University of Natural Resources and Life Sciences, Vienna

Department of Water, Atmosphere and Environment

Institute of Hydraulics and Rural Water Management

Master Thesis

DETERMINATION OF SOIL WATER BALANCE COMPONENTS AT A SITE IN NORTH-EASTERN AUSTRIA

Submitted by:

Claudio Lanza

Thesis advisers:

Univ.-Prof. Dipl.-Ing. Dr.nat.techn. Willibald Loiskandl

Dipl.-Ing. Dr. Reinhard Nolz

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Special thanks go to my Family and to my girlfriend Stefanie, who supported me strongly during my studies.

Abstract

Soil water content varies according to different inputs and outputs that are describable compiling a basic water-balance equation. Lysimeters, which use a weighing system to detect water content variations, are reliable instruments in order to accomplish soil water balance studies. EnviroSCAN® soil sensors use capacitance technology for detecting soil water content. In the present thesis a basic water-balance equation was solved by means of lysimeter and EnviroSCAN® sensors (installed in the lysimeter profile). Evapotranspiration, precipitation were compared on a later stage with references calculations or records, on annually, monthly and daily basis. Generally lysimeter deliver good results even if precipitation was greater than rain-gauge values and evapotranspiration was lower than the results of simulation. On the other hand it was not possible to achieve good estimation of soil water components by means of EnviroSCAN® measurements.

The impossibility to detect the first centimeters of the soil profile by means of EnviroSCAN® sensors and the effects of superficial processes could affect the estimation of both evapotranspiration and precipitation and generate errors and underestimations.

Kurzfassung

Der Bodenwassergehalt variiert gemäß verschiedener Input- und Outputdaten, die mit Hilfe einer Wasserhaushaltsgleichung beschrieben werden können.

Die wägbaren Lysimeter, die die Veränderung des Bodenwassergehaltes messen, sind verlässliche Geräte um Studien bezüglich des Bodenwasserkreislaufs durchzuführen. EnviroSCAN® Bodensensoren verwenden die sogenannte Capacitance-Technologie um den Bodenwassergehalt zu ermitteln. In der vorliegenden Arbeit wurde eine grundlegende Gleichung mittels einer Lysimeteranlage und EnviroSCAN® Bodensensoren, die im Boden des Lysimeters eingesetzt wurden, gelöst. Evapotranspiration und Niederschlag wurden in einem späteren Stadium mit Referenzberechnungen bzw. -methoden auf jährlicher, monatlicher und täglicher Basis verglichen. Auch wenn der Niederschlag mehr betrug als die Daten des Niederschlagsmessers und die Evapotranspiration geringer als die Ergebnisse der Simulation war, lieferten die Lysimeter grundsätzlich gute Ergebnisse. Andererseits war es jedoch nicht möglich gute Schätzungen über die Komponenten des Bodenwassers durch die EnviroSCAN® Bemessungen zu erhalten. Die Tatsache, dass die oberen 10 cm des Bodenprofilsmittels mittels der EnviroSCAN® Sensoren nicht gemessen werden konnten und die Auswirkungen von oberflächlichen Prozesse, könnten zu Unterschätzungen von Evapotranspiration und Niederschlag führen.

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1 INTRODUCTION

1.1 General context

Nowadays, water scarcity and food security are important global issues (United Nations, 2015). Irrigated agriculture is the biggest user of water (FAO, 2013; Trout, 2000). Thus, the optimization of the use of water in agricultural management and the maximization of yields are among the most important aims of the agricultural scientific community.

The main purpose of irrigation is to provide an ideal water supply for plant growth (Walker, 1989). An excess of irrigation leads to water losses through percolation (Dastane, 1978), which is the transfer from the soil storage to the groundwater, also known as deep drainage. On the other hand, an insufficient irrigation affects crops development (Loiskandl et al., 2014).

In order to improve the agricultural practices and the agricultural water management, a better knowledge of the hydrological cycle and its components is necessary, also in areas where data and experiments are available, such as the Marchfeld in Low Austria, where irrigation is practiced since long time. This region is also prone to draughts and there are concerns that the draughts and heat stresses will increase in future (Eitzinger, 2014).

1.2 The vadose zone

The continuous movement of water takes place in the atmosphere, in the vadose zone and in the groundwater environment. The vadose zone, also known as unsaturated zone, is the interface between the atmosphere and the groundwater environment (Fig.1).

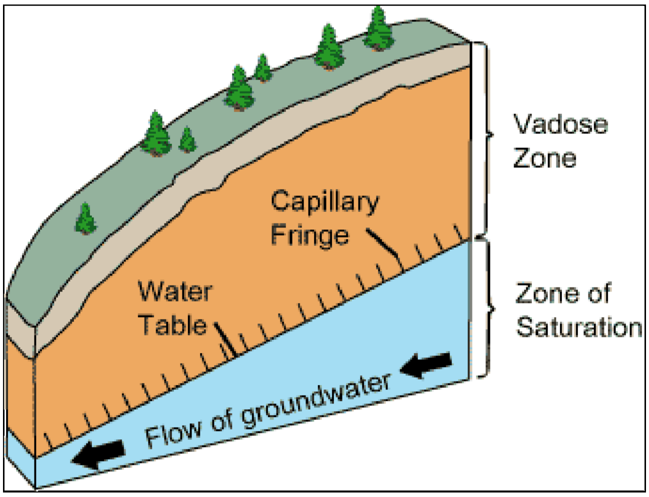


Figure 1: Illustration of the vadose zone (USGS, 2004).

It is known to be one of the most complex systems on earth and it is essential for the sustenance of life and for the agriculture production. It is usually constituted by soil and small voids, known also as pores (Dar, 2010; Kutilek and Nielsen, 1994; Rampazzo et al., 2013). The latter can be filled either with air or with water and they constitute the water reservoir of a soil (Loiskandl and Strauss-Sieberth, 2011). In this respect, a related parameter, called porosity (n_p), reflects how much water can be hold in the soil. Porosity is defined as follows (Eq.1):

$$n_p=V_p/V_{tot} \quad (1)$$

where V_p represents the volume of pores (sum of the volume of water and the volume of gas that fill the pores) and V_{tot} is the total volume.

1.3 Soil water components

The quantity of water held within the voids is known as soil moisture or soil water content. The soil moisture or soil water content can be defined as the volume of water (V_w) per volume of soil (V_{tot}) (Eq.2).

$n_l = V_w / V_{tot}$ (2)

According to Eq.2, n_l can be expressed in % or cm^3/cm^3.

The concentration of water in the profile can be also mathematically described as gravimetric water content (W) (Eq. 3):

$W = m_l/m_s$……………………………………………………………………………………………………(3)

where m_l is the mass of the liquid and m_s is the mass of the solid phase.

Gravimetric soil water content (W) can be expressed as water depth present in one meter of soil (mm/m) (Brouwer et al., 1995).

Soil water content changes positively or negatively, according to different inputs and outputs. Precipitation (P) and irrigation (I) are the main contributors to the soil storage, while evapotranspiration (ET) is the principal loss of water in the vadose zone (Dastane, 1978).

Precipitation represents the main natural water input in the vadose zone (Dick and Peschke, 1995). Even if precipitation, in some cases, can be considered as a synonym of rain, other minor phenomena like fog deposition and dew play a role in the hydrological system (Schulz, 2013). Dew is the appearance of water above a surface in form of droplets, due to condensation. Additionally, the term precipitation includes solid inputs such as snow and ice (Ahrens, 2011).

Evapotranspiration represents the largest water output of the soil system and it is the major cause of water depletion in the vadose zone (Abtew and Melesse, 2013; Allen et al., 1998). For vegetated surface, it is the sum of two crucial phenomena: evaporation (E) and transpiration (T). Evaporation and transpiration are difficult to distinguish (Allen et al., 1998), thus, a common approach, also applied in this thesis, is to consider the two terms together (Eq.4).

$$ET = E + T \quad (4)$$

Evaporation (E) refers, specifically in the present study, to the water loss from bare soil to the atmosphere. The evaporation rate from soil is influenced by many factors, such as the solar radiation, air temperature, air humidity and wind speed (Allen et al., 1998).

Transpiration (T) refers on the other hand, to the evaporation of water directly from the tissues of the plants. The water is taken by roots and transported to the dry organic matter of the plants. Water is then able to enter the atmosphere through the so called stomata. The stomatal openings and, thus, the quantity of water loss, are controlled by the plants (Abtew and Melesse, 2013).

A distinction has to be made between the actual (ET_a) and potential evapotranspiration (ET_p); the actual (ET_a) represents the real amount of evaporation that occurs in a specific situation. In contrast, the potential (ET_p) describes the maximal amount of evaporation which is possible when enough water is supplied (Allen et al., 1998; Loiskandl et al., 2014). ET_p is known as ET_0 (reference evapotranspiration) if a reference grass cover is employed. Grass is worldwide considered as the reference surface and it is used in order to determine the so called ET_0. According to Allen et al. (1998), the grass should have a height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. Furthermore the reference grass has to be well watered under optimal agronomic conditions and should entirely cover the soil surface.

If ET_p, from a soil covered by a chosen crop, and ET_0 are known, it is possible to determine the crop coefficient K_c (Eq.5):

$$K_c= ET_p/ET_0 \quad (5)$$

According to Allen et al. (1998), the basic crop coefficient, K_c, is the ratio of ET_p, observed for the crop studied, over ET_0 observed for the reference grass under the same conditions.

K_c is used in order to assess directly the amount of ET_p from a soil covered by a chosen crop and it is useful in the agriculture practice for determining the plant water requirements.

Furthermore, the upward movement of groundwater, known as capillary rise (CR), can fill the soil reservoir while on the other hand deep drainage, known also as seepage water (SW) depletes the amount of water within the vadose zone (Baumgartner and Liebscher, 1995; Loiskandl et al., 2014). Anyway, CR is only significant for shallow groundwater tables. Commonly, a depth of two meters below the root zone is assumed. Seepage water (SW), is an important input for the replenishment of the groundwater environment. This parameter reflects the downwards movement of a fluid, caused by gravity (Brouwer et al., 1995). SW is per definition not available for plants. Plant available water (PAW) is the difference between field capacity (FC) which is the volume of water and the permanent wilting point (WP). Field capacity is defined as the amount of water remaining in the soil two or three days after a rain or irrigation event. According to Brouwer et al., 1995, at field capacity the large pores are filled with air, while the small pores are filled with liquid. Permanent wilting point expressed the soil water content at which the plant dies (Brouwer et al., 1995).

1.4 Soil water equation

Considering the change of water content within the soil profile (ΔW), it is possible to set up a basic equation in order to point out the interconnections between the components explained above (Fig.2) (Eq.6) (Nolz et al., 2011):

$$P+I-ET-SW+CR\pm\Delta W=0 \qquad (6)$$

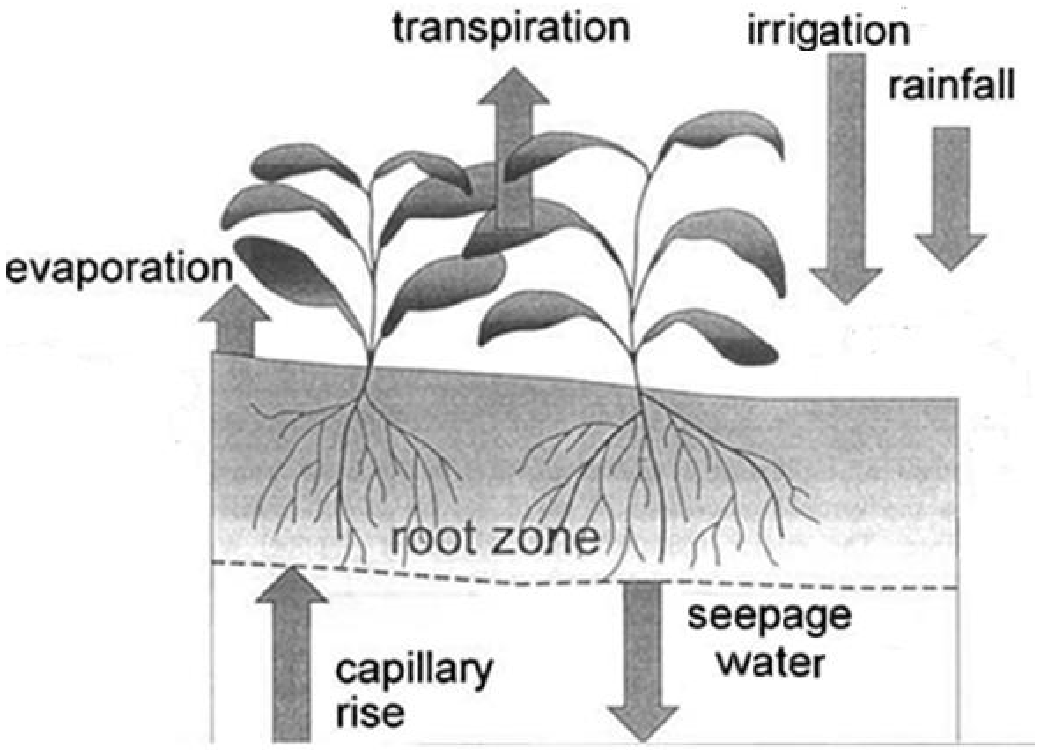


Figure 2: Representation of the components of the soil water balance (Allen et al., 1998).

1.5 Soil water content changes: Lysimeter and soil water sensors

Because of the high temporal dynamics and spatial variations of ΔW, the measurement of this parameter along time requires reliable equipment. A lot of techniques have been developed. ΔW can be determined among others by direct methods (lysimeter), gravimetric sampling, geophysical methods (soil moisture sensors) and remote sensing methods (Verstraten et al., 2008).

1.5.1 Lysimeter

Lysimeters are instruments, used in hydrological studies, principally constituted by a metal vessel, filled with soil. The metal vessel of this instrument allows the hydrological isolation of the soil profile through low and lateral boundaries (Fisher, 2012; Lanthaler, 2004). In particular, in the so called gravity lysimeter, capillary rise (that normally occur in nature) is impossible. Originally, they were used just for collecting seepage water (SW) and for studying the downwards movement of certain pollutants (Von Unold and Fank, 2007; Lanthaler, 2004). SW can be measured for example, without applied vacuum, by means of a tipping bucket, placed at the bottom of a soil profile of a lysimeter facility (Dastane, 1978; Lanthaler, 2004).

Nowadays it is additionally possible, through modern and precise weighing systems, to determine the mass changes of the system vegetation-surface-soil for any period of time, and thus the changes of soil water content (ΔW). Such lysimeters are known as weighing lysimeters (Baumgartner and Liebscher, 1995; Fisher, 2012; Nolz et al., 2011; Von Unold and Fank, 2005). Weighing lysimeters are considered by many authors as a reliable method in order to solve soil water balance (Nolz et al., 2011; Lanthaler, 2004). Anyway, they are expensive and the installation and the maintenance are elaborate and time-consuming. Furthermore, the lysimeter is susceptible to a range of factors, which are listed and discussed below, according to Lanthlaler (2004), and Nolz et al. (2011, 2013).

Oasis effects: A lysimeter provides a point measurement and the results may not be representative of a larger area. In order to reproduce accurately the vegetative, hydrological and climatic conditions of the surrounding area, a big deal of efforts is required. For example, the interruption of the natural soil profile can lead to irregularities of water movement and pressure. Seepage water may differ from the soil outside the vessel. The extent of this effect is highly dependent upon soil characteristics, plant growth and meteorological parameter and one of the key factors in this respect are the low boundaries conditions. Furthermore**,** the soil in the vessel must reproduce the same internal structure of the natural soil in the surrounding area. The organic layer of soil must not be mixed with the mineral horizon.

Environmental impacts: The measurements of the lysimeters are affected by environmental factors such as wind, snow or animals.

1.5.2 Soil capacitance sensors

Capacitance (capacity of a medium to store an electrical charge) soil water sensors are also valuable instruments in order to assess soil water changes (Paltineanu and Starr, 1998; Schwank et al., 2012) and they find applications in soil water balance studies (Cepuder and Nolz, 2007; Verstraeten et.al, 2008). Such methods are based on the dielectric properties of soil which vary according to water content changes (because the dielectric of water is much greater than the other components of the soil) (Skierucha and Wilczek, 2010). The soil dielectrical constant (ability to store charge) is measured by creating around each sensor a high frequency electrical field. As a further step, the volumetric soil water content (n_l), because of the high correlation between the latter and the dielectrical constant, can be determined (Paltineanu and Starr, 1997; Sentek, 2003).

One of the advantages of capacitance soil water content sensors is the continuous measurement of the water content in the soil at different depth (Paltineanu and Starr, 1997). However, sensors are in general responsive only if water reaches or leaves their zone of influence. Thus, sensors neglect phenomena that occur on the soil surface and cannot detect water beyond their electrical field, for instance near the soil surface (about 0-5 cm depth) (Paltineanu and Starr, 1997). Additionally, the probes are limited to a restricted number of sensors (Sentek, 2003) and, if the length of the probe is shorter than the depth of the soil profile, the whole soil profile cannot be considered.

Furthermore, in case of surface storage (water retained by depressions), the soil would be readily replenished (if evapotranspiration takes place) keeping the soil sensors at saturation and unable to detect the variations of the soil water components (Rahgozar et al., 2012). Other inaccuracies can be introduced by soil temperature variations (Evett, 2012).

1.6 ET and P determination

ET can be estimated from pan evaporation, microclimatological methods and solving energy balance or soil water balance (lysimeter or soil sensors) (Allen et al., 1998). Furthermore, ET can be computed by means of calculations and models. Anyway, at the moment, the only recognized formula for the calculation of ET_0 is the FAO Penman-Monteith; the method requires climatic parameters such as radiation, air temperature, air humidity and wind speed data. Additionally, ET_p for a specific plant can be derived by knowing K_c (Allen et al., 1998).

Rain gauges, disdrometers and remote sensing methods are nowadays used in order to measure precipitation (Dastane, 1978; Schulz, 2013). P can be also estimated, solving the soil water balance equation (Nolz et al., 2011).

2 HYPOTHESIS AND OBJECTIVES

Hypothesis

- Oasis effects and environmental factors don't affect the results of the lysimeter.

- The omitted measurements of the upper and lower layers and surface storage don't affect the results of the capacitance sensors installed in the lysimeter profile.

- Lysimeter and capacitance sensors, installed in the same soil profile, deliver similar estimations of ΔW.

Objectives of the thesis

Main objective of the present thesis was to assess ET, P at a site in north-eastern Austria on a monthly and daily basis, using soil water content data from a lysimeter and soil water content sensor. Furthermore evapotranspiration (ET) was approximated by means of FAO models with weather data as input parameters.

Specific study objectives were:

- Comparison of soil water content data (ΔW) as measured by lysimeter and soil water probes.

- Are model results, similar to lysimeter measurements? If not, what are likely reasons?

- Are rain records similar to lysimeter measurements? If not, what are likely reasons?

- Are model results, similar to water balance by measuring ΔW with soil sensors? If not, what are likely reasons?

- Are rain records in relation to soil sensors results? If not, what are likely reasons?

3 MATERIAL AND METHODS

3.1 Experimental site

3.1.1 Location

The soil water changes (ΔW) were measured by means of a lysimeter facility and EnviroSCAN® sensors (FDR technology) between January 2008 and December 2011. The experiment was conducted at the experimental farm of the University of Natural Resources and Life Sciences of Vienna (BOKU), located in Groß-Enzersdorf (48°12’N, 16°34’E; 157 m), NE Austria, in the region of Marchfeld (Fig.3).

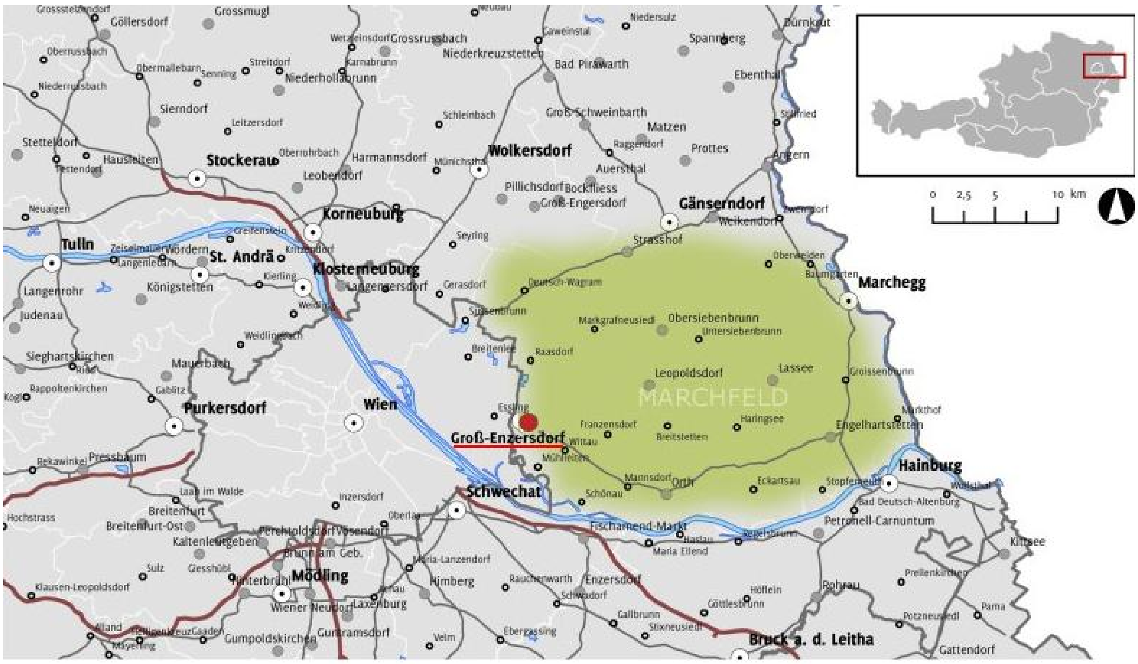


Figure 3: Location of the experimental farm of BOKU (Mubil, 2003).

