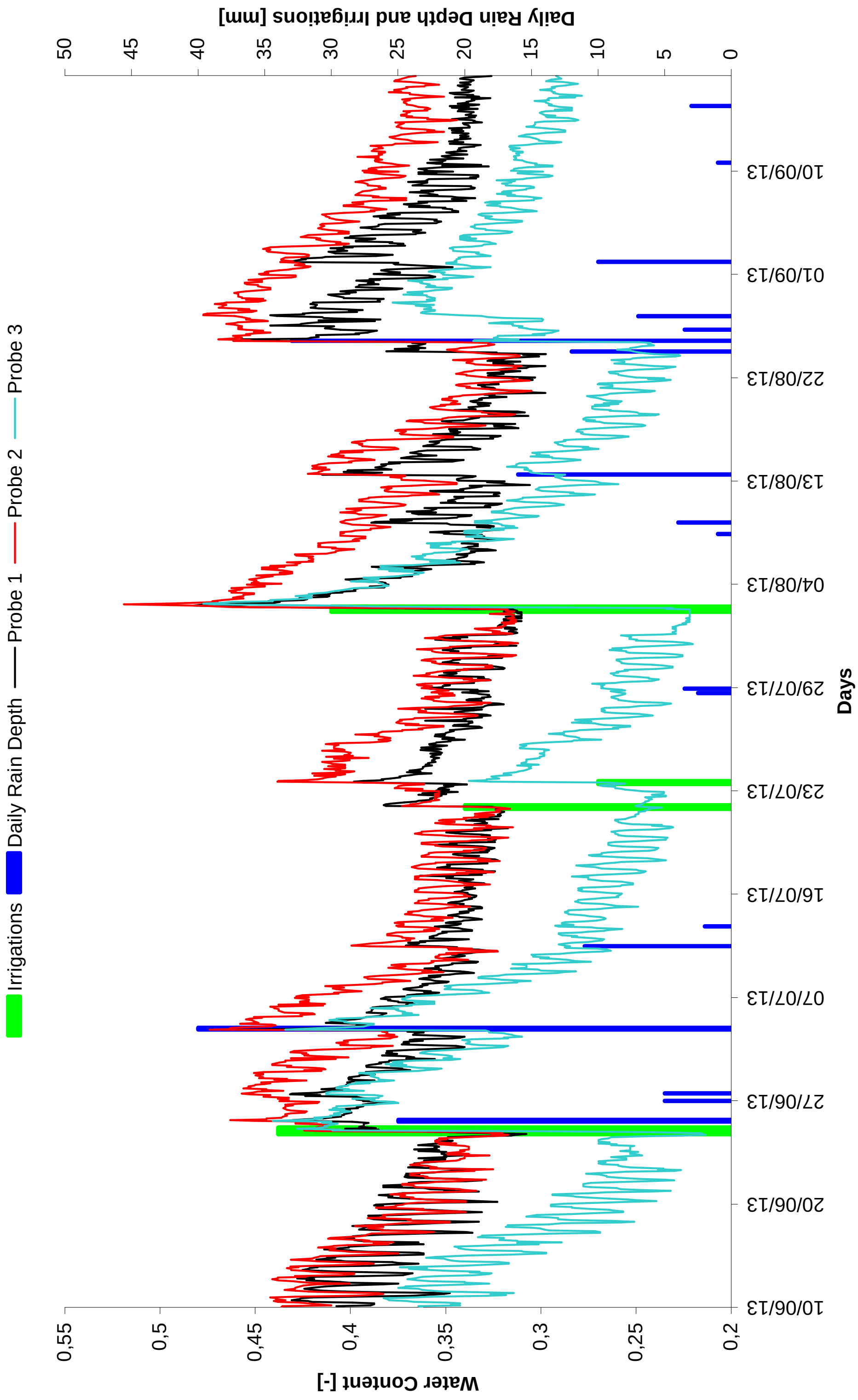


Figure 2.8 Water content of the whole period of acquisitions in Informed Site

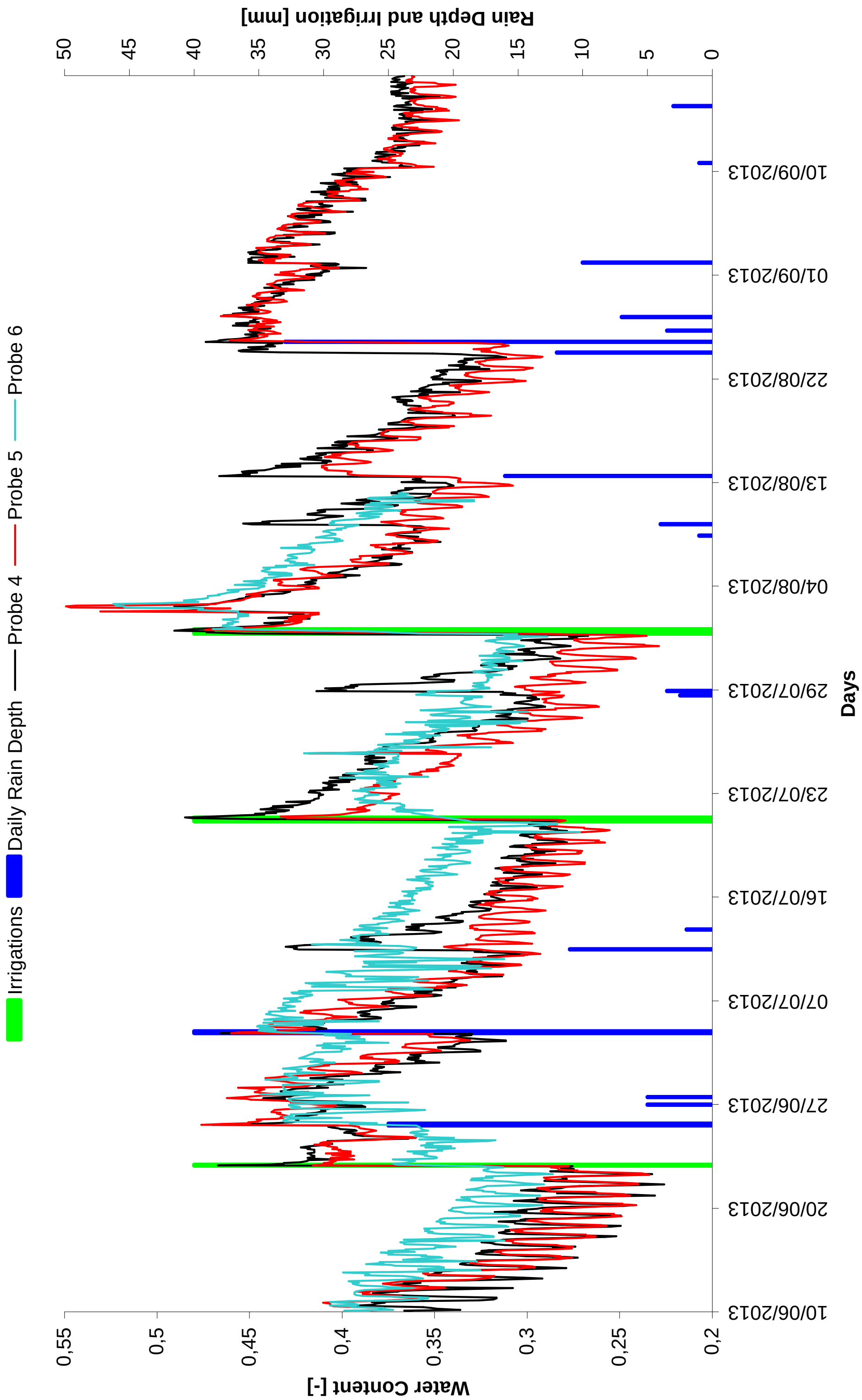
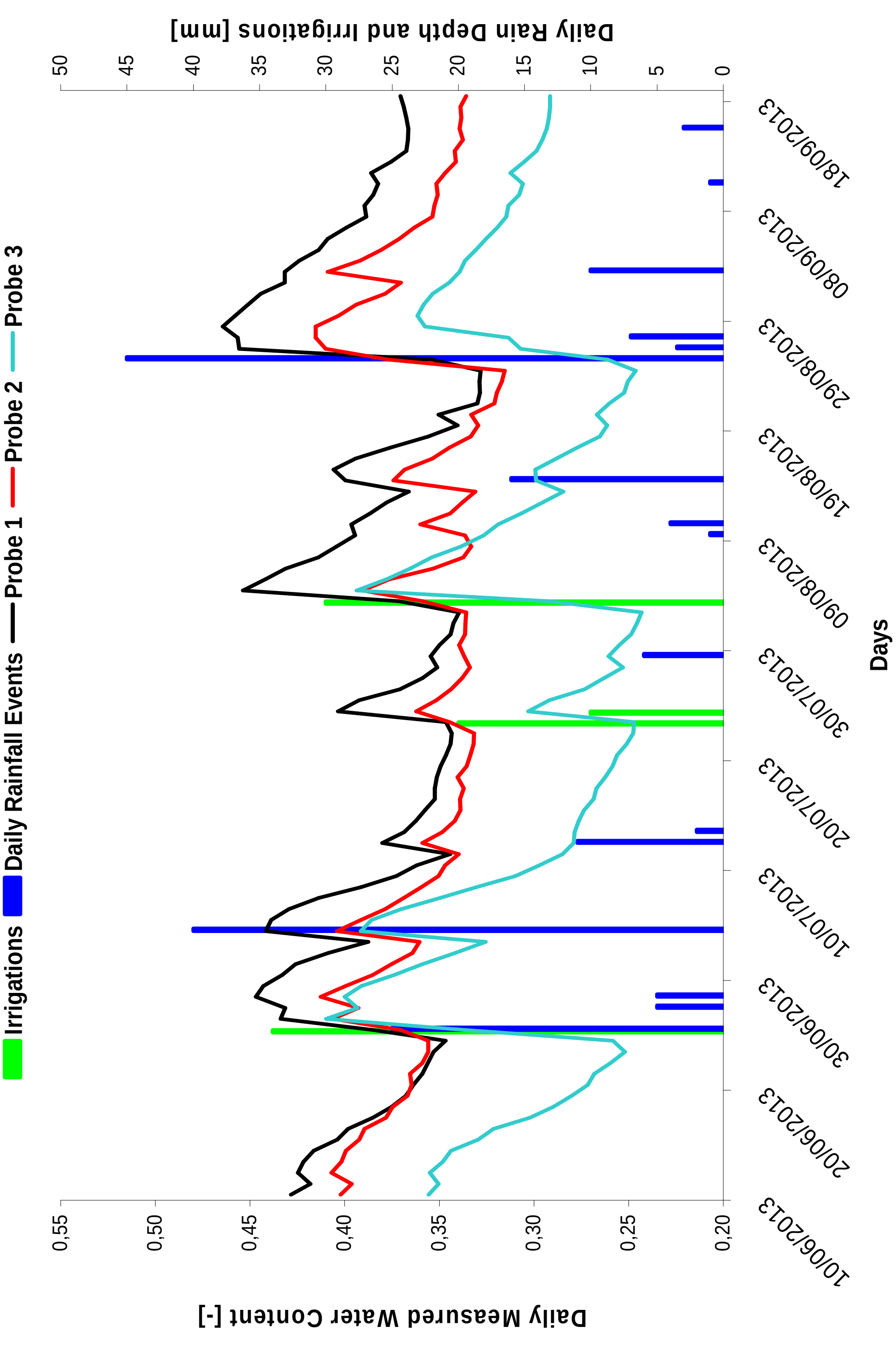
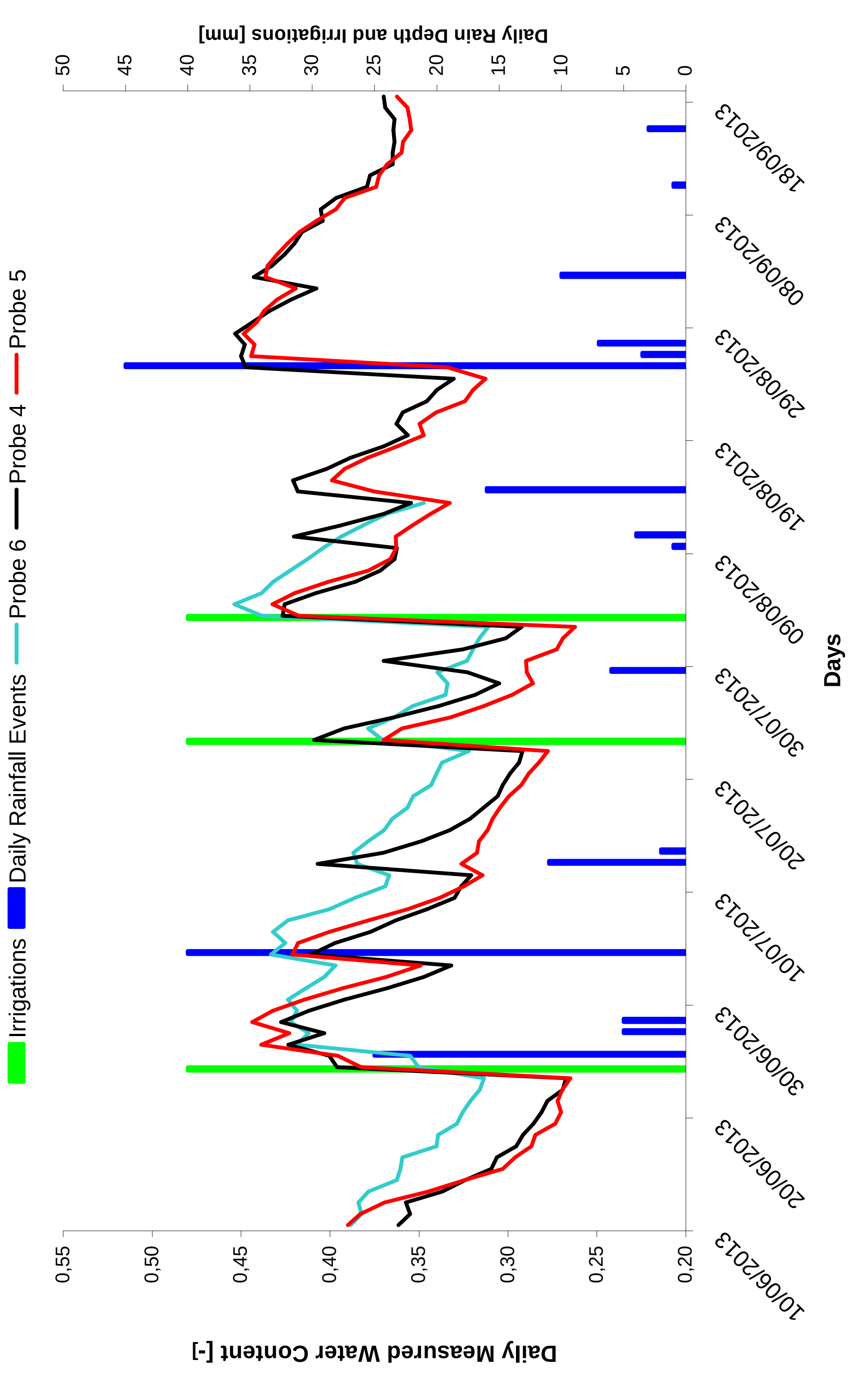


Figure 2.9 Water content of the whole period of acquisitions in Uninformed



2.10 Daily means of the whole period of acquisitions in Informed Site



2.11 Daily means of the whole period of acquisitions in Uninformed Site

2.4.1 First Period from June 10 to August 3, 2013

The first period of acquisition was influenced by two irrigation applications and to three rainfall events. The first irrigation was delivered on June 24 - 25: in the evening of June 25 an important rainfall brought 25mm of water. The second rainfall event brought 40mm of water on July 4 and a third event brought 13mm on July 12. First periods ends close to the last irrigation application.

Table 2.2 List of irrigation and precipitation events during the first period of acquisition

Site	Event Type	Start Date	End Date	Cumulative Water Height (mm)
Uninformed	First Irrigation	24/6 – 9.00	24/6 – 9.44	40
Informed	First Irrigation	25/6 – 15.25	25/6 – 16.48	33
Both Sites	Rain	25/6 – 19.55	25/6 – 23.43	25
Both Sites	Rain	27/6 – 17.28	28/6 – 10.36	10
Both Sites	Rain	4/7 – 5.32	4/7 – 10.58	40
Both Sites	Rain	12/7 – 1.03	12/7 – 2.57	11
Both Sites	Rain	13/7 – 22.03	13.07 – 23.00	2
Uninformed	Second Irrigation	23/7 – 9.25	23/7 – 9.46	40
Informed	Second Irrigation	23/7 – 11.33	23/7 – 11.44	20
Informed	Second Irrigation	24/7 – 9.17	24/7 – 9.28	10
Both Sites	Rain	29/7 – 12.31	29/7 – 14.20	2,5
Both Sites	Rain	29/7 – 20.09	29/7 – 21,59	3,5

In the Informed Site, for the whole acquisition period, the deepest probe, measured the lowest water content. The first irrigation on June 25 delivered 33mm of water to the field, while second irrigation was performed in two subsequent days: on July 23 20mm of water were delivered to the soil, and the following day other 10mm were added. The surface probes proved more sensitive to small rainfall impulses while probe 3 measured increased water contents only during intense events, and inputs with a small delay (due to the infiltration processes from the surface to the deepest layer of the root zone). The initial water content of the informed probes is shown in the following *Table 2.3*:

Table 2.3 Initial water content in Informed Site

Probe	Initial Water Content [-]
1	0,40338
2	0,4364
3	0,3622

For the whole acquisition period, uninformed site probes have measured higher soil water contents, probably due to the higher water delivered during irrigation applications. Jumps of soil moisture due to rainfall or irrigation inputs were more pronounced in this site maybe due to the larger water inputs and interaction with the surrounding portions of the field. Furthermore in the first phase the decreasing rate of soil moisture seems to have an higher slope with respect to that shown in the informed graph. This may be caused by larger evapotranspiration rates, caused by the greater development of maize plants in this site during the early stages of the experiments. Uninformed site irrigations where performed just before the informed irrigation applications delivering 40mm of water per application. However the Informed irrigations on the Informed Site influenced soil moisture dynamics in the Uninformed Site. This can be explained considering the morphology of the maize field and the location of the probes with the Uninformed Site which is closer to the drainage channel. The initial value of soil moisture for the uninformed site probes is shown in the following *Table 2.4*:

Table 2.4 Initial water content in Uninformed Site

Probe	Initial Water Content [-]
4	0,36217
5	0,3937
6	0,3854

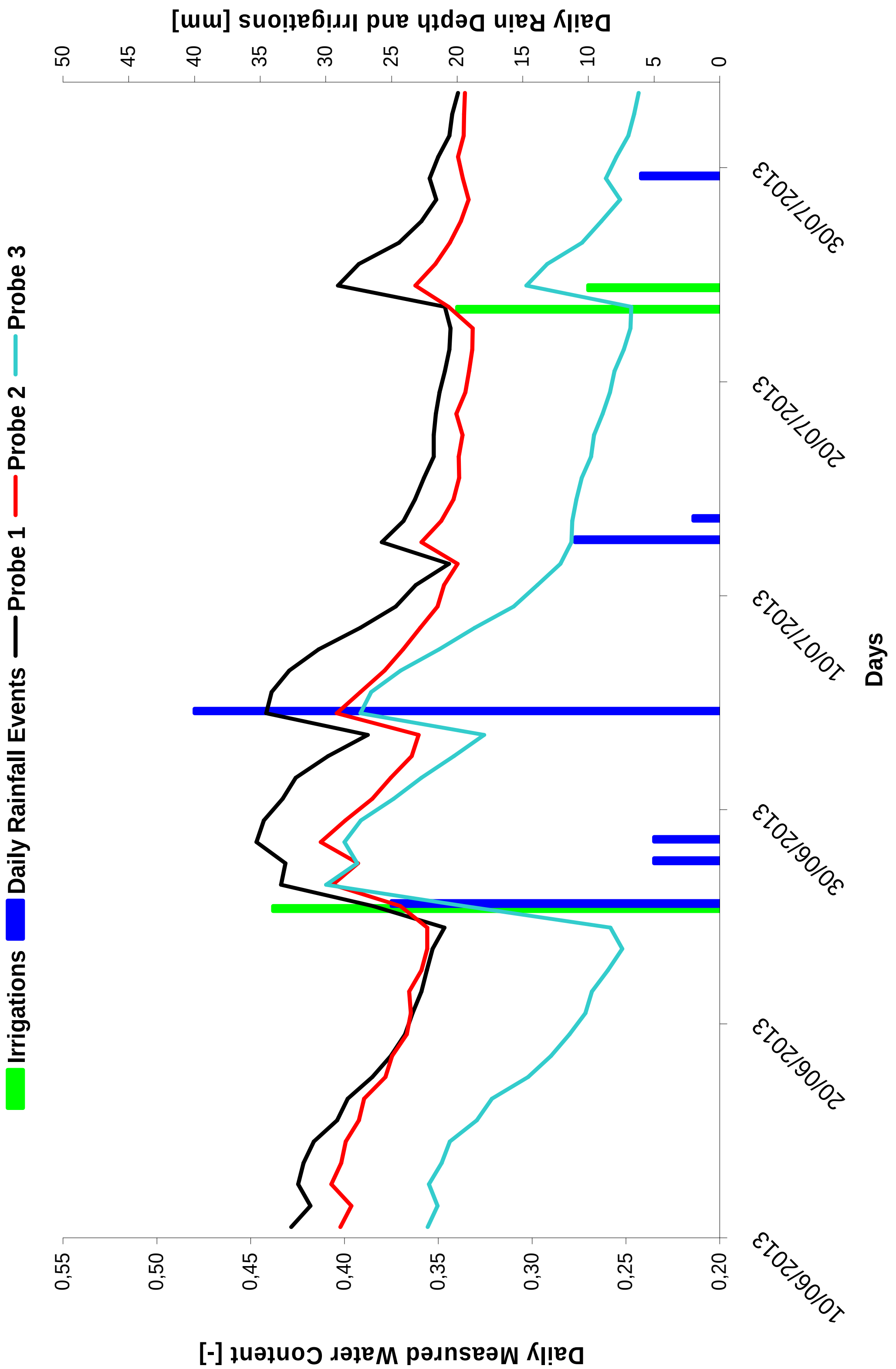


Figure 1.12 Daily means of the first period of acquisitions in Informed Site

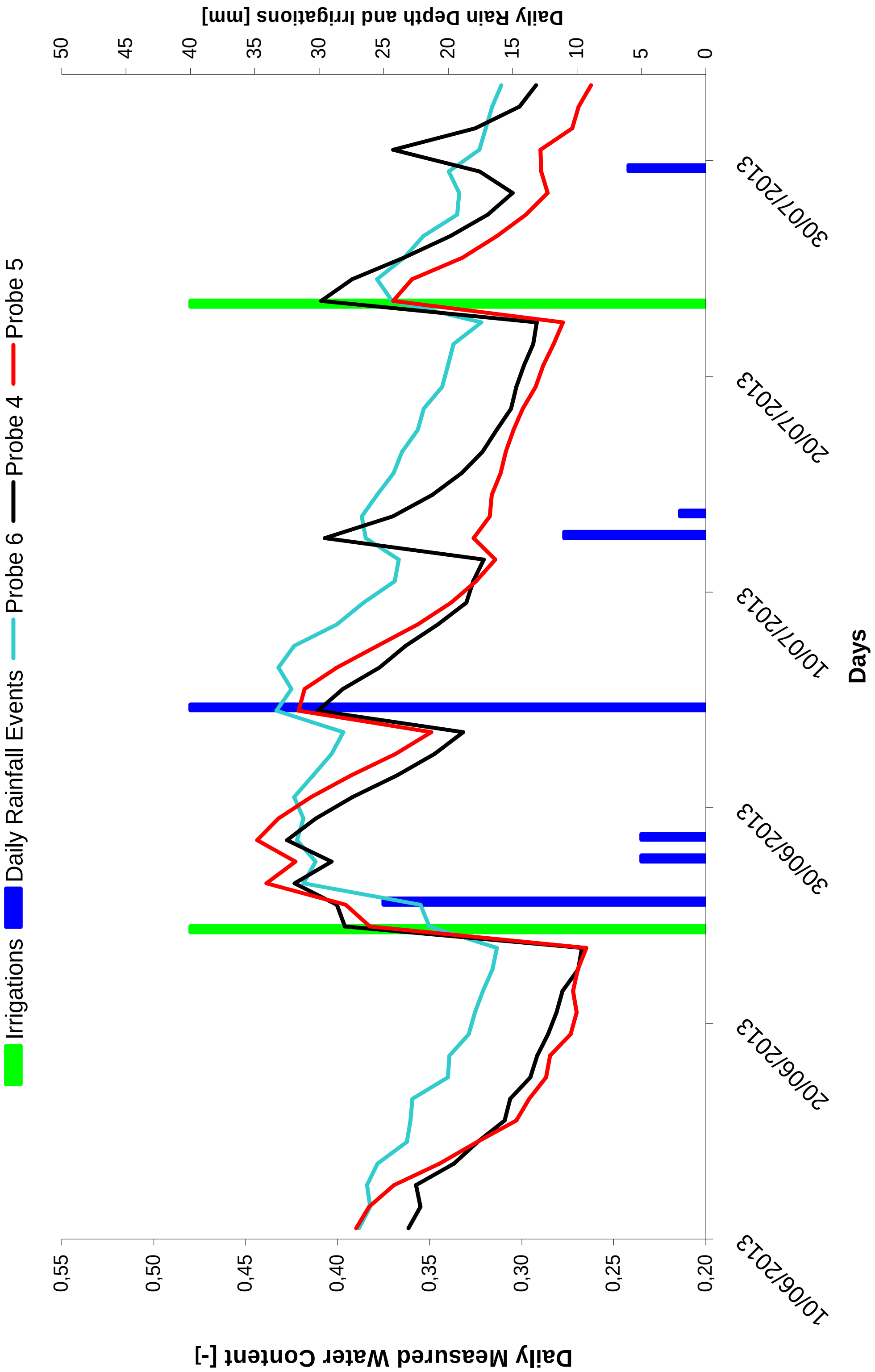


Figure 2.13 Daily means of the first period of acquisitions in Uninformed Site

2.4.2 Second Period from August 3 to September 18, 2013

The second period started on August 3 when, after a few dry days, some fractures appeared on the surface of the maize field. From this moment to the end of the acquisition period, fractures should have played a crucial role in the hydrological behaviour of the field. In particular fractures should have been able to create preferential pathway for water flow, and water redistributed between the two sites and the remaining portion of the field. In this a single irrigation took place, while in the last days some important rainfall events delivered 46mm of water on August 25, about 11mm in the two following days and 10mm on September 2. Another significant rainfall event was observed after the third irrigation on August 14 (16mm).

Table 2.5 List of irrigation and precipitation events during the second period of acquisition

Site	Event Type	Start Date	End Date	Cumulative Water Height (mm)
Uninformed	Third Irrigation	3/8 – 12.04	3/8 – 12.26	40
Informed	First Irrigation	3/8 – 16.41	3/8 – 17.03	23
Both Sites	Rain	9/8 – 2.59	9/8 –	1
Both Sites	Rain	10/8 – 2.10	10/8 –	4
Both Sites	Rain	14/8 – 10.18	14/8 –	16
Both Sites	Rain	25/8 – 0.12	25/8 –	12
Both Sites	Rain	25/8 – 21.26	25/8 -	33
Both Sites	Second Irrigation	26/8 – 19.35	26/8 -	3,5
Informed	Second Irrigation	27/8 – 23.49	27/8 -	7
Informed	Second Irrigation	2/9 – 1.53	2/9 -	10
Both Sites	Rain	10/9 – 19.48	10/9 -	1
Both Sites	Rain	15/9 – 18.39	15/9 -	3

Third irrigation application delivered 23mm of water in the Informed Site. The high soil moisture jump observed during this event may be caused by fractures which have brought into the site additional water from surrounding areas. During the last days of acquisitions all the informed probes have registered a slow decreasing of the soil moisture content because of the absence of rainfall events and low evapotranspiration rates. As expected, in the last part of the plant life cycle, the rate at which maize plants uptake water from the soil decreases. This behaviour is highlighted in the last part of the plot shown in (*Figure 2.14*), with soil moisture dynamics becoming almost flat.

The study of the behaviour of the Uninformed Site during the second phase of the experiment is more difficult due to the malfunctioning of probe 6, that didn’t allow a completely understanding of the soil moisture dynamics in the uninformed site. Probe 6 starts to malfunctioning on August 15. From that point on, soil moisture content measured by probe six were not considered reliable. Irrigation application at the start of the period delivered 40mm of water during the hottest hours of the days. Also in the uninformed plants a sharp decrease of evapotransipration rats in the last stages of experiment was observed.