This region covers an area of 1.000 km^2. Because of the fertile soil, the principal economic activity of Marchfeld is the agriculture that uses around 650 Km^2 (Götz, 2000). In Groß-Enzersdorf and in the surrounding area the soil is Chernozem; it is a black-colored soil containing a high amount of humus, and high percentages of phosphoric acids, phosphorus and ammonia.

Close to the experimental farm, meteorological data are collected by Zamg (Zentralanstalt für Meteorologie und Geodynamic) station. The following parameters are measured:

- Air temperature
- Precipitation
- Relative humidity
- Global radiation
- Wind velocity in 10 m height
- Net radiation

3.1.2 Period of the experiment

Because of breakdowns, due to temporary failure of internal components, no data are available in the following periods. The period with no data were not considered in the statistical analysis of results.

Lysimeter facility (data gaps)

- **2008:** 01/01 – 28/01
- **2009**: 27/06-24/08
- **2010**: 01/01-28/02,02/06, 22/09-23/09, 12/10-31/12
- **2011**: 14/02-15/02, 05/03-16/03

Figure 4 visualizes the periods in which no data were delivered from the lysimeter. The gaps indicate periods without available data.

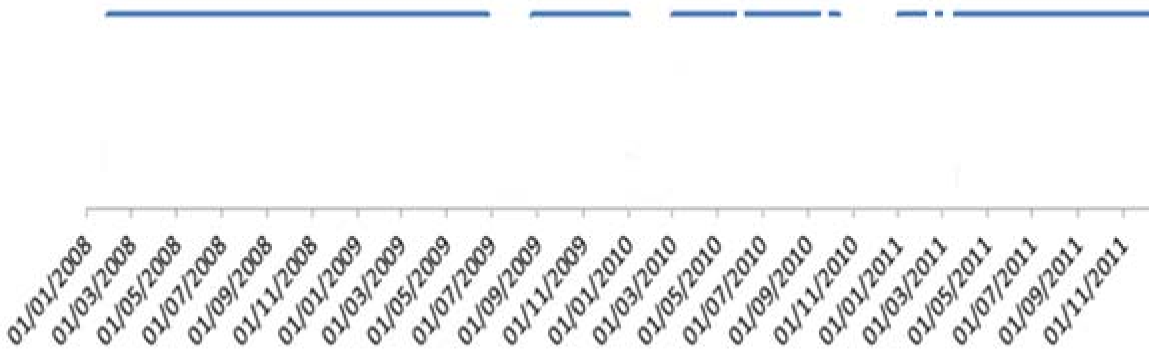


Figure 4: Lysimeter breakdowns (2008-2011).

<u>EnviroSCAN® sensors (data gaps)</u>

- 2008: 01/01-23/01, 13/02-20/02, 18/12-31/12
- 2009: 01/01-02/04
- 2010: 15/09
- 2011: 01/01-08/05

Figure 5 illustrates the breakdown periods of the EnviroSCAN® sensors considering a continuous line data, interrupted by gaps.

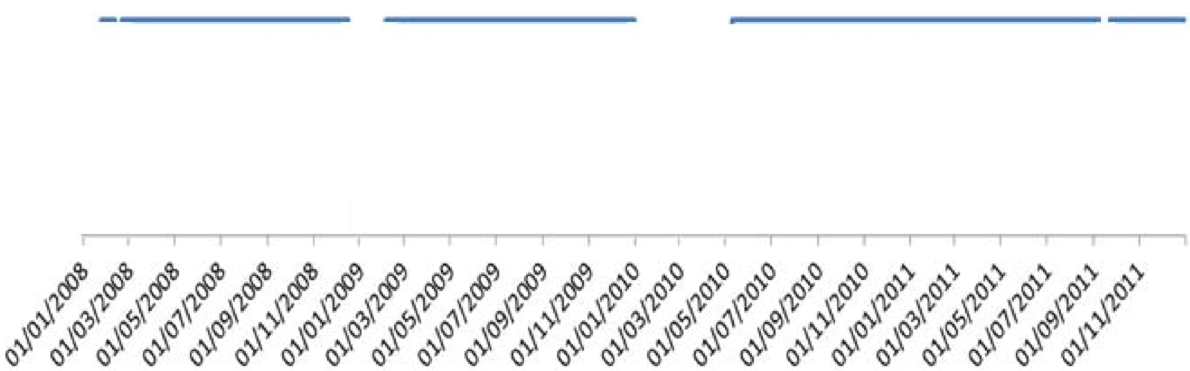


Figure 5: EnviroSCAN® breakdowns (2008-2011).

3.1.3 Climate and Weather

The climate in the Marchfeld area is defined as pannonic and shows continental features. The wintertime is normally cold and shows severe frost and limited covers of snow. On the contrary, the summertime is hot and it is associated with dry weather (Götz, 2000).

Figure 6 illustrates the climatic diagram of Groß-Enzersdorf. The average yearly temperature is around 9.9 °C and the yearly amount of precipitation is 551 mm. Around 1.900 hours of sun offer the ideal condition for an agricultural land use (ZAMG).

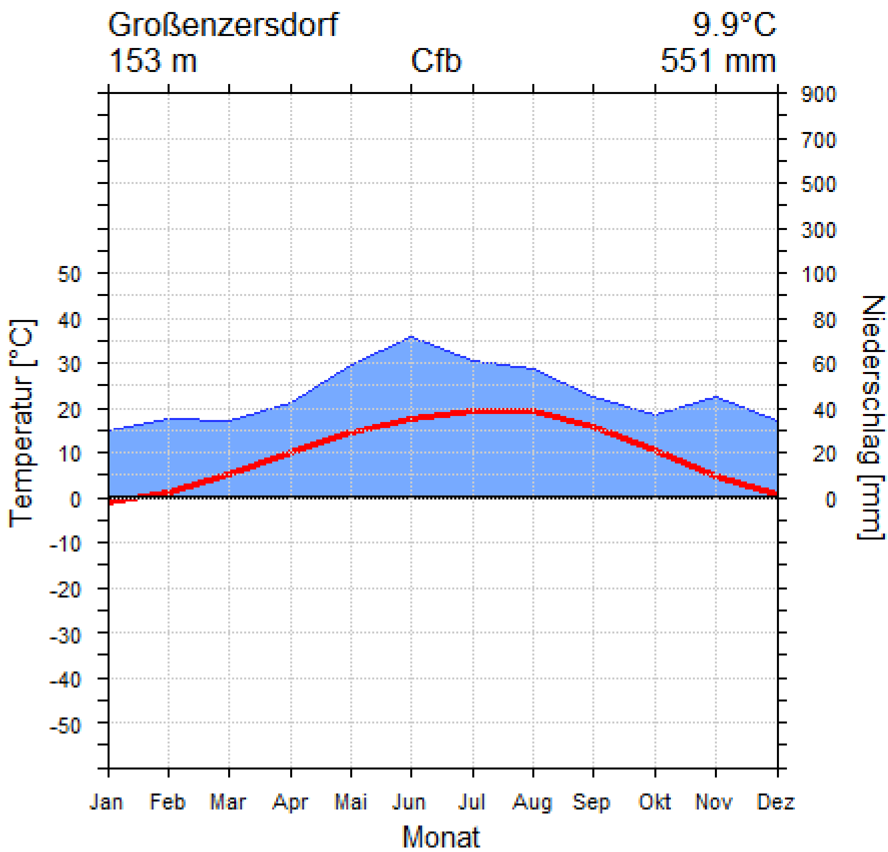


Figure 6: Climate diagram of Groß-Enzersdorf (1997-2010) (Bernhard Mühr, 2010).

A more detailed description of the weather and the climate for the years 2008, 2009, 2010 und 2011, is provided by the yearly reports of ZAMG (Fig.7, 8, 9, 10).

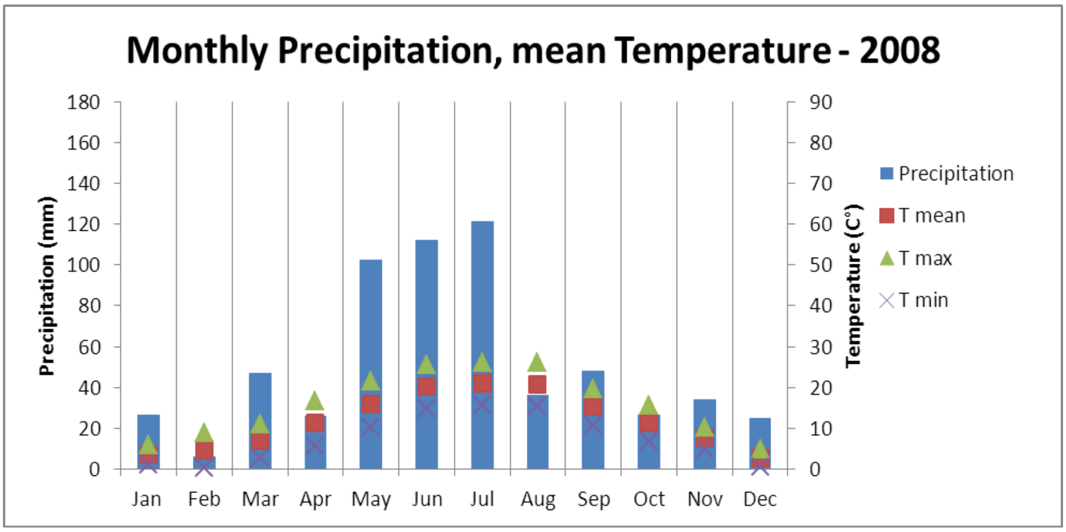


Figure 7: Monthly precipitation and Temperature (2008).

The year 2008 showed big amount of precipitation in summer, a part of the month of August. The summer was as usual hot but the previous months; April and May were colder than the average. The winter was warmer than the average and the lowest average temperature was always above the 0°C (ZAMG).

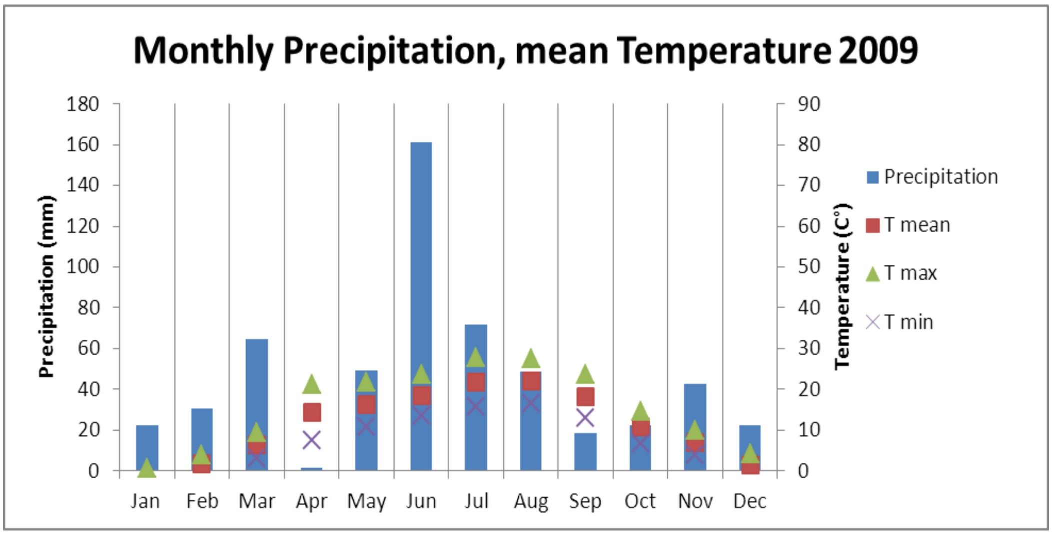


Figure 8: Monthly precipitation and temperature (2009).

The year 2009 is characterized by strong climate variations. In summertime a cold air depression was followed by the warmest days of the year. The winter showed untimely low temperatures and around Christmas a storm period was observed. The month of June was particularly rainy (ZAMG).

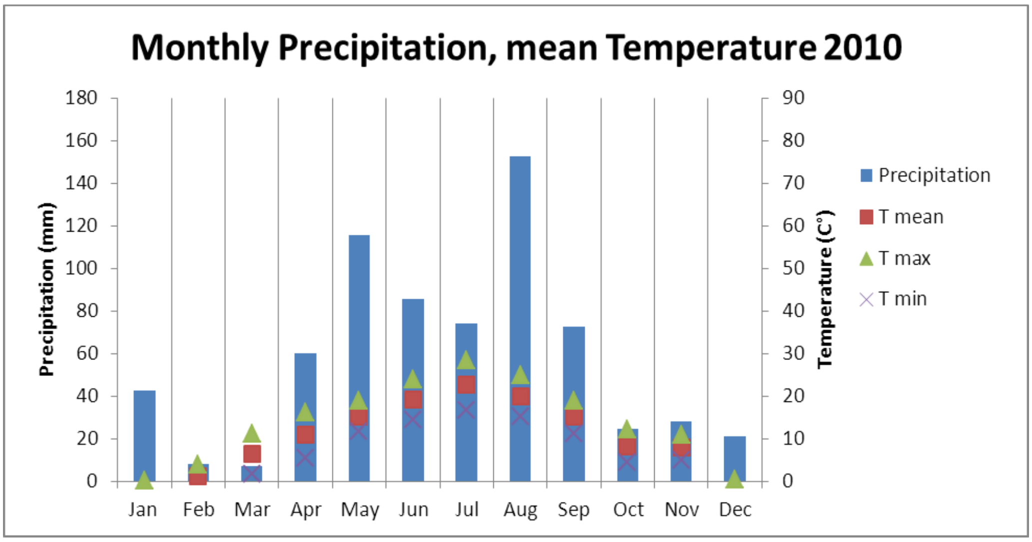


Figure 9: Monthly precipitation and temperature (2010).

The month of July was particularly dry and hot and the wintertime, above all the month of December, was characterized by low temperatures. October was very cold. Very small amounts of precipitation were observed in February, March, October and November (ZAMG).

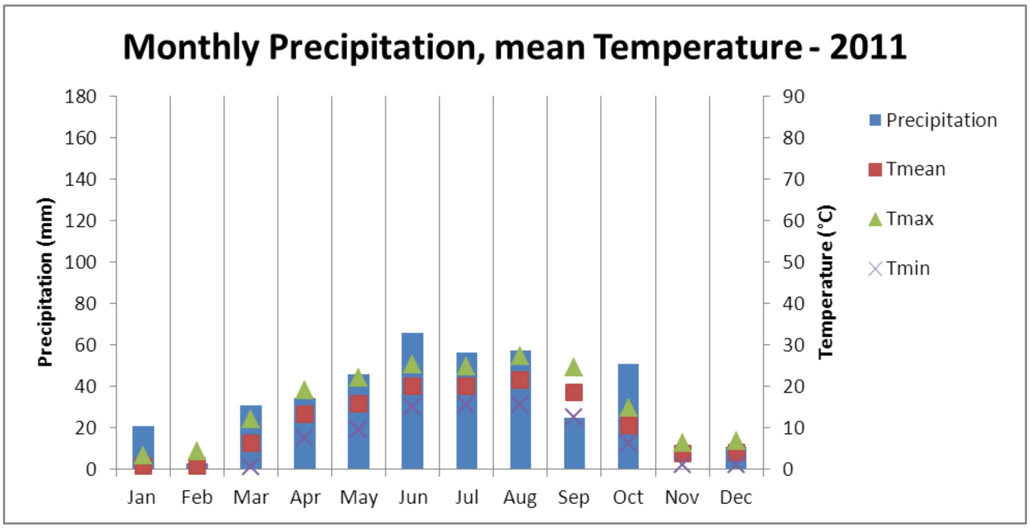


Figure 10: Monthly precipitation and temperature (2011).

The amount of precipitation is smaller with respect to the previous years. In November no precipitation was observed. Winter was cold and dry while summer was as usual hot and dry (ZAMG).

3.1.4 Lysimeter facility in Groß-Enzersdorf

The lysimeter facility in Groß-Enzersdorf is constituted by two large weighing lysimeters (Fig. 11) that are operated since 1982 in the experimental farm and were installed by the Swiss company "Compagnie Industrielle Radioelectrique"(Neuwirth and Mottl, 1983). They are managed and maintained by the Institute of Hydraulics and Rural Water-Management of the University of Natural Resources and Life Science (BOKU), Vienna.

The main purpose of this facility is to conduct studies on soil water balance, to measure soil water changes (ΔW) and volume of seepage water (SW) with high temporal resolution. In particular, the east-lysimeter (reference grass cover) and the west-lysimeter (crops cover) are used in order to assess ET (Neuwirth and Mottl, 1983; Nolz et al., 2009, 2011).

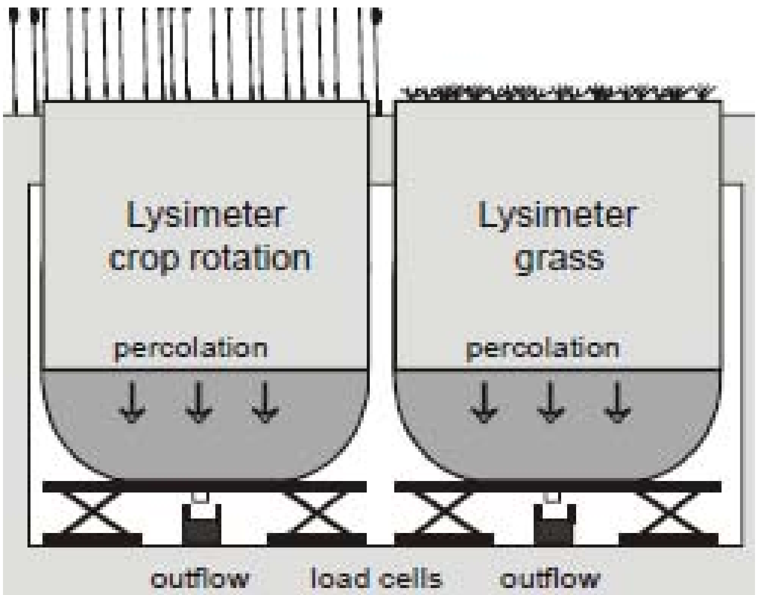


Figure 11: Schema of the lysimeter facility in Groß-Enzersdorf (Nolz and Cepuder, 2008).

The so called east-lysimeter was cultivated with grass during the four years of the experiment. On the other hand the west-lysimeter and its surroundings were grown with crops. The present master thesis considers, for the east-lysimeter, data from the whole period of the experiment, while taking into account the data of 2011 for the west-lysimeter.

The cylindrical vessel of both lysimeters has an inner diameter of 1.9 m (surface area = 2.85 m^2) and a hemispherical bottom with a depth of 2.5 m. The soil is constituted of sandy loam soil (0–140 cm) over gravel (140–250 cm). The porosity of sandy loam soil is between 35% and 40%, while gravel is constituted only by macropores and has a very low capacity to hold water (gravity lysimeter).

The changes of mass of the vessel and, thus, of the soil water changes (ΔW) were measured by a mechanical weighing system, which was connected to an electronic load cell. Seepage water (SW) was measured at a free draining outlet (atmospheric-pressure conditions) at the bottom of the lysimeter by means of a tipping bucket (Neuwirth and Mottl, 1983; Nolz et al., 2011).

3.1.5 EnviroSCAN® sensors in Groß-Enzersdorf

Soil water changes in the soil profile of the lysimeter were measured, in addition to the lysimeter, by means of the capacitance EnviroSCAN® measuring system, developed by the Australian company Sentek. The main components of the EnviroSCAN® sensors are the top cap, the access tube, the sensor electrodes, the sensors and the cable (Paltineanu and Starr, 1997; Sentek, 2003).

The access tube was installed directly in the lysimeter following the manufacturer's recommendations in order to achieve a good contact between tube and soil. The tube was equipped with sensors in 10 cm-intervals from 10 to 160 cm in order to measure the changes of water content in the soil at different depth (Nolz and Cepuder, 2012) (Fig.12).

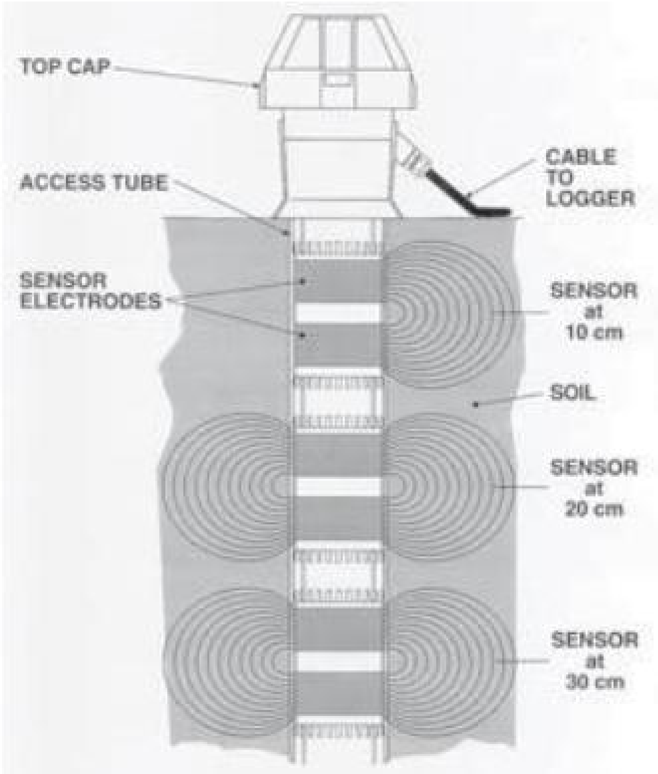


Figure 12: Schematic representation of the first 30 cm detected by the soil sensors (Nolz and Cepuder, 2008).

EnviroSCAN® sensors were not able to measure soil water content (n_l) in the first centimeters of the soil profile because the zone of influence is approximately 10 cm in length along the axis of the probe. Furthermore, during the experiment in Groß-Enzersdorf, the last 90 cm (between 160 and 250 cm), constituted by gravel, were not detected (Nolz and Cepuder, 2012).

3.1.6 Data management

Weighing data from lysimeters and data of the tipping bucket were measured every few seconds and stored every 10 minutes and collected on Excel sheets (Nolz et al. 2011). Starting from 10 minutes steps, it was possible to calculate W and SW additionally on an hourly and daily step (Tab. 1, 2). For the present thesis an Excel sheet for each year was provided by the Institute of Water, Atmosphere and Environment.

Table 1: Cumulative W and SW (hourly steps).

Hours	cum W (mm/m)	cum SW (mm/m)
01/01/2011 1.01	-0.01	0.00
01/01/2011 2.01	-0.04	0.00
01/01/2011 3.01	-0.07	0.00
01/01/2011 4.01	-0.11	0.00
01/01/2011 5.01	-0.14	0.00

Table 2: Cumulative W and SW (daily steps).

Day	cum W (mm/m)	cum SW (mm/m)
01/01/2011 7.07	-0.19	0.00
02/01/2011 7.07	-1.00	0.00
03/01/2011 7.07	-1.90	0.00
04/01/2011 7.07	-2.66	0.00
05/01/2011 7.07	-3.49	0.00

Excel sheets, based on 10-min data of EnviroSCAN®, were provided on hourly and daily steps. The absolute value of the soil water content was reported for each depth. The last column (Sum) represents the total soil water content (ΔW) of the soil system (Tab. 3).

Table 3: Cumulative W of soil sensors (daily steps).

Day	10 cm depth	20 cm depth	30 cm depth	40 cm depth	....	160 cm depth	Sum (mm/m)
01/01/2011 7.00	21.4	30.3	31.8	33.7	....	8.4	125.5
02/01/2011 7.00	22.4	30.0	31.6	33.6	....	8.3	126.0
03/01/2011 7.00	23.4	29.8	31.5	33.5	....	8.3	126.6
04/01/2011 7.00	23.4	29.6	31.4	33.5	....	8.3	126.2
05/01/2011 7.00	21.2	29.6	31.3	33.5	....	8.2	123.8

Considering both lysimeter and EnviroSCAN data, the values of the hourly (or daily) change of soil water (ΔW) are obtained by subtracting the value W_i with the previous value W_{i-1}.(Eq.7).

$$\Delta W = W_i - W_{i-1} \tag{7}$$

In the case of EnviroSCAN®, the operation can be accomplished for a single depth or for the whole soil profile (column "Sum").

The volume collected of the hourly (or daily) seepage water (SW) is easily obtained by subtracting the cumulative value SW_i with the previous cumulative value $SW_{i-1.}$ (Eq. 8)

$$\Delta SW = SW_i - SW_{i-1} \tag{8}$$

3.1.7 Assessment of soil water balance

Working within a lysimeter facility, it is possible to simplify Eq.6. Capillary rise (CR) can be not determined because the lower boundary is artificially separated from the groundwater by the metal vessel of the lysimeter (Lanthaler, 2004).

Consequently Eq. 6 can be reduced to the following, simplified equation (Eq.9):

$$P+I-ET-SW\pm\Delta W = 0 \tag{9}$$

The common approach, in order to calculate ET is to consider the typical lysimeter balance and to use records from rain gauges as input (Eq. 10).

$$ET = P+I-SW-\Delta W \tag{10}$$

Anyway, this approach can lead to implausible and negative values of ET if measurement errors occur (Nolz et al., 2011).

Thus, in the present master thesis, precipitation is directly determined from lysimeter and soil sensors data.

The measured and known parameters can be arranged on the left-hand side of the equation, and the unknown components of the water balance (P, I and ET) on its right-hand side (Eq. 11).

$$SW + \Delta W = (P+I) - ET \quad (11)$$

According to Nolz et al. (2011), a nominal time series ($\Delta W + SW$) was calculated on hourly basis from the soil water changes data ΔW and the cumulated seepage water SW. As a further step, it is assumed that the term ($\Delta W + SW$) equals ($P + I$) if positive. On the other hand a negative value of ($\Delta W + SW$) corresponds to ET.

Considering soil water changes as calculated by means of lysimeters (ΔW_{lys}) and by means of EnviroSCAN soil sensors ($\Delta W_{EnvSCAN}$), it is possible to assess P, I and ET according to Eq. 12 and 13, respectively:

$$SW + \Delta W_{lys} = (P_{lys} + I_{lys}) - (ET_{lys}) \quad (12)$$

$$SW + \Delta W_{EnvSCAN} = (P_{EnvSCAN} + I_{EnvSCAN}) - (ET_{EnvSCAN}) \quad (13)$$

The parameter I could be separated straightforwardly, because the respective dates were known from record keeping. For the purposes of the master thesis, precipitation (P) is considered as the sum of rain, snow, ice and dew. The soil water components were assessed on an hourly basis. Accordingly, P and ET were calculated as well for each day of the study period, from 7 am to 7 am of the following day (ZAMG-standards) and on a monthly and yearly basis.

3.1.8 Irrigation and operations of the lysimeter

East-lysimeter

Trying to reproduce the ideal reference surface for the measurement of ET_0, on the east-lysimeter and its surroundings grass was grown. Grass was cut frequently to a height of 10 cm. Weed control was executed manually. NPK fertilizer with microelements and long-term effect has been applied in order to guarantee an active growth and a uniform distribution of grass. Furthermore, the east-lysimeter was frequently irrigated, above all in the summer months, with the intent to provide the ideal water content for plants growths (Fig. 13).

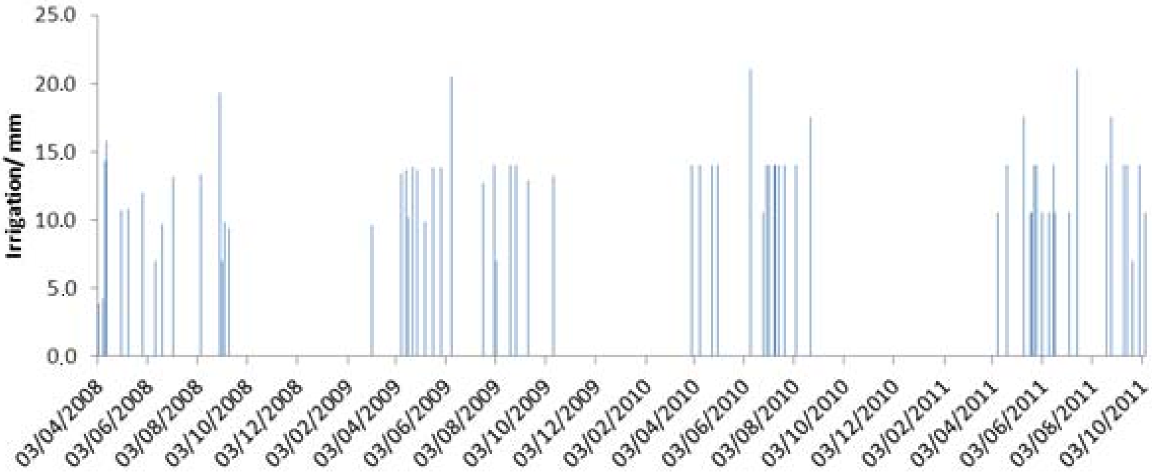


Figure 13: Irrigation events (2008-2011).

West-lysimeter

The data of the west-lysimeter were considered for the year 2011, when on the second lysimeter spring barley was grown. Weed control was executed manually and fertilizer was applied. Spring barley was irrigated five times; on the 20th and 21th April, on the 11th, 27th and 28th May. Total amount of irrigation was 40 mm over the total period of growth.

Spring barley seeds were sown at the lysimeter facility on the 24th of March and the harvesting took place on the 20th of July (118 days of growth). The growth of a plant is usually divided into different stages (Allen et al., 1998; Garvin et al., 2013).
In order to simplify the calculation of the crop coefficient (K_c), four different stages were chosen. Table 4 illustrates the number of days for each stage.

Table 4: Development stages of spring barley.

First stage	Second stage	Third stage	Fourth stage
21	25	48	24

3.1.9 ET_0 calculator and "Aquacrop"

ET_0 was calculated also by means of the FAO software "ET_0 Calculator". The latter is based on the FAO Penman-Monteith method. As already explained, although a lot of equations were formulated by many researchers, this method is the only recommended for the calculation of the reference evapotranspiration (ET_0) (Allen et al., 1998; Raes et al., 2012).
According to Allen et al., 1998 and to the "ET_0-Calculator" guide, the required meteorological parameters for the computation of ET_0 are the following (Fig. 14):

- solar radiation R_s (MJ m^{-2})
- maximum, mean and minimum air temperature T(°C)
- mean relative humidity RH^2(%) in 2 m height
- wind velocity U^2(m s^{-1}) in 2 m height

Input data description | Meteorological data and ETo | Plot data | Export results

Day		20	21	22	23	24	25	26
Month		July	July	July	July	July	July	July
Tmax	°C	25.3	18.4	22.6	20.6	18.4	18.2	17.9
Tmean	°C	20.7	16.5	18.7	18.1	16.1	15.6	16.6
Tmin	°C	16.0	14.5	14.8	15.5	13.7	13.0	15.2
RHmean	%	64.0	81.0	78.0	82.0	78.0	73.0	86.0
u(2)	m/sec	5.60	2.90	2.90	1.10	4.40	2.90	2.40
Rs	MJ/m2.day	12.89	5.70	11.79	10.90	8.34	5.99	5.18
ETo	mm/day	4.7	1.7	2.8	2.2	2.4	2.1	1.4

Figure 14: Input data of "Et_0 Calculator".

The meteorological data were obtained from the ZAMG station.

On the other hand, ET_p was calculated using the FAO software "Aquacrop". This program is a water crop productivity model developed by the Land and Water Division of FAO. The main purpose is the simulation of yield response to water of herbaceous crops. It particularly fits for the purpose of investigations under water stress conditions (Raes et al., 2012).

The input parameters for running simulations have to be included in the following subsystems (Fig. 15):

- soil (soil profile and groundwater)
- crop (development, growth and yield)
- climate (temperature, rainfall, CO^2 concentration, ET_0)
- management (agronomic practice such as irrigation and fertilization)

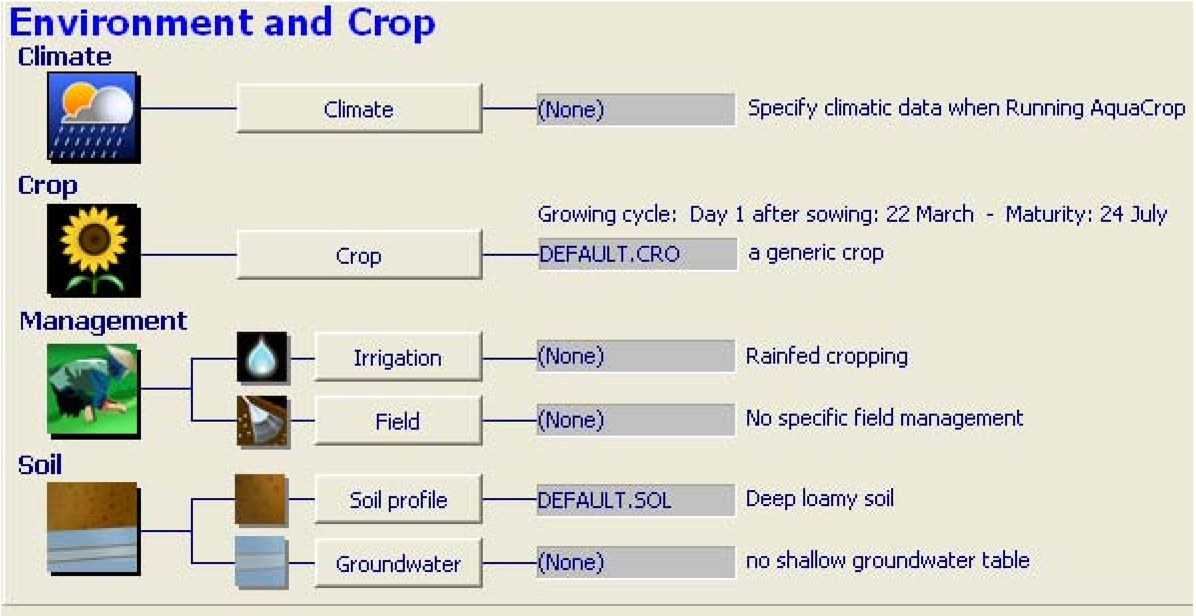
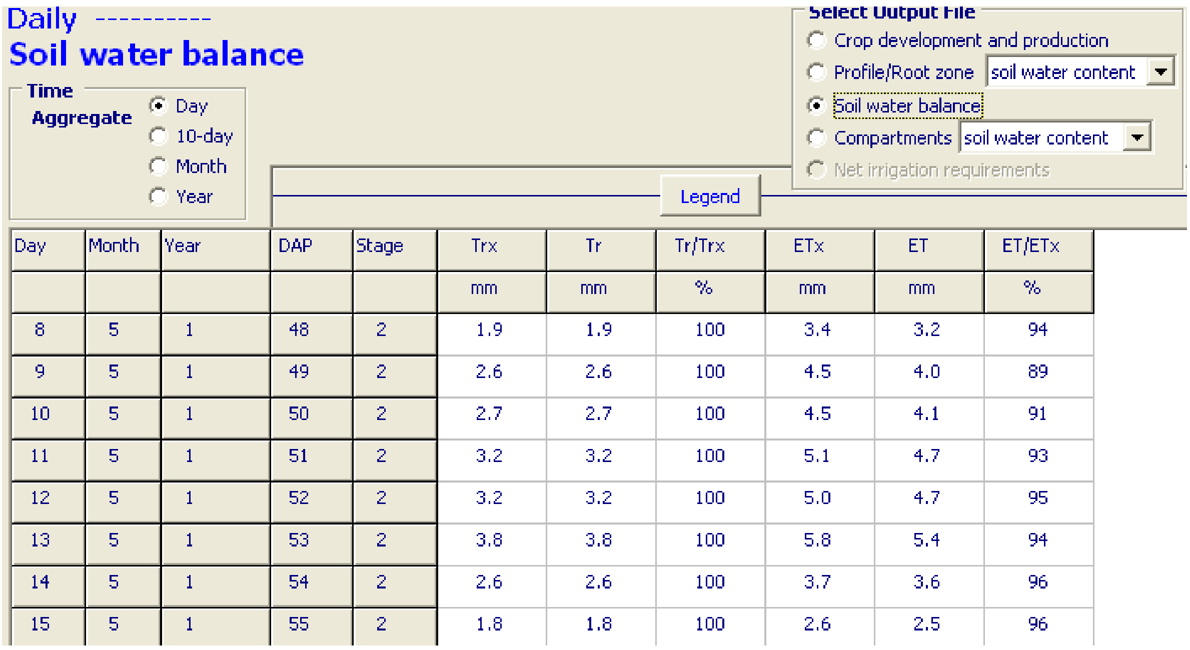


Figure 15: Input categories of "Aquacrop".

There are many applications of "Aquacrop". Interesting for our study is the soil water balance evolution of a soil covered by a selected crop. The software provided, among others, for each day after crop planting (DAP) the amount of potential transpiration (Trx), actual transpiration (Tr), potential evapotranspiration (ETx) and actual evapotranspiration (ET) (Fig. 16).



Day	Month	Year	DAP	Stage	Trx	Tr	Tr/Trx	ETx	ET	ET/ETx
					mm	mm	%	mm	mm	%
8	5	1	48	2	1.9	1.9	100	3.4	3.2	94
9	5	1	49	2	2.6	2.6	100	4.5	4.0	89
10	5	1	50	2	2.7	2.7	100	4.5	4.1	91
11	5	1	51	2	3.2	3.2	100	5.1	4.7	93
12	5	1	52	2	3.2	3.2	100	5.0	4.7	95
13	5	1	53	2	3.8	3.8	100	5.8	5.4	94
14	5	1	54	2	2.6	2.6	100	3.7	3.6	96
15	5	1	55	2	1.8	1.8	100	2.6	2.5	96

Figure 16: Soil water balance of "Aquacrop".

3.1.10 Reference data and statistical analysis

The results delivered by the software and ZAMG records are considered as references. Firstly, the latter were compared on a monthly and yearly basis to I, P and ET, determined solving Eq. 12 and 13 by means of lysimeter and EnviroSCAN® data. Secondly, a daily basis was considered, in order to get a more detailed view about the considered methods. ET measured by means of the east-lysimeter (reference conditions) was compared to the results of "ET_0 calculator", while ET measured by means of the records from the west-lysimeter were compared to the results of "Aquacrop".

In order to accomplish the comparison, the following statistic coefficients were considered:

- coefficient of determination (R^2)
- root mean square errors (RMSE)

R^2 describes the correlation and the accordance between two series.

According to Johnson et al. 2007, R^2 is mathematically expresses as following (Eq. 14):

$$R^2=1-(SS_{res}/SS_{tot}) \quad (14)$$

- SS_{res}=residual sum of squares
- SS_{tot}= total sum of squares

R^2 is automatically generated by Microsoft Excel.

The RMSE represents the sample standard deviation of the differences between two nominal data series (Johnson et al., 2007).

Johnson et al. described the average difference between two time series X and Y, using Eq. 15:

$$RMSE= \sqrt{\frac{\sum_{t=1}^{n}(Xt-Yt)2}{n}} \quad (15)$$

According to Eq. 5, during 2011 it was possible to calculate the crop coefficient (K_c) for spring barley considering ET measurements from soil water balance lysimeter and EnviroSCAN®. The K_c was consequently compared to the results of Nolz (2012) and to the FAO standards.

4 RESULTS

4.1 Soil water changes (ΔW)

4.1.1 Monthly sums ΔW 2008-2011

Considerable precipitation or irrigation supplied the soil water profile (e.g. June 2009, August 2010 and September 2011), leading to positive ΔW sums. A negative ΔW sum is an indication of predominant water withdraw, due principally to evapotranspiration (e.g. August 2008, June and July 2010).

ΔW_{lys} and $\Delta W_{EnvSCAN}$ delivered by the east-lysimeter, on a monthly basis, show meaningful differences, and in some cases such as July 2008 and October 2009, the results were conflicting (Fig. 17).