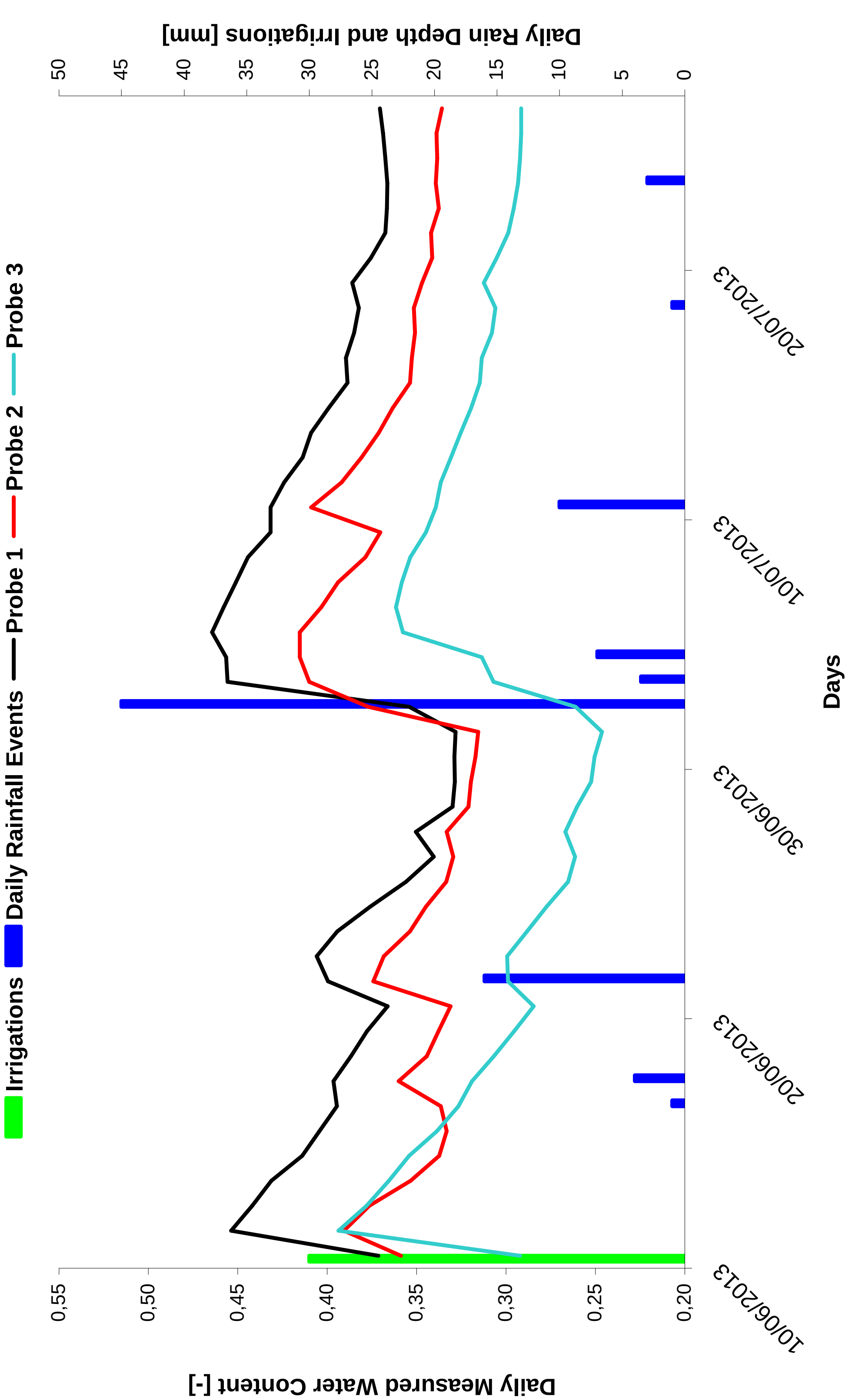


Figure 2.14 Daily means of the second period of acquisitions in Informed Site

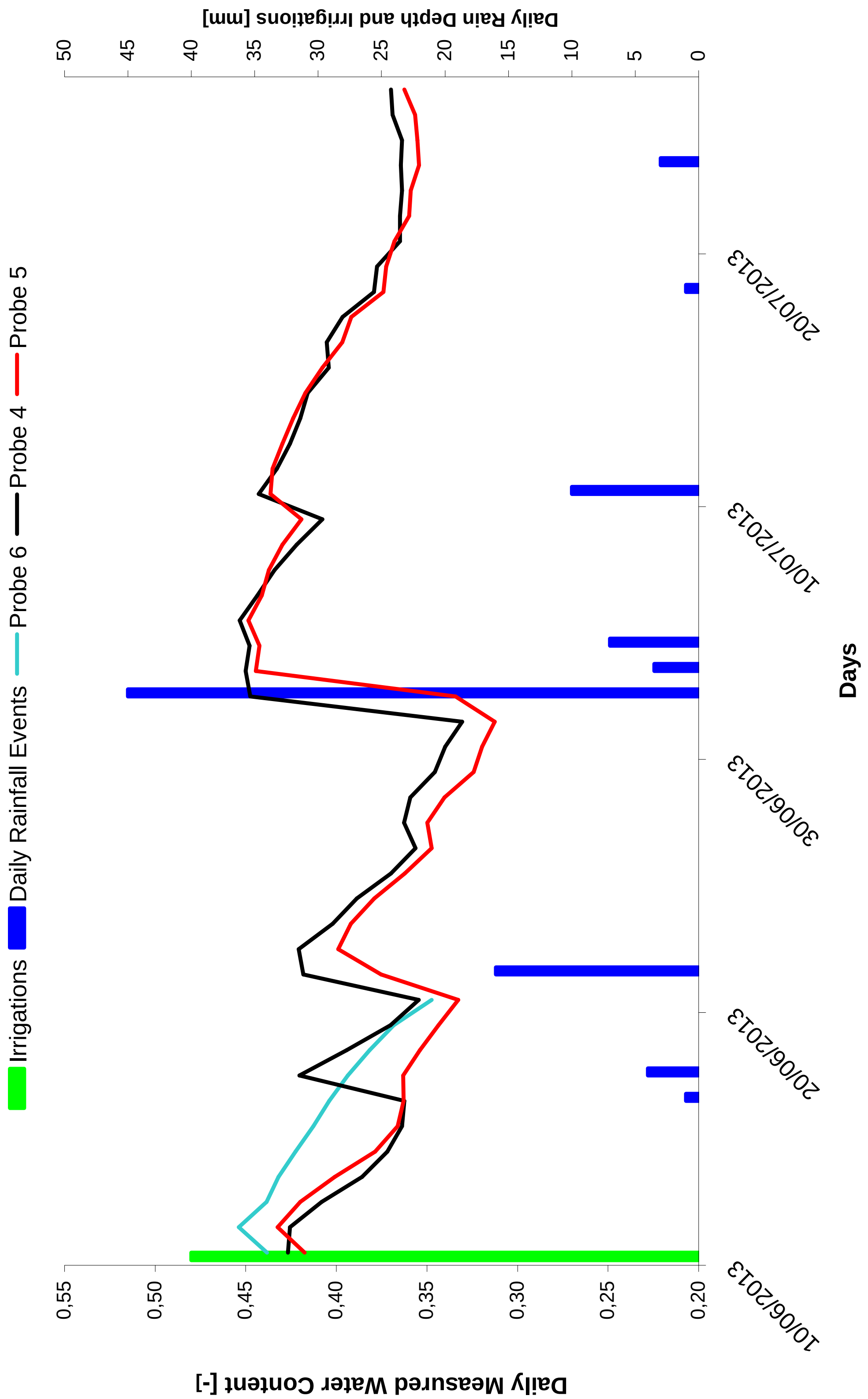


Figure 2.15 Daily means of the second period of acquisitions in Uninformed Site

Chapter 3

Modelling Soil Water Dynamics

Measurements of soil moisture provide useful information about the response of the root zone to infiltration inputs. However obtain useful information about the efficiency of differences irrigation schedules we have to consider the water balance in the root zone, where rain and irrigation represent the input terms and evaporation, transpiration and leaching the output ones. A schematic of the system is reported *Figure 3.1*.

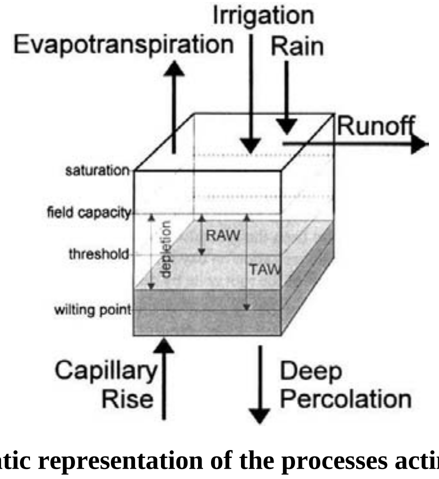


Figure 3.1 Schematic representation of the processes acting in the root zone

Soil water dynamics are typically a function of the soil depth therefore to completely reproduce the processes acting in the root zone and influencing the soil water content dynamics, it should be necessary to take into account the interaction between the different soils layers in which the root zone can be subdivided. This kind of models, however, is very complex and requires a large number of parameters. For the objective of this study, the spatial variability of the soil moisture along the vertical direction is disregarded. Instead a minimalist model with restricted number of parameters is employed in a lumped framework. The results are a parsimonious zero-dimensional model that considers a spatially averaged soil water content and homogeneous soil properties into the whole control volume. This simplification was obtained considering the vertical averaged soil moisture in both sites as shown in the *Figure 3.2*. Starting from vertical averaged water content derived from measurements of the six probes during the entire life cycle of maize, a numeric model was developed in order to simulate the soil water content dynamics in root zone. The model is based on a point water balance described by the following differential equation:

$$n \cdot Zr \cdot \frac{ds(t)}{dt} = I[s(t),t] - ET[s(t),t] - L[s(t),t] \quad (3.1)$$

Where n is the soil porosity, Zr the root zone depth [mm], s(t) the actual soil moisture, I[s(t),t] the infiltration function, ET[s(t),t] the evapotranspiration function and finally L[s(t),t] the leakages function.

The above equation can be solved using a Eulerian forward numerical scheme with a discrete temporal step of Δt=1h. Considering the relationship between water content (θ) and relative water content (s): $\theta(t) = n \cdot s(t)$, Equation *(3.1)* can be written as:

$$\theta(t+1) = \left[\frac{I[s(t),t] - ET[s(t),t] - L[s(t),t]}{Zr} + \theta(t) \right] \quad (3.2)$$

The objective of the model is to quantify losses through evapotranspiration and leaching. A comparison between the informed site and uniformed site results can provide useful information on possible strategies to optimize water use and avoid water losses. The model is calibrated using all 101 daily measurements of the probes (vertically averaged over the entire root zone depth). The model uses a temporal scale of one hour for a total of 2424 time steps. Equation (*3.2*) is applied at each time step.

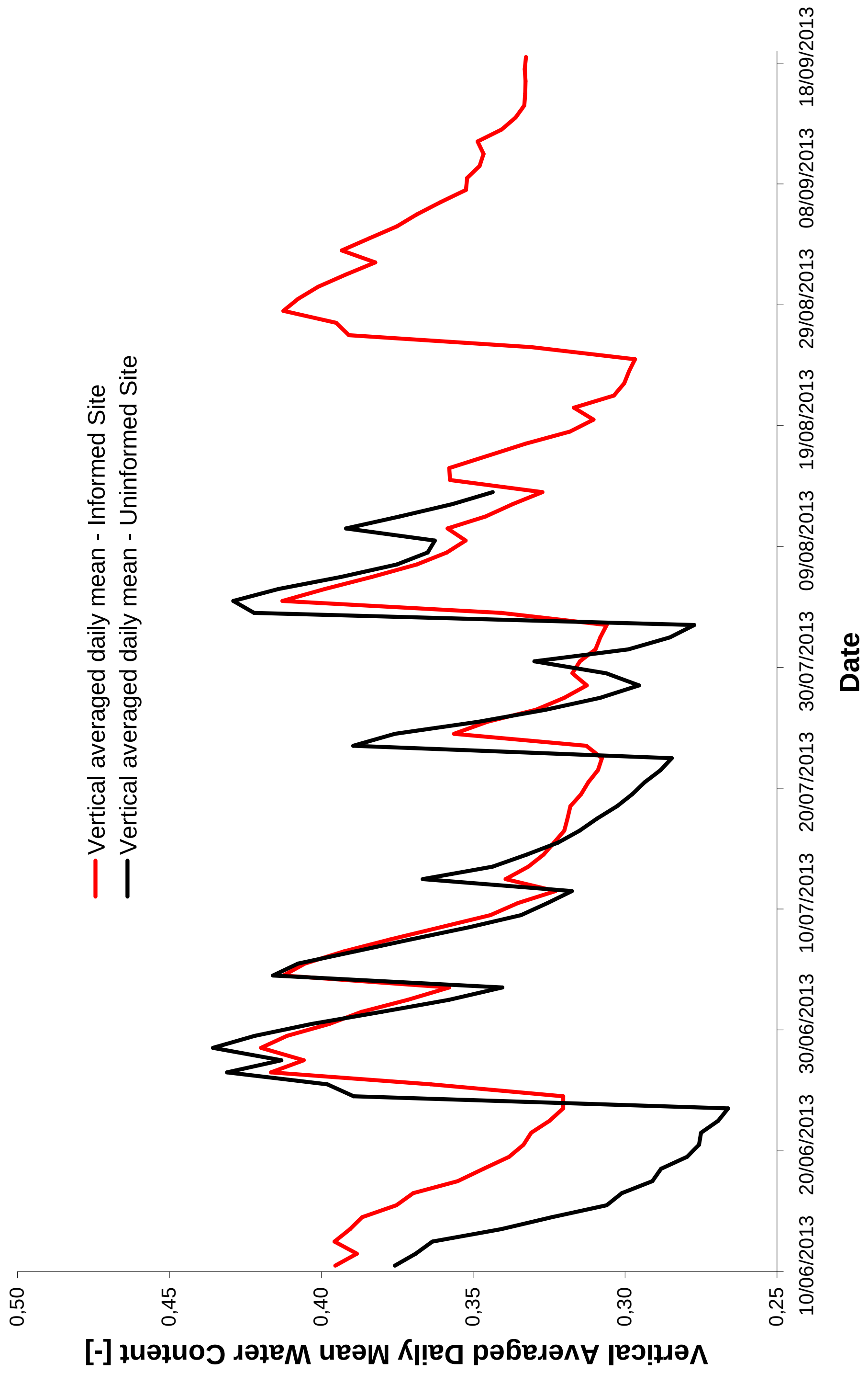


Figure 3.2 Vertical averaged soil moisture dynamics in Informed (red line) and Uninformed (black line) sites

3.1 Physical Processes

The root zone of a crop filed of the type analyzed in this thesis is an uncompacted topsoil layer that has relatively uniform properties and represents the zone where competition between evapotranspiration and percolation takes place. The root system of a maize plant can reach depths higher than 1m, but they are most developed in the first 40cm of soil. The growth of roots depends on the plant growth cycle and on water availability at different depths. In the water balance the root zone represents the control volume where percolation through the deeper soil layer, transpiration following the water uptake by roots, evaporation from all wet surfaces and infiltration through the soil surface, simultaneously take place.

Infiltration is the driving factor of the dynamics and depends from random rainfalls, programmed irrigations and soil/vegetation features. Infiltration represents the unique input of the root zone and describes the rate with which the water can infiltrate in to the deeper soil layers through the surface. Rainfalls and irrigations result in infiltration depth into the soil taking into account interception phenomena performed by canopy and soil surface which results in overland flow. There are two main reasons for which rain is no more able to infiltrate into the soil: rainfall intensity can be too high causing the exceed of the infiltration capacity at a given instant (Horton mechanism) or the cumulative rainfall volume is too high so as the soil becomes completely saturated (Dunne mechanism). Horton mechanism usually dominates in arid and semiarid climates, where storms are concentrated in short periods and characterized by high intensity, while Dunne mechanism becomes more important in humid climates, when rainfall is characterized by large annual volumes but lower intensities. There are many infiltration models available in order to separate infiltration fluxes from overland ones based on Horton/Dunne mechanisms.

The evapotranspiration is a combined process including both evaporation from soil and transpiration through plant leaves. In the evapotranspiration the water is transferred from the soil and plant surfaces into the atmosphere in the form of water vapour. The two terms of evpotranspiration are discussed in what follows.
Evaporation is the process whereby liquid water is converted to water vapour (vaporization) and removed from the evaporating surface. Energy is required to change the state of the water particles from liquid to vapour. Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide this energy.
Transpiration is performed by plants and consists in the vaporization of liquid water contained in plants tissues and cells, as well as the vapour movement into the lower atmosphere. Crops predominately lose water through stomata, small openings on the plant leaf (some μm) through which CO_2 is incorporated. The water, together with some nutrient, is taken up by the roots and transported through xylems up to the foliage. Vaporization occurs within the leaf, in the intercellular spaces, and the vapour exchange with the atmosphere is controlled by the stomata opening. Nearly all water taken up is lost by transpiration and only a tiny fraction is used by the plant. Stomata are mostly present in the lower part of the leave to avoid direct exposition to the Sun radiation and ensure a better control on the amount of water leaving the plant. Thanks to the action of some guard cells, plants are able to regulate the quantity of released water depending on the quantity of available soil water. When the soil water available is high also large amounts of CO_2 can be assimilated, and vice versa. Stomata openings create a continuum from soil to the atmosphere which is necessary to ensure a proper water gradient and allow for the water rise against gravity forces.
The driving force for evaporation and transpiration are similar: temperature, solar radiation, air humidity and wind speed, which plays an important role removing water vapour from the evaporating surface, avoiding the creation of equilibrium condition that would stop the evapotranspiration. Also the type of vegetation and the life-cycle are very important factors, besides soil water availability.

Evaporation and transpiration are treated together because they are controlled by similar driving factors. Evaporation usually dominates in bare soil and lakes while transpiration is prevalent in vegetated soils especially during wet periods.

Leakage represents deep infiltration processes and drainage from the root zone to surrounding areas. This form can be considered as the sum of lateral flow (L_h) and vertical flow (L_v):

$$L[s(t),t] = L_v[s(t),t] + L_h[s(t)t] \tag{3.3}$$

The lateral flow is a function of spatial gradients of water matric potential, while the vertical flow represent the deep percolation which is mainly induced by gravity. In order to have lateral flow in the root zone, there should be heterogeneity of soil properties and the presence of sinks able to sustain the water matric potential. Usually, in the root, zone the vertical downward movement dominates then the lateral flow component can be neglected. The magnitude of each term can be established according to the Darcy's Low. In particular, the water velocity along the vertical (z) direction is:

$$v_z(\vec{z},t) = -K[\vec{z}, s(t)]\frac{\partial \Psi_{tot}(z,t)}{\partial z} \tag{3.4}$$

Where K is the hydraulically conductivity of the soil and Ψ the matric water potential. All the water-balance terms are defined in function of saturation level and time. Relative water content dynamics influence the rate of infiltration, determining the amount of water that can infiltrate into the soil. The opening or the closing of stomata regulates the evapotranspiration rate and the leaching is appreciable when the soil moisture content crosses the field capacity threshold.

Some simplifying assumptions which allow a parsimonious description of the water balance: no interaction between soil moisture in the root zone and the underlying water table, negligible lateral subsurface water redistribution and uniform soil features and rooting depth. This simplification are often valid for most of agricultural settings where the use of monoculture homogenize rooting depth and, flat or gently sloping field do not allow significant lateral movements which are, however, take into account through a suitable parameter.
Model equations are reported below subdivided per process:

Infiltration – I[s(t),t]:

Infiltration process can be described by the following equation:

$$I[s(t),t] = P(t) + R(t) - O[s(t),t] \qquad (3.5)$$

Where P(t) is the rainfall depth through time, R(t) is the additional irrigation depth and O[s(t),t] is the overflow term, dependent on the actual soil moisture content. The total precipitation [P_{tot}(t)] that can infiltrates through the soil surface is represented by sum of rainfall and irrigation water depth fraction (P_s) as described by the following equation:

$$P_{tot}(t) = P(t) + R(t) \qquad (3.6)$$

Overflow is produced by the remaining water that cannot infiltrate into the soil through the surface and remains over it giving rise, to ponding and runoff phenomena. The Model employed uses a simple combination of Dunne and Horton infiltration model summarized by the following equation:

$$s(t)<1\begin{cases}P_s(t)<K_i \rightarrow I[s(t),t]=P_s(t)\\ P_s(t)>K_i \rightarrow I[s(t),t]=K_i\end{cases} \quad s(t)\geq 1 \rightarrow I[s(t),t]=0 \tag{3.7}$$

If the relative soil water moisture is lower than 1 (the soil is unsaturated) the infiltration rate can assume, at most, the threshold value $K_{i,}$ otherwise the infiltration rate is equal to the precipitation intensity. K_i is a threshold value which represents the maximum fraction of precipitation that reaches the ground surface able to actually infiltrate into the root zone. This parameter is typically highly time-variable and dependent on the soil moisture content.

<u>Evapotransipration – ET[s(t),t] :</u>

To evaluate ET terms, the FAO method is employed. The basic principle of this procedure is to separate the dependences on climate, vegetation and water availability, by dividing the calculation procedure in three steps.

The first step consists on the calculation of the reference potential evapotranspiration (ET_0). Reference potential evapotranspiration is defined as the evapotranspiration rate of a reference crop, which is an hypothetical culture with a height of 12cm, a fixed soil vegetation resistance of 70 s/m and an albedo of 0,23. In practise this is an active grassland during the growing season with unlimited water availability. The reference crop is useful to separate the effects of climate and vegetation features and make comparison among different crops. Different methods to evaluate ET_0 exists. In this study the Penman-Monteith equation was used which is a combination method obtained combining the energy balance with a mass transfer method. The procedure requires the definition of suitable resistance factors. Surface resistance parameter describes the resistance of vapour flow through stomata opening, total leaf area and soil surface, while aerodynamic resistance describes the resistance from vegetation upward and involves friction from air flowing over vegetative surfaces. ET_0 is daily evaluated starting from climatic data.

$$ET_0 = \frac{0,408 \cdot \Delta \cdot R_n + \gamma \cdot \dfrac{900}{T + 237,3} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0,34 \cdot u_2)} \tag{3.8}$$

Where ET_0 is the reference evapotransiration rates expressed in [mm d^{-1}], Δ is the slope of vapour pressure curve [kPa $°C^{-1}$], R_n the net radiation at the crop surface [MJ m^{-2} d^{-1}], T is the mean daily air temperature at 2m height [°C], u_2 is the wind speed at 2m height [m $s\text{-}^{1}$], e_s and e_a are the saturation and actual vapour pressure respectively [kPa] and γ is the psychrometric constant [kPa $°C^{-1}$]
The equation uses standard climatic data such as solar radiation, air temperature, humidity and wind speed. For the calculation of ET_0 hourly data gauged by a meteorological station were employed namely: solar radiation, mean temperature, wind velocity and air humidity.

The evapotraspiration process is determined by the amount of energy available to vaporize water. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year and it is called solar radiation. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons. The solar radiation absorbed by the atmosphere and the heat emitted by the earth increase the air temperature that exerts such a controlling influence on the rate of evapotraspiration. In sunny warm weather the loss of water by evapotraspiration is greater than in cloudy and cool weather.

For the evaluation of ET_0, minimum and maximum hourly temperature (T_{min} and T_{max}) and mean hourly temperature (T_{mean}) are used. All temperature data are expressed in [°C].

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} \tag{3.9}$$

The difference between the water vapour pressure at the evapotranspiring surface and the surrounding air is a key factor for the vapour removal. In humid weather where the humidity of air is close to saturation, only a small amount of additional water can be stored and hence the evapotraspiration rate is lower than in arid regions. Minimum and maximum hourly air humidity were used for the calculation of the evapotranspiration of the reference crop. Air humidity is a dimensionless factor. The evaporation process depends to a large extent on the air removal rate that is governed by the wind speed and turbulence in the atmosphere. When water evaporates the air above the evaporating surface gradually increases its humidity. If the humid air is not removed and replaced with dry air the evaporation rate decrease. Wind speed is expressed in [m/s] and it is typically measured at 2m above ground.

Net radiation at the crop surface (R_n) is the difference between the incoming and outgoing radiations of both short and long wavelength. It depends on geographic position, period, temperature and vapour pressure. Net radiation is the balance between the energy absorbed, reflected and emitted by the earth’s surface and can be estimated using an energy balance on the field surface:

$$R_n = (1-\alpha) \cdot R_s - R_{nl} \tag{3.10}$$

The solar radiation (R_s) is a fraction of the extraterrestrial radiation (R_a) and indicates what a given site receives from the Sun during a day. Solar radiation estimation needs to takes into account for cloud scattering. The following formula is a good empirical approximation that empirically accounts for cloudiness through the root square of difference between maximum and minimum temperatures:

$$R_s = 0{,}18 \cdot \sqrt{T_{\max} - T_{\min}} \cdot R_a \tag{3.11}$$

Extraterrestrial radiation (R_a) is the solar radiation received ate the top of the earth's atmosphere on a horizontal surface. The local intensity of the radiation is determined by the angle between the direction of the Sun's rays and the normal to the surface if the atmosphere. This angle will change during day and will be different at different latitudes and different seasons. Extraterrestrial radiation is a function of latitude, date and time of day.

$$R_a = 459 \cdot G_{sc} \cdot dr \cdot [\omega_s \cdot \sin\varphi \cdot \sin\delta + \sin\omega_s \cdot \cos\varphi \cdot \cos\delta] \tag{3.12}$$

The net long wave radiation (R_{nl}) represents the solar radiation absorbed by the earth and converted in heat energy. The difference between outgoing and incoming long wave radiation is called net long wave radiation. As the outgoing long wave radiation is almost always greater than the incoming long wave radiation, R_{nl} represent an energy loss. R_{nl} can be calculated as:

$$R_{nl} = 0{,}5 \cdot \sigma \cdot (T_{\max}^4 - T_{\min}^4) \cdot (0{,}34 - 0{,}14 \cdot \sqrt{e_a}) \cdot 1{,}35 \cdot (\frac{R_s}{R_{s_0}} - 0{,}35) \tag{3.13}$$

Where e_a is the actual vapour pressure and R_s/R_{s0} is the relative shortwave radiation. (R_s/R_{s0}) is the ratio of the solar radiation (R_s) to the clear-sky solar radiation (R_{s0}). R_s is the solar radiation that actually reaches the Earth's surface in a given period (*Eq. 3.12*), while R_{s0} is the solar radiation that would reach the same surface during the same period but under cloudily conditions. R_{s0} can be expressed as:

$$R_{s_0} = (0,75 + 2 \cdot 10^{-5} \cdot z) \cdot R_a \qquad (3.14)$$

where z is the elevation above the sea level, expressed in meters, of the station.

The slope of saturation vapour pressure curve (Δ) at a given temperature is calculated as:

$$\Delta = \frac{4098 \cdot \left[0,6108 \cdot \exp\left(\frac{17,27 \cdot T_{mean}}{T_{mean}} \right) \right]}{(T_{mean} + 237,3)^2} \qquad (3.15)$$

While the psychrometric constant (γ) is given by:

$$\gamma = 0,665 \cdot 10^{-3} \cdot P \qquad (3.16)$$

Saturation vapour pressure deficit (VPD) is the difference between the saturation (e_s) and the actual vapour pressure (e_a) for a given time period.

$$VPD = e_a^* - e_a \qquad (3.17)$$

The mean saturation vapour pressure is related to air temperature, it can be calculated from the air temperature. The relationship is expressed by:

$$e_a^* = \frac{e^*(T_{\max}) + e^*(T_{\min})}{2} \qquad (3.18)$$

where $e^*(T_{min})$ and $e^*(T_{max})$ are the saturation vapour pressures at the minimum and maximum temperature respectively:

$$e^*(T) = 0,6108 \cdot \exp\left(\frac{17,27 \cdot T}{T + 237,3}\right) \tag{3.19}$$

The actual vapour pressure (e_a) can be derived from the dew point temperature (T_{dew}), the temperature to which the air needs to be cooled to make the air saturated:

$$e_a(T_{dew}) = 0,6108 \cdot \exp[\frac{17,27 \cdot T_{dew}}{T_{dew} + 237,3}] \tag{3.20}$$

Daily Reference evapotranspiration obtained is reported in the following graph:

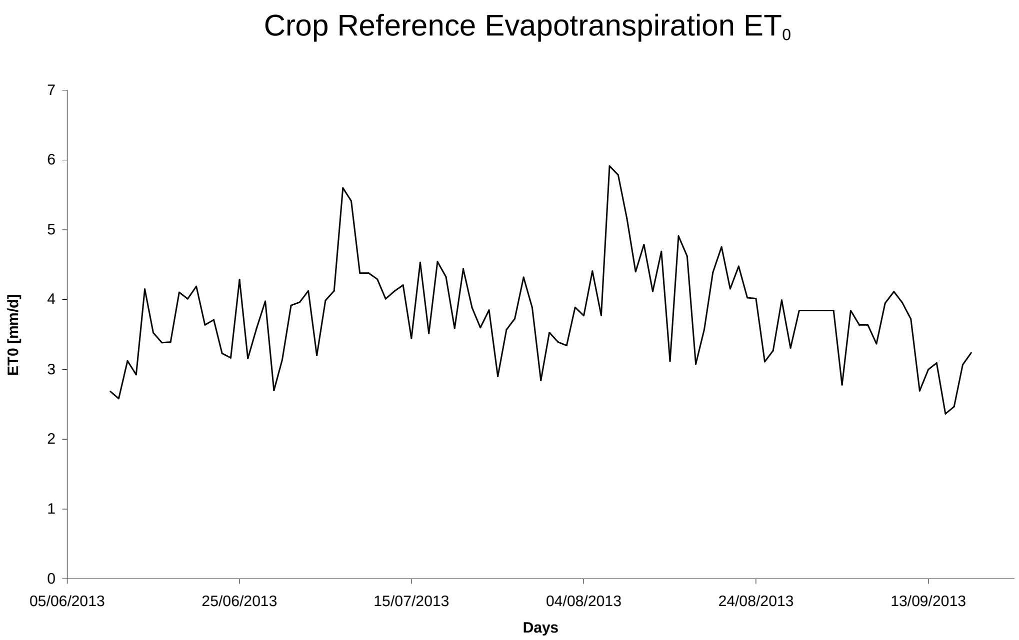


Figure 3.3 Daily values of crop reference evapotranspiration

Second step consists in the calculation of the potential evapotranspiraton (ET_c). The potential evapotranspiration of the actual crop is obtained multiplying the reference potential evapotranspiration (ET_0) and a crop coefficient (kc), that express the ability of a given vegetation cover, to evapotranspire more or less than the reference crop during its growing season. Crop coefficients are parameter defined in function of the vegetation type and of the growing season of the plant and can be easily found in literature (FAO).

$$ET_c(t) = kc(t) \cdot ET_0 \tag{3.21}$$

An example of the crop coefficient variability during the four different stages of the life cycle of a plant is illustrated in *Figure 3.4*. According to the FAO approach, kc can be described by 7 parameters. L_{in}, L_{dev}, L_{mid} and L_{end} are respectively the initial period, development period, mid season period and late season lengths. These 4 parameters describe the duration of the four stages in which the life of a plant can be subdivided and they are defined in function of the type of plant considered. Crop coefficients assume a constant value during initial period (kc_{in}) and mid season period (kc_{mid}) while in development period and in late season its pattern is linear since the kc_{end} is assumed.

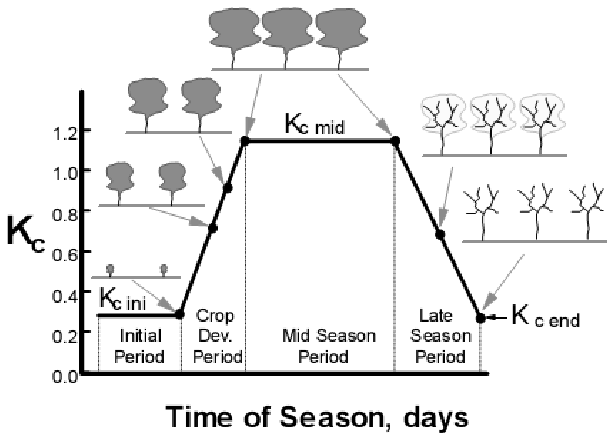


Figure 3.4 Schematic of the generalized kc curve with four crop growth stages and three kc values (Allen et al., 1998)

The FAO manual suggests for the parameters the values reported in *Table 3.1* and *Table 3.2*.

Table 3.1 Field corn plant crop coefficient suggest by FAO

Period	Crop Coefficient Value
Initial Period (kc_{in})	0,3
Midseason Period (kc_{mid})	1,2
Ending Period (kc_{end})	0,35 – 0,6

Table 3.2 Field corn plant growth stages length in Spanish climate suggested by FAO

Period	Days [d]
Initial Period Length (L_{in})	30
Developing Period Length (L_{dev})	40
Midseason Period Length (L_{mid})	50
Ending Period Length (L_{end})	30
Total [d]	150

Etc represent the maximum value of ET for a given crop at a given time (under given climate conditions) in the absence of water stress.

Finally, the third step allows for the calculation of the actual evapotranspiration (ET). It was observed that under limited soil moisture contents, plants reduce the rate at which they take water from the soil solution through roots. Plants are able to perform an osmotic adaptation decreasing gradually the opening degree of stomata in order to compensate the cell loss of pressure and turgor. It is possible to identify two particular soil moisture thresholds: incipient stress point (s^*) and wilting point (s_w):

- The Incipient stress point (s*): Indicates the soil moisture level below which the osmotic adaptation of plant is insufficient to compensate the decrease of energy of soil water and stomata start to closing. Incipient stress point depend on both soil and vegetation features.

- The Wilting point (s_w): Indicates the soil moisture level below which no water flow from the roots to the leaves can take place and the stomata are fully closed. Also the wilting point depends on both soil and vegetation features.

To evaluate the actual evapotraspiration of the crop it is necessary to multiply Etc and a water stress factor (k_s), function of the soil water availability, in order to take into account the partial or completely closure of stomata during drought periods.

$$ET[s(t),t] = k_s[s(t)] \cdot ET_c(t) \tag{3.22}$$

The water stress reduction factor defined in function of the actual soil moisture level can be well modelled by Fedds model (1978):

$$k_s[s(t)] = \begin{cases} 0 \rightarrow if : s < s_w \\ \dfrac{s(t) - s_w}{s^* - s_w} \rightarrow if : s_w \leq s(t) \leq s^* \\ 1 \rightarrow if : s(t) > s^* \end{cases} \tag{3.23}$$

When the soil moisture content is higher than the incipient stress point the evapotranspiration is maximum and equal to Et_c, while, when the water content decrease under the incipient stress threshold the stomata start gradually to closing reducing linearly the evapotranspiration from Et_c to 0 when soil moisture is lower than the wilting point (*Figure 3.5*).

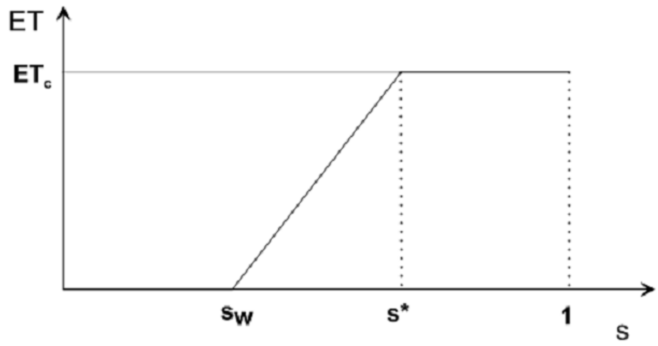


Figure 3.5 ET curve as a function of s

Leaching – L[s(t),t]

When the later subsurface flows are neglected the leakage can be modelled considering Clapp-Hornberger model:

$$L[s(t)] = K_{sat} \cdot s(t)^b \qquad (3.24)$$

Where K_{sat} is the hydraulic conductivity at saturation conditions and b is an empirical parameter determining the non-linearity degree. In unsaturated soil we define two critical levels of the soil moisture content:

- Field capacity (s_{fc}): value of s above which the movement of water is appreciable. Below s_{fc} the hydraulic conductivity is too small, and the water is strongly attracted to soil particles. It define the amount of water that remain in the soil after gravitational water has drained away, in other terms the field capacity is the amount of water held by soil after infiltration rate has materially decreased.

- Hygroscopic point (s_h): value of s below which the water molecules are too strongly attracted by the soil grains and can not be extracted from soil.

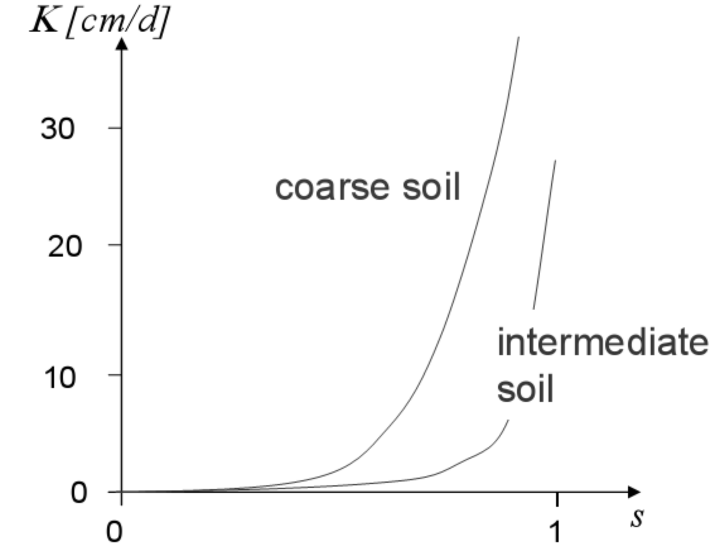


Figure 3.6 Example of hydraulic conductivity (K) curve defined in function of soil moisture in different soils

3.2 Model Parameters and Calibration

The following tables contain all the parameters used by the model developed, subdivided into constant parameters and calibrated parameters. The calibrated parameters are just 4 whereas the value of most the parameters involved can be defined based on observation evidence or literature.

Constant parameters:

Table 3.3 List of constant parameters used for modelling soil moisture dynamic

Symbol	Parameter	Description
Zr	Root Zone Depth	Depth of the root zone [cm]
ϑ^*	Incipient Stress Point	Water content for the incipient point stress [-]
ϑ_w	Wilting Point	Water content for the wilting point [-]
n	Porosity	Porosity of the root zone
t_1	Fracture Time	Time in which fractures is assume to appear
kc_{mid}/kc_{in}	Middle Crop Coefficient Ratio	Ratio between crop coefficient in the middle and in the initial phases of plant life cycle
kc_{end}/kc_{in}	Ending Crop Coefficient Ratio	Ratio between crop coefficient in the ending and in the initial phases of plant life cycle
L_1	Initial growth phase	Duration of the initial growth phase of maize plant associated with the kc_{in} crop coefficient [d]
L_2	Middle growth phase	Duration of the middle growth phase of the maize plant associated with the kc_{mid} crop coefficient [d]

Calibrated parameters:

Table 3.4 List of calibrated parameters used for modelling soil moisture dynamics

Symbol	Parameter	Description
K_{sat}	Saturated Hydraulic Conductivity	Hydraulic conductivity in saturation condition [cm/d]
b	Clapp-Hornberger parameter	Exponent of the Clapp-Hornberger low [-]
Kc_{in}	Initial Crop Coefficient	Crop coefficient value in the initial phase of plant life cycle [-]
α	Fraction of water input delivered from the surrounding sites	Parameter that consider fracture action [-]

Constant parameters:

- Root zone depth (Zr): Considering the positioning depths of the three probes and the greater development of the root system, it was considered a constant root zone depth of 40cm. Several preliminary model results have highlighted the best performance of model with a constant value of the root zone equal to 40cm. Deeper development of roots or soil compaction processes are not relevant and not taken into account during the entire period. The relative shallow depth of root zone, avoid any type of interaction with groundwater tables.
- Incipient stress point (ϑ^*): Observing the soil moisture dynamic measured by the six probes is evident that the evapontraspiration rate decrease under approximately the threshold of $\theta^* = 0,325$. When soil moisture fall below the incipient stress threshold the water content starts to decrease with an exponential behaviour.

- Wilting point (ϑ_w): It was assumed that on the whole acquisition period the plant never be completely stressed. This is a realistic assumption whereas plant never shows to be wilting and droughts where never long enough to allow drastic drops of soil moisture content.

- Porosity (n): The laboratory analysis gave a value of porosity in the range (0,44-0,48). However, preliminary analysis suggested to increase of the porosity value up to 0,5. The differences between the two values can be explained considering the practical impossibility to distinguish between the porosity (n) and the root zone depth (Zr). In water balance equation, the two parameters are strongly linked each other and physically represent the total void volume in the root zone. Approximately we can say that porosity should be equal to 0,45 while root zone is 45cm.

- Fracture time (t_1): Represents the time at in which fractures have appeared in the field. Superficial and underground fracture were observed especially in the Informed Site but most likely were present also in the Uninformed site. Fractures tend to form after drought periods and consist in soil enlargements macro pores and soil channels which can facilitate the redistribution of water among sites. Fractures were first observed between the second and third irrigations, during a drought period, hence it was decided to set t_1 equal to 1300 hour, (55 days).

- Crop coefficient ratios (kc_{mid}/kc_{in} & kc_{end}/kc_{in}): The ratio kc_{mid}/kc_{in} and kc_{end}/kc_{in} were fixed considering the crop coefficient values (k_c) suggested bay FAO manual [*Allen et al., 1998*] in order to reduce the number of calibrated parameters. The dynamics of the crop coefficient during the life cycle of a maize plant show constant values during the initial and middle periods and a linear trend between them and in the last period. The model does not consider linear variation of the crop coefficient but only uses three constant values. In order to take in consideration linear behaviour of kc, mean value are considered for initial and ending phases:

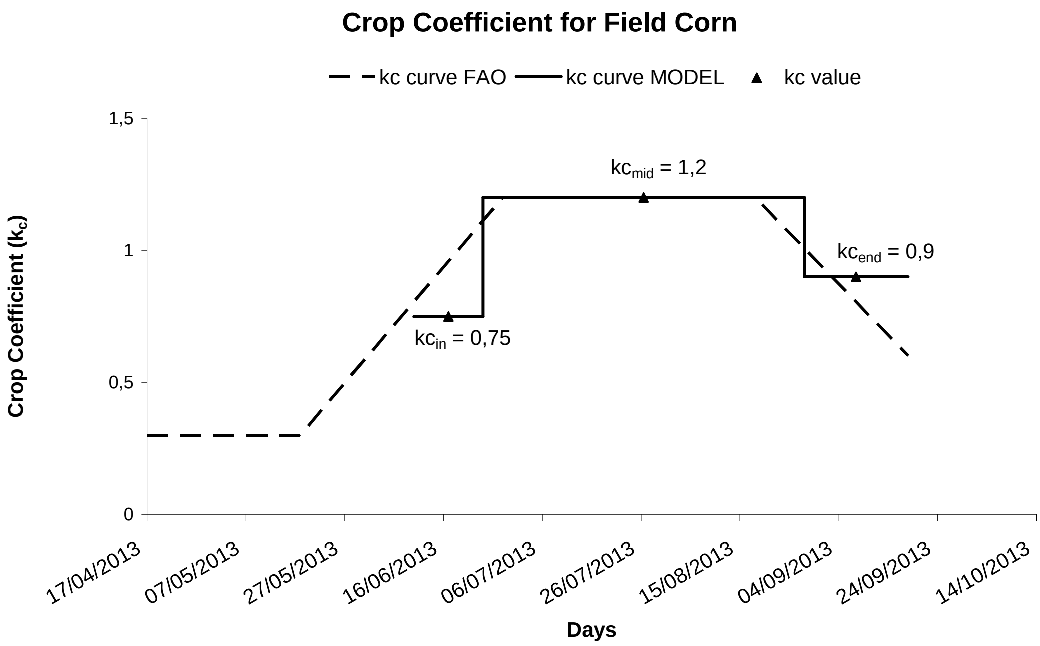


Figure 3.7 Crop coefficient curve for field corn plants

Under these assumptions, the initial crop coefficient (kc_{in}) defines the entire life cycle of the plant provided that the ratios kc_{mid}/kc_{m}=1,6 and kc_{end}/kc_{in}=1,2 are fixed as:

$$\frac{kc_{mid}}{kc_{in}} = 1,6 \qquad\qquad \frac{kc_{end}}{kc_{in}} = 1,2 \qquad (3.25)$$

- Initial and Middle growth phases (L_1-L_2): Indicate the length of each of the three growth period in which the plant life cycle is subdivided. In this study it was chosen an initial growth period associate at kc_{in} crop coefficient value of 15 days and a duration of the middle growth period associated at kc_{mid} crop coefficient value of 66 days. The last period of 20 days represent the ending period of the plant life cycle and it is associate with the kc_{end} crop coefficient.

Calibrated parameters:

- Hydraulic conductivity at saturation (K_{sat}): Hydraulic conductivity at saturation indicates the water flow velocity through a fully saturated medium. Root zone is quite always unsaturated, and then K_{sat} represent only the maximum value of water velocity. K_{sat} depends on soil properties like structure and texture which is assumed to be constant for entire period of acquisitions. Hydraulic conductivity leads the water losses through percolation in the deepest layer of the root zone.

- Exponent of Clapp-Hornberger low (b): The exponent determines the non-linearity degree of Clapp-Hornberger low.

- Initial crop coefficient (kc_{in}): Ratios between mid season and initial crop coefficients and between ending and initial crop coefficient were fixed. Initial crop coefficient kc_{in} during the initial growing period (L_{in}).

- Fraction of water delivered by surrounding areas (α): Represents the contribution of additional water inputs into control volume that flow through fractures. α is defined as a fraction of the total precipitation fallen in the surrounding areas of the considered site after fracture formation at t_1. Considering the position of the two sites α acts only on rainfalls and uninformed irrigations for the Informed parameters calibration and on rainfalls and both uninformed and informed irrigations for the Uninformed parameters calibration. The parameter α influences the inputs like described by the following equations:

$$P_{tot,\inf}(t) = P_{\inf}(t) + R_{\inf}(t) + \alpha \cdot (P_{un\inf}(t) + R_{un\inf}(t))$$
$$P_{tot,un\inf}(t) = P_{un\inf}(t) + R_{un\inf}(t) + \alpha \cdot (P_{un\inf}(t) + R_{un\inf}(t) + R_{\inf}(t)) \qquad (3.26\text{-}3.27)$$

The total amount of inputs during the second period ($t>t_1$) in the Informed Site is calculated summing rainfalls and informed irrigation water depths to a fraction (α) of the total input in the surrounding areas irrigated with traditional method. This latter fraction represents the water delivered to the Informed Site by the surrounding areas through fractures. In the same manner, the total amount of inputs during second period in the Uninformed Site is calculated summing rainfalls and uniformed irrigation water depths to a fraction (α) of the total input in the surrounding areas which include both Informed Site and other portion of field irrigated with traditional method. While rainfall inputs are simultaneous all over the field, irrigation in Informed Site is delayed of 4 hours with respect to that applied in the Uninformed Site.

Not all the parameters can be estimated through laboratory analysis, part of them can only be meaningfully derived by calibration. The parameters are calibrated in such a way that the model reproduces consistently the observed data measured by probes. For this purpose it was used a Markov Chain Monte Carlo (MCMC) simulation, an algorithm for the sampling of high-dimensional posterior distribution. MCMC searches the minimal discrepancy between the model predictions and observations. This can be done mathematically by minimizing the square errors between model and observations. The basis of the MCMC method is a Markov Chain that generates a random walk through the search space with stable frequency stemming from a fixed probability distribution. DREAM algorithm uses a multiple chains, three in this case, significantly enhances efficiency [*Vrugt and Braak*, *2008*]. This type of method is susceptible to over-parameterization with the consequence of deteriorating the forecasting capabilities of the model. Calibration was performed considering the daily mean soil moisture content because of the different time step used between model (dt=1h) and TDR instrument (dt=2h and dt=15min during irrigation). Calibration, of the whole set of parameters, was performed considering vertical mean averaged along the root zone in the Informed site. The calibrated set of parameters was after applied to the Uninformed site (*Chapter 4*). A small adjustment using MCMC were necessary to have a better modelling of the uninformed measured data. In this latter case the calibration was performed only on two parameters: porosity and α.

Primary search spaces for each parameter were defined in the Informed Site:

Table 3.5 Search spaces for MCMC calibration algorithm

Parameter	Min Value	Max Value	Note
K_{sat}	0 cm/d	240 cm/d	From clay to sand K_{sat} range
b	0	100	
kc_{in}	0	3	
α	0	1,5	Unknown surfaces of the field involved

Chapter 4

Model Results

The calibration of the model parameters on Informed Site provided the values reported in *Table 4.1 and 4.2*:

Table 4.1 Standard Parameter Set for Informed Site

Parameter	Calibrated Value
K_{sat}	94,2 mm/h
b	33,4
kc_{in}	0,61
α	0,57

Table 4.2 Porosity in Informed Site

	Value
n	0,5

This parameters set was labelled as “Standard Parameter Set”. Root mean squared error R was considered to evaluate the model performance. Obtained time series with daily means values are reported in *Figure 4.1*. The figure shows that the minimalist model is able to reproduce well ($R \approx 10^{-2}$) the soil moisture dynamics measured from the Informed probes. This means that the calibrated parameters are representative of the soil and vegetative properties of the investigated site.
An overestimation of the evapotranspiration rate is visible before the second irrigation while an underestimation occurs afterwards. The differences, between calculated and observed values, can be explained through an erroneous estimation of Et_0 in this period by the Penman-Monteith equation. Furthermore, this period is interested by fractures formation, which were conveniently assumed to take place on August 3 even though a state of incipient soil failure was observed also during previous days. Non-uniformity of water application and imminent fracture formation could may have driven some water redistribution phenomena that cannot be simulated by a simple water-balance model of the type employed in this paper.

The parameter α moves fundamental to simulate soil moisture dynamics in the last part of the experiment. Without the additional water input implied by α, the water content calculated by the model would be largely overestimated. This means that the two plots, 30m apart from each other, were hydraulically connected and this interaction was further enhanced by fractures. Fractures have supplied water to the two plots from surrounding sites. Hence the soul moisture jumps are disproportionated to the input delivered to the considered sites. α represent the fraction of precipitation (or irrigation depth fell into the Uninformed Site) that reaches the Informed Site through fractures. The 57% of the Informed Site through soil fractures. Fractures features like dimensions, depths, lengths or functioning are unknown, so the influence of fracture on the water balance can be described only through a calibration parameter α. On August 25 events, the model overestimates the soil water content probably due to a incorrect rainfall rate distribution related to a lack of information or because of interception phenomena. The saturated hydraulic conductivity K_{sat} and the exponent b obtained from calibration, are higher with respect to the parameter typically associated a clay loam of the type observed in the filed, indicating an higher percentage of sand in the first 40cm of soil. The value of K_{sat} indicates a moderately infiltration rate through the deeper soil layer in the Informed Site while crop coefficients are included in the range suggested by the FAO manual for maize plants.

The standard parameter set was also applied to the Uninformed Site. A small adjustment of the porosity was necessary to account for small heterogeneity in soil properties between the two different sites. Calibration on porosity value ranging [0,45 0,55] gives a result of 0,52. The calibration in the Uniformed Site was performed based only on the first 65 soil moisture. The lack of information in the ending period do not allow for a comparison between measured and predicted data, but the good agreement between model observation during the first 65 days is considered sufficient to infer the reliability of the model forecasting in the last part of the simulation (*Figure 4.2*). In this site a different temporal distribution of the crop coefficient was used in order to take to account the different height of plants at the beginning of the acquisition period. So, initial crop coefficient was set to be equal at the middle season crop coefficient. The standard deviation root mean square error for the first 65 data is lower than that obtained in the Informed Site ($R=1,8 \cdot 10^{-2}$). The worse performance of the model are probably due to small differences in soil properties. The results obtained are tough judged satisfactory. Values of soil moisture calculated in the Uninformed Site are generally higher than that obtained in the Informed Site. This fact can be justified considering the large amount of water delivered through irrigation and the higher porosity. In accordance to what observed in the Informed Site, and for the same reasons already discussed earlier, evapotranspiration is underestimated during the period between the second and the second irrigation.

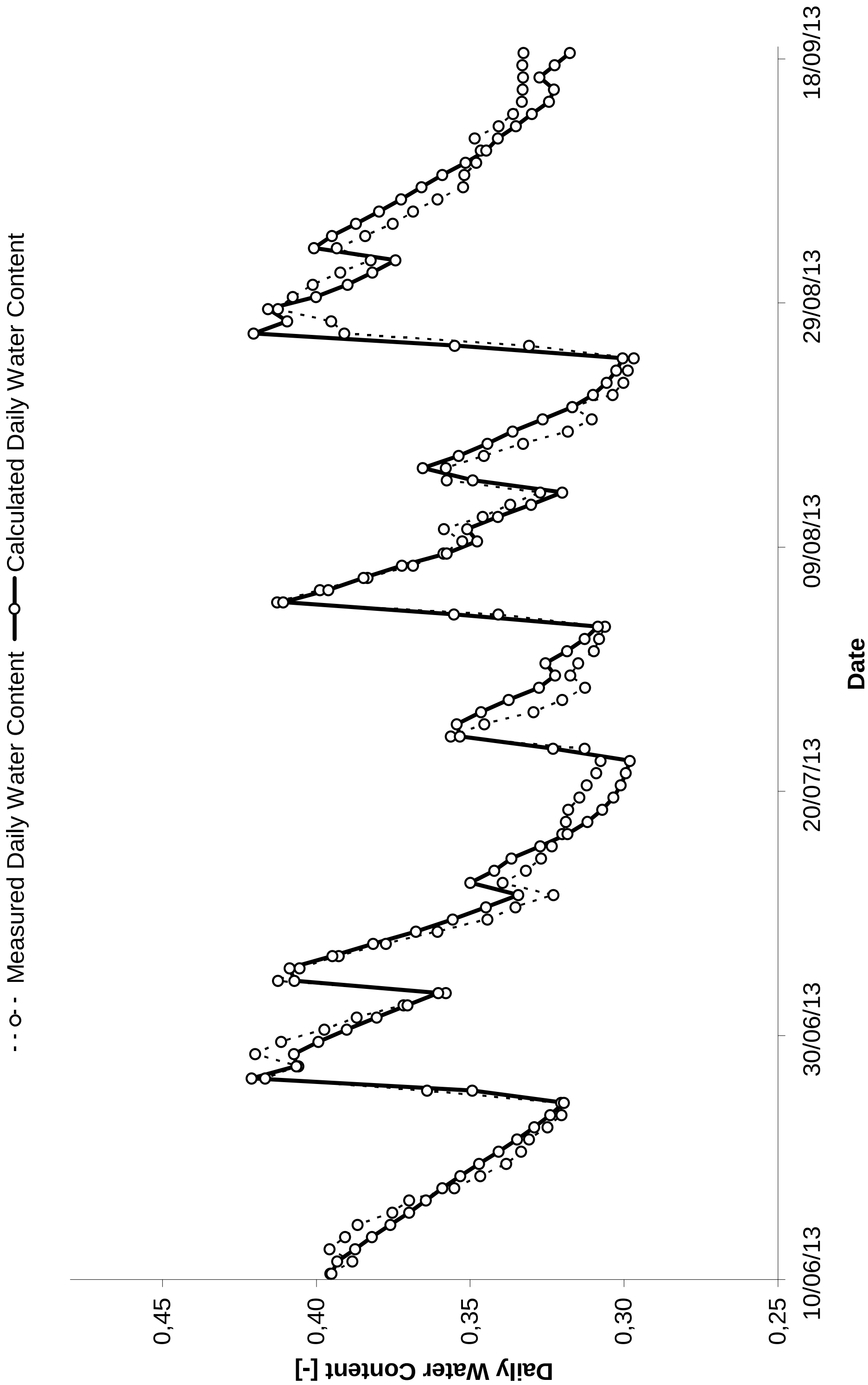


Figure 4.1 Daily water content calculated by model (continuous line) and measured (dashed line) in Informed Site during the whole acquisition period

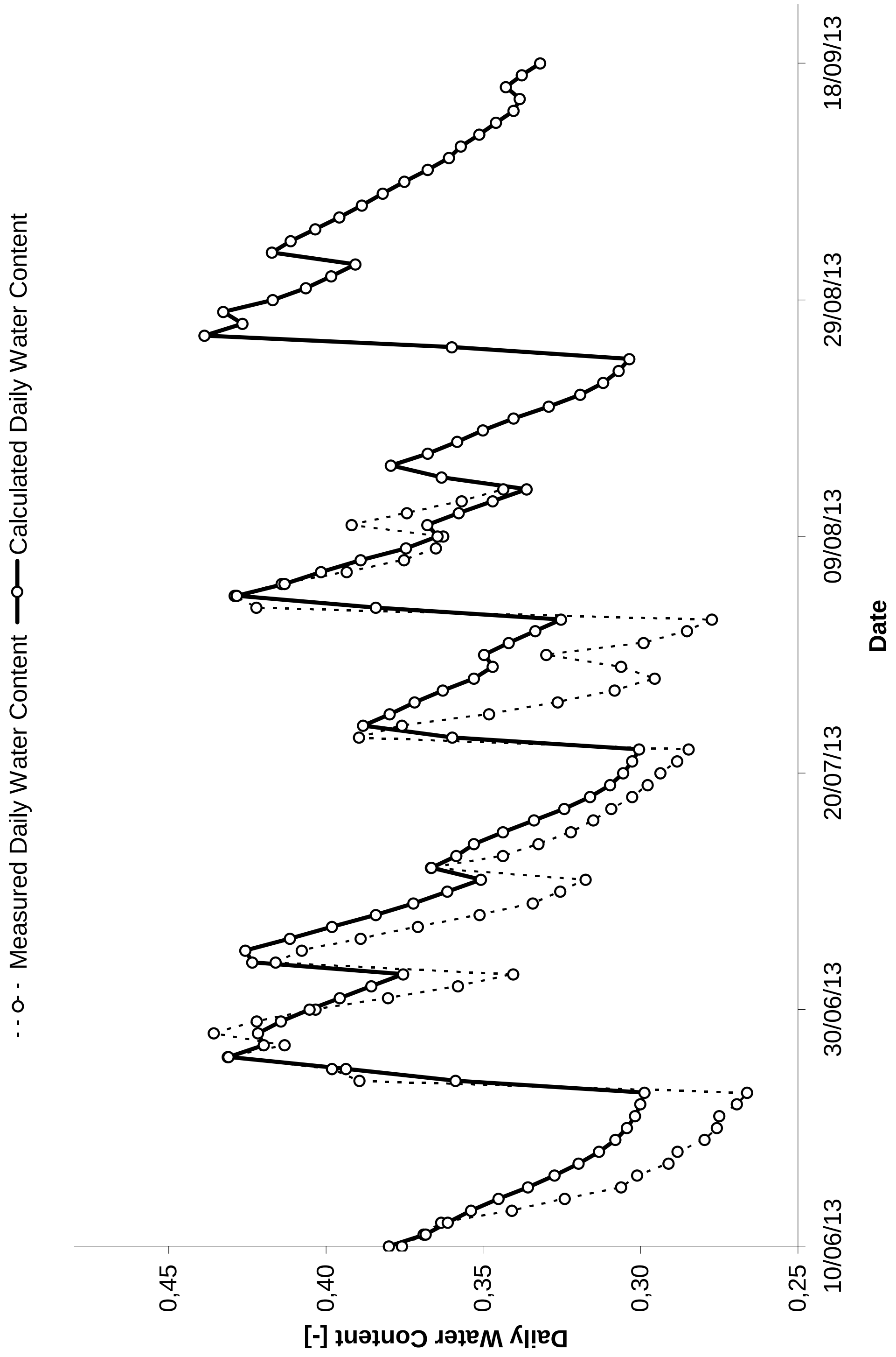


Figure 4.2 Daily water content calculated (continuous line) and measured (dashed line) in Informed Site during the whole acquisition period

4.1 Rainfall and Irrigation Events

The Standard Parameter Set was applied also to single events in order to assess the model capability of reproducing soil moisture dynamics at sub-daily timescales (minutes). For this purpose a set of significant events was considered: two rainfall events (on July 4 and August 25) and three irrigation applications June 25, July 23 and August 3. In these simulations, the input/output hydrologic fluxes are provided at sub-daily timescales. For the whole period of acquisitions, rain gauge has measured the cumulative rain depth during all events but no information about the time variability of rain intensities is available. Then, the hourly distribution of rain depth measured by a meteorological station nearby was used, to obtain the hourly distribution of rainfall (*Figure 4.3*). Accordingly, the reference evapotranspiration was evaluated using hourly meteorological data accounting for day-night cycles of temperature humidity and solar radiation. Therefore, the reference evapotranspiration is not constant during the whole day. An example of Et_0 variation in a day of the interested period is reported in *Figure 4.4*.