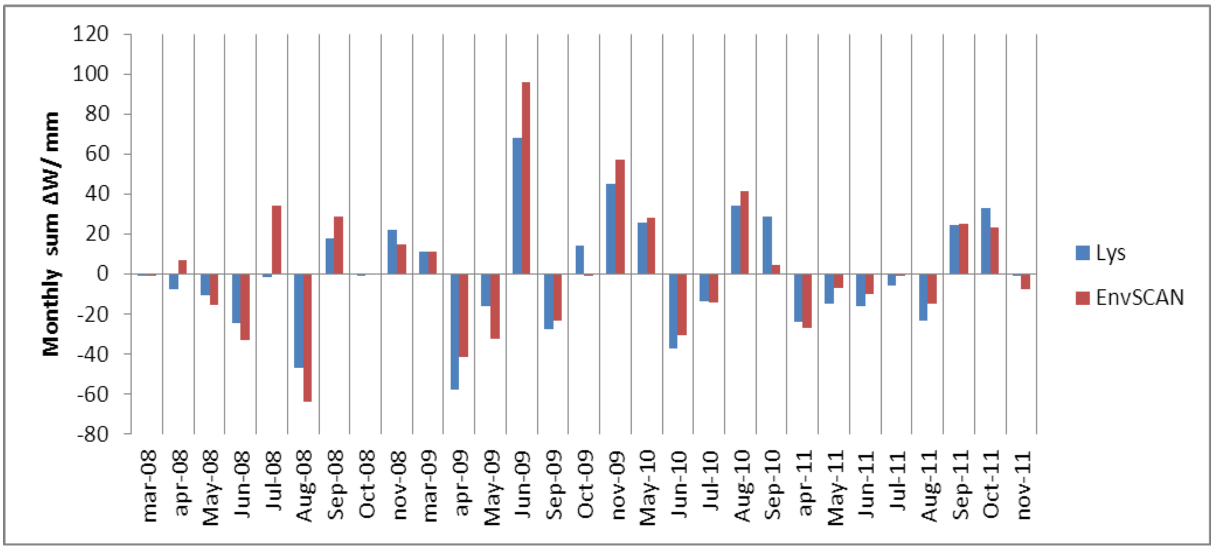


Figure 17: East-lysimeter, monthly sums of ΔW in mm (2008-2011).

The estimations of soil water content changes delivered by the instruments at the west-lysimeter, during the growth of spring barley, show also meaningful differences on a monthly basis (Tab.5).

Table 5: West-lysimeter, monthly sums of ΔW in mm (2011).

2011(West)	ΔW_{lys}	$\Delta W_{EnvSCAN}$
Apr	-16.6	-8.4
May	-57.5	-55.5
Jun	-82	-66.5
Jul	17.4	12.2

The monthly sums provide just a rough overview about EnviroSCAN® and lysimeters. At this stage, it is only possible to assert that the two methods deliver different results. In order to reach definitive conclusion, a more detailed analysis is necessary.

4.1.2 Daily ΔW 2008-2011 and operation modes

The soil water content changes, on a daily base, measured by means of the sensors ($\Delta W_{EnvSCAN}$) were compared to the soil water content changes measured by means of the lysimeter (ΔW_{Lys}). In order to get a general overview of the performance of the soil sensors and the lysimeter, the period of the experiment not affected by breakdown periods was selected (Fig. 18).

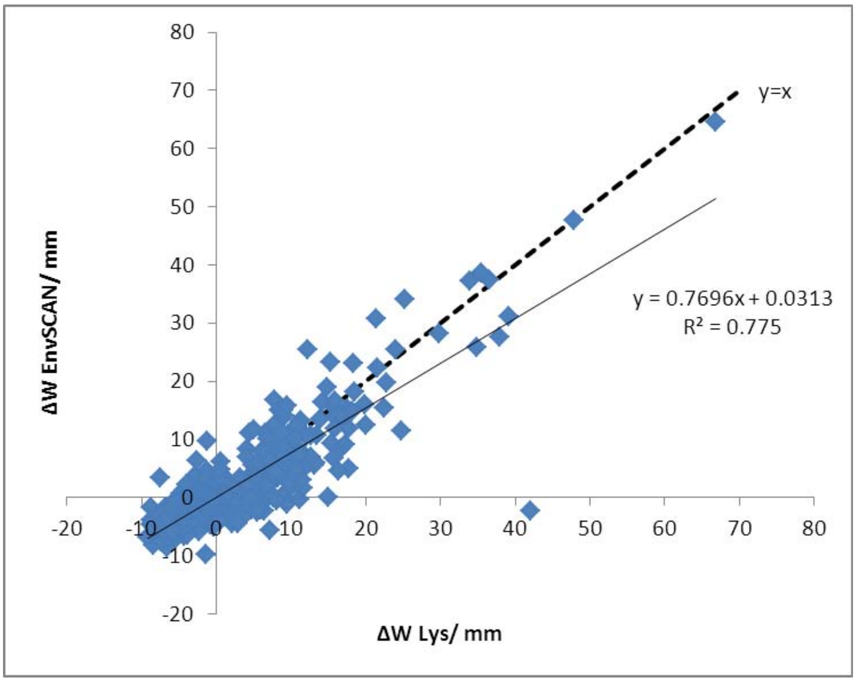


Figure 18: Daily ΔW_{Lys} vs $\Delta W_{EnvSCAN®}$ (2008-2011).

EnviroSCAN® sensors underestimated soil water changes. Both negative and positive variations of ΔW_{lys} were generally greater than those of $\Delta W_{EnvSCAN}$. The R^2 value (0.775) and the large RMSE value (3.04 mm) indicated a divergence between the two methods. This finding is consistent with the monthly sums of ΔW.

It was difficult to explain the occurrence of some outliers in the measurements delivered by the soil sensors during 2009 and 2011. Outliers are data having abnormal distance from other values, measured with other systems. Strongly overestimated (or underestimated) soil water changes (ΔW) would lead to absurd ET and P values.

In addition to the magnitude of the measurement, the time scale of variations of ΔW, in response to external factors (such as precipitation and solar radiation), is also an important aspect. Generally, lysimeters and EnviroSCAN® sensors, compared on an hourly basis, show synchronized reactions and are very responsive to rain, irrigation or evapotranspiration.

The rain event on 3rd June and 4th August 2011 were selected in order to illustrate in more detail the operation mode of the different instruments. In both cases the sensors had a smaller but well-timed reaction (Fig. 19, 20).

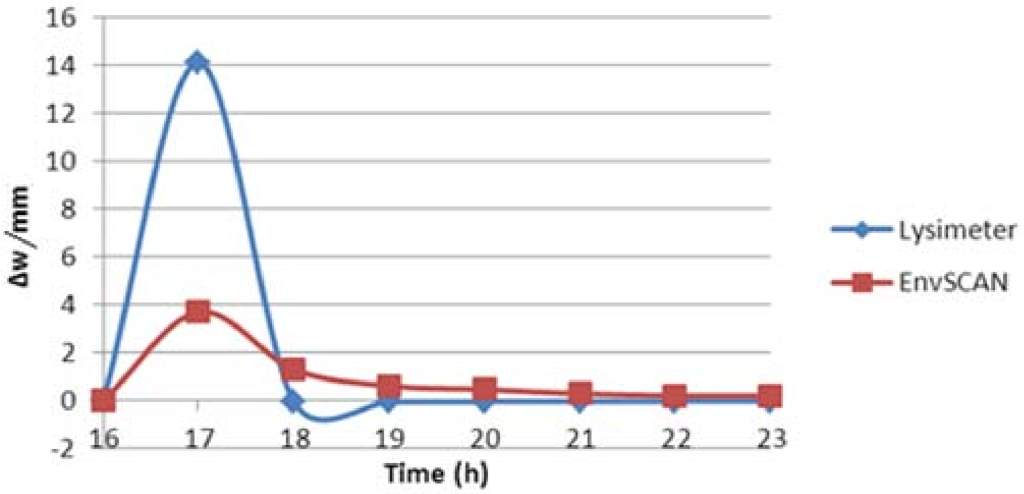


Figure 19: Soil water content after the rain event on the 3rd of June, as measured by Lysimeter and soil sensors.

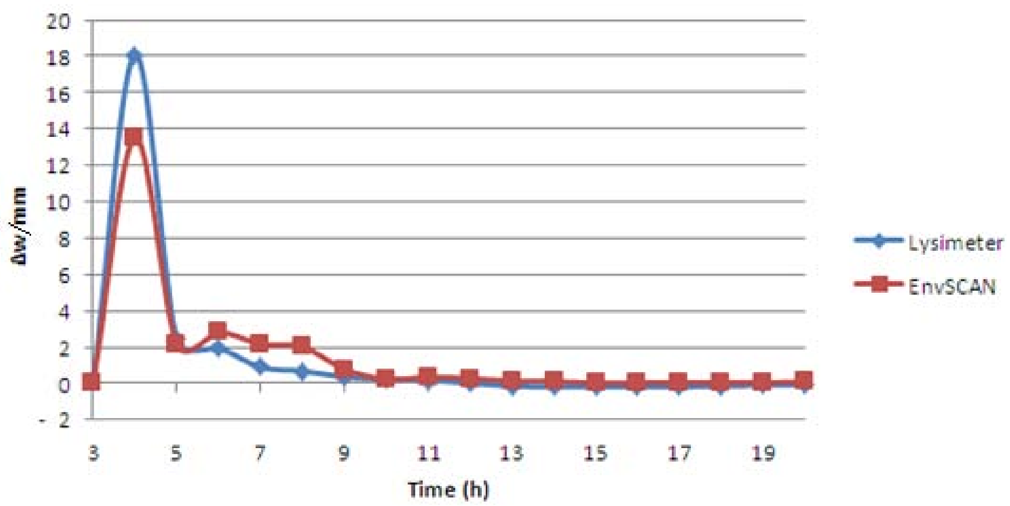


Figure 20: Soil water content on the 4th of June, as measured by Lysimeter and EnviroSCAN.

In some isolated cases the sensors were not able to detect the rain event. As example, figure 21 illustrates the rain event of the 30th June 2011. The lysimeter mass recorded 1.7 mm within one hour while the sensors recorded an increase of 0.1 mm.

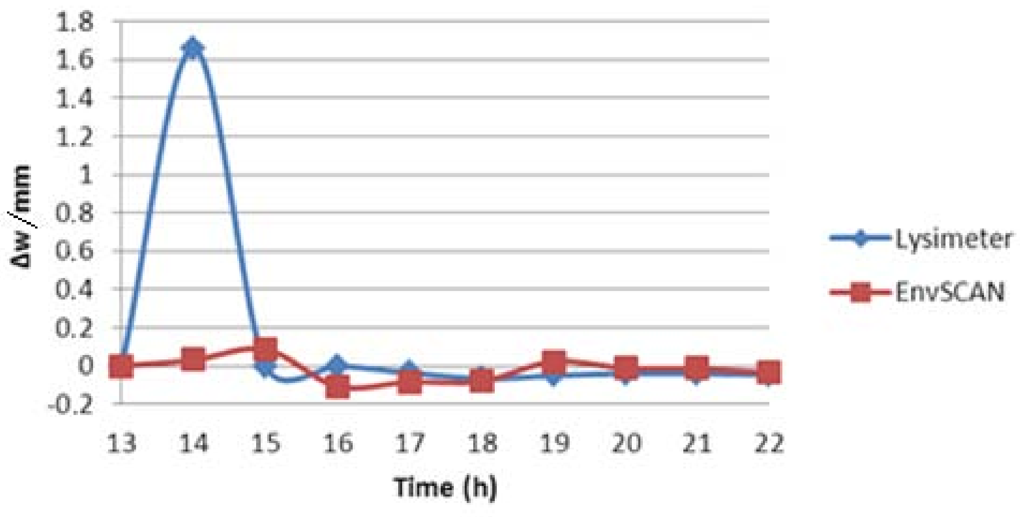


Figure 21: Soil water content as measured on the 30th of June, as measured by Lysimeter and EnviroSCAN®.

Considering irrigation events, a similar trend was observed. Figure 22 illustrates the different reactions of the weighing system and the EnviroSCAN® sensors to the artificial application of water on the east-lysimeter on 10th May 2011. Also in this case it is possible to observe that the reaction is synchronized but, on the other hand, ΔW_{lys} is larger (50% more) in respect of $\Delta W_{EnvSCAN}$.

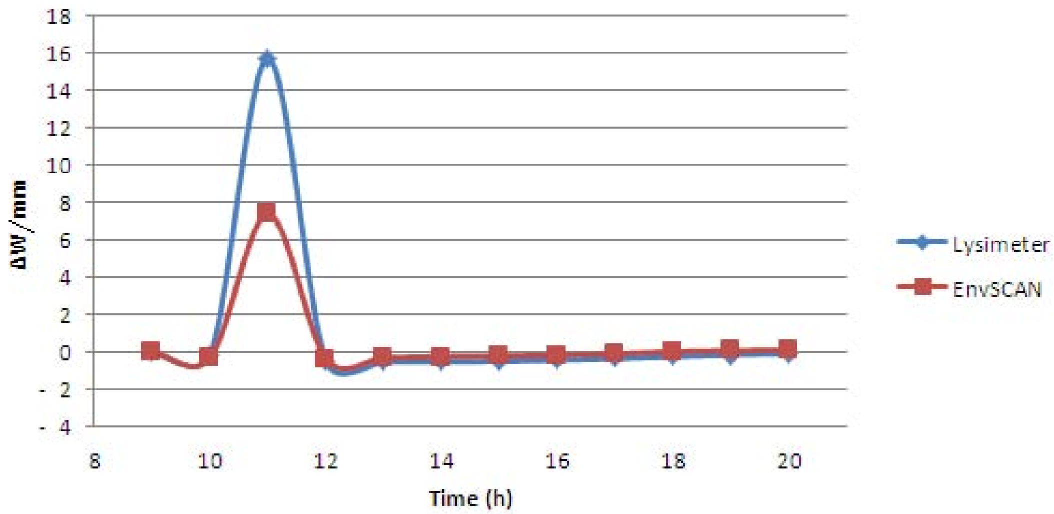


Figure 22: Soil water content on the 10th of May, as measured by Lysimeter and EnviroSCAN® sensors.

The 26th June 2011 was selected in order to illustrate the reaction of the lysimeter and the soil sensors to intense radiation and high temperature. As well in this case, the sensors underestimate the soil water content variations (ΔW) (Fig. 23).

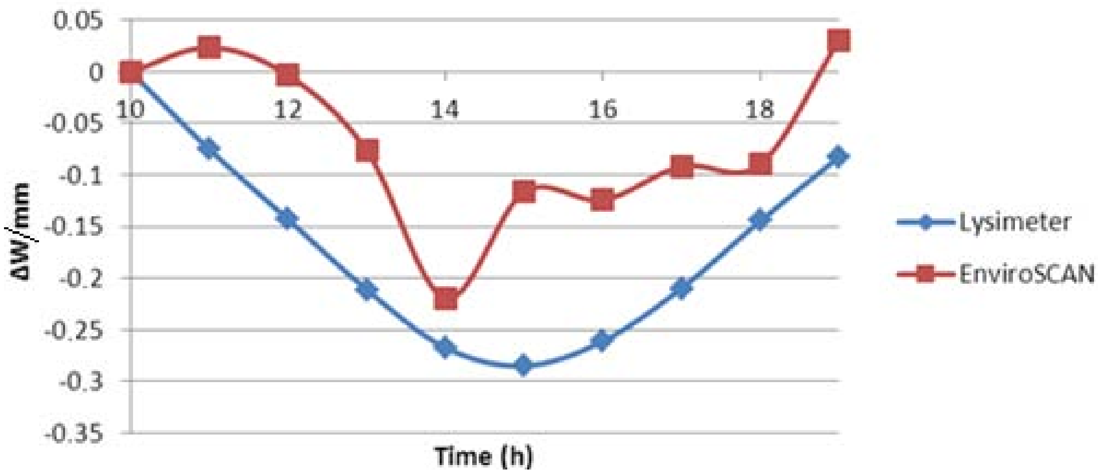


Figure 23: Soil water content on the 26th June 2011, as measured by Lysimeter and EnviroSCAN® sensors.

Further indications of the different operation modes of the lysimeter and soil sensors are provided by the comparison, on an hourly basis, between ΔW_{lys} (the whole profile) and $\Delta W_{EnvSCAN}$ (only at 10 cm depth). One of the advantages of the use of lysimeter is the possibility to detect surface phenomena, such as dew formation, in addition to soil water changes (Nolz et al., 2011). Dew is usually a nocturnal phenomenon and it occurs only above the soil and vegetation surface. Analyzing the night between the 6th of July and the 7th of July 2011 (no rain, according to the ZAMG station) and the data delivered by the east-lysimeter, it is possible to observe dew formation (Fig.24). On the other hand, the EnviroSCAN® soil sensors were able to detect soil water content changes (ΔW) only in the zone of influence (approximately 10 cm in length along the axis of the probe) and thus, no dew was detected.

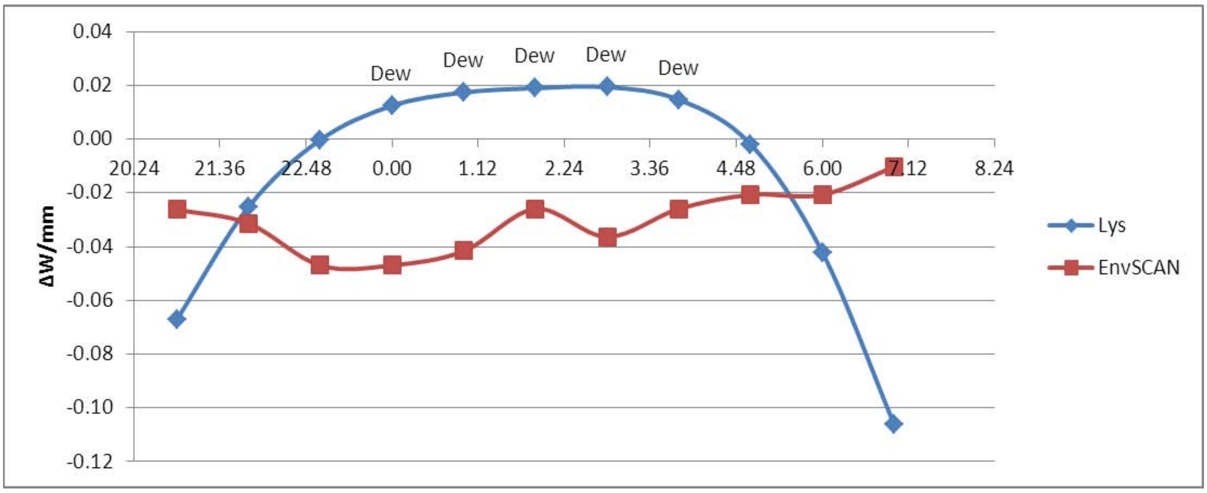


Figure 24: Dew formation in the night between 6th and 7th July 2011, as measured by east-lysimeter and EnviroSCAN® sensors.

The weak reaction of the EnviroSCAN® sensors to superficial water processes can also be seen analyzing the reaction to snow deposition. Snowfall occurred on the 25th of January 2011 and only the lysimeter (because sensible to weight change) detected the deposition of snow (Fig. 25).

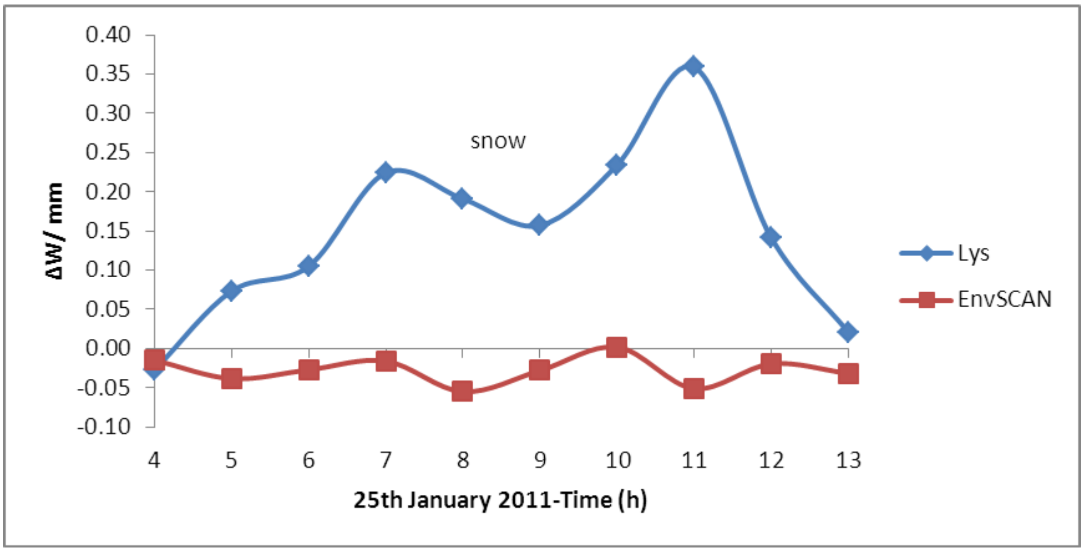


Figure 25: ΔW as measured by lysimeter and soil sensors during snowfall.

4.2 Evapotranspiration, lysimeter vs simulation

4.2.1 Annual and monthly sums

ET_0, calculated by means of "ET_0 calculator" (ET_{calc}), was comparable to ET calculated by means of the grass lysimeter (ET_{lys}) The annual amounts delivered by the lysimeter (considering breakdown periods) were reasonable, even if generally slightly lower (Fig.26). The yearly divergences in 2008, 2009 and 2010 were respectively 55 mm, 92 mm and 41 mm. During 2011, the annual divergence between lysimeter and simulation was around 100 mm. In July 2011 (30 mm of divergence), it is probable that the water supply was insufficient to guarantee reference conditions (Nolz et al., 2011).

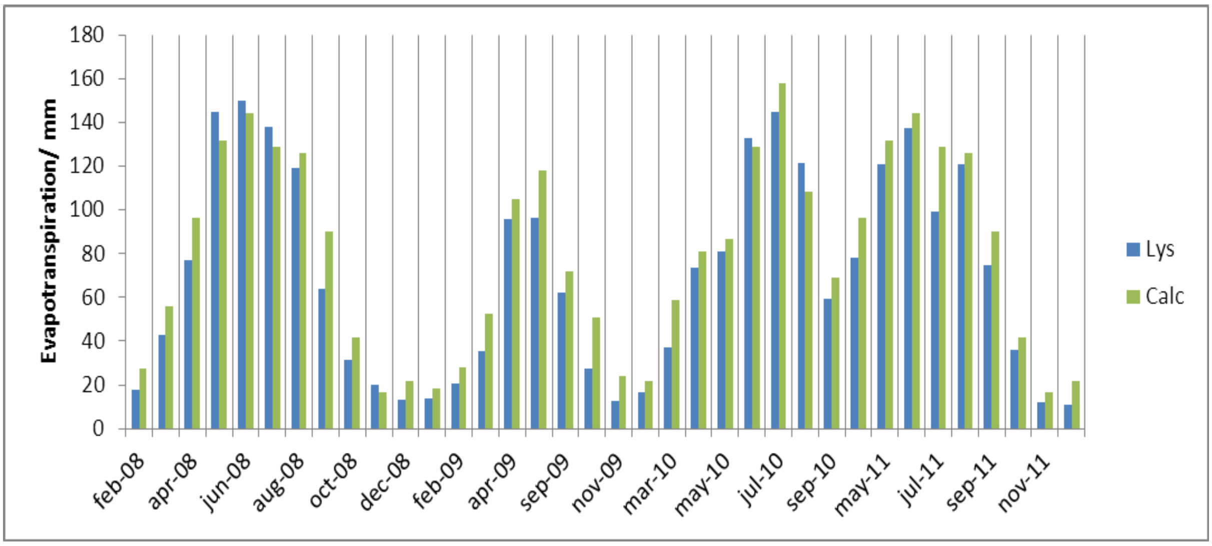


Figure 26: Monthly sums of ET_0 as measured by lysimeter vs ET_0 calculated by means of "ET_0 calculator" (2008-2011).

Lysimeter show always seasonality, reacting to temperature and solar radiation. The biggest depths of ET_0 are always measured in summertime, in accordance with the results delivered by "ET_0 calculator".

The west lysimeter also delivered reasonable results. Considering the vegetative period of spring barley (April, May and June) the monthly amounts of ET are comparable to the results delivered by "Aquacrop"(Fig.27).

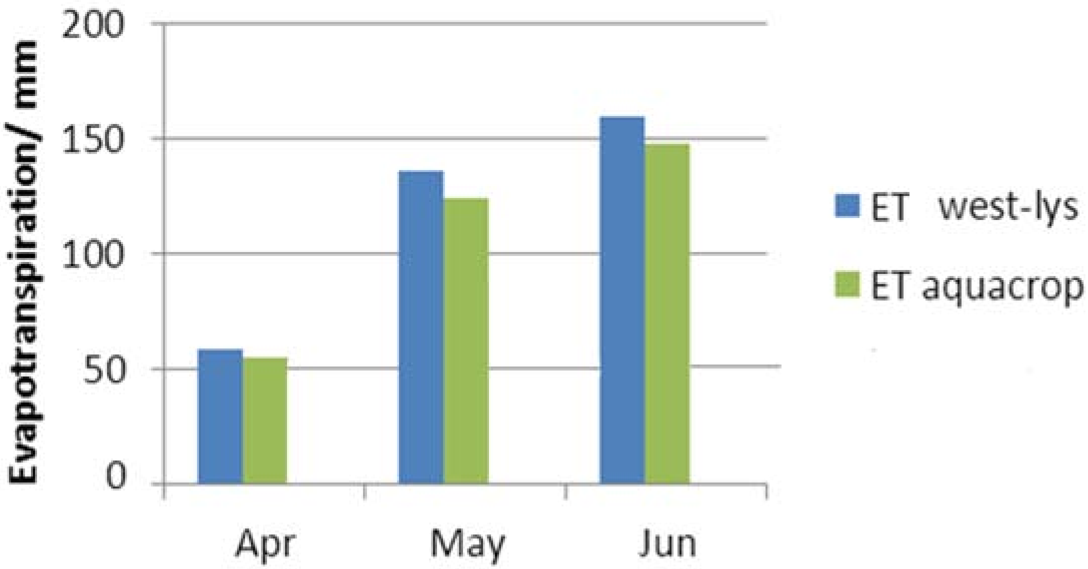


Figure 27: Monthly sums of ET as measured by lysimeter and ET calculated by means of "Aquacrop" (2011, west-lysimeter).

4.2.2 Daily basis

East-lysimeter

The FAO software "ET_0 calculator" generally delivered greater results in comparison to the lysimeter (Fig.28).

However, on a daily basis, ET_{calc} and ET_{lys} show good correlation, expressed by large R^2 values and small RMSE coefficient (Tab. 6).

Table 6: ET_{lys} vs ET_{calc}, annual RMSE (mm).

Years	RMSE (Etlys vs Etcalc)
2008	0.66 mm
2009	0.74 mm
2010	0.57 mm
2011	0.68 mm

The biggest RMSE coefficient (0.74 mm), as well as the lowest R^2 (0.8548), were calculated for 2009. Anyway, during this year, the lysimeter data between the 27th of June and the 24th of August were not available due to a breakdown.

Generally, the trend lines indicate underestimation of ET_{lys} at small rates and overestimation at larger rates. One likely reason, as already explained, could be a suboptimal supply of water. Reference conditions are reached only if the soil is kept close to field capacity.

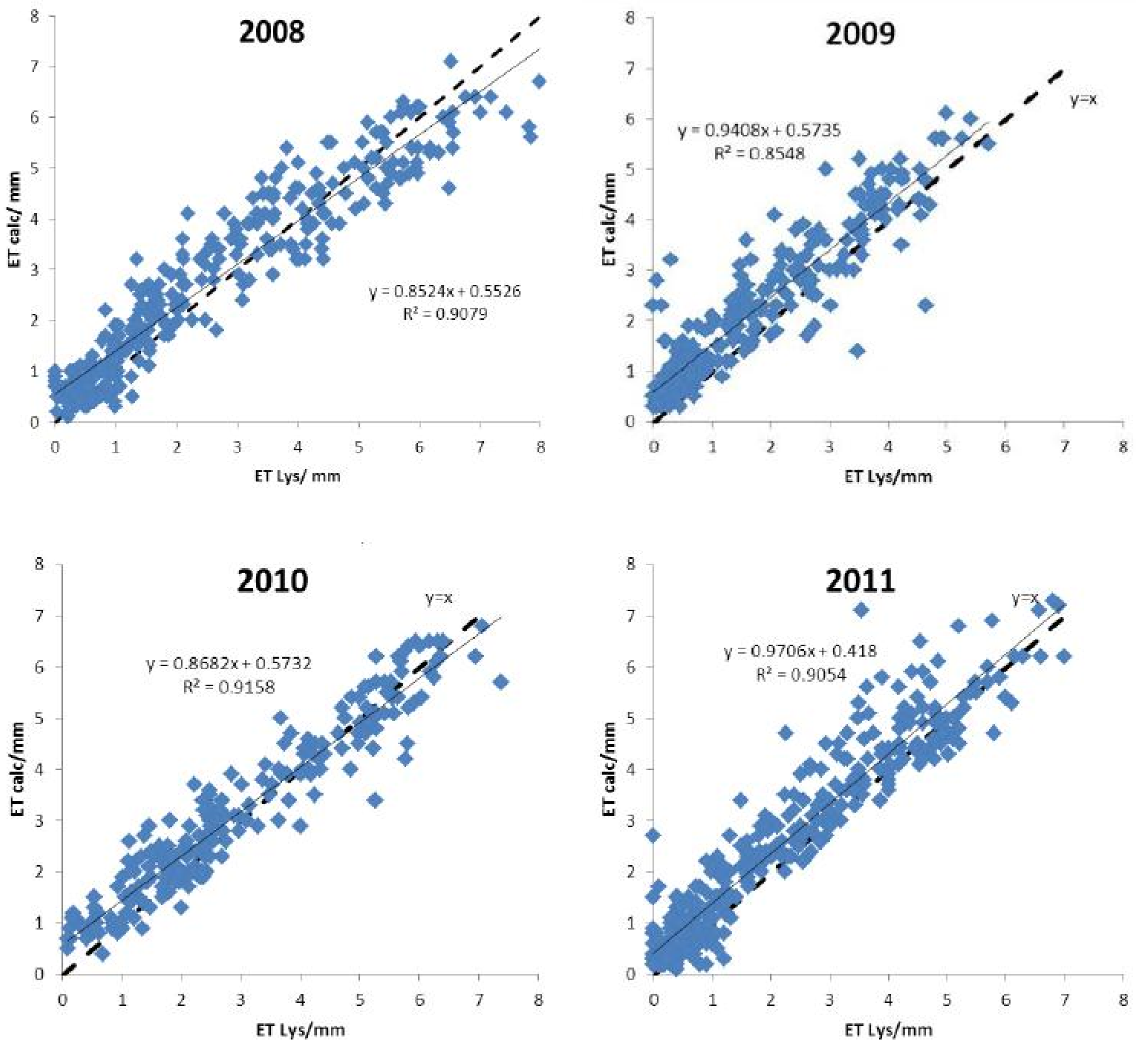


Figure 28: Daily ET_{lys} vs ET_{calc}.

West-lysimeter (2011)

The west-lysimeter was used in order to assess the loss of water due to evapotranspiration on a surface covered by spring barley. The results delivered by the west-lysimeter were compared with those calculated by means of "Aquacrop" (Fig. 29). Only the vegetation period were considered (between the 24th of March and the 20th of July). No breakdown affected the results during this period. The simulation generally delivered greater results in respect to the lysimeter and the RMSE coefficient was 1.04 mm. Soil, weather, crops and management parameters were introduced into the simulation, according to the indication of the Department. One of the likely reasons of the differences between the lysimeter and the simulation could be again an insufficient application of water on the crops cover. Furthermore, it should not be forgotten that lysimeter is a point measurement and thus, it is representative only of a small area (oasis effect).

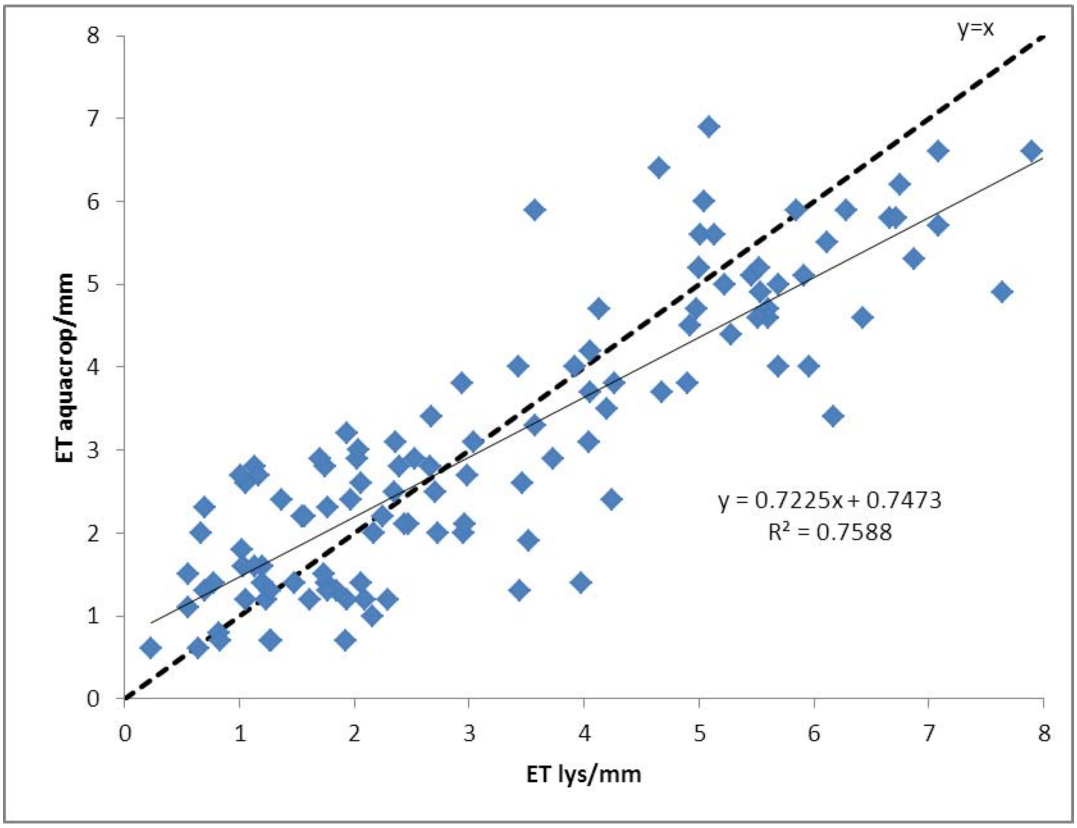


Figure 29: Daily ET_{lys} vs $ET_{Aquacrop}$ (2011).

Although the accordance between the west-lysimeter and the simulation is not perfect, it was possible to derive a good estimation of the crop coefficient of spring barley (K_c).

The crop coefficient was assessed following the procedure described in chapter 1.3 The results are illustrated in table 7.

Table 7: K_c calculated by means of east-lysimeter and west-lysimeter (2011).

	First stage	Second stage	Third stage	Fourth stage
Day	21	25	48	24
Mean Et (west-lys)	1.4	2.37	5.27	2.31
Mean Eto	2.15	3.14	4.41	4.14
Kc	0.65	0.75	1.20	0.56

The values of the crop coefficient are comparable to the results of Nolz et al. (2012) (0.53/0.79/1.14/0.47) and to the indication of FAO for the whole growing season (Kc_{mid}= 1,15).

4.3 Precipitation, lysimeter vs records

4.3.1 Annual and monthly sums

Precipitation depth assessed by means of lysimeter was always greater in comparison to the measurements recorded in the ZAMG station (Fig.30). In 2011 the annual amount of P_{lys} was 20% larger than P_{ZAMG}. Differences can be introduced during snowfall in wintertime; considering January 2009 (mean temperature under 0°C), the overestimation was larger than 50%. In January 2011 it was possible to observe the same magnitude of difference. In summertime, even if the monthly amounts of P_{lys} were always bigger, lysimeters and the ZAMG station delivered comparable results. Furthermore, it is important to remember that P_{lys} includes not only rain but also minor components such as dew formation and fog deposition, while a rain gauge is not responsive to these phenomena (Habib et al., 2001).

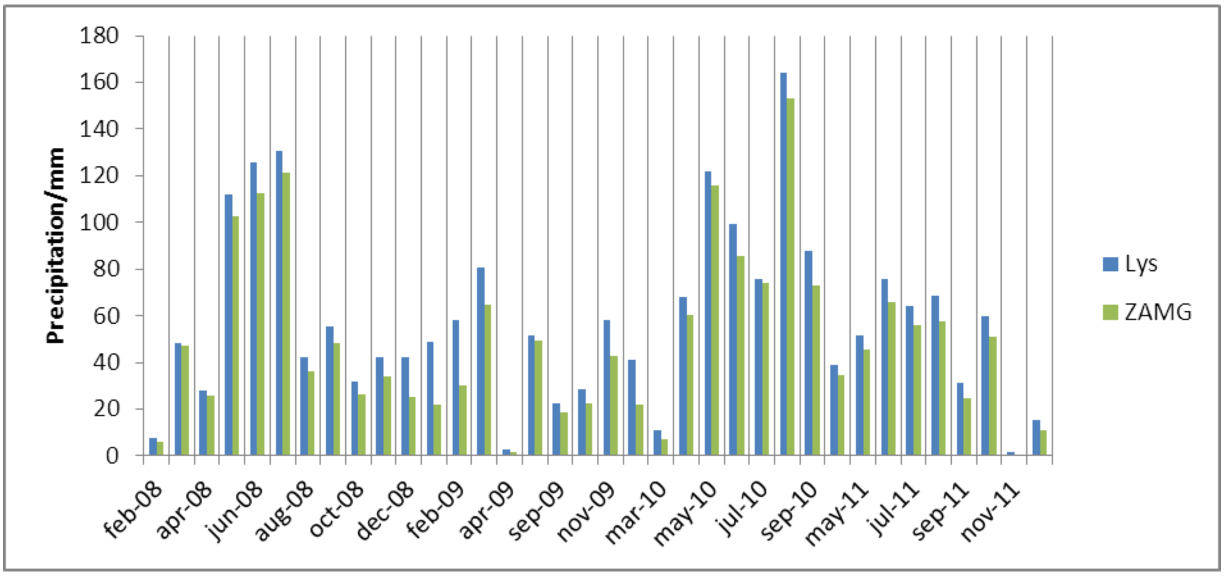


Figure 30: Monthly sums of P as measured by lysimeter vs P recorded by the ZAMG station (2008-2011).

A similar trend can be observed analyzing the precipitation, determined by means of west-lysimeter (Fig.31). P_{lys} was generally greater than the ZAMG-records. However the monthly differences between the two methods are smaller than 15% and similar to the results delivered in summer by the east-lysimeter. Because the lysimeter is sensible mass changes, the increase of biomass during the growing season can lead to errors. No data form winter and autumn were considered because the growth of spring barley was between the 24th of March and 20th of July (March and July were not considered, on a monthly basis, because the sums are incomplete).

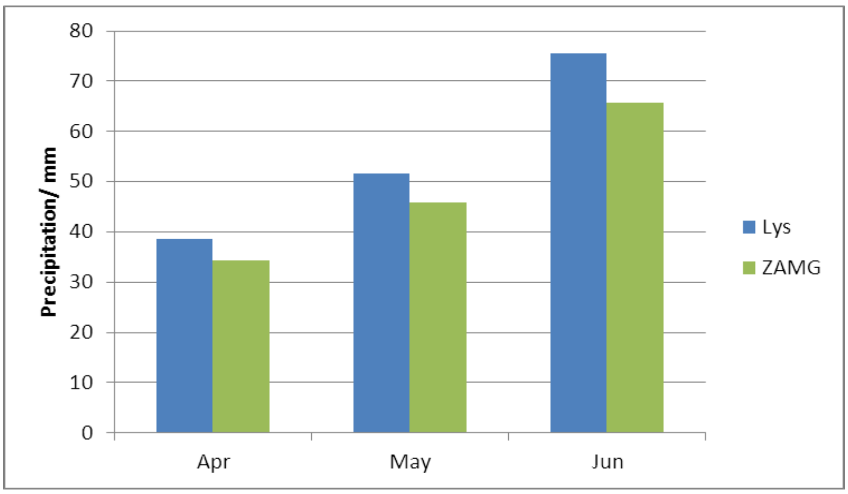


Figure 31: Monthly sums of P as measured by west-lysimeter vs P recorded by the ZAMG station (2011).

4.3.2 Daily basis

East-lysimeter

Precipitation depth on a daily basis, calculated by means of the east-lysimeter showed good accordance with the ZAMG recording (Fig. 32). The lowest R^2 and the largest RMSE were again calculated during 2009 (Tab. 8), when, because of a breakdown, it was not possible to collect data from the east-lysimeter during summertime.

Table 8: P_{lys} vs P_{Zamg}, annual RMSE (mm).