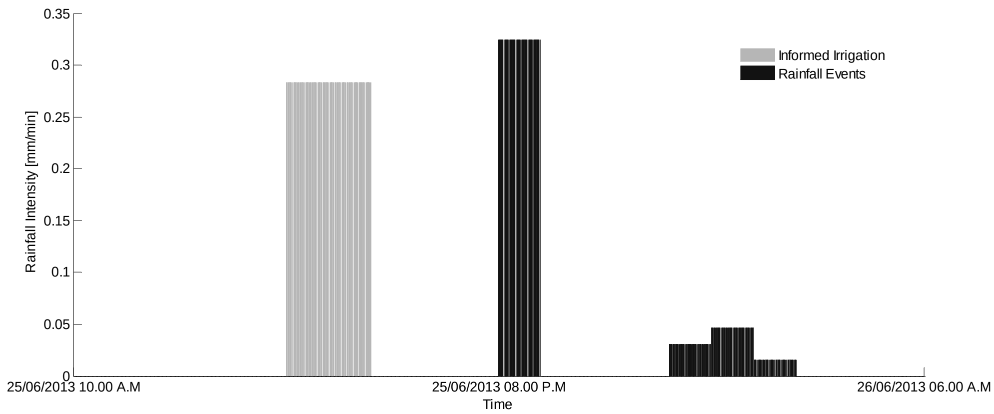


Figure 4.3 Example of rain intensities distribution (black bars) and irrigations (grey bars) in an event.

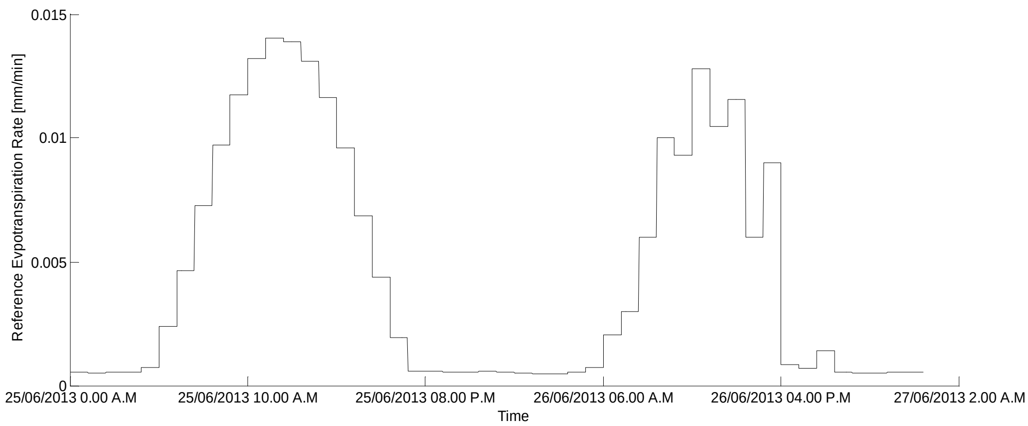


Figure 4.4 Example of reference evapotranspiration (Et_0) in an event

Soil moisture dynamics in the Informed and Uninformed sites during the various events identified are discussed in the following sections.

First Irrigation (June 24-26):

On June 24 the farmer decided to deliver to the Uninformed Site 40mm of water. The irrigation, performed with the hose reel, started at 9.00 AM and lasted for 44 minutes. In the following days, the observed soil moisture observations suggest to irrigate also the Informed Site: irrigation started at 3.25 PM on June 25 and finished after 83 minutes, delivering 34mm of water on the field. The same day, at 7.55 PM an unexpected rainfall 25mm of rain in almost 4 hours. The comparison between observed soil moisture and the time series of soil water content provided by the model applied with the standard parameter set is shown in *Figure 4.5.*

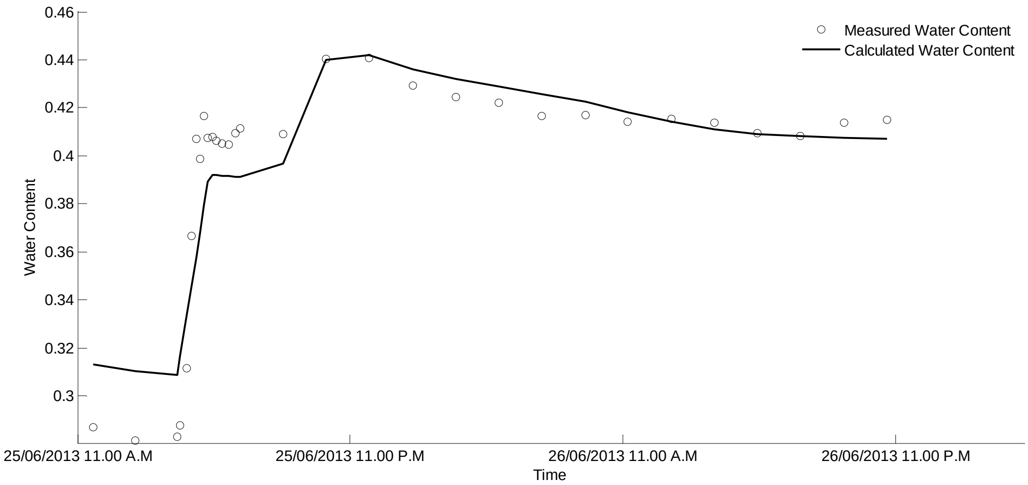


Figure 4.5 Application of Standard Parameter Set on June 25 events in Informed Site

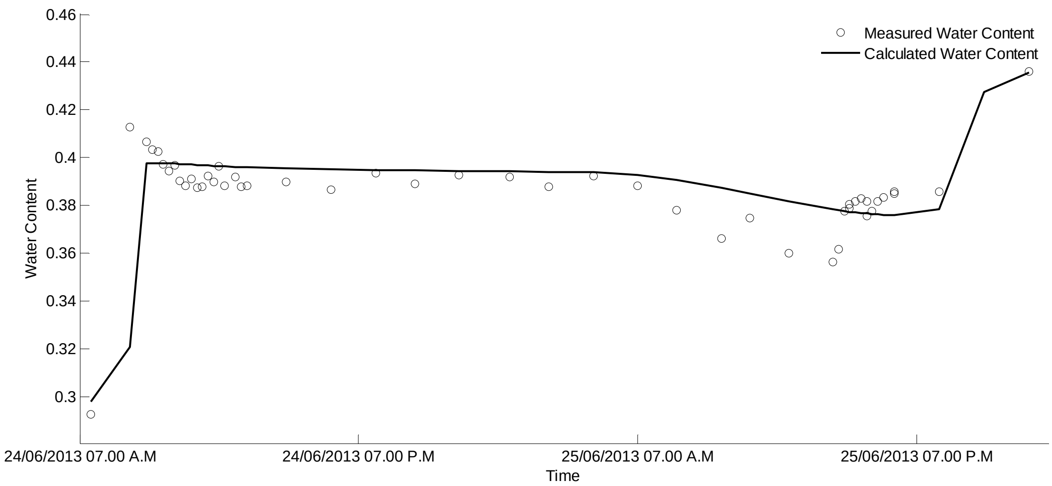


Figure 4.6 Application of Standard Parameter Set on June 25 events in Uninformed Site

The initial value of soil moisture is defined based on the results from the Daily Model. High frequency fluctuations of the observed soil moisture in the Uninformed Site are a clear sign of hydraulic connections between the monitored site and the surrounding soil, as well as water redistribution.

Rainfall Event (July 4):

On July 4an important rainfall event brought 40mm of water all over the crop field from 5.32 AM to 11.00 AM. The simulation started at 00.01 AM of July 4 and finished at 11.59 PM of July 5.

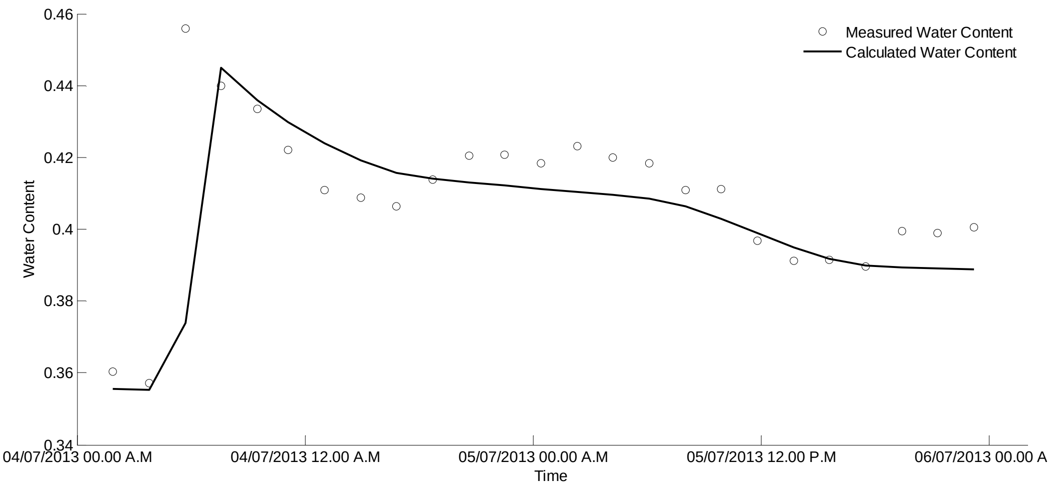


Figure 4.7 Application of Standard Parameter Set on July 4 events in Informed Site

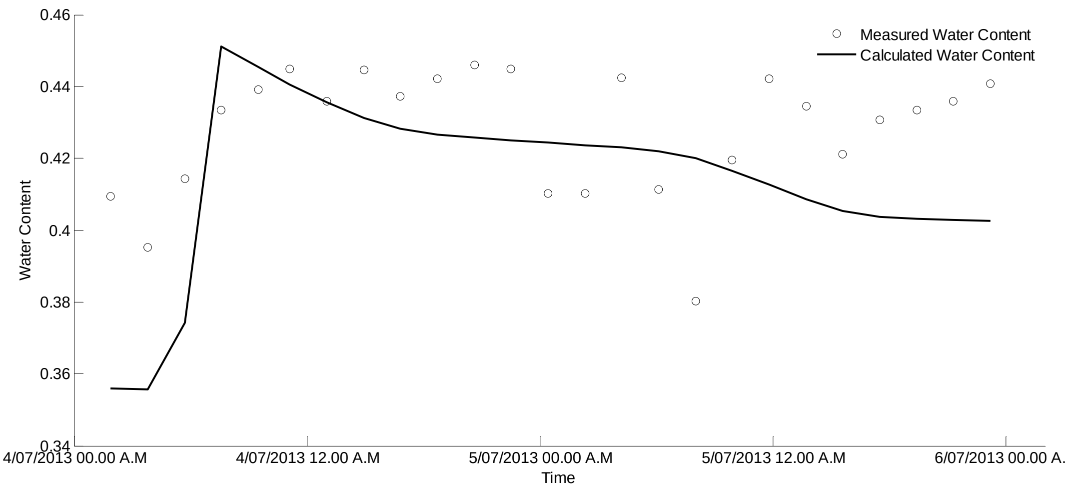


Figure 4.8 Application of Standard Parameter Set on July 4 events in Uninformed Site

This is the most important rainfall event of the monitoring period, where a direct comparison between the two different sites response is allowed. The simulation reproduces quite well the pattern of observed data in the informed site while in the Uninformed Site some evident soil moisture fluctuations from July 4 to July 5 were not properly reproduced by the model. Considering that no calibration was carried out during the events, in view of the simplicity of the model used, the performances obtained are judged satisfactory. Furthermore, the delay of picks are due to a distribution or, also, to the presence of ponding.

Second Irrigation (July 23-24):

Second irrigation was delivered on the Uninformed site at 9.25 AM of 23rd June to avoid water losses through excess of evaporation. The irrigation in Uninformed site had a duration of 21 minutes bringing, like, 40mm of water (*Figure 4.10*). A few hours later also Informed site was irrigated by delivering an amount o 20mm of water in 12 minutes. Because of the reduced increase of soil moisture in the Informed site, it was decided to deliver other 10mm at 9.17 AM on June 24. (*Figure 4.9*). Daily Model has just highlighted the difficulties encountered during the reproducing of the second irrigation period. This problem is enhanced at minute time scale in particular during the second part of the irrigation in Informed site. As just mentioned before, this is because a multiplicity of causes like evaporation, during the first application, performed in the hottest hours of the days and high wind velocity which cannot assure the uniformity of irrigation. In fact, the first observed jump of soil moisture is lower than the second in spite of the larger amount of water provided. In the Uninformed site this problem seems to be less evident maybe because of the irrigator. In fact, larger sprinklers may allow for higher efficiencies also during windy days.

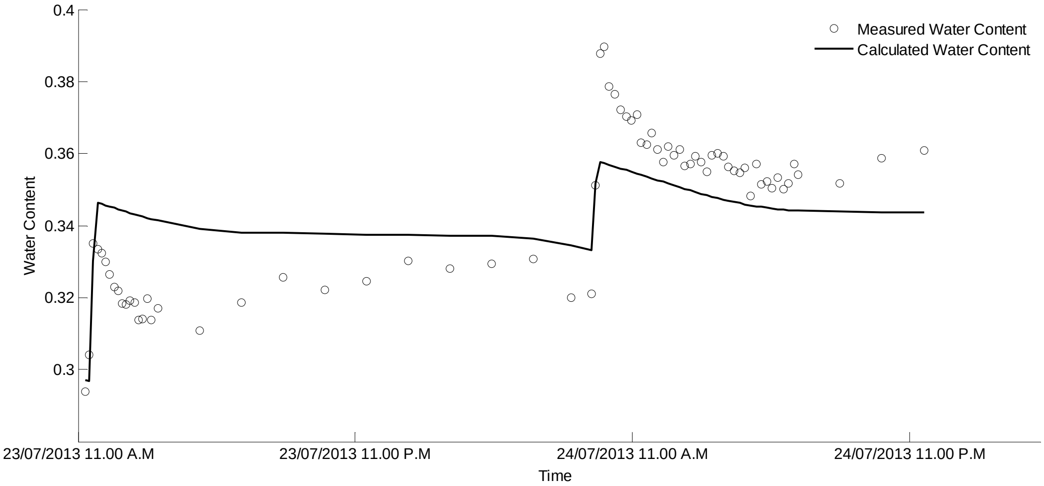


Figure 4.9 Application of Standard Parameter Set on July 23 and 24 events in Informed Site

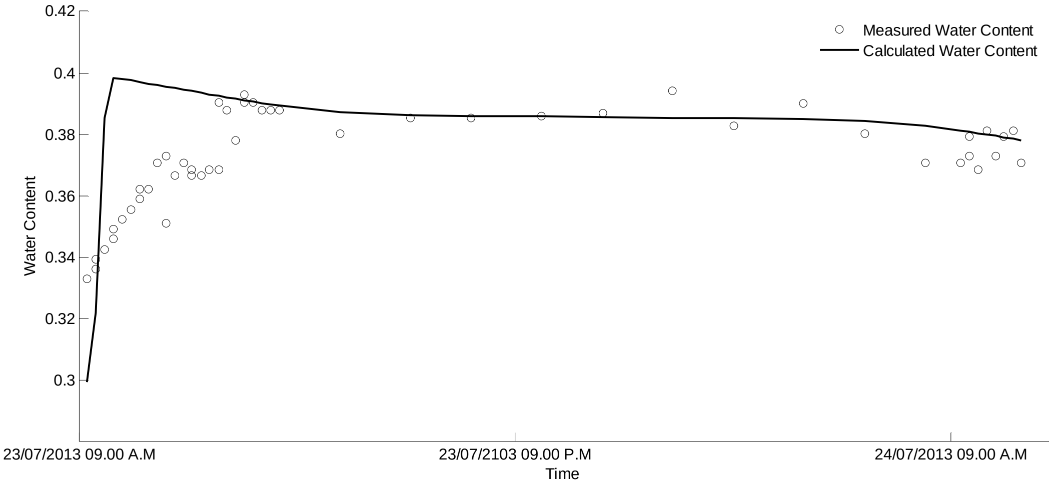


Figure 4.10 Application of Standard Parameter Set on July 23 and 24 events in Uninformed Site

Third Irrigation (August 3):

The third irrigation was performed right after the fracture development, on August 3 at 12.00 AM for the Uninformed site and at 4.40 PM for the Informed site. The water amount delivered to the Uninformed site was 40mm, distributed in 23 minutes while the Informed site received 30mm in the same period. From the plots shown in *Figure 4.11* and *Figure 4.12* general agreements between calculated and measured data can be noticed in both the monitored sites. Moreover the plots graphs, evidence the interaction between the two sites during the irrigation application, enhanced by fractures.

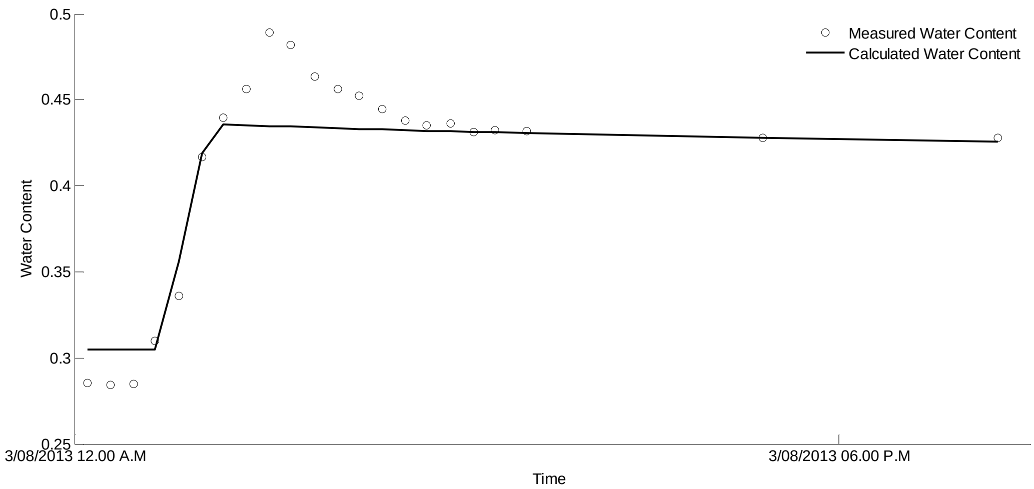


Figure 4.11 Application of Standard Parameter Set on August 3 events in Informed Site

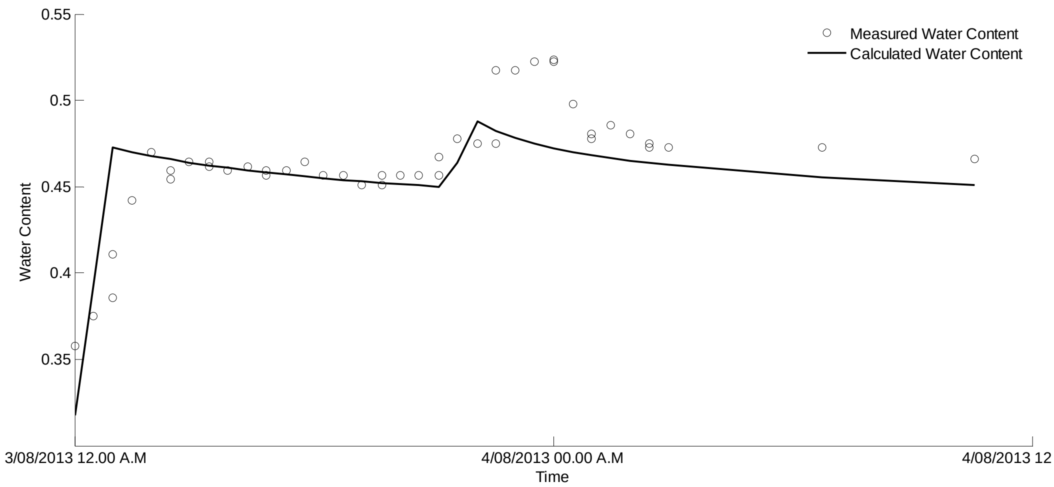


Figure 4.12 Application of Standard Parameter Set on August 3 events in Uninformed Site

In the Informed site simulation a delay of 4 hour was applied to the uninformed irrigation application in order to make simultaneous the two events. This delay represents the time required to the water to move from the surrounding zones to the informed probes. Informed probes have not registered any jump of soil moisture in the hour before the Informed irrigation, but the jump registered during Informed irrigation is higher than that expected considering the water amount delivered on this site. This can be explained considering a simultaneous water input in to the control volume both through the surface (Informed irrigation) and fractures (Uninformed irrigation). In the Uninformed simulation the amount of water able to reach the uninformed probes coming from the Informed site is very fast. In fact, Uninformed probes, has registered a very quick response meanings that the site where the probes are positioned is strongly influenced by the Informed inputs. Is not possible to better describe the features of the water flow because of the lack of information about fractures and areas involved. The right amount of water that flows from a site to another and its velocity are regulated by a series of soil hydraulic and structure properties and also by contribution surfaces extent that cannot be easily and properly estimated in this case. The water flux that bring water from Informed site to the Uninformed probes probably flows through larger superficial soil fractures and the water flow is enhanced by the gently slope of the crop field. Maybe, the amount of water able to reach the Informed probes, comes form the surrounding areas through deeper and slower fractures system.

Rainfall Event (August 25)

The last important event was observed during 25th August night. A very intensive rainfall brings 33mm of water in few hours. In this case the simulation was performed only on the Informed site because of the malfunctioning of the sixth probe in the Uninformed site during this period. The simulation starts at 9.00 PM and finish at the end of the following day. In the end of the simulation another small rainfall event bring 3,5mm of water at 7.30 PM.

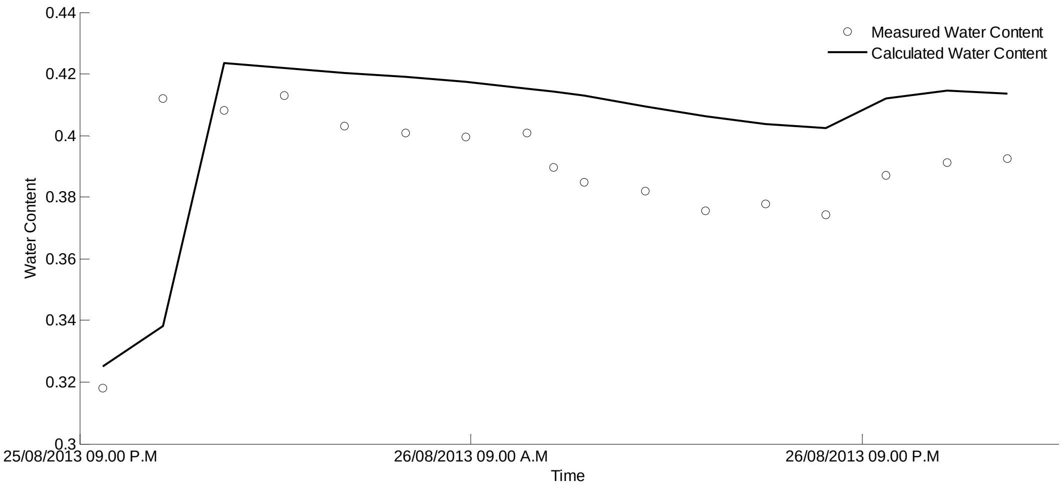


Figure 4.13 Application of Standard Parameter Set on August 25 and 26 events in Uninformed Site

In this case infiltration rate was decreased in order to simulate an higher water losses during the event. This variation can be not due to a variation of interception phenomena but to an higher evapotranspiration rate. In fact, during night hours, the solar radiation is null, so the Et_0 calculated with Penman-Monteith equation is minimum. Probably, in this case the equation not simulates well the evapotranspiring processes and effective Et is higher. Another explanation can be done considering the effect of fracture on leaching term. In fact, fracture can have locally and temporally increase the hydraulic conductibility of the soil increasing the water losses. Simulation on the Uninformed site is not significant because of the averaged data available for this period are obtained by a model prediction and a comparison with observed data is then meaningless.

4.2 Water Balance

Inserting *Equation 3.25* for the evaluation of the leaching term L, and *Equation 3.23* evapotranspiration in the water balance (*Equation 3.1*), the following differential equation is obtained:

$$n \cdot Zr \cdot \frac{ds(t)}{dt} = I[s(t),t] - ks[s(t)] \cdot ET_c - K_{sat} \cdot s(t)^b \qquad (4.1)$$

In between events infiltration is equal to zero, so the mass balance equation can be rewritten as:

$$n \cdot Zr \cdot \frac{ds(t)}{dt} = -ks[s(t)] \cdot ET_c - K_{sat} \cdot s(t)^b \qquad (4.2)$$

In this cases s(t) decreases in time depending on the evapotranspiration and leakage on climate variations. The leakage term is activated only when s(t) is greater than s_{fc} hence, if s(t) is comprised between s_{fc} and s*, Et_c is constant and equal to 1, meaning that evapotranspration removes a constant amount of water, producing a constant decrease of soil moisture content. When s(t) is comprised between s* and s_w, ET = $ksET_c$ and ET has a linear behaviour while the solution of the differential equation is an exponential dynamics of s. In the worst case, if s(t) is lower then s_w, ET is zero. The decreasing of s is higher when the soil is close to saturation and then leaching process is activated, so when s(t) is higher than s_{fc}.

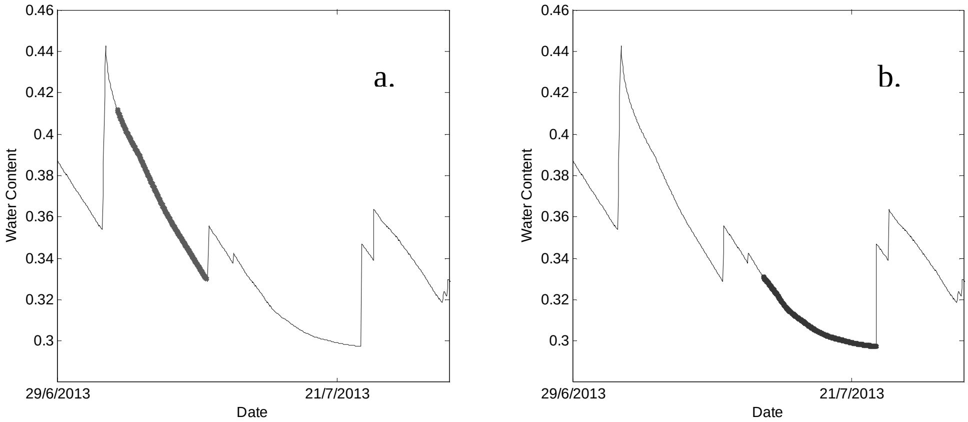


Figure 4.14 Examples of linear (a) and exponential (b) behaviour of soil moisture during dry periods

During rainfall events, ET and L are much smaller than the infiltration rate I [s(t),t] and the mass balance equation becomes:

$$n \cdot Zr \cdot \frac{ds}{dt} = I[s(t),t] \tag{4.3}$$

The typical response of soil moisture to a rainfall event is a sharp increase, clearly visible in *Figure 4.15*. In the following we discuss in more details the different input rates that form the water balance equation.