Years	RMSE (Plys vs P ZAMG)
2008	0.67 mm
2009	1.12 mm
2010	0.4 mm
2011	0.87 mm

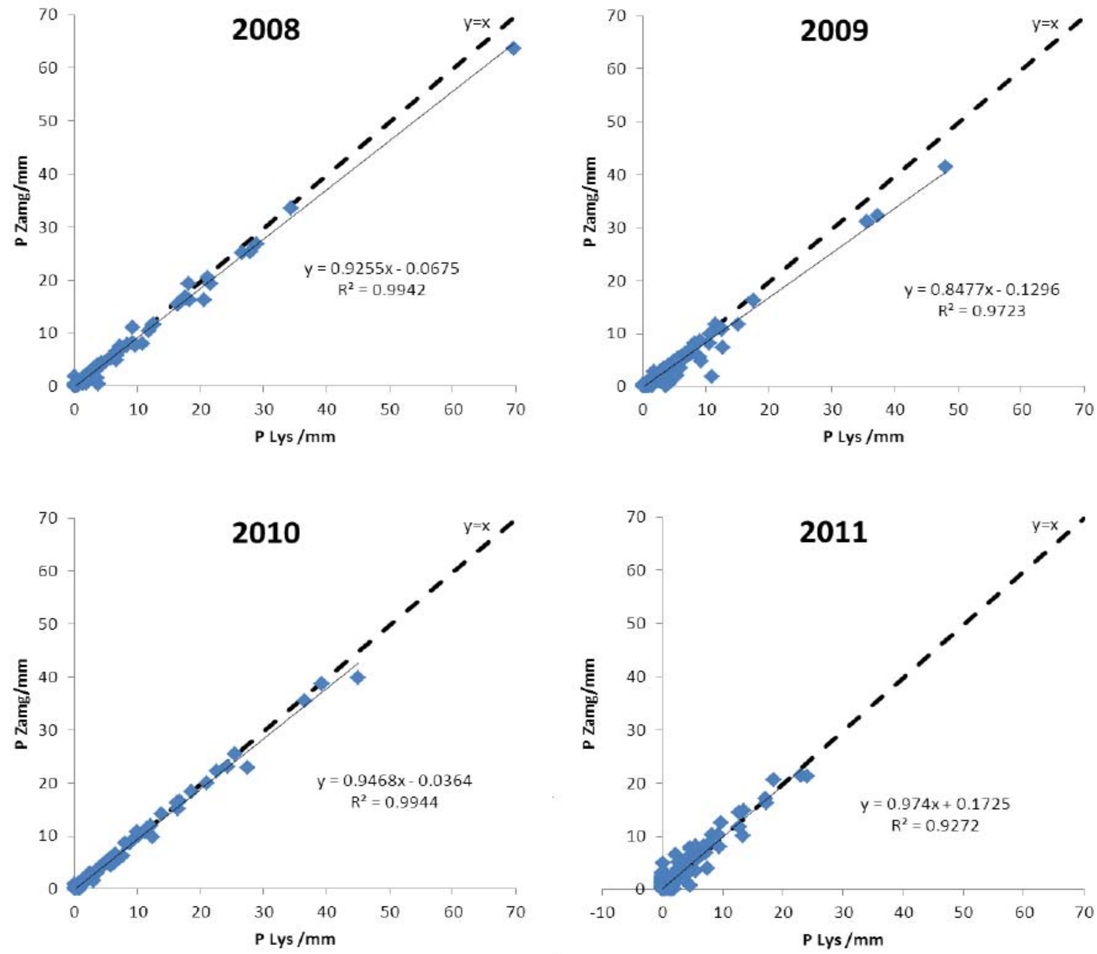


Figure 32: Daily P_{lys} vs P_{Zamg}.

According to Nolz et al. (2011), the divergences between ZAMG and lysimeters can be explained considering the larger receiving surface. Through lysimeters it is also possible to detect all forms of precipitation (e.g. snow, fog condensation, snow and dew) while rain gauges, on the other hand, generally underestimate these phenomena (Habib et al., 2001). Considering data of the coldest period of the experiment (December 2008, January 2008, February 2009, December 2009, January 2011, February 2011), during which snow and fog deposition occurred, R^2 (0.8048) and RMSE (1.36 mm) expressed the worst correlation and accordance (Fig. 33).

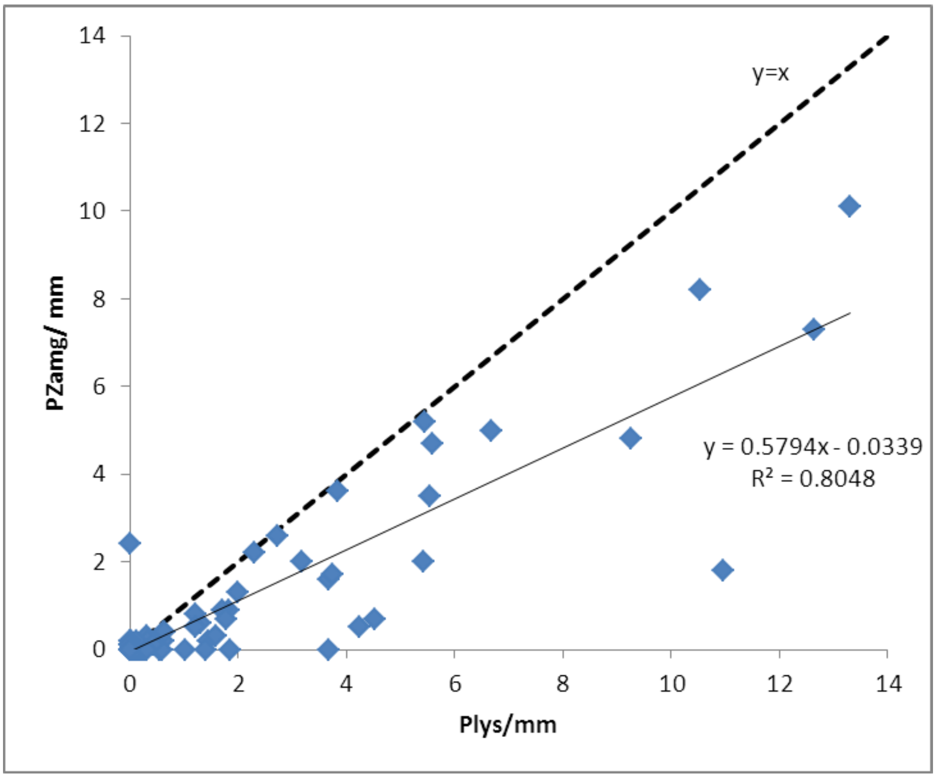


Figure 33: Precipitation as measured by means of lysimeter vs precipitation recorded by ZAMG station, during wintertime.

West-lysimeter

Precipitation depths calculated by means of the west-lysimeter and the records of the ZAMG station showed good correlation and accordance (Fig. 34), expressed by a large R^2 coefficient (0.9795) and a small RMSE (0.69 mm).

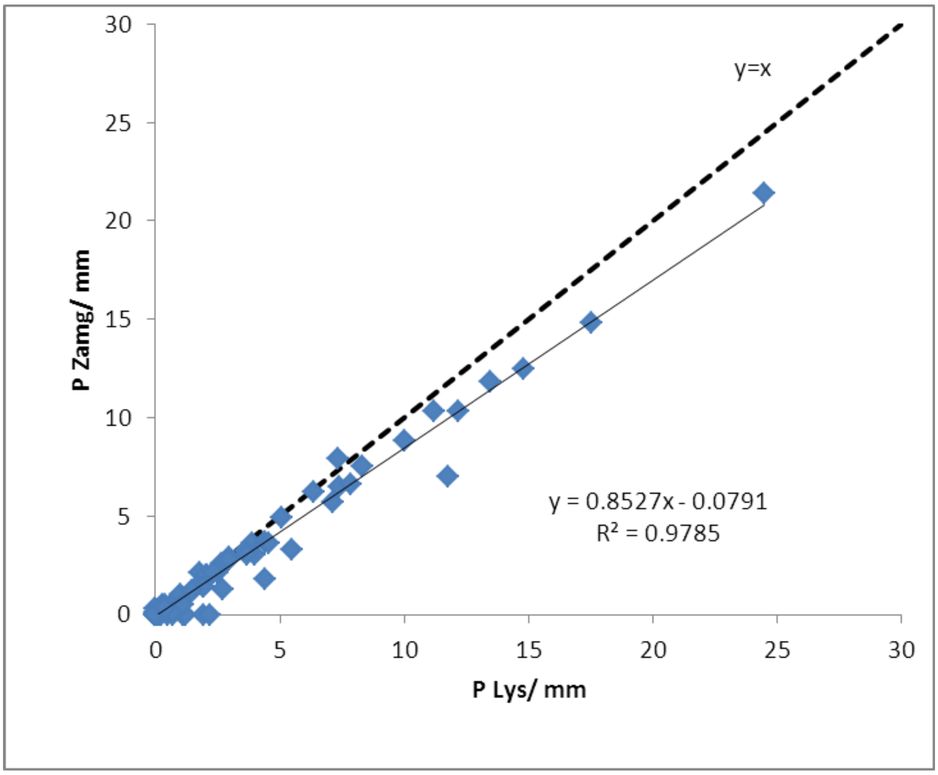


Figure 34: Daily P_{lys} vs P_{Zamg} (2011, west-lysimeter).

The reasons of divergences are the same described in the previous chapter. As well in this case, the divergence was bigger during the coldest months of the year. During 2011 snowfall occurred from the 23rd and the 26th of January. According to the lysimeter measurements, this event was 10.7 mm while the ZAMG station detected only 3.9 mm.

4.4 Evapotranspiration, EnviroSCAN® vs simulation

4.4.1 Annual and monthly sums

ET_0 calculated by means of soil sensors ($ET_{EnvSCAN}$) was strongly lower with respect to ET_{calc}. The difference was relevant and of the same magnitude over the entire period of the experiment (317 mm, 289 mm, 350 mm, 378 mm in 2008, 2009, 2010 and 2011 respectively). The biggest differences were recorded in summertime. For example, considering 2011, in May, June and July the differences were respectively 63.1 mm, 60.8 mm and 63.8 mm (Fig. 35).

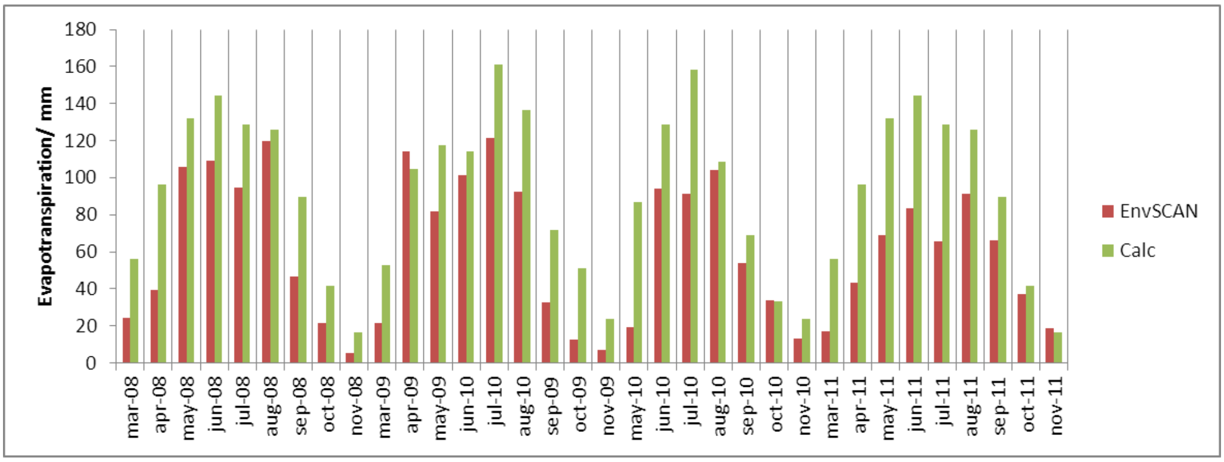


Figure 35: Monthly sums of ET as measured by lysimeter, vs ET calculated by means of "ET_0 calculator" (2008-2011).

ET determined by means of the west-lysimeter was also underestimated in comparison to the results of the simulation (Fig. 36). Only in April 2011 was the estimation similar. Anyway the differences in May and June are respectively, 30% and 47%.

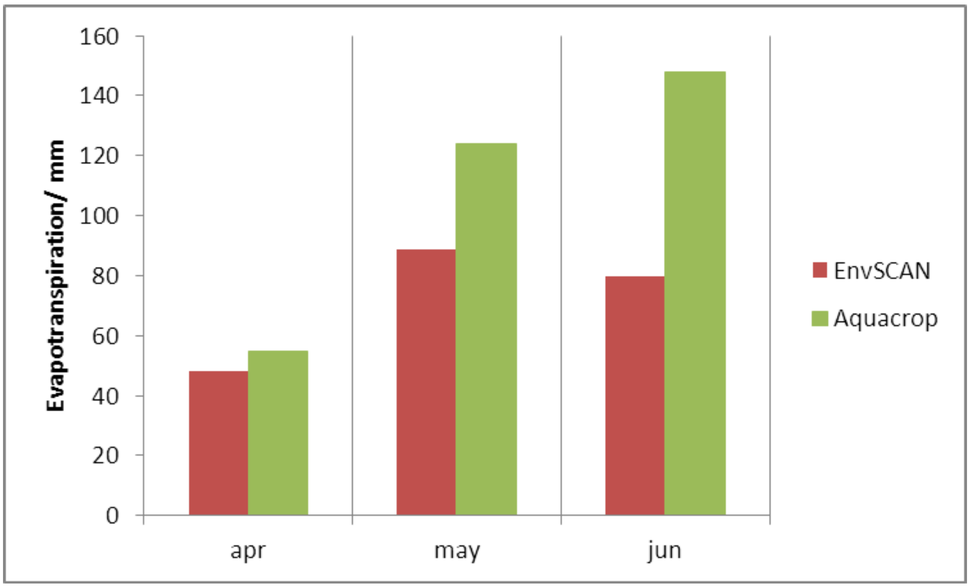


Figure 36: Monthly sums of ET as measured by west-lysimeter vs ET calculated by means of "Aquacrop" (2011).

4.4.2 Daily basis

East-lysimeter

$ET_{EnvSCAN}$ on a daily basis was generally strongly underestimated in comparison to the results of the simulation (Fig. 37). Low R^2 coefficients and very large RMSE express no accordance and no correlation (Tab. 9). This evidence is consistent with the results on a monthly and yearly basis. The worst results were calculated during 2009 and 2010.

Table 9: $ET_{EnvSCAN}$ vs ET_{calc}, annual RMSE (mm).

Year	RMSE (mm)
2008	1.76
2009	2.66
2010	2.48
2011	1.71

The results indicated that the soil sensors measurements are not sufficient in order to determine with acceptable accuracy the evapotranspiration rate.

Probably, a part of the precipitation doesn't water reach the zone of influence of the sensors and losses due to evapotranspiration cannot be detected. Additionally, it cannot be excluded that the low layer (160 cm- 250 cm) is involved in some relevant water dynamics and that surface storage and delayed infiltration affect the results delivered by the sensors. A discussion about the EnviroSCAN® results is conducted in the section 5.

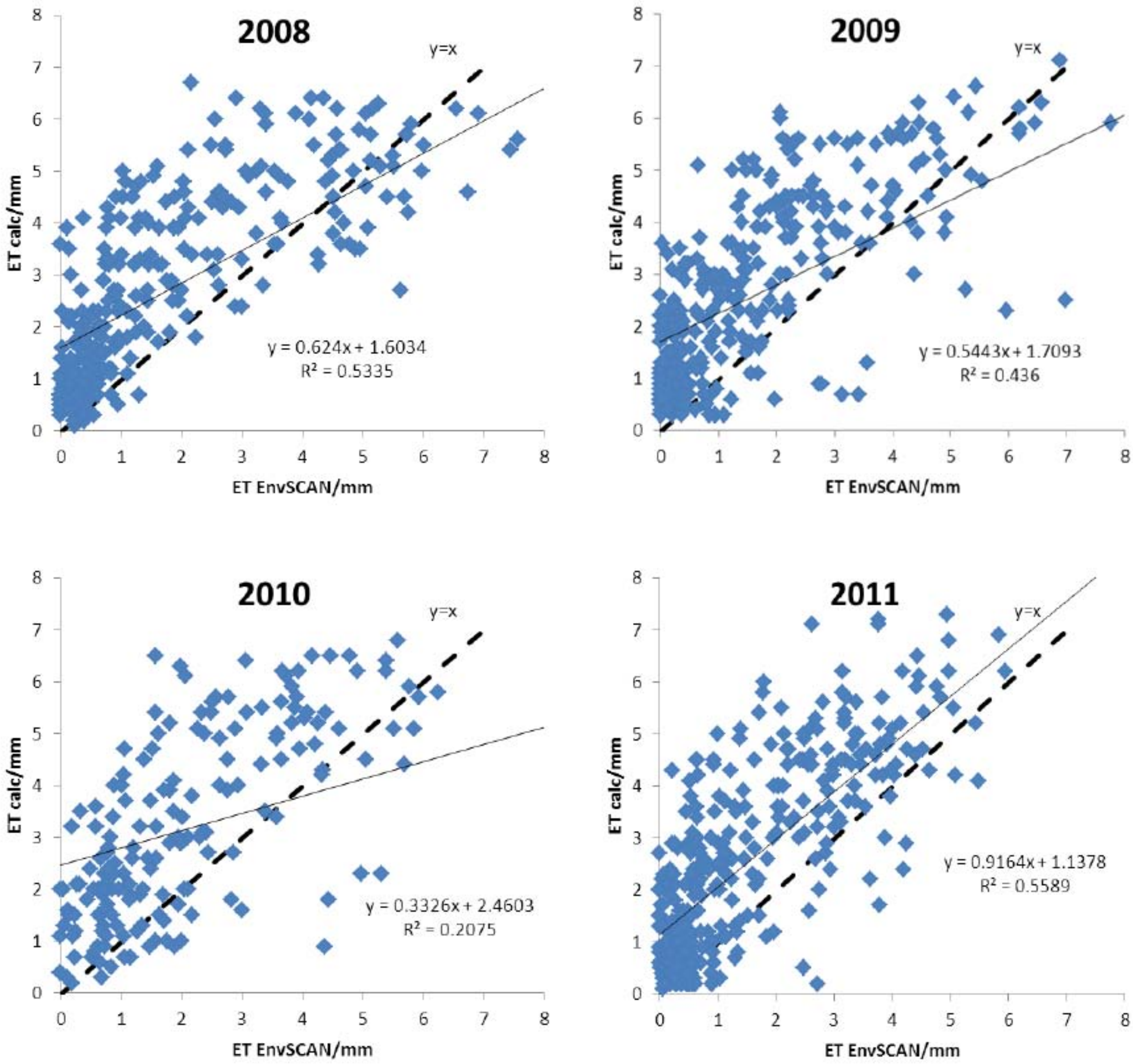


Figure 37: Daily $ET_{EnvSCAN}$ vs ET_{calc}.

West-lysimeter

The results from the sensors installed in the west-lysimeter are consistent with the measurement of the east-lysimeter (Fig. 38). ET was strongly underestimated and R^2

and RMSE were respectively 0.4854 and 1.65 mm. They indicate very low accordance between results delivered by EnviroSCAN® data and "Aquacrop".

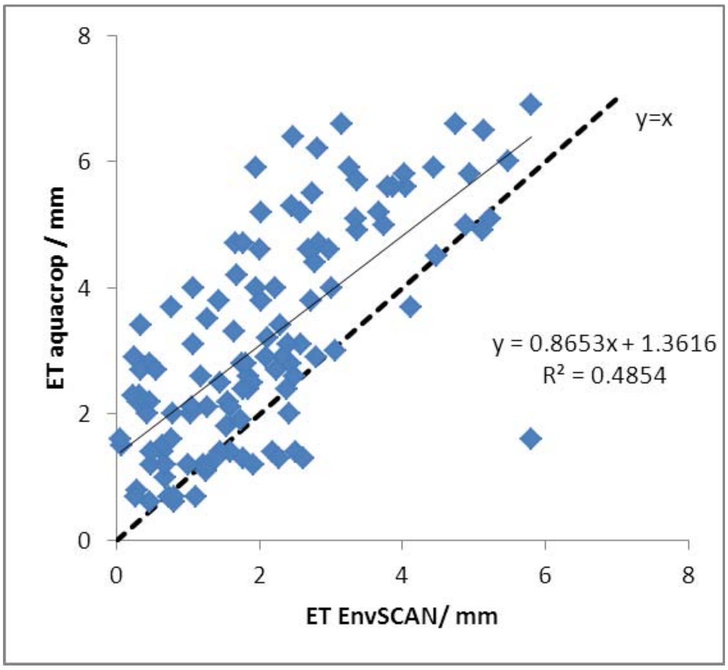


Figure 38: Daily $ET_{EnvSCAN}$ and $ET_{Aquacrop}$ (2001, west-lysimeter).

The same issues described below and in the introduction could be the reasons of the underestimation.

By means of soil sensors data, it was possible to derive an estimation of the crop coefficient of spring barley (K_c). The results are illustrates in table 10.

Table 10: Kc calculated by means of soil sensors installed in the east-lysimeter and west-lysimeter (2011).

	First stage	Second stage	Third stage	Fourth stage
Day	21	25	48	24
Mean Et (west-lys)	1.57	1.95	2.99	0.99
Mean Eto	1.41	1.79	2.39	3.13
Kc	1.11	1.09	1.25	0.32

The values of crop coefficient are not comparable to the results of Nolz et al. (2012) (0.53/0.79/1.14/0.47), to the lysimeter (0.65/0.75/1.20/0.56) and to the indication of

FAO (Kc_{mid}= 1.15). Especially the first and the second stages show meaningful differences.

4.5 Precipitation, EnviroSCAN® vs records

4.5.1 Annual and monthly basis

$P_{EnvSCAN}$ was generally strongly underestimated. The annual amounts of $P_{EnvSCAN}$ were in 2008, 2010, 2011 (east- and west-lysimeter) between 20 % and 25 % smaller. During 2009 the difference between measurements and determination was only 2.5 %, even if the monthly amounts show significant differences (Fig. 39).