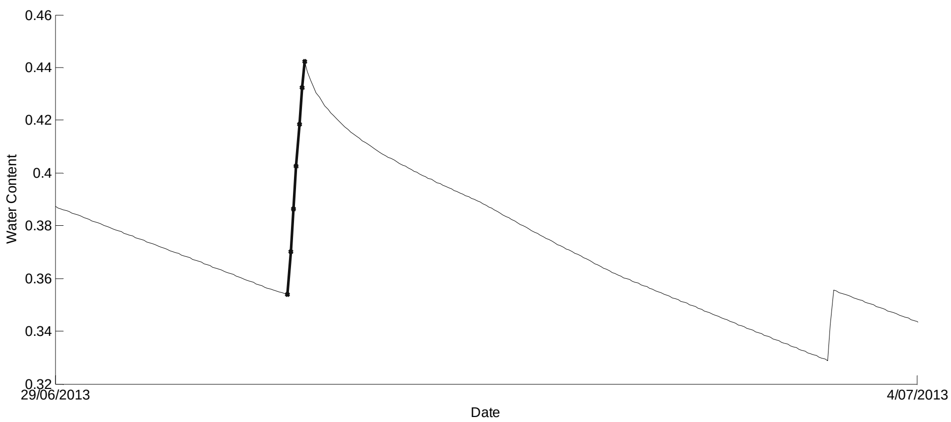


Figure 4.15 Examples of soil moisture "jump" during rainfall event

Infiltration rate I[s(t),t]:

Rainfall and irrigation rates are defined as a function of the time and specified at different timescales depending on the simulated scenarios. Rainfall data are available at hourly intervals. Sum of this two entities describe the overall amount of water delivered on the field by the precipitation. Rainfall is a random event while irrigation timings and amounts were decided by the farmer, for the Uninformed site, and considering the water content deficit for the Informed site starting the 55th day to the end of the calibration parameters acquisition period, α plays a crucial role in the definition of the infiltration term. In fact, an important amount of water has flowed underground through fractures representing another source of water input for the two sites. Is not possible to precisely define the right extent of the two areas that contribute to increase the water input in the localized control volumes, because of the complexity of the fracture system and their functioning in the crop field. Considering the whole period of acquisition, the infiltration rate is equal to the precipitation rate because no overland is produced, and all the water fallen on the both sites through irrigation or rainfall events is able to infiltrate into the soil. Cumulative water infiltration through ground surface or control volume soil boundaries, including the contribution of the calibrated parameters α at minutes and daily time scale, on the whole period of acquisition, are reported in the following graphs for both sites:

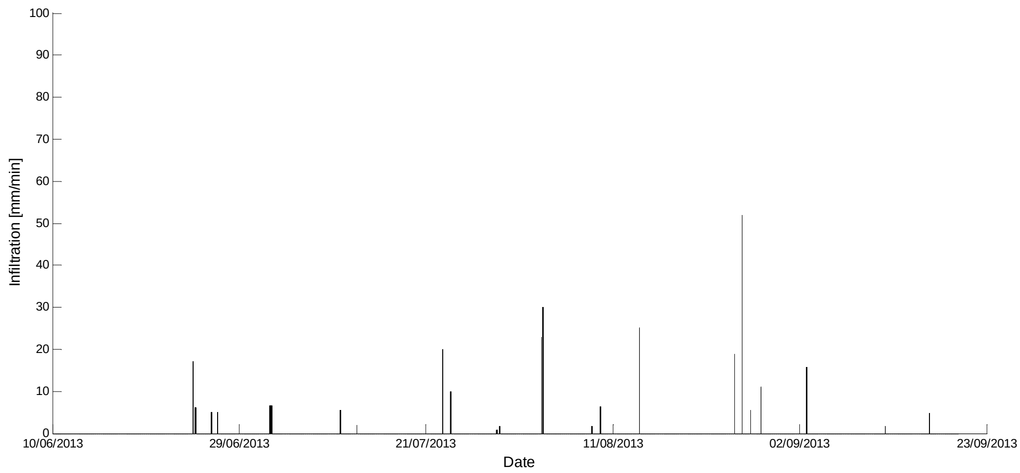


Figure 4.16 Hourly infiltration depth in Informed Site during the whole period of acquisitions

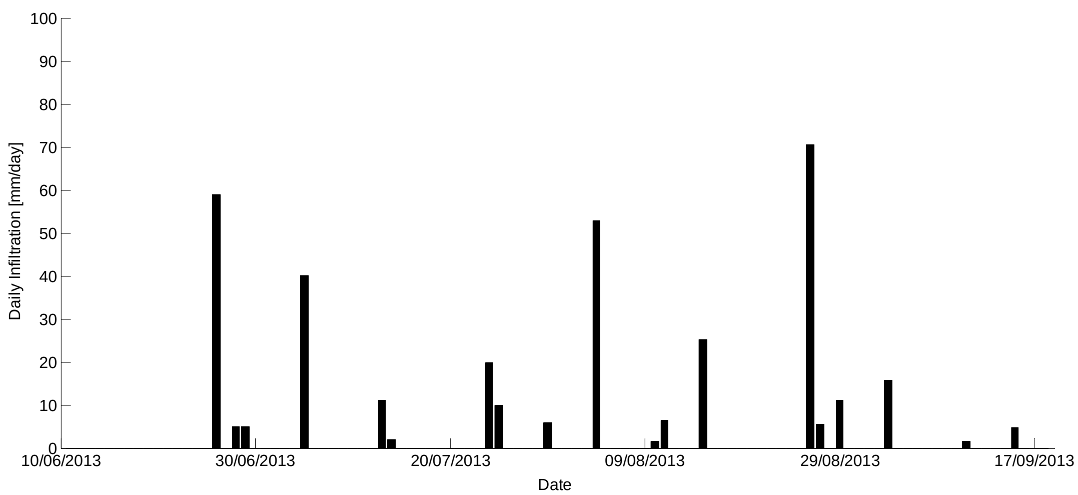


Figure 4.17 Daily infiltration depth in Informed Site during the whole period of acquisitions

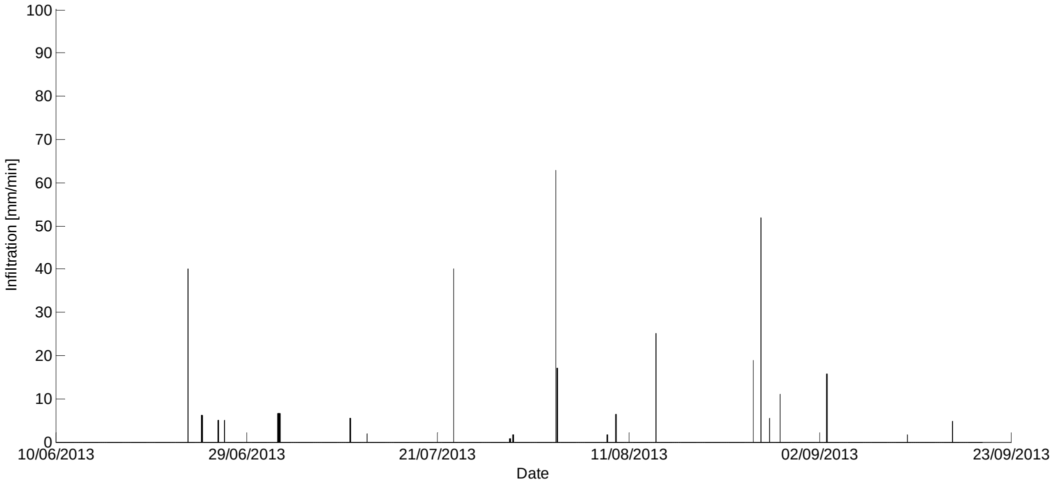


Figure 4.18 Hourly infiltration depth in Uninformed Site during the whole period of acquisitions

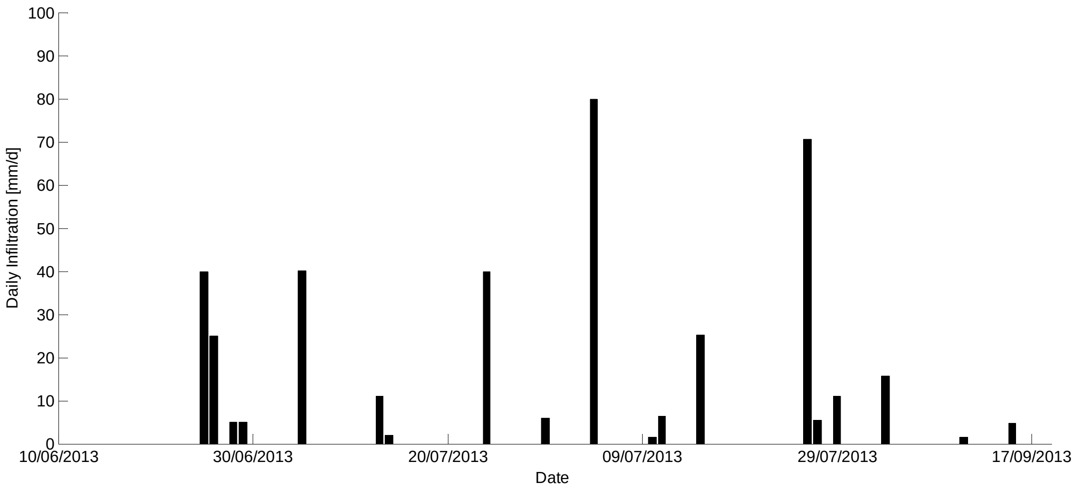


Figure 4.19 Daily infiltration depth in Uninformed Site during the whole period of acquisitions

Evapotranspiration: ET[s(t),t]:

Reference evapotranspiration Et_0 in the Daily Base Model was evaluated using the Penman-Monteith equation starting form daily average meteorological data. This means that the value of Et_0 is constant, for the entire day and the fluctuations due to the day-night alteration cannot be simulated. This simplification can be done only in a daily base model where the calibration is performed considering the daily mean value of the soil moisture. In the event model a mean value of Et_0 is not representative and fluctuations of solar radiation, temperature and humidity have to be taken into account to better reproduce the daily soil moisture dynamics. This can be noticed in rainfall event fallen during night hours or irrigation application which have delivered water in the hottest hour of the days. Potential evapotranspiration Et_c is defined in function of the crop coefficient which assumes the values 0,61, 0,98 and 0,73 during respectively the initial, middle and end growing periods. The change of growing period is noticeable considering the slope of soil moisture decreasing during no-rain days in no-stress conditions. The middle season period start on 24th June and ending on 28th August is characterized by an high decrease of the soil moisture slope due to the higher value of crop coefficient and thus ET_c. In this season the plant carbon assimilation rate is maximum.

Actual evapotranspiration Et is, finally, dependent on the actual value of saturation. Evapotranspiration is potential when the soil moisture is above the incipient stress point s* while it is null when soil moisture drops down under the wilting point stress s_w. When the soil moisture is between s* and s_w actual evapotranspiration decrease linearly with the decreasing of water content from a maximum value equal to Etc (s(t) = s*) to a null value (s(t) = s_w). *Figures 4.20-4.21* show the relationship between the three different evapotranspiration calculated by FAO method: blue areas indicate the reference evapotranspiration, red areas the potential maximum evapotranspiration of the considered maize field, while green areas is related to the actual evapotranspiration rate taking into account the water availability in the soil. In the graphs the presence of some red areas indicates that the evapotranspiration is not always maximum and the maize plants have been stressed in some periods. Furthermore, the presence of blue areas all over the whole period indicate that the maize plant evapotraspires at a lower rate with respect to the reference grass crop.

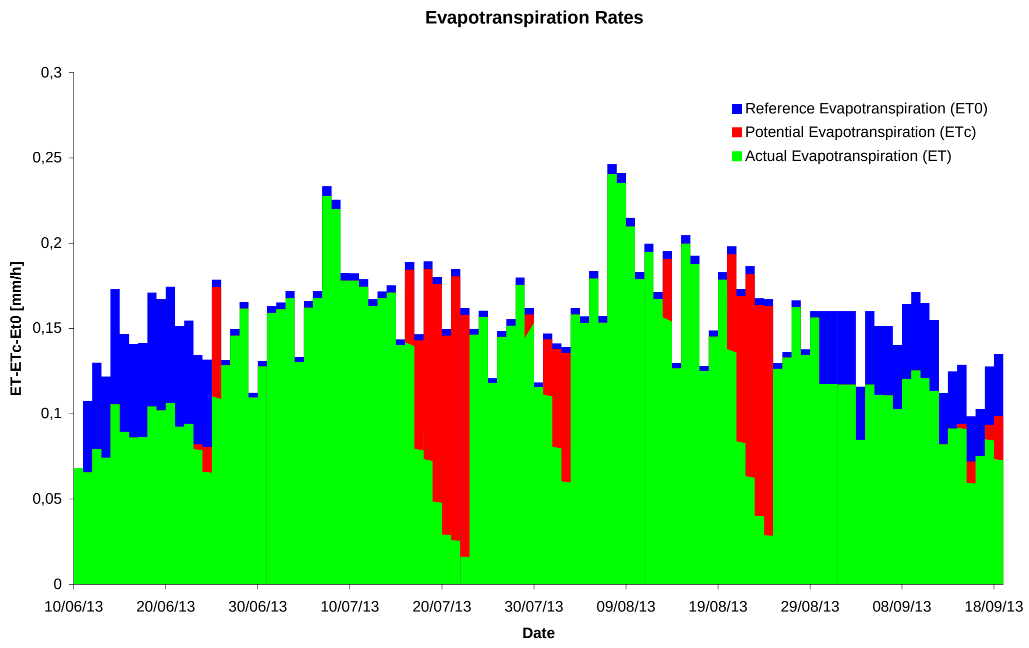


Figure 4.20 Relationship between hourly Reference Evapotranspiration Et_0 (blue areas), Potential Evapotranspiration Et_c (red areas) and Actual Evapotranspiration Et (green areas) in the Informed Site for the whole acquisition period

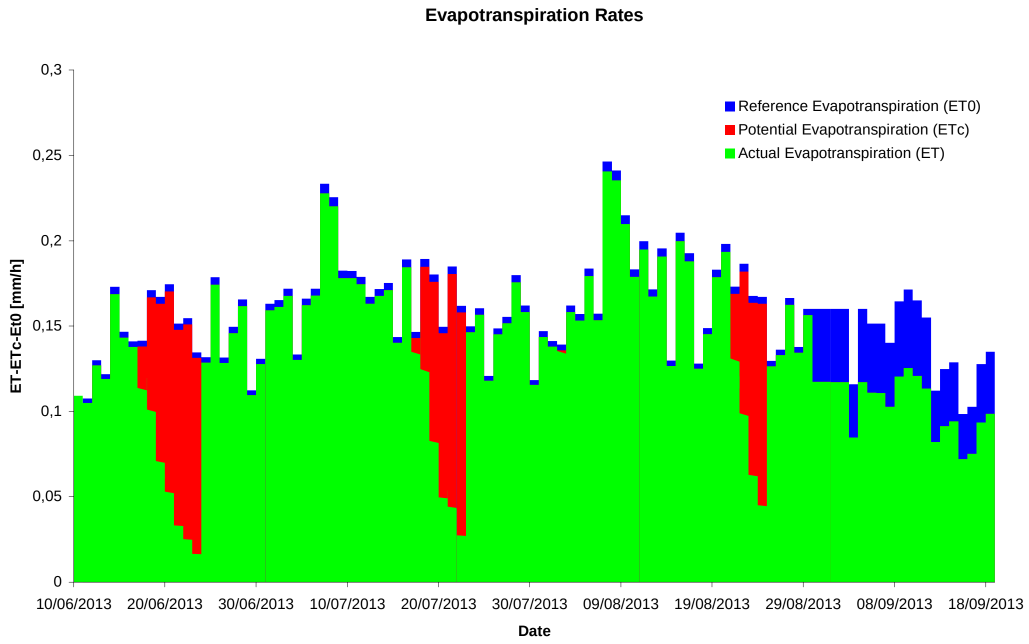


Figure 4.21 Relationship between hourly Reference Evapotranspiration Et_0 (blue areas), Potential Evapotranspiration Et_c (red areas) and Actual Evapotranspiration Et (green areas) in the Uninformed Site for the whole acquisition period

Climate condition of temperature, solar radiation and relative humidity are considered the same for both sites. The differences in the duration of stress periods between the two sites are then due to different soil water content, and in the initial phase, to the larger site of the plants in the Uninformed Site. Considering the daily value of Et_c, calculated summing the entire hourly Et_c in a day, is possible to highlight the different seasons of growth of the maize plant defined by the three values of the crop coefficient. Potential evapotranspiration depends only on climate data of the site and on the growing season.

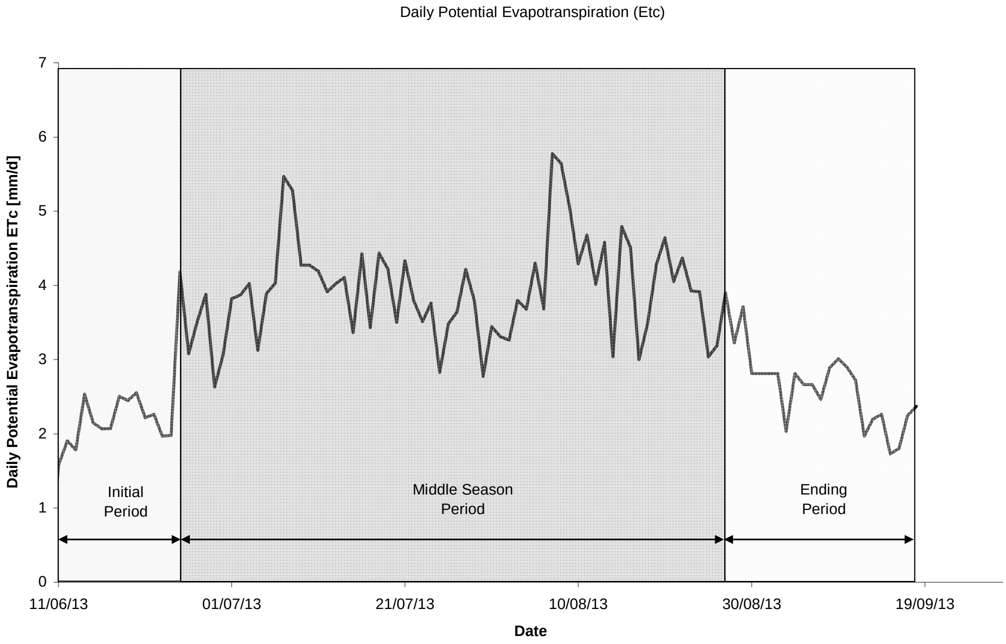


Figure 4.22 Daily Potential Evapotranspiration Et_c in different growing seasons for the Informed Site

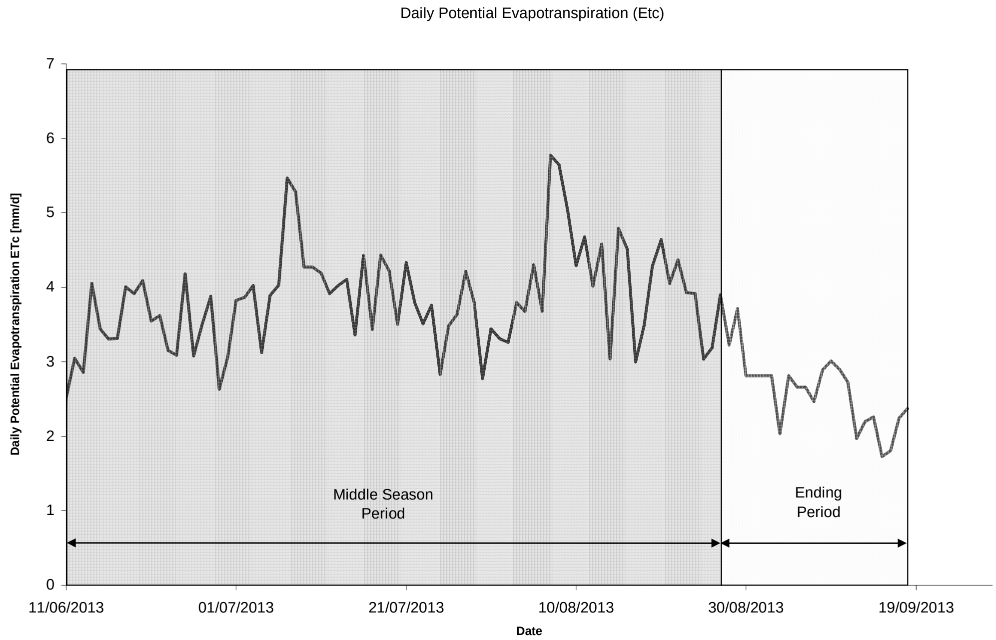


Figure 4.23 Daily Potential Evapotranspiration Et_c in different growing seasons for the Uninformed Site

Leaching [s(t),t]:

Percolation phenomena trough the deeper soil layer is lead by soil capacity s_{fc} threshold. This value is intrinsically defined by the combination of parameters K_{sat} and b describing the Clapp-Hornberger low. The Higher is b the greater is the rate with which the leakage reaches the K_{sat} threshold, while the higher is K_{sat} than higher is the maximum leaching rate. Increasing the value of the exponent the soil capacity threshold increase and the leaching phenomena activate at higher soil water content. The same effects can be achieved by increasing K_{sat}. Calibration assigns a value of 94,2 mm/h to K_{sat} and a b value of 33,4. These values identify a soil capacity s_{fc} of 0,407 for the Informed Site and of 0,425 in the Uniformed Site. This small difference can be attributed to the different characteristics of the soil of the two sites, and not probably to porosity.

Figures 4.24-4.25 show how the leaching process is activated only during rainfall or irrigation applications when the soil moisture exceeds the value of s_{fc}. For a better comparison between the amount of water interested to leakage in the two sites and its distribution along the whole acquisition period, graphs of leaching term are reported in *Figure 4.26*:

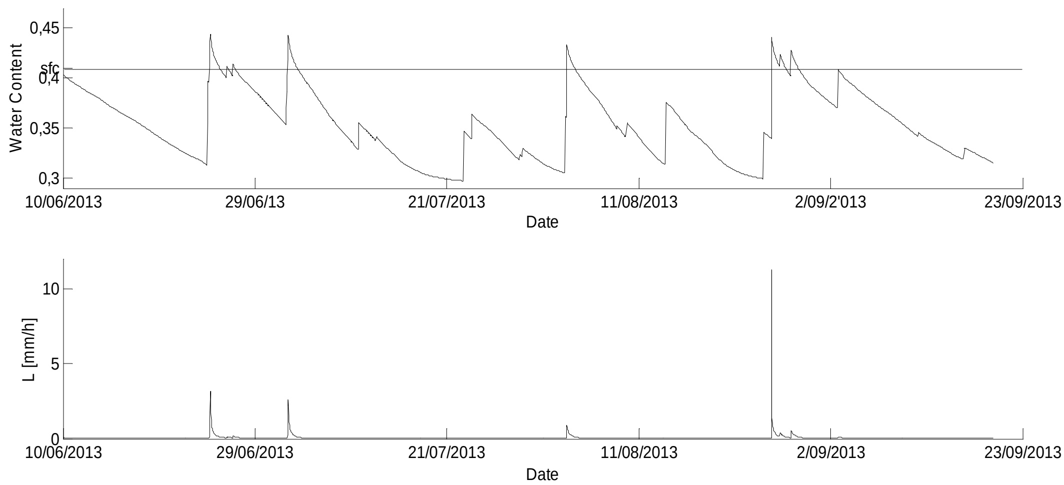


Figure 4.24 Soil moisture time series (upper graph) with field capacity threshold and hourly leaching (lower graph) in Informed Site.

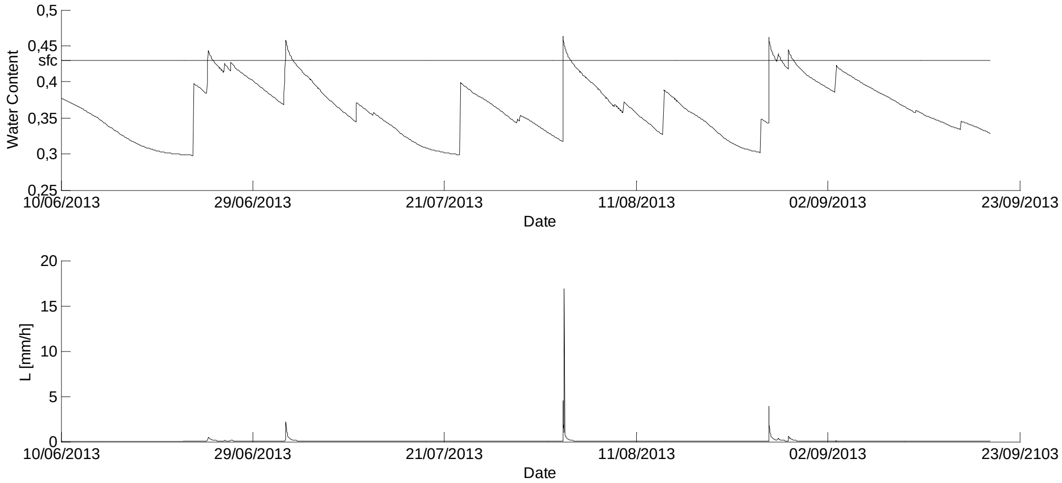


Figure 4.25 Soil moisture time series (upper graph) with field capacity threshold and hourly leaching (lower graph) in Uninformed Site.

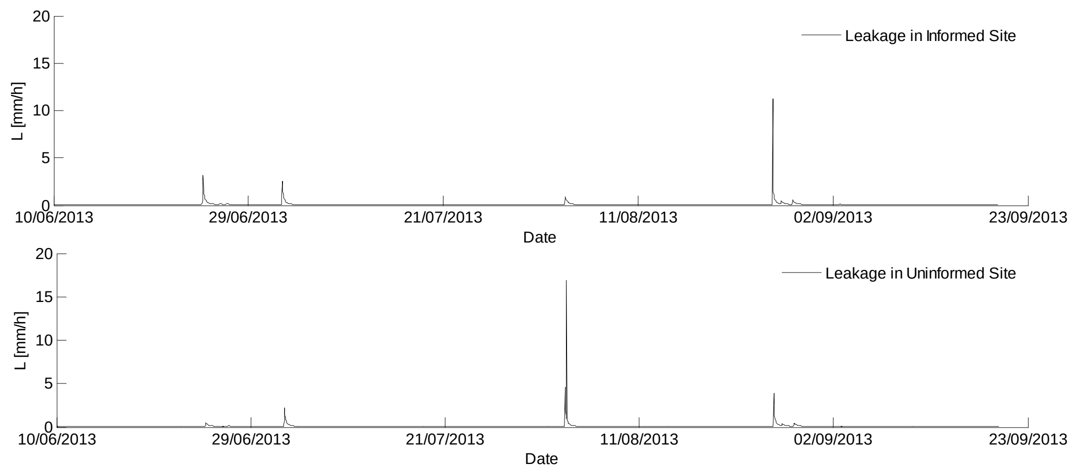


Figure 4.26 Comparison between hourly leaching in Informed Site (upper graph) and in Uninformed Site (lower graph)

Soil capacity and the incipient stress point delimit the optimal range for s in which the evapotranspiration is unrestricted and all the water is efficiently used by plant and leakages are zero. The ideal goal of irrigation activities is to furnish water to the field in order to keep the relative soil moisture content within the optimal range. The corresponding volume of water that needs to be provided to the field is called the Readily Available Water (RAW) and can be calculated as:

$$RAW_{\inf} = Zr \cdot (\vartheta_{fc} - \vartheta^{*}) = 400mm \cdot (0,407 - 0,325) = 34mm$$
$$RAW_{un\inf} = Zr \cdot (\vartheta_{fc} - \vartheta^{*}) = 400mm \cdot (0,425 - 0,325) = 40mm \qquad (4.4)$$

Delivering an amount of water higher than the RAW is sub-optimal because some water is lost by deeper percolation, while furnishing an amount of water lower than RAW is not efficient because of the reduced time interval to the following irrigation application. Only a well performed monitoring of the soil moisture content in the crop field and a right knowledge of the soil properties can lead to a better water management dictating the timing and the optimal amount of water to be delivered at each application. Plant tends to use soil water as much is possible to assimilate carbon with the higher rate possible defined by the potential evapotranspration rate. Thus, if the water content in the soil is greater than s* the plants transpire at maximum rates and growth and hence crop productivity are maximized. On the other hand, if s(t) is larger than s_{fc}, leaking increases and some water is lost and not fully used by plants, then decreasing the efficiency of the irrigation. In the periods when soil moisture is smaller than s_w the plant activity is reduced due to water scarcity. If such a period is prolonged in time, plant stress become irreversible and a loss of productivity occurs. In *Figure 4.28* the hourly data calculated by the model are reported in a graph together with the field capacity, the incipient stress and the wilting thresholds. The figure shows that the irrigation application were well performed delivering the right amount of water and with the right timing in the Informed site where the water balance was applied. However a further optimization of the water use can be done as described in the following chapter. In the Uninformed Site a larger amount of water was lost, but the farmer decided cleverly on the timing of irrigation applications. In the following figure water losses defined as a function of water content are summarized. The optimal range of soil water content is between incipient stress point (θ*) and field capacity (θ_{fc}). In partial stress conditions the stomata in the leaves are partially closed and evapotranspiration decrease while in full stress condition the stomata are completely closed and there is no evaportranspiration.

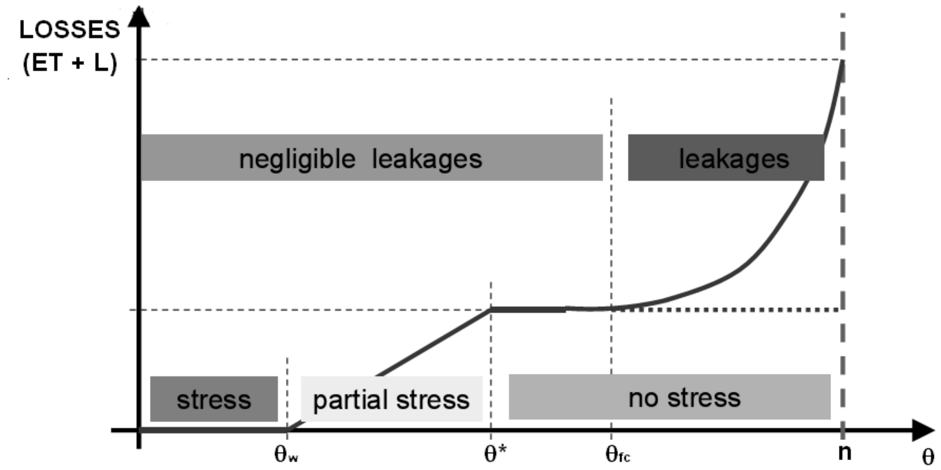


Figure 4.27 Water losses in function of the water content in root zone.

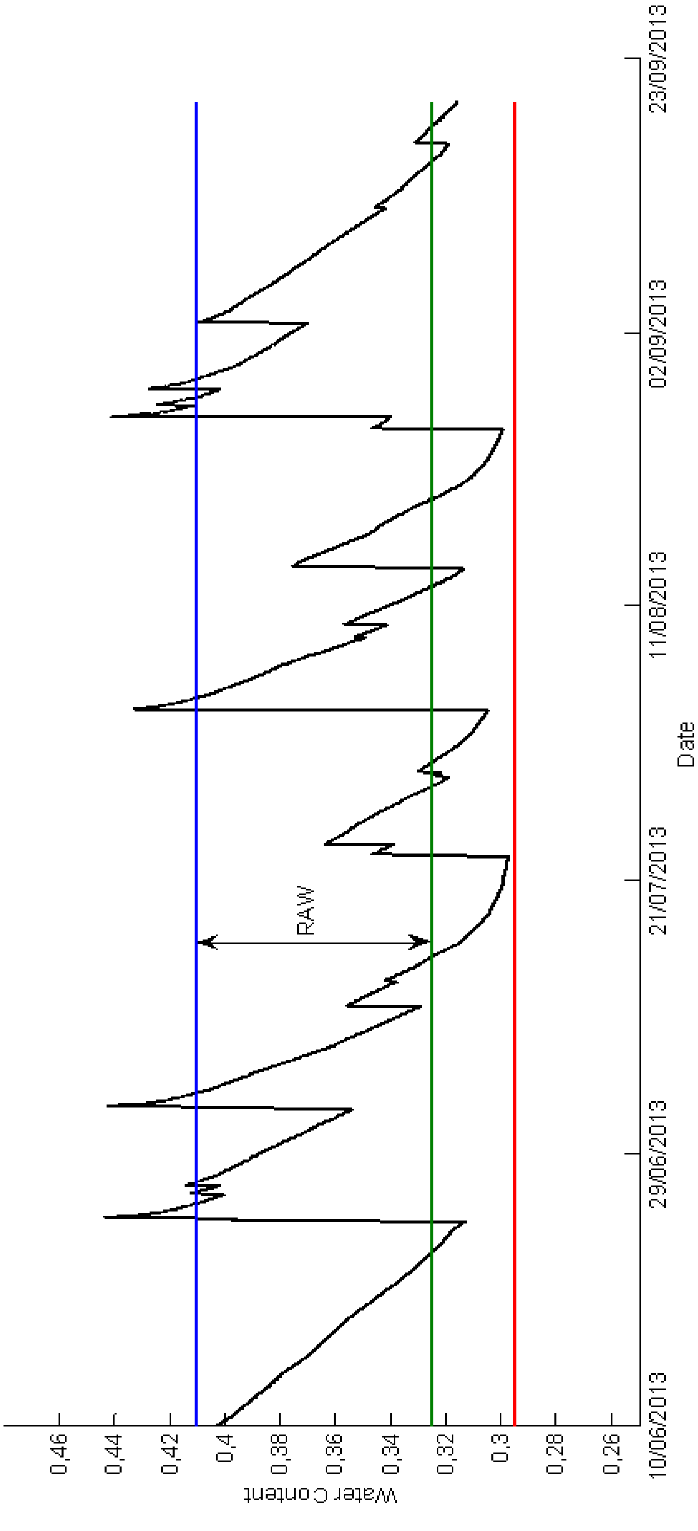


Figure 4.28 Soil moisture time series and thresholds: wilting point s_w (red line), incipient stress point s* (green line) and field capacity s_{fc} (blue line) in Informed Site

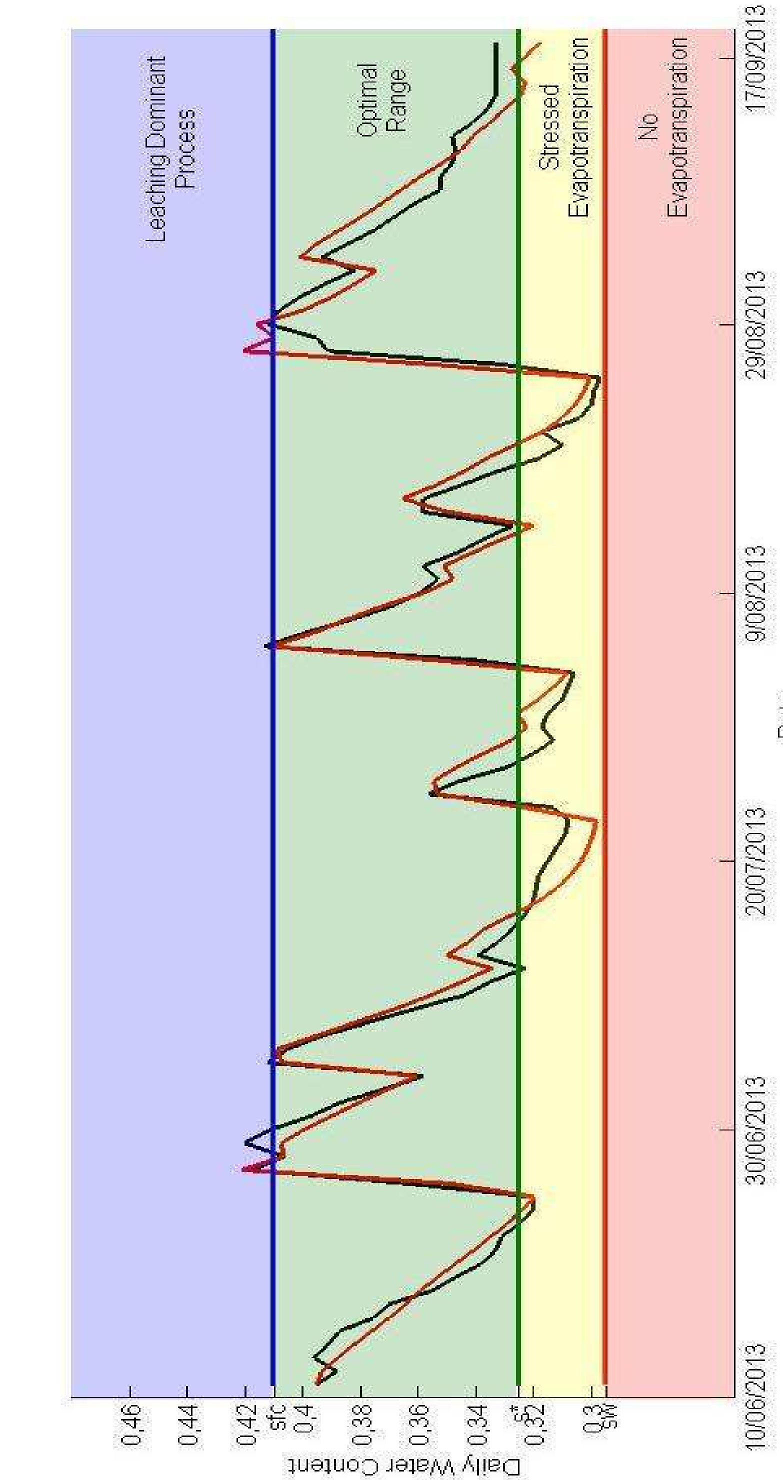


Figure 4.29 Daily soil moisture time series calculated (red line) and measured (black line) in Informed Site. Coloured areas indicate s range in which leaching process is dominant (blue area), the optimal s range (green area), range for which evapotranspiration is partially stressed (yellow area) or completely stressed (red area).

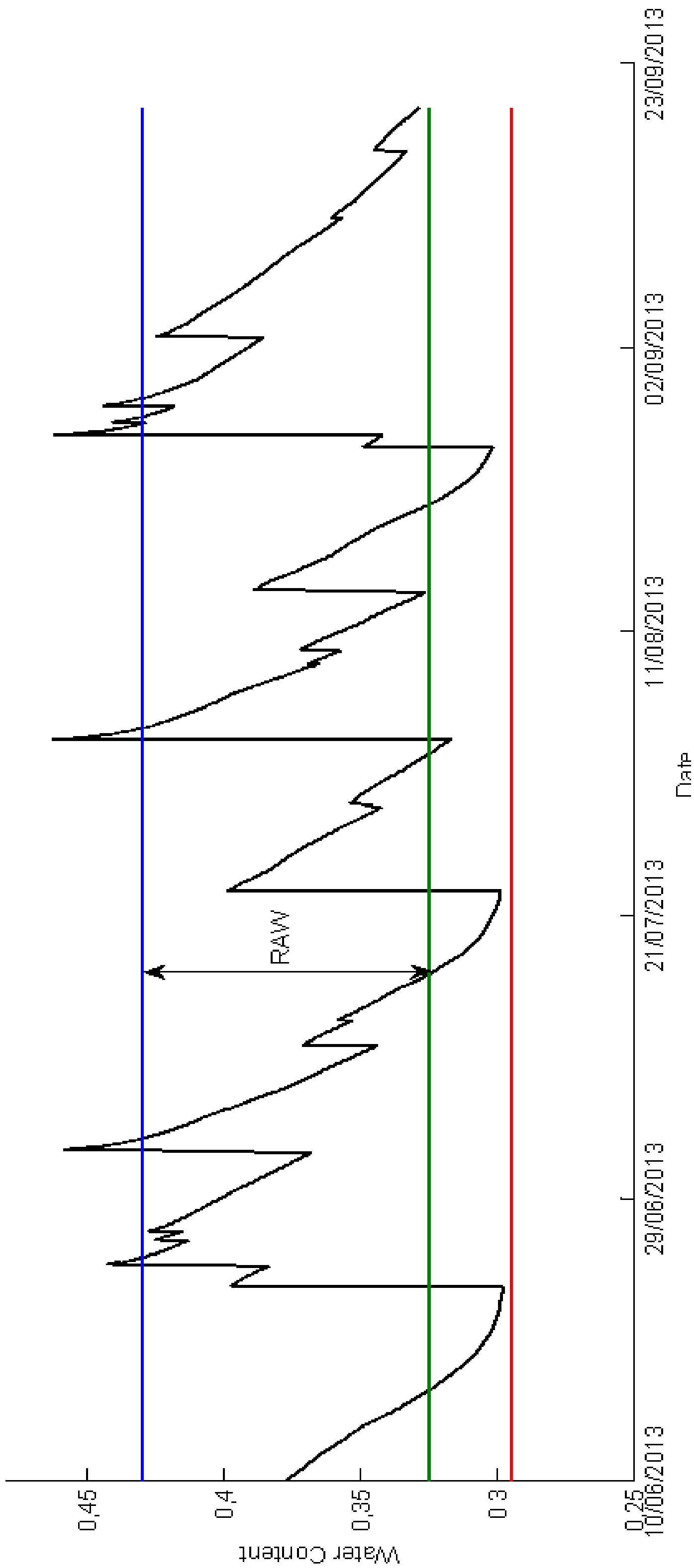


Figure 4.30 Soil moisture time series and thresholds: wilting point s_w (red line), incipient stress point s* (green line) and field capacity s_{fc} (blue line) in Uninformed Site

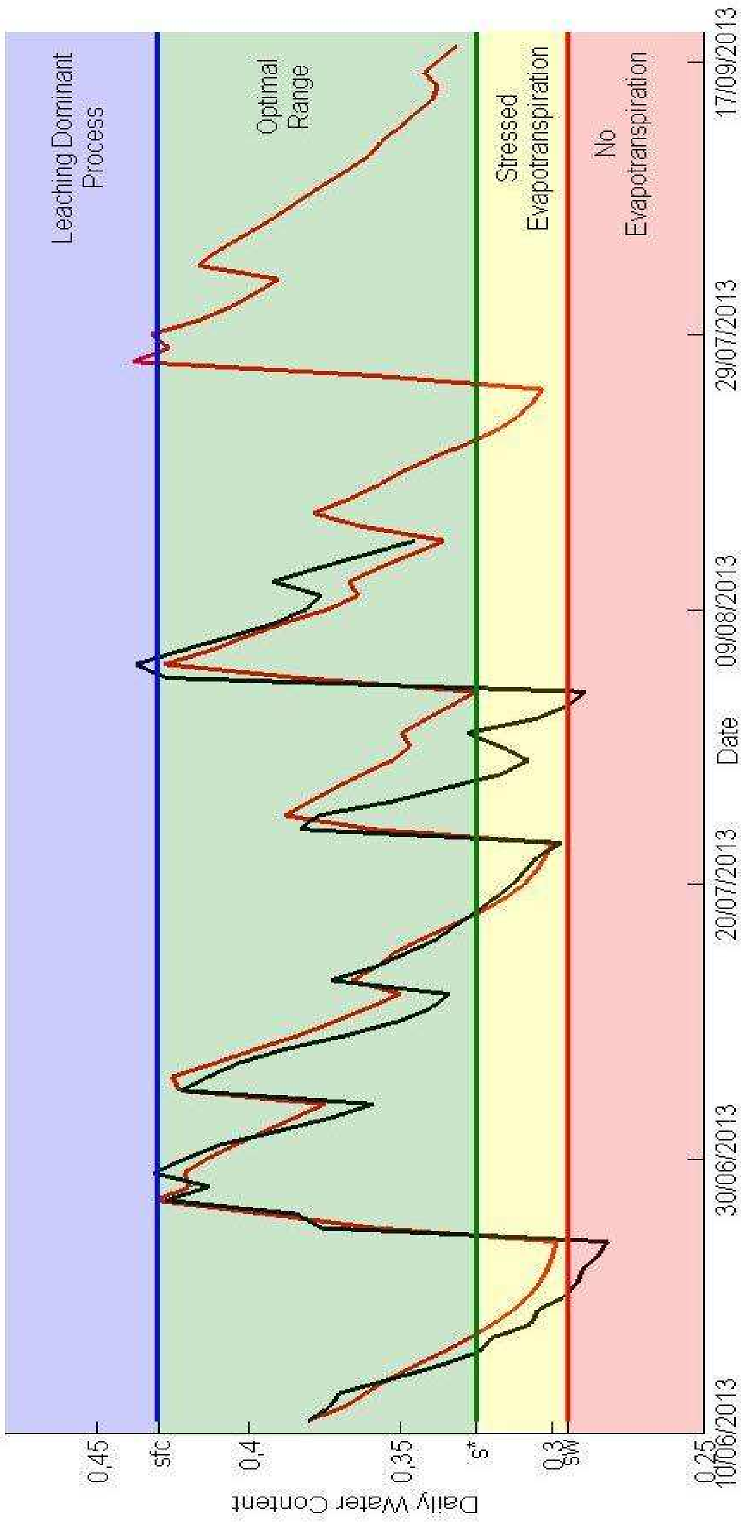


Figure 4.31 Daily soil moisture time series calculated (red line) and measured (black line) in Uninformed Site. Coloured areas indicate s range in which leaching process is dominant (blue area), the optimal s range (green area), range for which evapotranspiration is partially stressed (yellow area) or completely stressed (red area)

The integrals of P, I, O, ET and L terms of the water balance equation over the whole period of acquisition, represent the partitioning of the total amount of water delivered to the field and helps understanding the efficiency of the irrigation schedules used in the two different sites.
Considering the whole period of acquisitions of the Informed Site, ET term represents the 77% of the total losses (ET+L) equal 388mm, while L is at 23%. Total precipitation is equal to 353mm and 35mm represents the difference of the soil water between the final and initial time of the whole period. The same percentages are evaluated for the Uniformed Site but the total amount of losses is higher and equal to 415,5mm. In the following pie chart the losses percentage for both sites are shown:

$$
\begin{aligned}
ET &= \int_0^T ET[s(t),t]dt \\
I &= \int_0^T I[s(t),t]dt \\
O &= \int_0^T O[s(t),t]dt \\
L &= \int_0^T L[s(t),t]dt \\
\Delta s &= \int_0^T \Delta s(t)dt
\end{aligned}
\tag{4.5}
$$

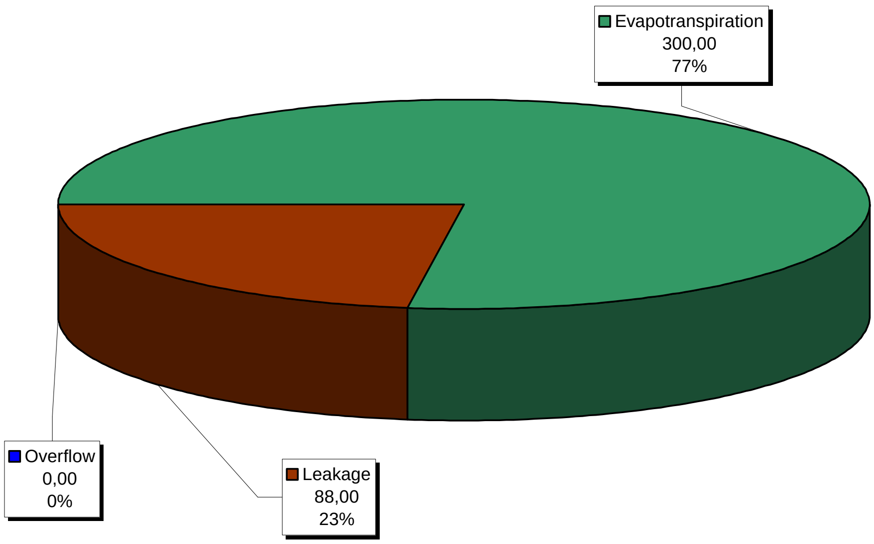


Figure 4.32 Percentage of ET, L and O water balance terms with respect to the total losses in Informed Site

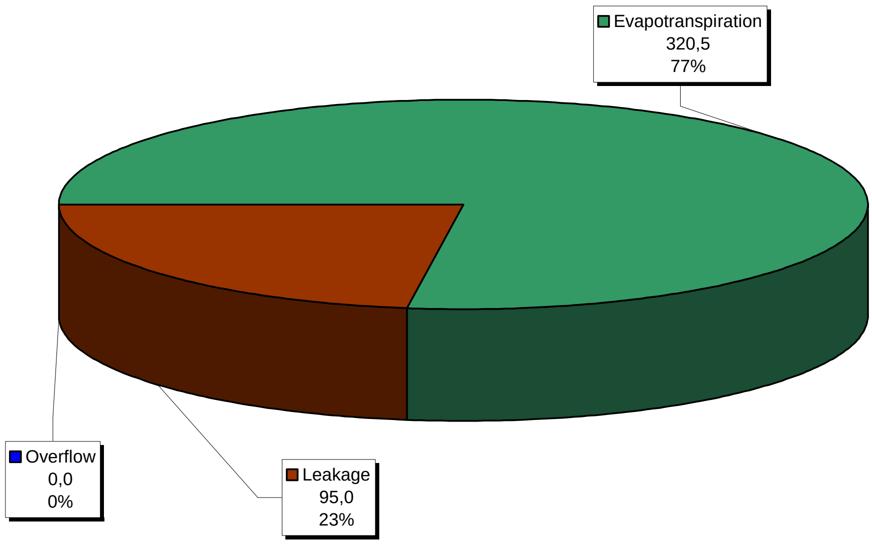


Figure 4.33 Percentage of ET, L and O water balance terms with respect to the total losses in the Uninformed Site

The total amount of water actually used by plants in the Informed Site during the whole period of acquisition, represents only 88% of the total potential evapotranspiration. The difference of 39mm indicates the evapotranspiration losses due to the low water content availability and the consequent partial closing of stomata. This fraction of water should be assimilated by plants, if soil water availability was not limited, a condition represented by an s value below the incipient stress point. Actually evapotranspirated water in the Informed Site is equal to 300mm while in the Uninformed Site is 320,5mm. Of this large amount of water only a small part is evapotranspired in stressed condition in both sites, indicating a good performance of the irrigation schedule in both cases. In the Informed Site 48mm is evapotranspired in stressed conditions and the remaining 252mm with maximum rate. In the other site the amounts of water are respectively of 33mm and 287,5mm. The percentages of evapotranspiration are very similar, 11% in the Uninformed Site and 12% in the Informed Site, meaning that the two schemes adopted have similar water losses in terms of evapotranspiration deficit. Evapotranspiration deficit is defined as the difference between potential and actual evapotranspiration. This value is null when plants are no stressed and increases during partial or completely stressed periods.

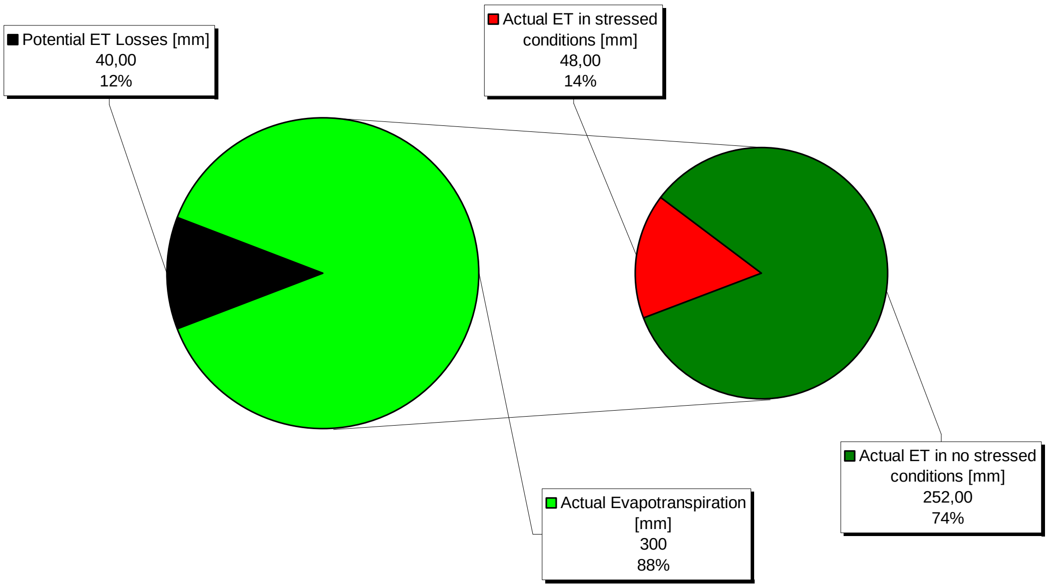


Figure 4.34 Evapotranspiration partitioning in: Potential ET losses (black), Actual ET (light green), Actual ET in stressed condition (red) and in optimal condition (dark green) in the Informed Site.

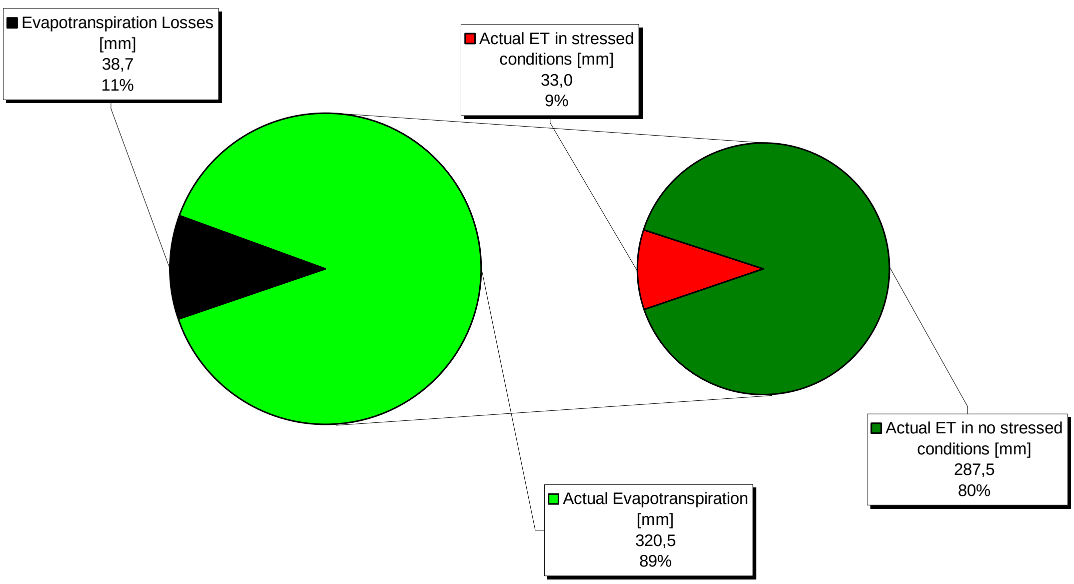


Figure 4.35 Evapotranspiration partitioning in: Potential ET losses (black), Actual ET (light green), Actual ET in stressed condition (red) and in optimal condition (dark green) in the Uninformed Site.

Notice that the percentage of actual evapotranspiration is quite the same in both sites thought in the Informed Site plants are less developed. Plants in the Uniformed Site are slightly large implying a slightly larger total evapotranspiration. Cumulate losses can be plotted as a function of time:

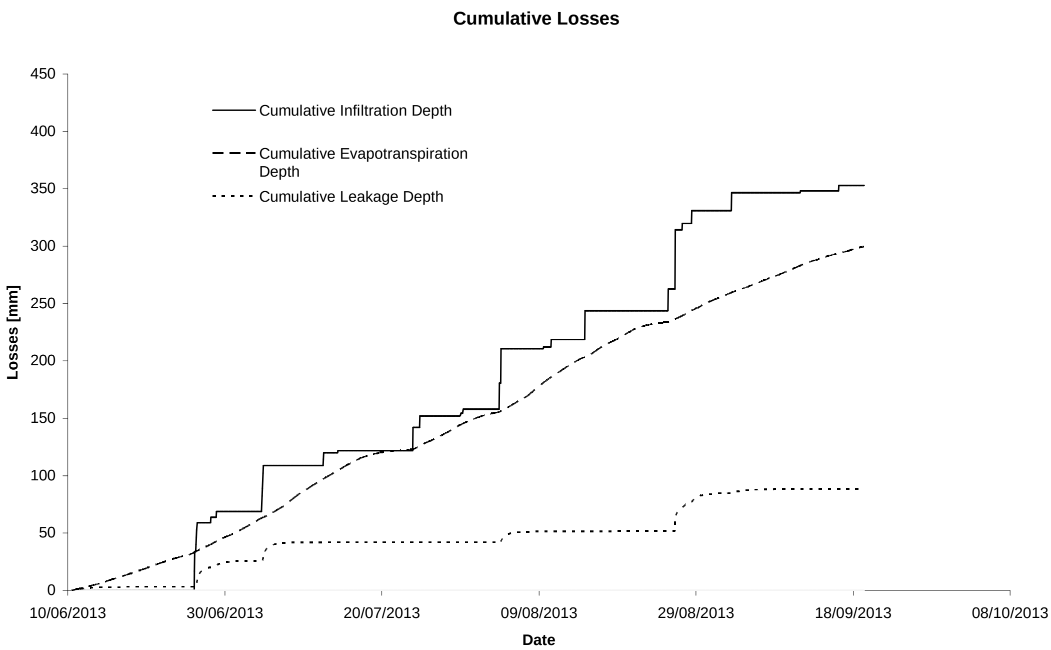


Figure 4.36 Cumulative losses partitioned in ET (dashed line) and L (dotted line) with respect to the cumulative I (continuous line) in Informed Site.