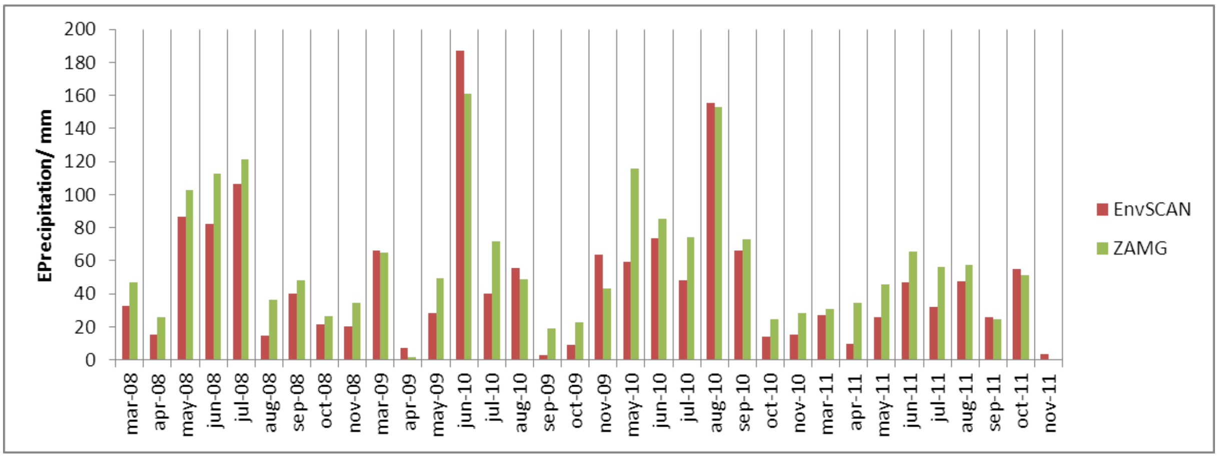


Figure 39: Monthly sums of P as measured by EnviroSCAN® sensors vs P recorded by the ZAMG station (2008-2011).

The west-lysimeter delivered good results in April but the sums in May and June are strongly underestimated (Fig. 40). In June the soil sensors detected only the 23% of precipitation recorded by the ZAMG station.

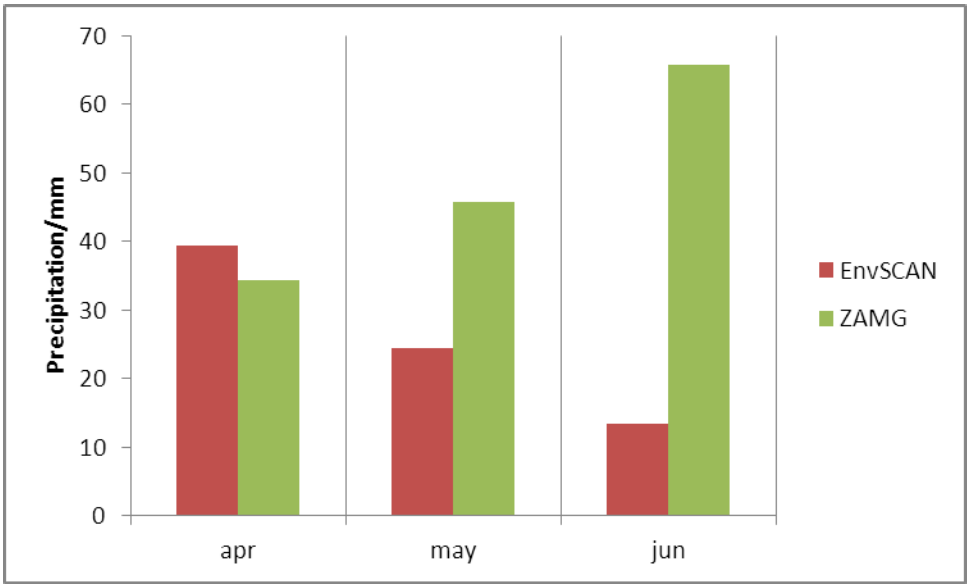


Figure 39: Monthly sums of P as measured by EnviroSCAN® sensors vs P recorded by the ZAMG station (2011).

4.5.2 Daily basis

Precipitation on a daily basis, calculated by means of soil sensors, was generally underestimated (Fig. 41). RMSE and R^2 indicate low accordance and correlation (Tab. 11). The results are consistent with the monthly and annually sums of precipitation.

Table 11: $P_{EnvSCAN}$ vs P_{Zamg}, annual RMSE (mm).

Year	RMSE (mm)
2008	2.16
2009	2.96
2010	2.43
2011	1.99

The estimation of precipitation provided a further indication of the low capacity of soil sensors to cover all the water dynamics occurring within the soil profile.

If a part of the water doesn't water reach the zone of influence zone of the sensors, the volume of precipitation would be underestimated. Additionally, in this case too, depression storage and delayed infiltration could have a direct bearing on the results delivered by the sensors.

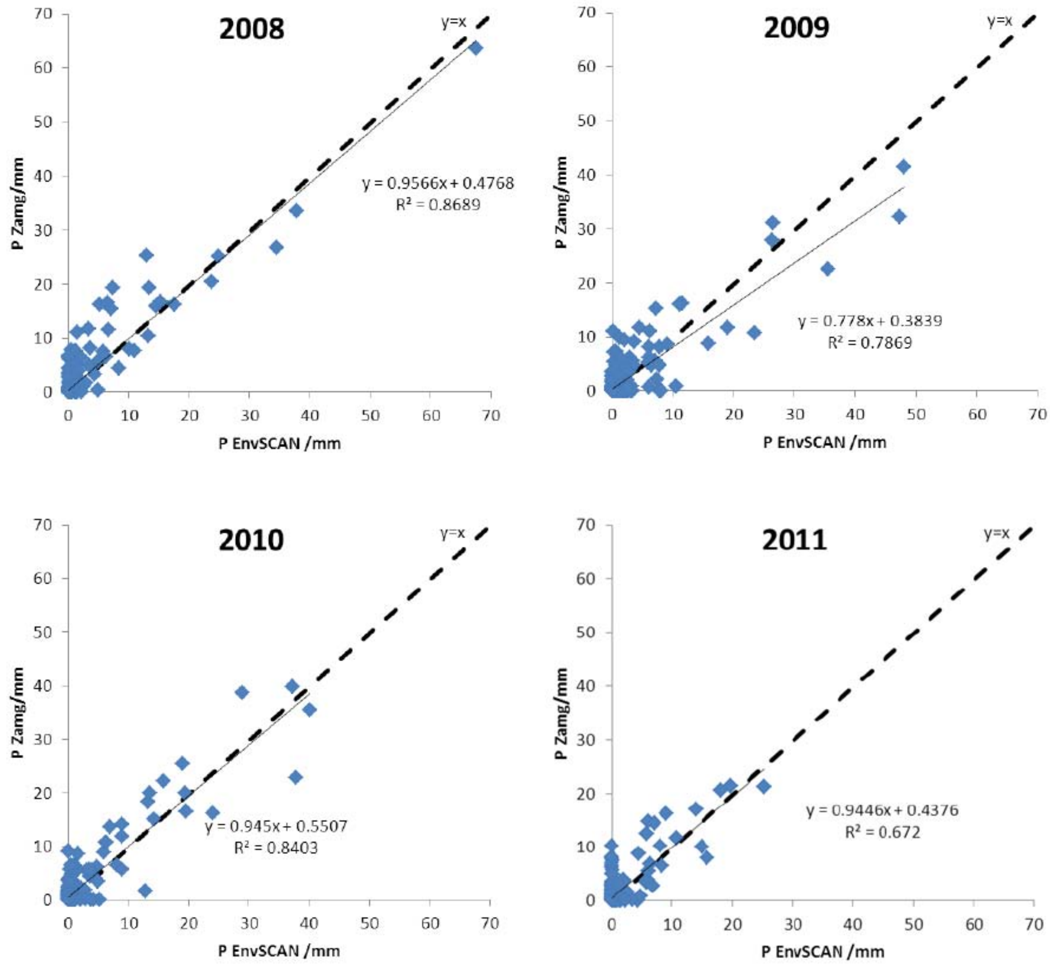


Figure 40: Daily $P_{EnvSCAN}$ vs P_{Zamg}.

West-lysimeter

The soil sensors, installed in the west-lysimeter, delivered also a strongly underestimated approximation of daily precipitation depth (Fig. 42). This evidence is expressed by a very low R^2 (0.4027) and a big RMSE (2.33 mm).

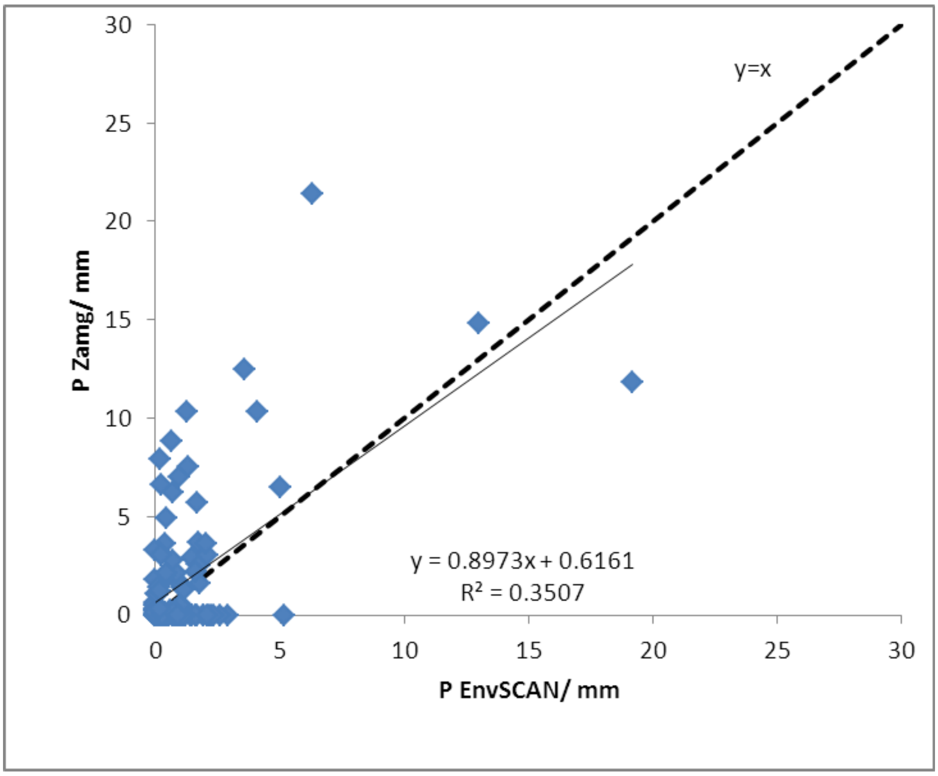


Figure 41: Daily $P_{EnvSCAN}$ vs P_{Zamg} (2011, west-lysimeter).

The results delivered by the EnviroSCAN® sensors are discussed in detail in the following chapter.

5 EnviroSCAN® SENSORS DIFFERENCES

During the experiment in Groß-Enzersdorf, it was not possible using soil sensors data to solve the soil water balance and to achieve good estimation of its components.

In order to analyze the findings which emerged from the statistical analysis presented in the previous chapters, the results delivered by the sensors were compared to those delivered by the lysimeters. Because 2011 was affected by a limited number of breakdowns, east-lysimeter data from this year were mostly considered for the following analysis. No information is available about water flux in the soil, because tensiometric measurements were not accomplished.

In the first part, it is discussed whether the cumulative differences ET_{lys}-$ET_{EnvSCAN}$ and $(P+I)_{lys}$-$(P+I)_{EnvSCAN}$ follow a similar evolution and have a similar magnitude on a monthly and yearly basis.

Successively, the possible causes leading to unreliable results in the interpretation of sensors data are discussed. In particular, the omitted measurement of the upper (0 cm -5 cm) and lower layers (160 cm-250 cm) and the possible effects of interception, depression storage and delayed infiltration are analyzed. In the last part of the chapter is discussed as to whether the differences between the methods are correlated to external factors, such as temperature, moisture condition, potential evapotranspiration and precipitation depth.

5.1 Lysimeter vs EnviroSCAN®

If a certain quantity of water does not reach the zone of influence of the sensors, it can be assumed that the quantity of undetected water entering the system (P+I) should approximately coincide with the undetected water leaving the system (ET). This fact is evident analyzing the divergences between lysimeter and soil sensors, on annually and monthly basis.

The quantity of precipitation that is not detected by the sensors roughly coincides, on annually basis, to the divergence between ET_{lys} and $ET_{EnvSCAN}$ (Fig. 43).

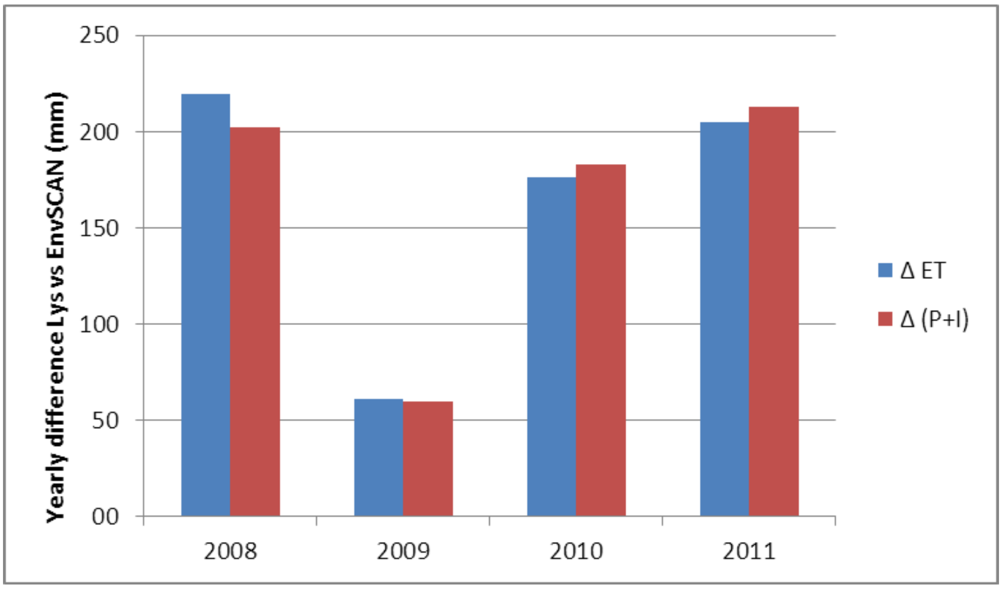


Figure 42: Yearly differences lysimeter vs EnviroSCAN® sensors.

The monthly differences confirm this trend. Figure 44 illustrates shows a good accordance between the terms ET_{lys}-$ET_{EnvSCAN}$ and $(P+I)_{lys}$-$(P+I)_{EnvSCAN}$. On a daily basis it was not possible to observe a similar trend, probably because of redistribution processes and delayed infiltration within the soil profile.

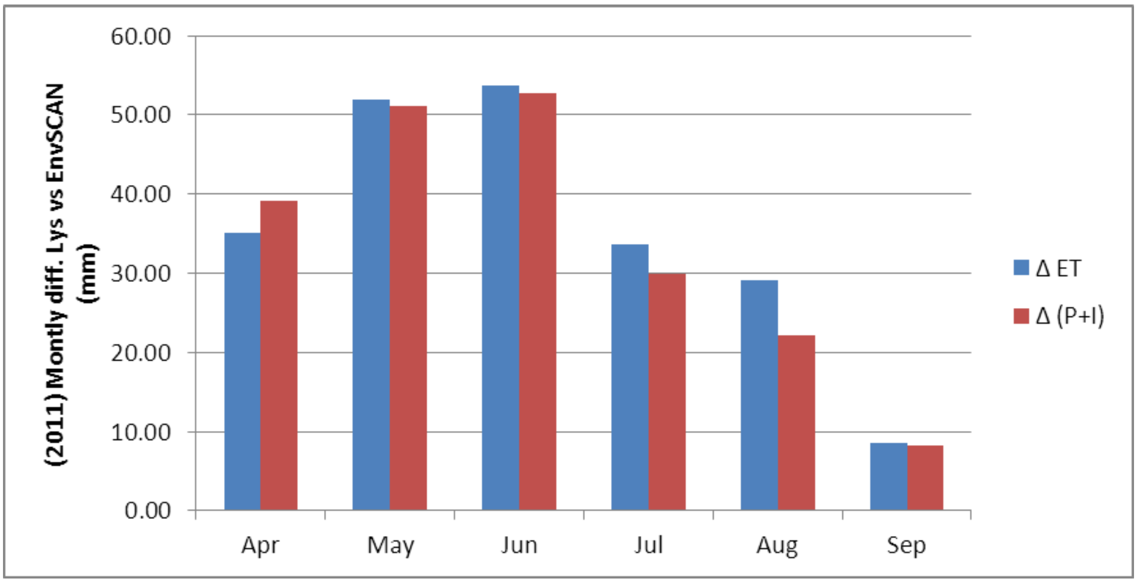


Figure 43: Monthly differences lysimeter vs EnviroSCAN® sensors (2011).

Additionally, the cumulative differences ET_{lys}-$ET_{EnvSCAN}$ and $(P+I)_{lys}$-$(P+I)_{EnvSCAN}$ for 2011 are illustrated in figure 45. The differences follow a very similar trend and are well balanced over the year. Divergences between the two methods become significant between day 50 and 100 (around March) and diminish gradually after day 250 (September).

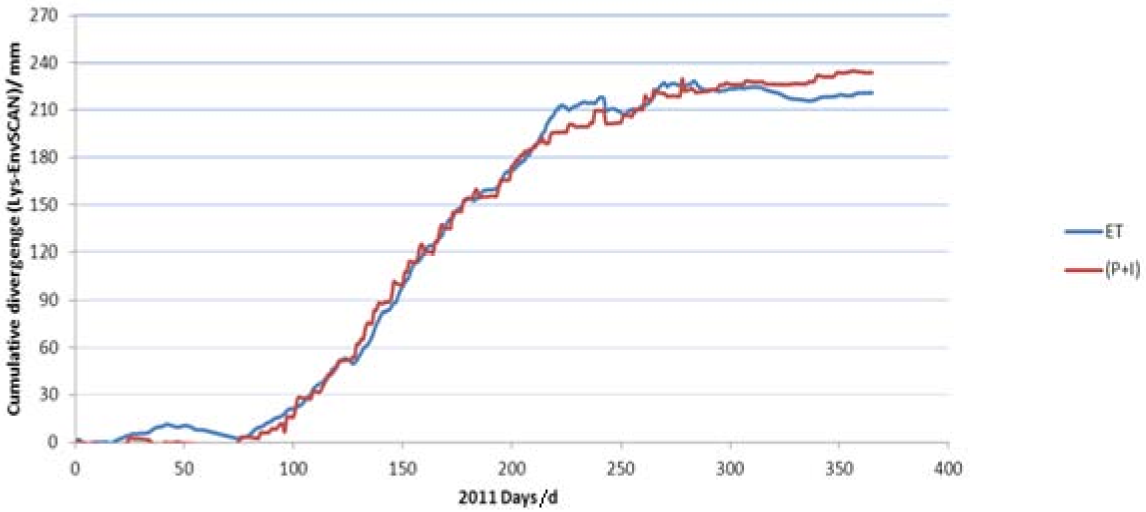


Figure 44: Cumulative daily differences lysimeter vs EnviroSCAN® sensor (2011)

5.2 Water dynamics in the upper and lower layer

In order to get reliable results, it is important to consider all the layers that are involved in relevant water dynamics. One question that needs to be asked is whether the omitted layers (upper and lower) play a crucial role in the soil water balance and are likely reason why the amounts of evapotranspiration and precipitation are underestimated.

Water dynamics are known to be more variable in the first centimeters of soil. On the other hand, the deeper layers are generally subject to weaker variations.

An indication of weak dynamics of the lower layer is provided by the volume of SW collected by the tipping bucket (Fig. 46).

The total outflow volume collected by the east-lysimeter (grass cover) in the period between January 2008 and December 2011 was around 414 mm. The volume collected of SW during 2011 in the west-lysimeter (Spring barley cover) was around 43 mm Thus, SW plays a minor role in the soil water balance in comparison to ΔW and the low layers are not involved in important water dynamics.

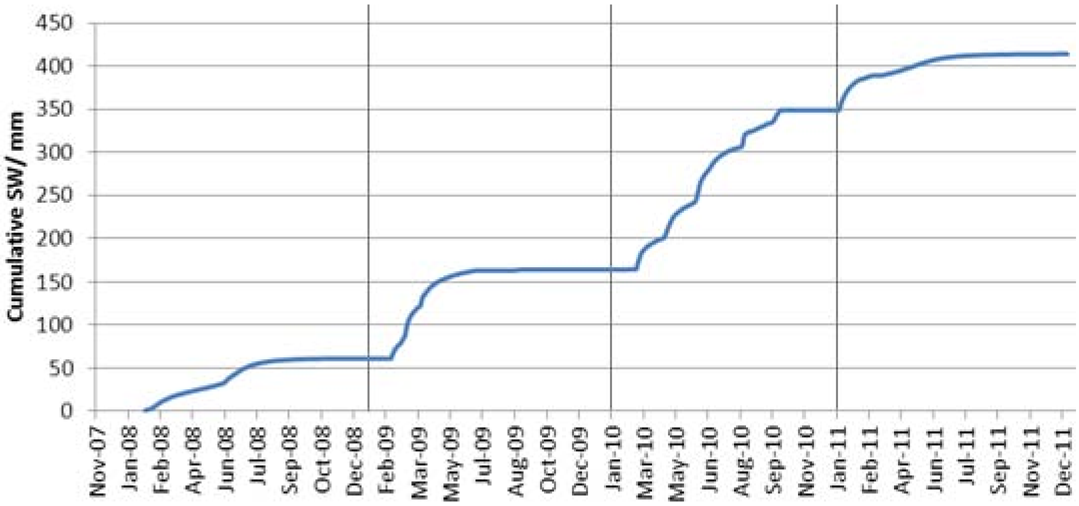


Figure 45: Cumulative SW as measured by the tipping bucket in the east-lysimeter (2008-2011).