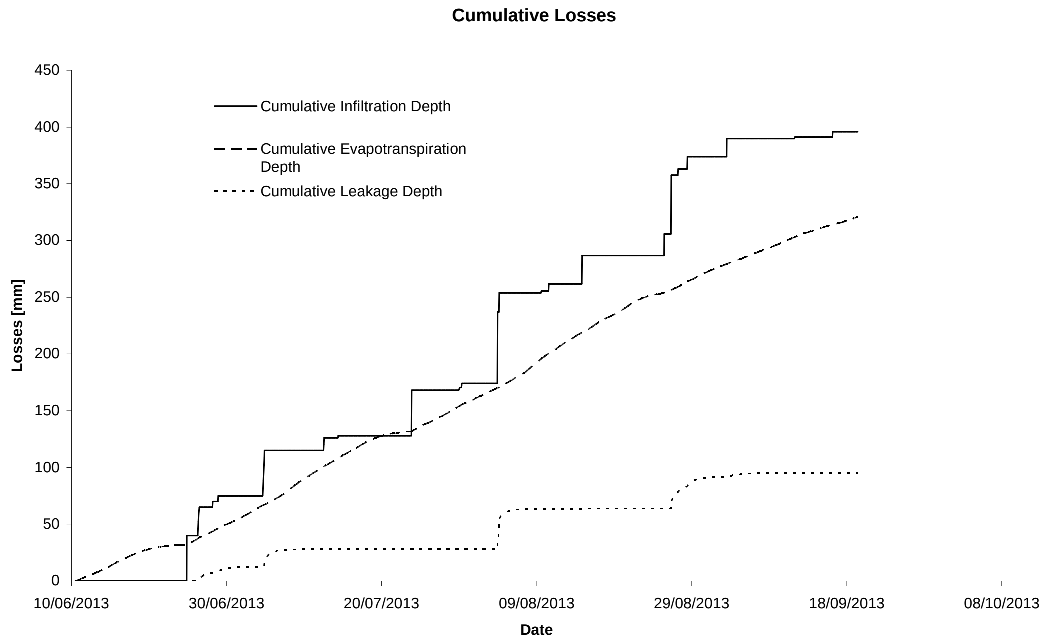


Figure 4.37 Cumulative losses partitioned in ET (dashed line) and L (dotted line) with respect to the cumulative I (continuous line) in Uninformed Site.

Figures 4.36-4.37 describe the pattern of the losses in the two sites with respect to the cumulative infiltration volume. Overland flow in both cases is zero for the whole period and the only losses are represented by evapotraspiration and percolation. The above graphs is shown that leaching "jumps" occur in correspondence of infiltration "jumps" while evapotranspiration increases quite linearly. This step pattern of leaching curve is due to the conceptual functioning of the L term in the water balance equation that becomes significant only above the field capacity threshold. So the leaching term is relevant only in the presence of water inputs while remains quite constant during the other days. Total losses represent outputs from the control volume over which the water balance is applied, but only a fraction of this water is really not used by plants and it is represented by the sum of evapotranspiration deficit and leakages. In the Informed Site the amount of total water lost is equal to 128mm while in Uninformed Site 134mm.

Another interesting observation is represented by the fraction of water, which reaches the sites through fractures, as described by the parameter α. This parameter takes into account the morphologic characteristics of the two localized sites in which water balance was applied. So, this value of α, becomes meaningless of used outsides the control volume considered. For the Informed Site the amount of input water coming from the contributing areas is equal to 74,5mm and represents 21% of the total incoming water. In the Uniformed Site fractures bring in 91,5mm of water which represents 23% of the total water inputs. Important is the percentage of irrigation with respect to the total water entering the control volume. In the Informed Site this percentage is 3% lower then in the Uniformed Site. This shows the effective water saving in the Informed Site both in terms of total amount of water (94mm vs 120mm) and in percentage with respect to the total amount of water received by the sites (27% vs 30%).

The subdivision of the different input terms in the water balance is shown in the following pie chart (*Figure 4.38* and *Figure 4.39*):

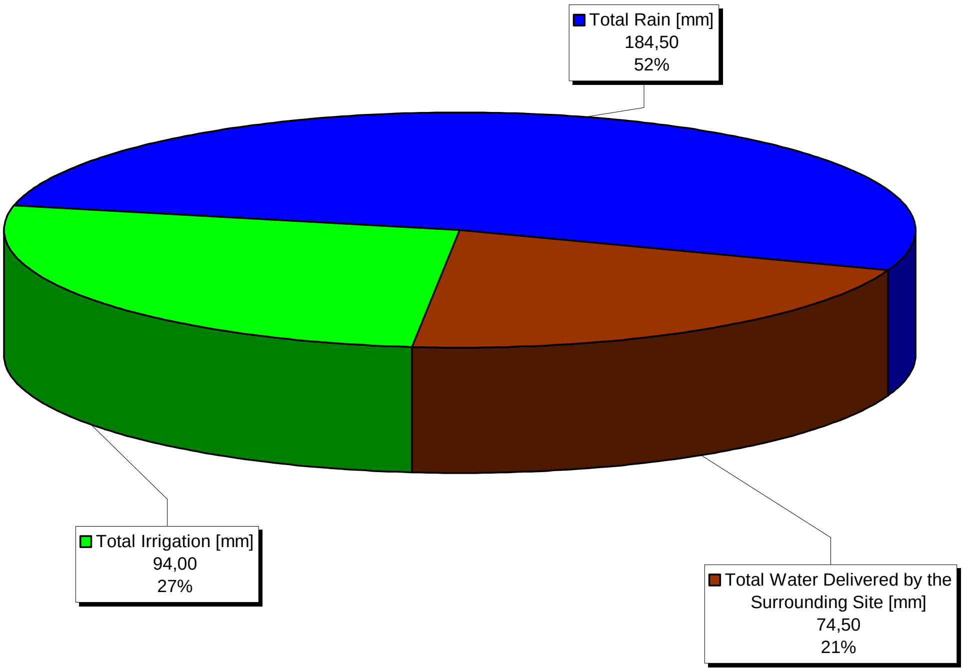


Figure 4.38 Partitioning of infiltration in: irrigation (light green), rain (blue) and water delivered by the surrounding sites (brown) in the Informed Site.

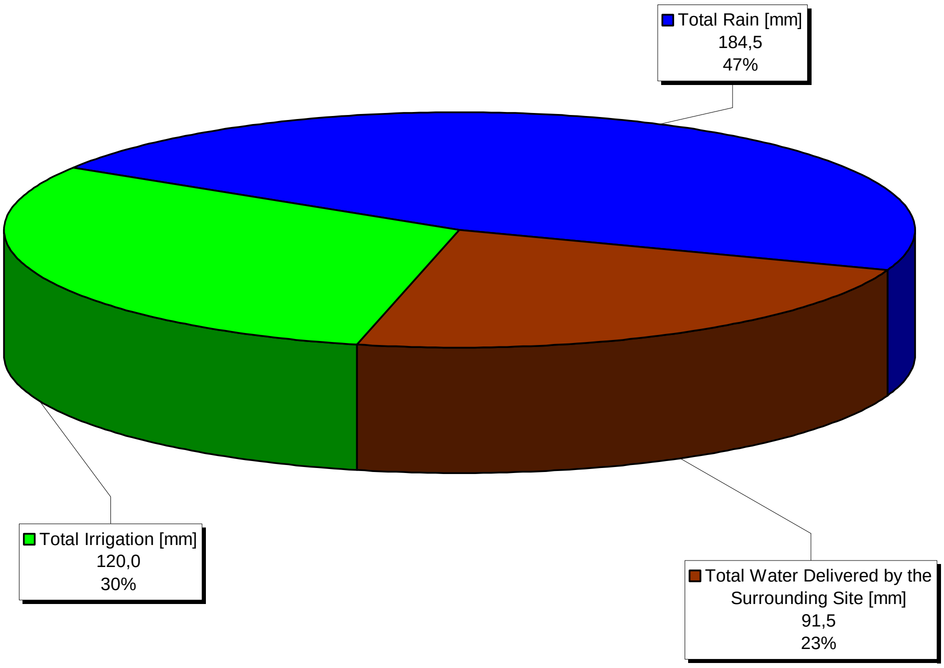


Figure 4.39 Partitioning of infiltration in: irrigation (light green), rain (blue) and water delivered by the surrounding sites (brown) in the Informed Site.

To eliminate the dependencies on the soil characteristics, that display clearly spatial heterogeneity, such as porosity, two other scenarios were studied in order to verify the response of soil moisture in the two probe groups to different irrigation schemes applied:

- Scenario 1 – Traditional Irrigation Scheme: The entire crop field is irrigated with traditional irrigation method with amount and timing decided by farmer. In this case three irrigations of 40mm are performed on 24/6 – 23/7 and 3/8.
- Scenario 2 – Water Balance Irrigation Scheme: all the crop field is irrigated with water balance scheme with amount and timing decided grown the actual soil moisture. In this case three irrigations are performed: 34mm on 25/6, 30mm on 23-24/7 and 30mm on 3/8.

Responses to the two different scenarios were studied for each probe group: Informed Probes and Uninformed Probes.
For the Informed Probes application of scenario 1 results into larger water losses due to the greater amount of water delivered to the soil. In the Informed Site, RAW volume is equal to 34mm, so the application of higher irrigation depth produces larger percolation rates. Scenario 2 decreases of about 4% the amount of waste. The pie charts reported below show the percentage of leaking and evapotranspiration with respect to the total water losses:

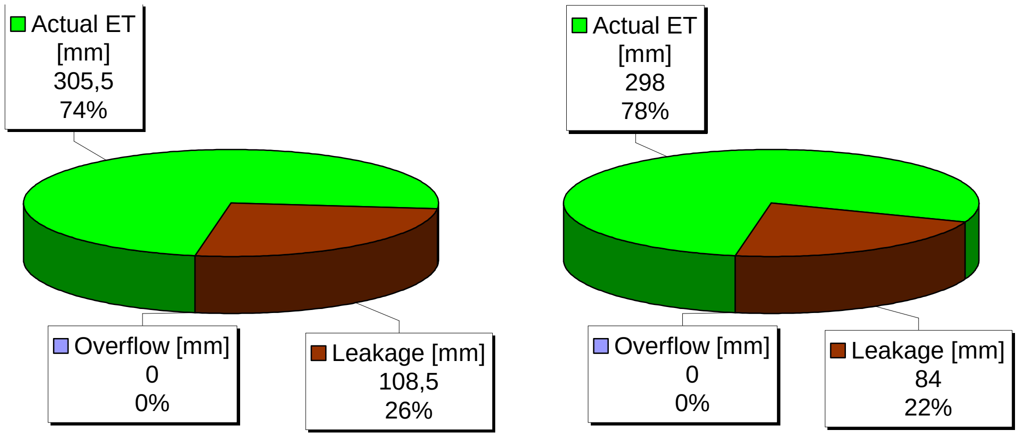


Figure 4.40 Comparison between water losses through leaching (brown areas) and evapotranspiration (green areas) in the Informed Site with the two different scenarios

Comparison between the leaking terms in the two scenarios for the Informed Probes is reported below. *Figure 4.41* shows the differences between the leaking term at time t of scenario 2 and scenario 1. Negative values indicate lower water losses through percolation with Water Balance Scheme application to the entire crop field. These values are observable during the three irrigation applications, and in particular during the third one. In fact, the soil water jump during irrigation performed on 3rd August is influenced by water coming from surrounding areas. If the whole crop field is irrigated with the traditional method the amount of water that flows through fractures to the Informed Probes is higher.

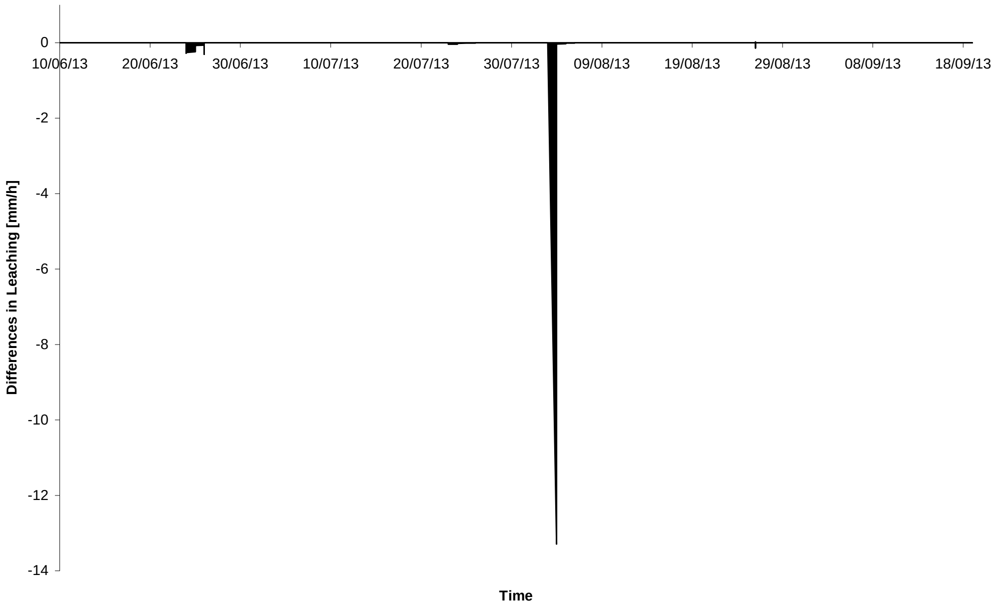


Figure 4.41 Differences between losses obtained with scenario 2 and 1 applied to the Informed Site.

Similar results were obtained applying the two scenarios to the Uninformed Probes. If the entire crop field is irrigated with amounts of water decided on the base a Water Balance Scheme, the leaked volume of water would be lower than that obtained with a Traditional Method (scenario 1). In particular, in this site a Traditional Method would results in overland flow during third irrigation. This is due to the action of fractures which bring a great amount of water to the site where the Uninformed Probes are located. The higher water content does not allow for further water infiltration leading to losses due to water flowing at the soil surface. Comparison between losses percentages in the two scenarios are reported below:

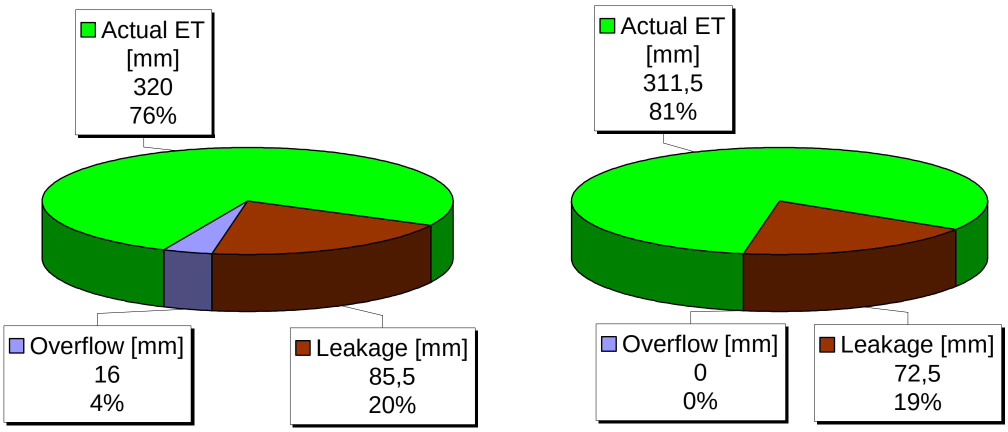


Figure 4.42 Comparison between water losses through leaking (brown areas) and evapotranspiration (green areas) in the Uninformed Site for the two different scenarios

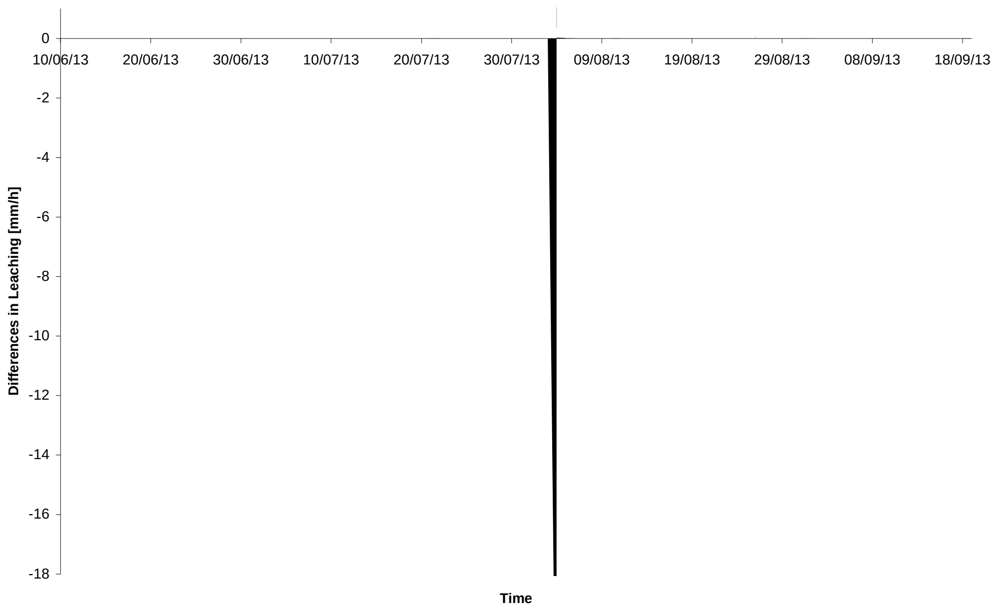


Figure 4.43 Differences between losses calculated in scenario 2 and 1 in the Uninformed Site.

Water savings represent a benefit for framers only if they have no negative impacts on productivity. The Informed and Uninformed Site are then compared, under productivity profiles, in the next chapter, through the utilization of several indices.

Chapter 5

Discussion

Water savings should be a primary objective for farmers as irrigation represents one of the major costs of agricultural activities. Water management has to be performed at its best in order to minimize losses and maximize field productivity. Then, a simple comparison between the total amounts of water used is not sufficient to establish the efficiency of a giver irrigation scheme and a comparison of the field productivity is recommended. In the field site used in this study, a complex fracture system played crucial role on soil moisture dynamics and jointly with small scale spatial heterogeneity of soil and vegetation properties, makes a comparison between the two different sites in term of water savings problematic. In fact, the Informed Site have also received water from the surrounding areas, while plants grown in the Uninformed Site have received water from the surrounding areas irrigated according to the uniformed procedure, as well as from the informed site. Crop yield depends on the total amount of water received during the entire season which comprised rainfall, irrigation water and lateral inputs through soil fractures. On the other hand, the total amount of water received by field, cannot be considered economics index, hence it is necessary to focus only on the irrigation water that represents an actual cost for farmers. In this chapter a comparison between the two sites is performed through the use of some productivity indexes that can link water use to crop yield, or in other terms, costs to profits. Indexes of productivity, have to be taken carefully into account for an optimal management of user resources and they can be considered good terms of comparison for the two sites investigated. Is the extrapolation of the results obtained to regional scales, in terms of water savings, has been done by considering the effective amount of irrigation water saved thanks to information available on soil moisture. Extrapolation to allow larger scales provides an approximate indication about the savings allowed by a better management of water resources during agricultural activities.

5.1 Water Savings

Comparing the total amount of irrigation water delivered to the Informed Site to that delivered to the Uninformed Site it is possible to evaluate the actual water savings a soil-moisture accounting irrigation scheme. In the Uninformed Site farmer applied a traditional scheme which consists in delivering always the same amount of water at each irrigation application. Water delivered to the field is defined based on the experience. Irrigation interval can be fixed, as driver by the rate of evapotranspiration, or flexible. In the latter case the application dates are decided based on the plant health, possibly taking into account rain forecasting. *Figure 5.1* illustrates an example of irrigation scheme with fixed irrigation timing. In this study, farmer intelligently furnishes water to the field at not-fixed time interval. However, the absence of instruments able to monitor soil moisture in Uninformed Site, may lead to water losses through leaching losses or water stress. In general, especially in the case of fixed intervals, traditional irrigation schemes do not represent the best solution in term of sustainable use of water resources because of the high losses.

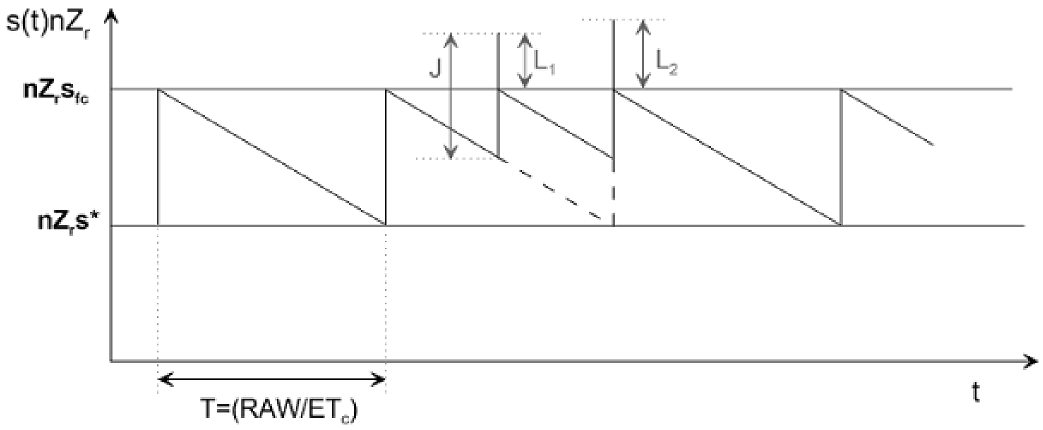


Figure 5.1 Traditional Irrigation scheme at fixed intervals.

In the Informed Site, instead, a water balance irrigation scheme was applied that accounted for the available measurements of soil moisture. In this case water is delivered with flexible dates accounting for the soil moisture. Irrigation is applied considering the actual soil water deficit. Rainfall events between two applications delay the subsequent application and irrigation is performed with the proper amount of water (that is equal to the RAW, see *Chapter 4*). The number of application is generally lower than that obtained with the traditional method and the water savings are significant. In this study the number of application for the two different irrigation schemes were deliberately chosen to be equal. This type of irrigation scheme requires probes and instruments able to monitor soil moisture and process the measured data. Installation and maintenance of this type of instrument represents a low cost for farmer, which can be amortized thanks to significant water savings. Water balance irrigation scheme, coupled with a sprinkler irrigation technique, can represent the best efficiency/cost ratio for many type of crops and soils. In *Figure 5.2* a representative scheme illustrates the comparison between water balance and traditional irrigation schemes. While traditional scheme has fixed applications timing, water balance allows for delays when rainfalls increase soil moisture.

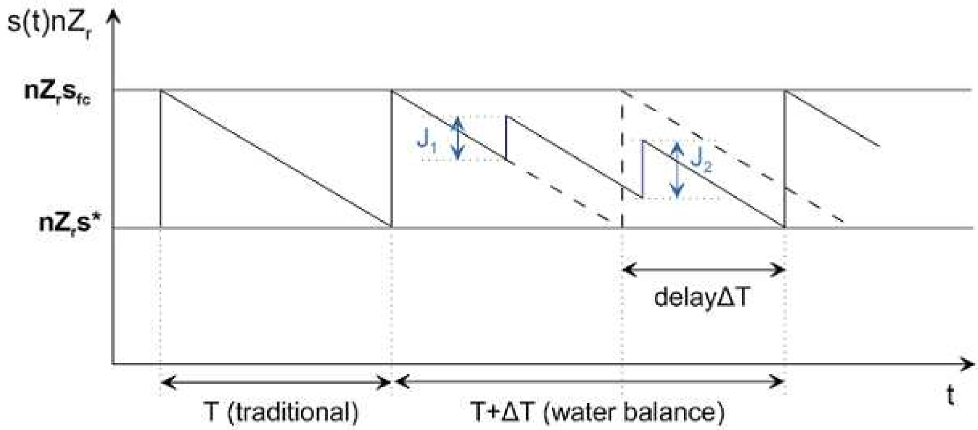


Figure 5.2 Water Balance Irrigation scheme

In this study the Informed Site has received a total irrigation depth of 94mm while the Uninformed Site was irrigated with a total amount of 120mm water. Savings, in terms of water depth, are about 26mm. If we consider the total amount of water received by the two sites, taking into account rainfalls and fractures activities, the total water saving increases to 43mm. The efficiency of the irrigation scheme applied can be evaluated only taking to account the field productivity. In fact, a simple water saving can results in a lower productivity due to the higher plant stressing, in particular, when stressed period occur during the flowering season of the maize plant. Water productivity (WP), as suggested by [*Pereira, 2007*] can be defined as the ratio between the actual yield (Y_a) and the water used [kg/m^3] per hectare of surface, refers to the total water use (TWU), including rainfalls and other water inputs (*Equation 5.1*). However, is better to referring only to the irrigation water used (IWU) like described in the following equations:

$$WP = \frac{Y_a}{TWU} \tag{5.1}$$

$$WPI = \frac{Y_a}{IWU} \tag{5.2}$$

The FAO manual [*Allen Et Al., 1998*] addressed the relationship between crop yield and water use by proposing the use of a simple equation where relative yield reduction is related to the corresponding relative reduction in evapotranspiration. Specifically, the yield response to ET is expressed as:

$$(1 - \frac{Y_a}{Y_{MAX}}) = K_Y \cdot (1 - \frac{ET_a}{ET_{MAX}}) \tag{5.3}$$

Where Y_{MAX} and Y_a are the maximum and actual yields, ET_{MAX} and ET_a are the maximum and actual evapotranspiration rate, and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses. The yield response factor includes many biological, physical and chemical processes involved in the linkage between production and water use by crops. K_y values are crop specific and vary over the growing season according to growth stages [*Doorenbos and Kassam, 1971*]:

- $K_y>1$: crop response s very sensitive to water deficit with proportional larger yield reductions when water use is reduced because of stress.

- K_y<1: crop is more tolerant to water deficit, and recovers partially from stress, exhibiting less than a proportional reduction in yield with reduced water use
- K_y=1 yield reduction is directly proportional to reduced water use

The FAO suggested a set of K_y values defined as a function of the growing season during which water stress conditions occur. Typically flowering and yield formation stages are more sensitive to stress, while stress occurs during the ripening phases or in the vegetative phases if it has a limited impact, provided the crop is able to recover from stress in subsequent stages. *Figure 5.3* shows the different maize plant growing season and *Figure 5.4* the related K_y values suggested by the FAO manual:

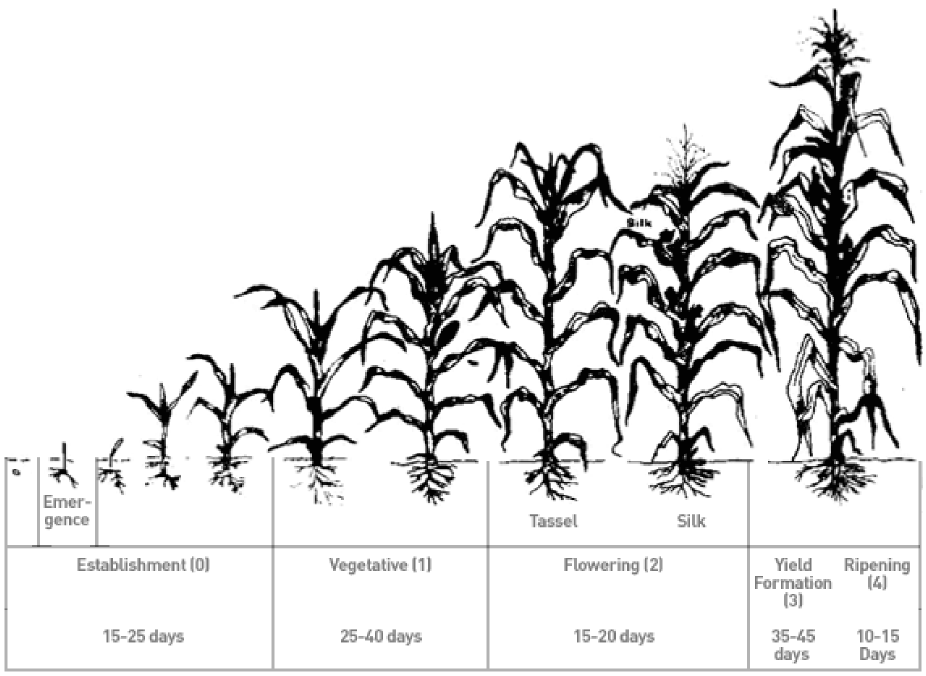


Figure 5.3 Maize plant growing seasons (FAO)

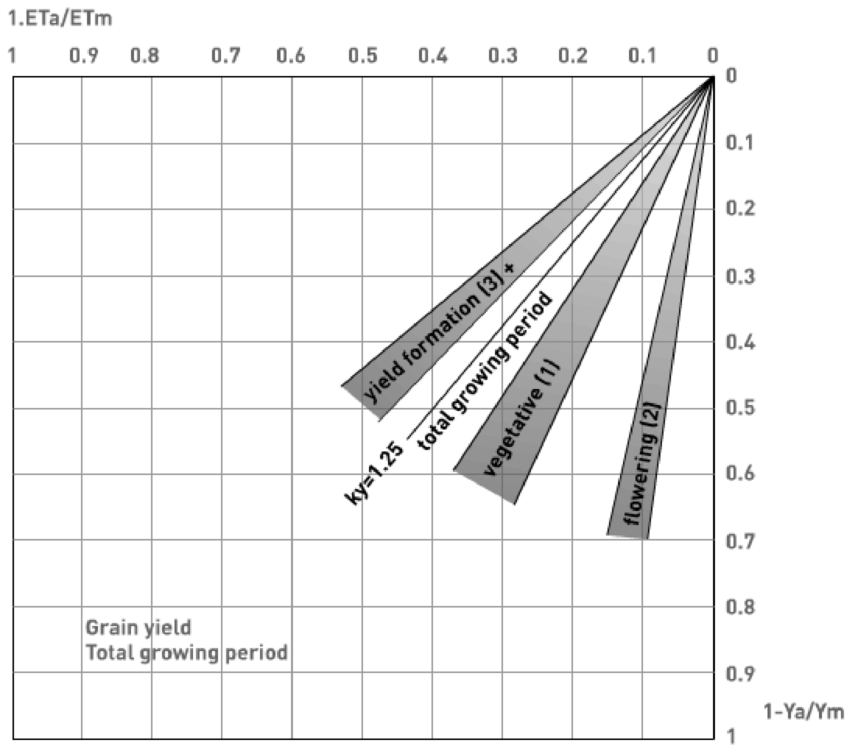


Figure 5.4 K_y value in function of evapotranspiration and yield deficits (FAO)

Right after the end of the acquisition period, two samples of corn have been collected from each site. The harvesting was performed by collecting the maize row above the probes and two adjacent rows, so as to cover an area of about $4m^2$ (0,0004ha). Plants have been weighted separately for the two sites, before removing and weighting the corncobs. The numbers of grains of a representative number of corncobs was calculated for each site before removing the cobs and weight the grains. A sample of grain for each site was analyzed in the laboratory to estimate the specific weight and relative humidity of the two samples. All the information derived from the laboratory analysis are reported in *Table 5.1*, which shows that no significant differences were observed between the two samples derived from the two sites. Small differences of productivity can be explained by the small scale differences in the fertility of the soil, but it can be also related to the sampling procedure adopted.

Table 5.1 Harvest data

	Informed Site Sample	**Uninformed Site Sample**
Number of plants	27	26
Number of corncobs	29	29
Total weight of the plant [kg/plant] - W_b	12,5	15,5
Total weight of the corncobs [kg/cob]	9	9
Average number of grains per corncob [grains/cob]	619	639
Total weight of the grains [kg] - W_g	7,3	7,4
Seed temperature [°C]	20	19
Relative humidity	25,7	25,9
Specific weight [kg/hl]	72,8	72,6
Weight of grains per plants [kg/plants]	0,27	0,285
Weight of grain per weight of plant [kg/kg]	0,584	0,477

The total weight of grains (W_g) represent for farmer the actual crop yield which can be expressed per unit of surface considering the surface of sampling (A=0,0004 ha):

$$Y_{a,\inf} = \frac{W_{g,\inf}}{A} = 18250 \frac{kg}{ha}$$

$$Y_{a,un\inf} = \frac{W_{g,uninf}}{A} = 18500 \frac{kg}{ha}$$

Result confirms the similar productivity of the two sites in terms of tons of grains. Water productivity (WP) is then evaluated considering *Equation 5.1* as:

$$WP_{\inf} = \frac{Y_a}{TWU} = 51,7 \frac{kg}{ha \cdot mm}$$
$$WP_{un\inf} = \frac{Y_a}{TWU} = 46,7 \frac{kg}{ha \cdot mm}$$

The results suggest that water productivity in Informed site is higher of about 6% than in the Uninformed Site though the lower weight of grains harvested because of the lower quantities of water used. For the farmer interests total water use is not a useful parameter to taking into account, because of is not correlated with the costs related to irrigation practises. Than the total irrigation water used (IWU) was used instead the TWU like described by equation *Equation 5.2*:

$$WPI_{\inf} = \frac{Y_a}{IWU} = 194,1 \frac{kg}{ha \cdot mm}$$
$$WPI_{un\inf} = \frac{Y_a}{IWU} = 154,2 \frac{kg}{ha \cdot mm}$$

This parameter is strictly linked to the economic returns of the crop because of the irrigation activities represent on of the major costs for agricultural activities. Informed Site irrigation water productivity is higher of about 22% with respect to the water productivity in the other site. This data suggest important money saving during irrigation applications for the farmer.

The method suggest by FAO was finally applied in order to evaluate the maximum yield obtainable in absence of stressed evapotranspiration during the whole period as described by *Equation 5.3*. In Informed Site, stressed evapotranspiration occur predominantly during the middle season when the yield is forming. Accordingly yield response factor was set equal to *Figure 5.1*. Employing a linear decrease of yield productivity, proportional to the decrease of evapotranspiration rate.

$$Y_{MAX,\inf} = Y_a \cdot \frac{ET_{MAX}}{ET_a} = 20683 \frac{kg}{ha}$$

Where ET_{MAX} is equal to 340mm and ET_a to 300mm. Ensuring an optimal range of soil moisture during the whole season and then avoid any stressed condition, the maximum yield obtainable is the 13% higher with respect to that actually obtained (Y_a) in Informed Site. In Uninformed Site, stressed condition was present in different growth stages of plant, then K_y was set to 1,25 like indicated in *Figure 5.2*.

$$Y_{MAX,un\inf} = \frac{Y_a}{1 - K_y \cdot (1 - \frac{ET_a}{ET_{MAX}})} = 21379 \frac{kg}{ha}$$

Where ET_{MAX} is equal to 359mm and ET_a to 320,5mm.
So, in the Uninformed Site, in optimal condition the maximum yield obtainable is 15% higher then the actual yield.

The comparison between these two sampling sites can suggests that a water balance irrigation scheme, coupled with a continuous monitoring of the soil moisture, can then decrease significantly irrigation water volumes (22%) assuring a satisfactory productivity. The crop yields obtained in the two sites are the final products of a carbon assimilation process performed by plants which have used a total amount of water of 353mm and 396mm respectively in Informed and

Uninformed Site. Equal productivity is then obtainable with a difference of 43mm of water depth. The total amount of water received by each site investigated includes water coming from surrounding zones, which amount, is strongly correlated to fractures disposition and characteristics. So, productivity indexes and yields obtained from previous formulas cannot be applied to different sites.

The efficiency (E) of each irrigation can be easily calculated by considering the ratio between water stored in root zone (I-L), readily available for the roots, and total infiltrated water (I):

$$E = \frac{I - L}{I} \qquad (5.4)$$

The farmer has applied a traditional irrigation scheme in which the amount of water delivered at each application is fixed (40mm) and the timing is decided observing the plant leaves and rainfall events meteorological predictions. In Informed Site the total amount of water delivered at each application was decided considering the actual soil moisture and soil-vegetation features. In the following table are summarized the three irrigation application:

Table 5.2 List of irrigation applications in the two sites during the whole period

	Irrigation Application	Date	Infiltration [mm]	Leakage [mm]	Efficiency
Informed Site	First Irrigation	25/6	34	0	100%
	Second Irrigation	23/7	30	0	100%
	Third Irrigation	3/8	30	6,9	77%
Uninformed Site	First Irrigation	24/6	40	0	100%
	Second Irrigation	23/7	40	0	100%
	Third Irrigation	3/8	40	23,5	41%

Efficiency in the Informed Site is optimal during the first and second application while during the last irrigation was delivered an amount of water higher than that necessary to reach the field capacity. This is due to fractures that have brought a consistent volume of water from the Uninformed areas to the Informed Site during the previous Uninformed irrigation. The first and second irrigations were applied with the right timing when the evapotranspiration was stressed, while third irrigation should been delayed in order to avoid water losses trough percolation. Above table shows clearly the higher efficiency of the water balance method compared with the traditional one. In the Uniformed Site, in fact, efficiency of the third irrigation results to be extremely lower than in the Informed Site. Also in this case the greater amount of leached water is due to fracture's action rather than to a bad irrigation application. To avoid these losses the farmer should have avoided fracture formation, which redistribute in an unpredictable manner soil water. A well performed rainfall forecasting could have avoided losses during the first rain (June 25) by delaying the first irrigation application.

Other interesting data related to the comparison between the two irrigation schemes adopted in this study can be derived from the following indexes:

- Kilograms of biomass (W_b) per hectare produced per 1mm of infiltration depth

$$B_{\inf} = \frac{\mathrm{W}_{\mathrm{b,inf}}}{\mathrm{TWU}_{\mathrm{inf}}} = 88{,}5 \frac{kg}{ha \cdot mm} \tag{5.5}$$

$$B_{\mathrm{uninf}} = \frac{\mathrm{W}_{\mathrm{b,uninf}}}{\mathrm{TWU}_{\mathrm{uninf}}} = 97{,}8 \frac{kg}{ha \cdot mm} \tag{5.6}$$

- Kilograms of grains (W_g) produced per kilograms of biomass

$$G_{\text{inf}} = \frac{W_{g,\text{inf}}}{W_{b,\text{inf}}} = 0{,}58 \tag{5.7}$$

$$G_{\text{uninf}} = \frac{W_{g,\text{uninf}}}{W_{b,\text{uninf}}} = 0{,}48 \tag{5.8}$$

Indexes are calculated per hectare of field. The first index confirms the largest grown of the Uninformed plant's probably due both to larger amounts of water received and higher field fertility, while the second index highlights the higher productivity of Informed Site which is able to produce 20% of grain weight more per plant weight than Uninformed Site. Plants in the Uninformed Site are higher but the corncobs and grain weights. Two sites have registered an equal productivity in terms of total grain weight, but the Informed site has received 43mm less than the Uninformed site. Part of this difference of water amount delivered to the field depends on site properties like porosity, fracture development, position of site within the entire crop field and its morphology. We can reasonably assume that, between these factors, the one that has had the greater influence on the different behaviour of soil moisture is the different functioning of fracture systems which have brought 17mm of water in the Uninformed Site more than in the Informed one. The remaining difference represents the different amount of water delivered to the field by irrigation, and represents the 60% of the total water difference between the two sites. As much reasonably, we can assume that the productivity is lower, but at least equal, in the two sites also in the absence of the fractures. Therefore we can, conclude that a significant saving (23mm) has been obtained without compromising the productivity of maize field.

5.2 Extrapolation to Regional Scale

Starting from the data discussed in section 5.1, an extrapolation to a larger scale was performed in order to quantify the real advantages allowed by suitable soil moisture monitoring in agricultural soils. Extrapolation was first performed on the whole maize field hosting the experiment and than on the total maize surfaces irrigated in the Veneto Region.

The surface of the maize field hosting the experiment in approximated equal to 10ha. Total water volume (TWV) and irrigation water volume (IWV) delivered to the field can be than calculated as:

$$\mathrm{TWV_{uninf}} = \mathrm{TWU_{uninf}} \cdot \mathrm{S} = 396 \cdot 10^{-3} \cdot 10 \cdot 10^{4} = 39600 m^{3} \quad (5.9)$$

$$\mathrm{TWV_{inf}} = \mathrm{TWU_{inf}} \cdot \mathrm{S} = 353 \cdot 10^{-3} \cdot 10 \cdot 10^{4} = 35300 m^{3} \quad (5.10)$$

$$\mathrm{IWV_{inf}} = \mathrm{IWU_{inf}} \cdot \mathrm{S} = 94 \cdot 10^{-3} \cdot 10 \cdot 10^{4} = 9400 m^{3} \quad (5.11)$$

$$\mathrm{IWV_{uninf}} = \mathrm{IWU_{uninf}} \cdot \mathrm{S} = 120 \cdot 10^{-3} \cdot 10 \cdot 10^{4} = 12000 m^{3} \quad (5.12)$$

Where TWU is the total water used [mm], IWU is the total irrigation water used [mm] and S the field surface [ha]. *Equation 5.12* minus *Equation 5.11* suggests a difference in between the two sites equal to 2600m^3 of irrigation volume. Assuming a capital cost for farmer to irrigate one hectare of field of about 5€ per millimetre of water delivered. Costs can be estimated for the entire crop field:

$$IC_{inf} = IWU_{inf} \cdot C \cdot S = 94 \cdot 5 \cdot 10 = 4700€ \quad (5.13)$$

$$IC_{uninf} = IWU_{uninf} \cdot C \cdot S = 120 \cdot 5 \cdot 10 = 6000€ \quad (5.14)$$

Where IC is the total irrigation cost expressed, IWU is the total amount of irrigation water [mm], C is the cost of irrigation activities and S the field surface expressed in hectares. Considering the purchase cost of the TDR instrument and the relative installation and maintenance cost (C_{TDR}) of about 100€ per years for a 10 hectares field (considering 10 years of instrument operation) the effective saving (IC’) for farmer is calculate as:

$$IC'_{inf} = IC_{inf} - C_{TDR} = 4600 \frac{€}{y} \quad (5.15)$$

$$IC'_{inf} = IC_{inf} - C_{TDR} = 5900 \frac{€}{y} \quad (5.16)$$

The comparison results into 1300€ saved which represent the 22% of the total irrigation cost in the Uninformed Site. Data represent an approximation of the real irrigation cost on field because of the non linearity between costs and millimetres of water delivered.

Extrapolation can be extended to a regional scale considering the total amount of irrigated surfaces of maize in Veneto. Maize crop cover about the 25% of the total Italian cereals crop surfaces and about 13% of the total Italian cultivated areas as shown in *Figure 5.5* [*Istat*, *2010*].

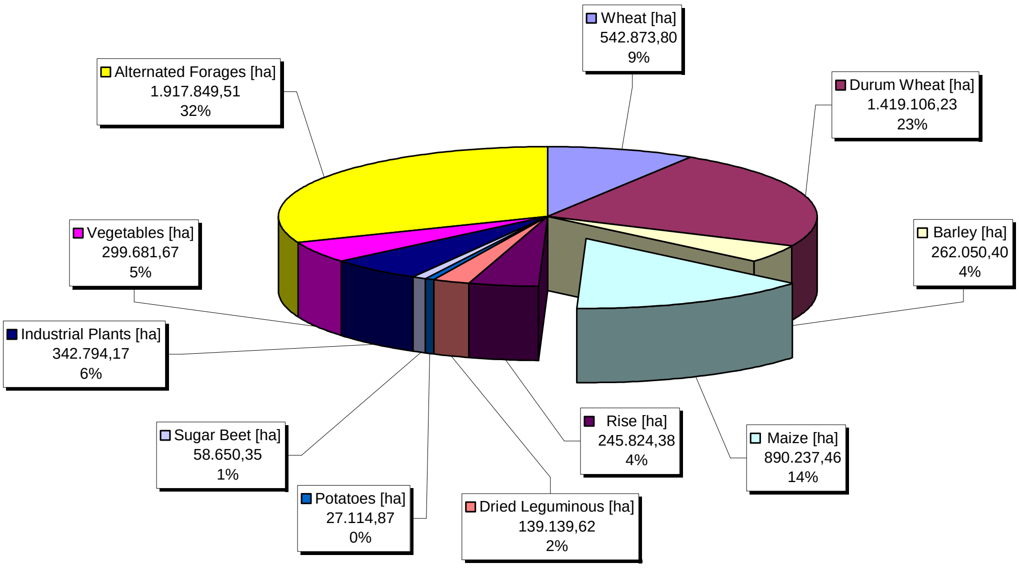


Figure 5.5 Hectares of cereal's cultivated surfaces in Italy

Of the total maize cultivated surfaces in Italy, 519.080 ha (58%) are represented by irrigated lands. In Veneto we can find the 17% of this total irrigate maize croplands present in Italy for a total of about 90.000ha (*Figure 5.6*). *Figure 5.7* shows the different irrigation system adopted on irrigated corn field.

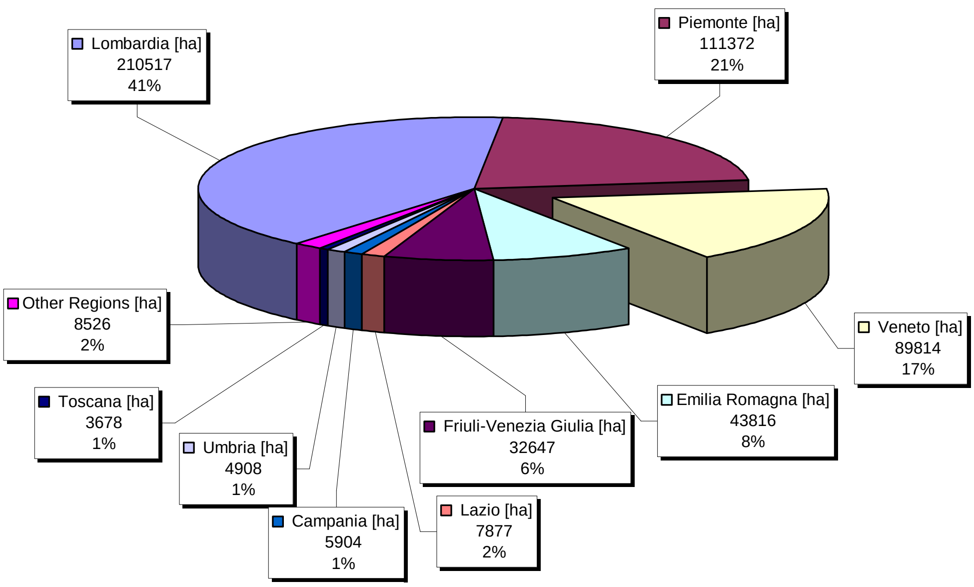


Figure 5.6 Hectares of irrigated maize in Italy

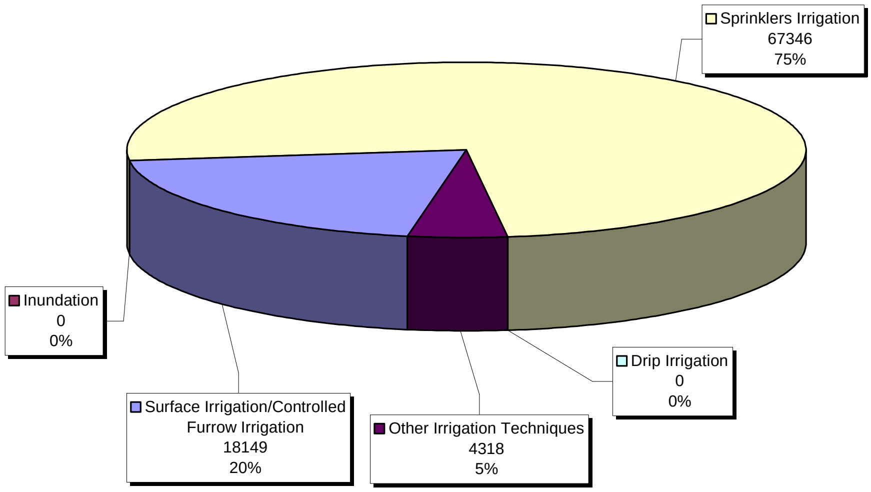


Figure 5.7 Hectares of irrigated maize field in Veneto subdivided by irrigation method adopted

Most of the sprinkler irrigated lands (S_s), don't use any type of soil moisture monitoring with the objective to reduce the water losses. An extrapolation to regional scale, of the water saving percentage obtained in the studied maize field, can give an estimation of the total water volume and money saved.

Total water volume used for sprinkler irrigation on maize field in Veneto is 192.803.257 m^3 [*Istat, 2010*]. Assuming reasonably that the most of the sprinkler irrigated lands has no provided with soil water monitoring system, we can consider a total amount of 192,8 Mm^3 of water that could be better managed by coupling water balance method to soil moisture monitoring. This value is obtained considering an average water saving of 22% as indicated by our experiment. Considering this percentage of savings, about 42,4 Mm^3 of water volume (V_s) can be saved at regional scale. Mean irrigation water depth saved (I_s) is then equal to:

$$I_s = \frac{V_s}{S_s} = 63mm \tag{5.17}$$

Where S represents the total irrigate corn field surfaces in Veneto Region using sprinkler system. Monitoring the dynamics of the soil moisture into crop field it is possible to saving an average irrigation water depth of 63mm. Assuming a mean irrigation application of 40mm it is possible to convert this data in euros saved (E_s):

$$E_s = I_s \cdot C \cdot S_s = 21.000.000€ \tag{5.18}$$

Considering the TDR installation and maintenance costs (C_{TDR}) of about 10€/ha per year effective earn (E_s') amount can be estimated as:

$$E_s' = E_s - 10 \cdot S_s = 20.300.000€ \tag{5.19}$$

In 2010 maize field yield in Veneto was of about 10 tons per hectare (Y), and the price of maize was 20€ per tons (P_y). Assuming no change or limited changes in field productivity it is possible to calculate the total amount of profits (P) obtainable from maize field in Veneto:

$$P = Y \cdot S_s \cdot P_y = 171.000.000€ \tag{5.20}$$

So savings in irrigation water volume represents about the 10% of the total profits obtainable from irrigated maize field in Veneto Region.

All the data reported above are to be considered as approximated values of savings. A lot of other factors influences the productivity and the costs of maize production like soil type and texture, maize type, sowing period, irrigation scheme adopted, but first of all rainfall variability. Further this comparison was performed using water savings obtained in a very small maize field in 2013 and data about surfaces and water volumes registered by Istat three years before. Price of maize and water, surfaces cultivated with maize, irrigation volumes and techniques change every year in function of the variability of market’s low and meteorological events. So the precision of the extrapolation decrease with the increasing of the spatial and temporal scale adopted. However, we can conclude, that 10% of euros saved is a reasonable value considering that, unfortunately, soil water monitoring systems are practically not used and irrigation scheduling is dictating only by farmer experience, that, for how good it could be, can never be as precise as objective measurements like those provided by probes.

Chapter 6

Conclusions

Water is one of the more important factors that influence the quantity and quality of crop yield. A well performed management of water in agriculture activities, can then, increasing the field productivity and minimizing the water losses and costs. Irrigation is needful when water delivered by rainfall events is not sufficient to ensure a good water content in soil. Often, irrigation timing is decided based on the farmer experience, observing plants leaves and surface soil moisture. In reality, plant’s health is dictating by the dynamics of the soil moisture present in deeper soil layers where roots are located. Here, in root zone, a multiplicity of processes contributes to continuously modify the water content influencing the water uptake rate performed by root system. Soil water that can be readily used by plants is defined as RAW (Readily Available Water) and it is linked to soil and crop characteristics. The farmer objective should be that to maintain the soil moisture in the optimal range in which the water can be uptake by plants for assimilate carbon, and losses due to leaching are minimal. To reaches this target, farmers have to modified their approach to the agriculture activities, integrating their own sensibility gained with annual experience, with modern measure instrument able to furnishes objective information about the actual soil water content and dictating irrigation timing. Underground probes, positioned at different depths in root zone, have to be coupled with informatics systems and modern irrigation techniques in order to maximize the efficiency of the irrigation applications. There are three main concepts at the base of a good irrigation water management: uniformity of the water distribution, amount of water delivered and timing of applications. While the first one is a design parameter relative to the chosen irrigation method, the other two are strongly linked to the soil moisture dynamics. In fact, the amount of water that should be delivered to the field during an irrigation application depends on the soil properties, on the actual soil moisture, on the amount of water that could be stored and finally on the evapotranspiration rate of plants during the actual growing stage. Thanks to modern probe installation the timing between two subsequent irrigation applications can be decided considering the actual soil moisture and soil-plants characteristics. Probes, positioned in the root zone, can measure continuously the soil moisture; data are after send to a transmission station that elaborates them through a water balance and displays results in graphic terms. The chance to know at every time the soil moisture profile in crop field facilitates the management of irrigation applications, providing useful indications about best irrigation practices.

This thesis investigates soil moisture dynamics experimental data and models. In 2013 the soil moisture of a maize crop field in Albettone, Veneto, was continuously monitored for the whole season by six underground probes connected to a TDR instruments. Probes were subdivided in two groups: an Uninformed Site irrigated with a tradition method based on farmer experience and an Informed Site where the amount of water and timing of each application was decided elaborating the measured data and applying a water balance scheme. The acquisition period lasted for 101 days in which three irrigation application were performed. Finally a minimalist Model was developed in order to evaluate the different components of the water balance as well as soil and vegetation properties. The model allowed an estimate of the water saving in the Informed Site. The total amount of water received by the two sites where probes were positioned was, found to be, strongly affected by fracture formation. The effect of fractures was modelled as an additional water input. Model performances were judged satisfactory, and soil moisture dynamics properly reproduced at the daily and sub-daily time scale the measured data in the investigated maize field via the calibration of reduced number of parameters. Final results suggest that thanks to soil moisture monitoring a water saving of about 22% with respect to the total amount of water delivered by farmer on the Uninformed Site (120mm) has been achieved without compromising the crop productivity in terms of grain weight. A comparison between the two different irrigation schemes is achieved comparing the cumulative losses obtainable in the same site eliminating any dependencies on soil properties. Water productivity, was then evaluated considering the total amount of water used and the total irrigation water used. Water in Informed Site result to have more productivity with respect to that delivered by farmer in Uninformed Site in terms of crop yield, but it is lower in terms of kilograms of biomass per millimetres of total water used. Finally an extrapolation to field and regional scale, has allowed for an approximate estimation of the euros saved if, in all sprinkler maize field in Veneto, was applied a water balance scheme coupled with a soil moisture monitoring during agriculture activities and all surface irrigate maize field were converted to sprinkler irrigation techniques. Results suggest that the total incoming euros from the yield selling can be increased of about 10% considering the irrigation water saved.

Monitoring soil moisture probes and water balance irrigation scheme can represent an important step for the improvement of the environmental quality and preservation. Water delivered to plants, when uptake rate is maximum, avoid for nutrients washout with consequent benefits also in nutritional terms for plants.

Further experiments should be performed in order to have more detailed description of the hydrologic processes investigated of the water balance scheme and assuring for more uniformity in water distribution during irrigation. The comparison between an Uninformed and an Informed Site should be performed in two separate fields with same crop and climate characteristics and similar soil properties in order to avoid any type of hydraulically interference between the two sites. TDR instrument sensitivities to external factors like temperature should be checked in laboratory to increasing knowledge about the reliability of the probe's measurements. Finally, a more precise study on costs and benefits of probes usage in crop field could provide a more reliable estimate of the earnings induced by water savings allowed by hydrologic measurements.

References

- Allen R.G., Pereira L.S, Raes D. and Smith M.; Crop evapotranspiration – *Guidelines for computing crop water requirements*; FAO Irrigation and drainage paper 56 (1998).

- Bartolini R.; *La nuova agricoltura – Percorsi agronomici sostenibili per i cereali*; Edagricole (2012)

- Doorenbos J.,Kassam A.H.; *Yield response to water*; Irrigation and Drainage Paper, FAO n.33 (1971).

- Greco M., Bellini G.; *Caratteristiche strutturali delle aziende agricole*; Istat; VI Censimento generale dell'Agricoltura; (2010).
- Hupet F., Vanclooster M.; *Interseasonal dynamics of soil moisture variability within a small agricultural maize cropped field*; Journal of Hydrology 261; 86-101; Elsevier; (2002).

- Milly P. C. D.; *A minimalist probabilistic description of root zone soil water*; Water resources research; vol. 37, no3, pages 457-463; USGS; (march 2001).

- Pereira L. S.; *Relating water productivity and crop evapotransiration*; Center of Agricultural Engineering Research, Institute of Agronomy, Technical University of Lisbona, Trapada de Ajuda, 1349-017, Lisbon, Portugal, CIHEAM; (2007).

- Porporato A., D'Odorico P., Laio F., Ridolfi L., Rodriguez-Iturbe I.; *Echohydrology of water-controlled ecosystems*; Advances in Water resources 25; 1335-1348; Elsevier; (2002).

- Quinones H., Ruelle P. and Nemeth I.; *Comparison of three calibration procedure for TDR soil moisture sensors*; Irrigation and Drainage 52, 203-217; DOI: 10.1002/ird.095; (2003).

- Scott B. Jones, Jon M. Wraith and Dani Or; *Time domain reflectometry measurement principles and applications*; Hydrological Processes 16, 141-153; Scientific Briefing; (2002).

- UN WATER; *Managing Water under Uncertainty and Risk*; The United Nations World Water Development Report 4; Volume 1; (2012).

- Vico G., Porporato A. From rainfed agriculture to stress-avoidance irrigation: I. *A generalized irrigation scheme with stochastic soil moisture*, Advances in Water Resources 34; 263-271; Elsevier; (2011).

- Vico G., Porporato A.; *From rainfed agriculture to stress-avoidance irrigation: II. Sustainability, crop yield, and profitability*; Advances in Water Resources 34, 272-281; Elsevier (2011).

- Vico G., Porporato A.; *Traditional and microirrigation with stochastic soil moisture*; Water resources research; vol. 46 issue 3.

- Vrugt A., Braak C.,Clark M., Hyman J.,Robinson B.; *Treatment of input uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte Carlo simulation*; Water Resources research; vol.44, W00B09, doi:10.1029/2007WR006720; (2008).

Websites

- http://www.fao.org/home/en/
- http://www.istat.it/it/

Ringraziamenti

Voglio ringraziare tutti coloro che mi hanno sostenuto in questo percorso universitario e che mi hanno permesso di arrivare a questo importante traguardo. Prima di tutto la mia famiglia che ha "finanziato" i miei studi anche per due anni più del dovuto, e che ha saputo sempre darmi buoni consigli nei momenti necessari.

Un particolare ringraziamento ai miei compagni di avventura Stefano e Martino, che sono riusciti a rallegrare le sessioni d'esame fin dal primo anno universitario.

Grazie a Giulio, un amico su cui poter sempre contare nonostante i chilometri di distanza e a Valentina, amica fidata d'infanzia. Ringrazio anche tutti gli amici della compagnia per aver allietato serate e vacanze trascorse assieme.

Sicuramente il più grande ringraziamento va a Silvia, l'unica ad avermi sempre sostenuto e consigliato nelle mie scelte e ad avermi concretamente aiutato nella realizzazione di questa tesi. Grazie anche per tutto ciò che da quattro anni assieme condividiamo.

Infine un sentito ringraziamento al prof. Botter per la pazienza e la disponibilità prestatami e al prof. Putti per la preziosa collaborazione. Un grazie anche ad Elisa ed Elia per avermi fornito i dati e gli strumenti necessari allo sviluppo di questo lavoro.