The evolution of soil water content at different depths, as measured by EnviroSCAN®, provides also relevant information. Figure 47 shows the evolution of the first (10-20-30 cm) and last three layers (140-150-160 cm) detected by the soil sensors in summer 2011 (June-August). The first layer (10 cm depth) shows the strongest variations in soil water content, while the last layers reveal a slow decrease (due to seepage water) and no reaction to events of evapotranspiration and precipitation.

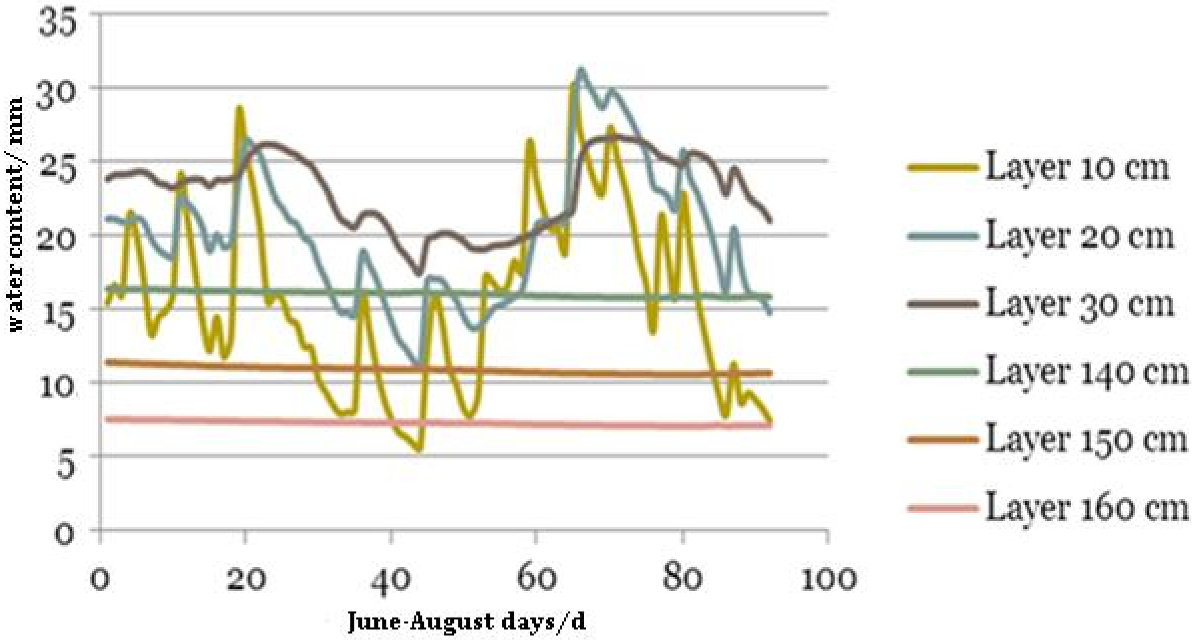


Figure 46: Soil water content (mm) at different deepness as measured by the soil sensors.

This evidence can be seen analyzing in more detail the response of soil water sensors to water inputs. The following figures (Fig. 48, 49) show the reactions of the different measured layers, after the irrigation event on the 5th July and during five selected days in January, respectively.

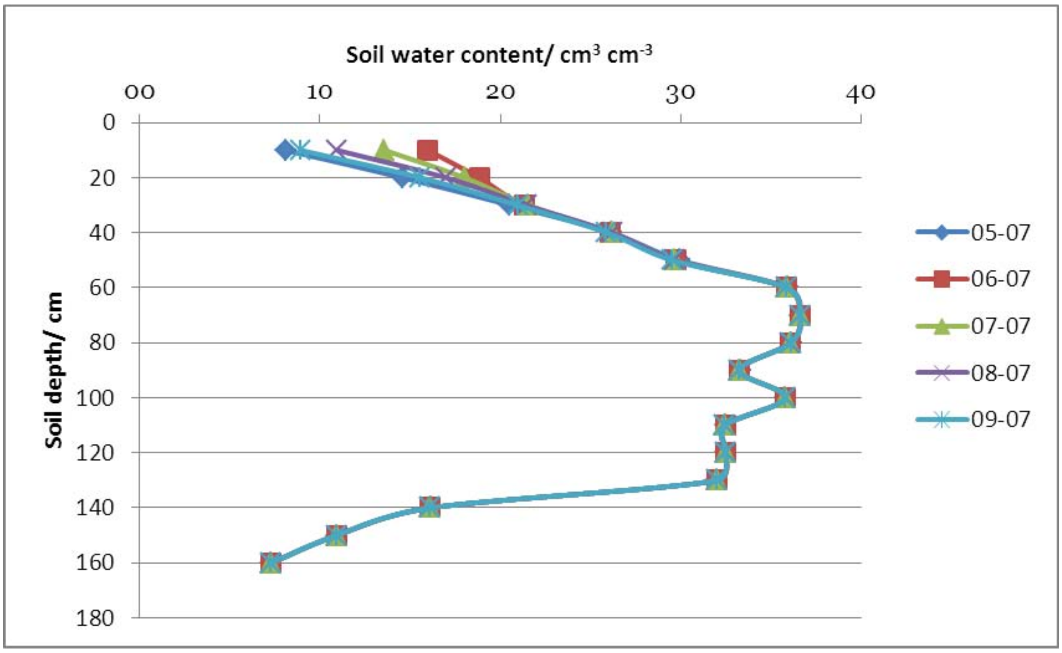


Figure 47: Soil water content as measured by the sensors between the 5th and the 9th of July .

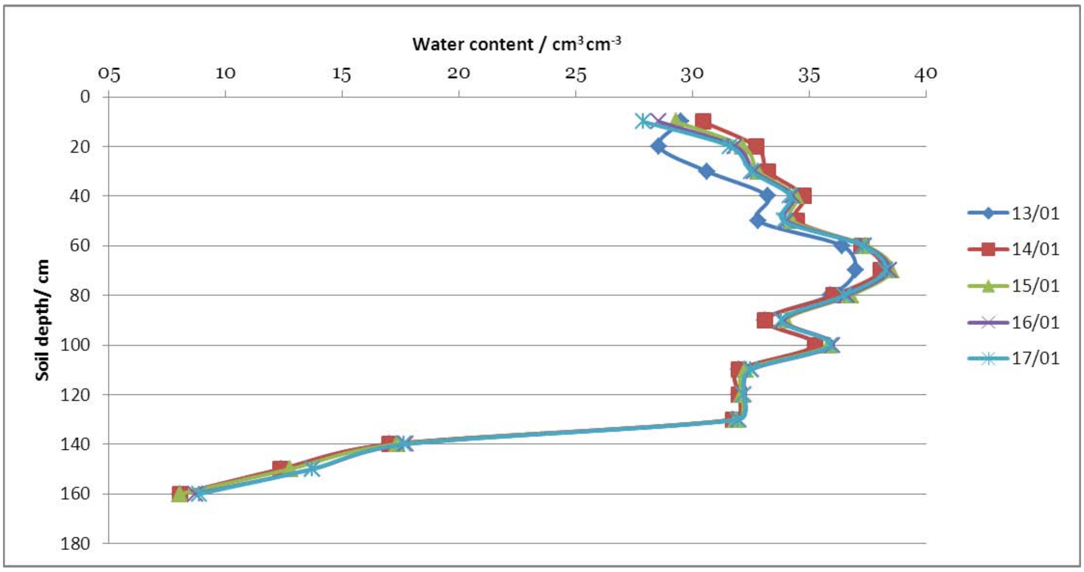


Figure 49: Water content as measured by the sensors between the 13rd and the 17th of January.

The variation of the last layers is always limited and this founding is consistent with the low volume of seepage water collected during the experiment. Only during winter a more intense change occurs.

On the other hand, the 10 cm layers react strongly to precipitation and evapotranspiration events.

Figure 50 illustrates the average, the maximum and the minimum values of the water content in the soil profile as measured by the soil sensors.

Even if some relevant variations due to downward movement are noticeable at depth 150 cm, the first layers are again those involved in the more meaningful variations.

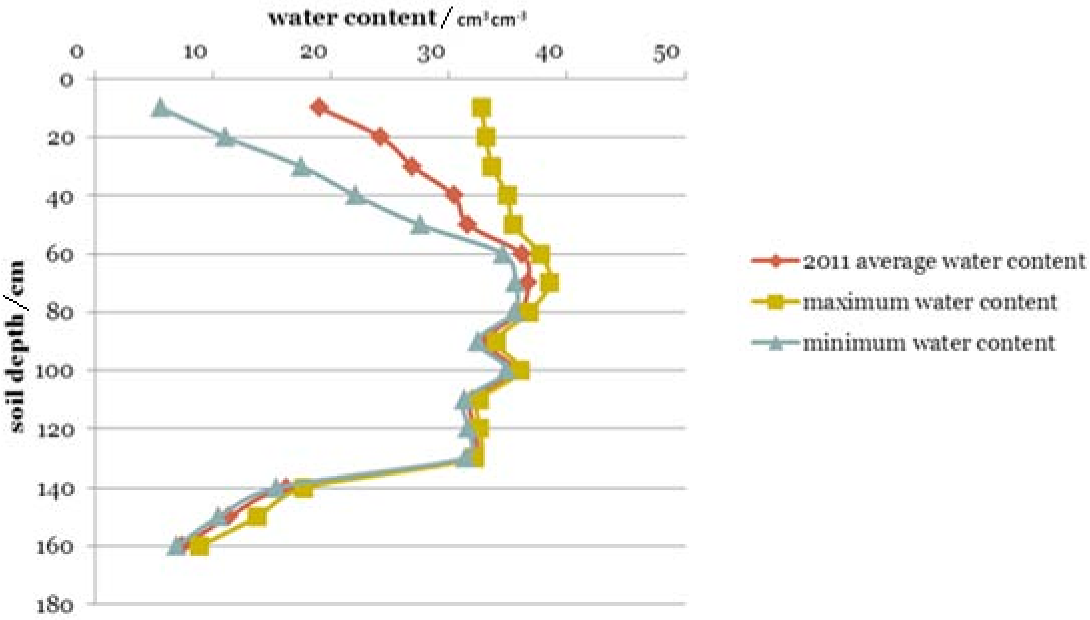


Figure 48: Average, maximum and minimum soil water content in the soil profile as measured by the soil sensors.

It can be concluded that probably the omitted measurement of the last layers doesn't affect the results delivered by the EnviroSCAN® sensors while, on the other hand, information about water dynamics in the first layer (0-5 cm) could be possibly improve the estimation of the soil water balance components.

5.3 Effects of interception, surface storage and delayed infiltration

Interception of vegetation, surface storage and infiltration are important superficial processes that control the amount of water entering the soil system and thus, they could affect the measurements delivered by the sensors. Through interception, a part of the precipitation is trapped on the vegetation surface and never infiltrates into the soil profile. It is expected at a later stage that this volume of water gradually evaporates. The terms "surface storage" refer to the capacity of soil to retain water in its depressions. In case of depression storage the soil would be readily replenished (if evapotranspiration takes place) keeping the soil sensors at saturation and unable to detect the variations of the soil water components. In the same way, after a rain event (or irrigation application), ET (negative changes of W) would not be detected by the first sensors because of the downward propagation of the infiltrated water and redistribution processes.

Consequently both negative and positive variations would be generally underestimated (Fig. 19, 20, 22, 23) and in some cases not detected (Fig. 21).

In order to describe the effect of surface storage and delayed infiltration, the reactions on hourly scale of the east-lysimeter and of the sensors (just the first 10 cm) after rain events were analyzed. Two different days in July 2011 were selected, in which, according to the lysimeter data, precipitation was followed by evapotranspiration.

Figure 51 illustrates the evolution of ΔW on the 21st July (1.3 mm ZAMG) between and 16h 20h. The lysimeter measured negative values of ΔW (evaporation), while the soil sensors recorded positive values one to four hours after the precipitation event ceased (delayed infiltration).

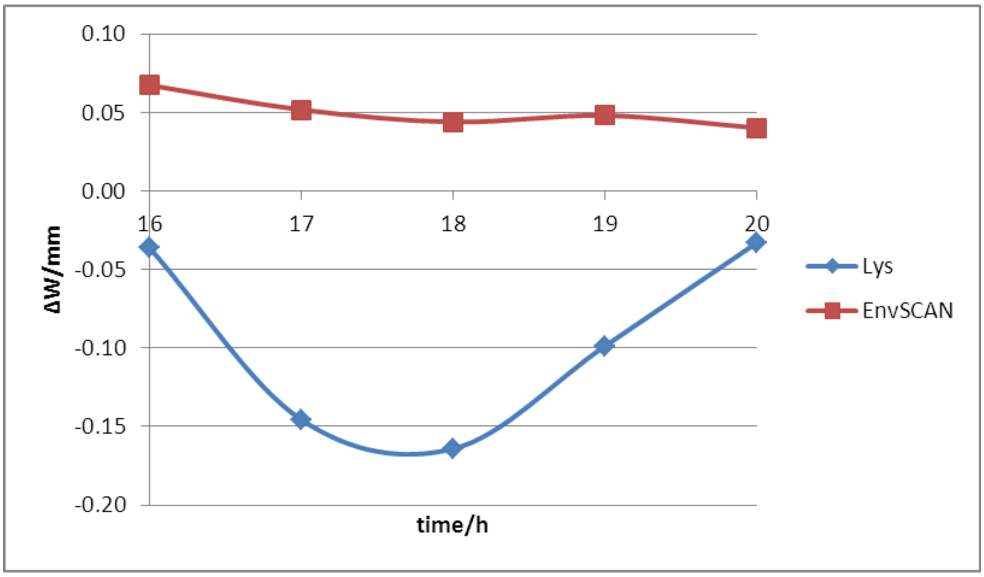


Figure 49: ΔW on the 22st July between and 16h 20h as measured by lysimeter and soil sensors.

The same can be observed on the 23th July between 7h and 13h. The lysimeter indicated a high evaporation rate (negative ΔW) while the soil sensors indicated an increase of the soil moisture till 11h and a small decrease between 11h and 13h (Fig. 52).

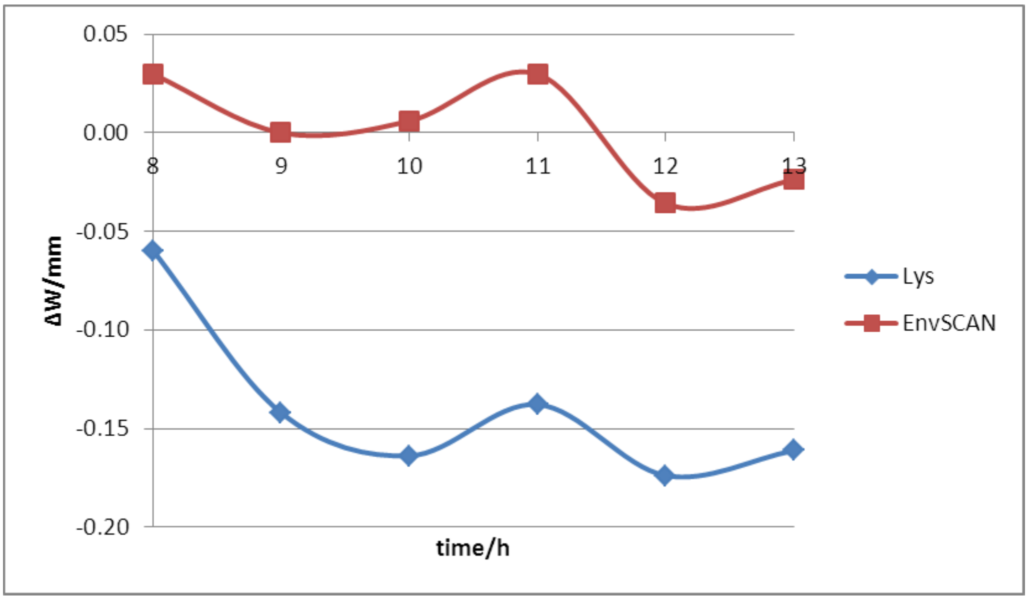


Figure 50: ΔW on the 23th July between 8h and 13h as measured by lysimeter and soil sensors.

Consequences of delayed infiltration and water replenish from depression storage or vegetation surface lead to underestimation of both evapotranspiration and precipitation.

5.4 Influence of environmental factors

A discussion, in the pages below, follows whether the differences are introduced by an inaccuracy inherent in the system. Likely causes may be imperfect calibration of measurement instruments or changes in the environment (e.g. temperature and soil moisture) which interfere with the measurement process.

Daily differences of the term (P+I) occur if water enters the system. If no water infiltrates into the system, no divergence is recorded. The month of August was selected in order to illustrate the evolutions of daily water input (daily I+P) as measured by the east-lysimeter and the daily difference of (P+I) (Lys-EnvSCAN). As figure 53 shows, the picks of the curves are synchronized.

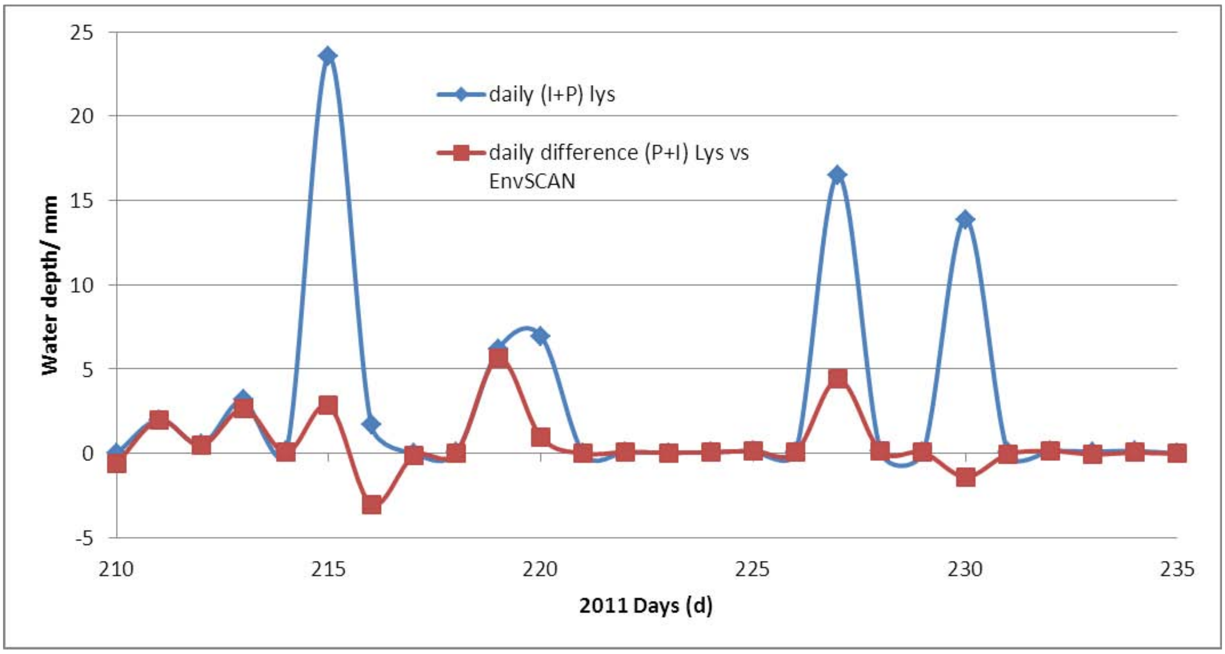


Figure 51: Daily (I+P) as measured by lysimeter vs daily difference (P+I).

Anyway, the magnitude of the difference is independent of the amount of water entering the system. The coefficient of correlation (measurement of the degree of interdependence between two time series), considering the period April-December, is significant but low (0.53). Furthermore, observing figure 53 it is possible to notice the variability of the difference. The first two picks are similar. The difference does not change at day 215, even if a great amount of water enters the system (>20 mm). (P+I) at day 230 is almost 15 mm. In this case we observe that soil sensors have a similar reaction in comparison to lysimeters.

The daily water input (P+I) also affects the daily divergence between ET_{lys} and $ET_{EnvSCAN}$ (Fig. 54). In this case the picks do not coincide but a delayed propagation of the divergence is observed (in the next 24-48h). This is probably the effect of water redistribution processes within the soil profile. The period between the beginning of July and the end of August was chosen in order to illustrate the evolution of the daily difference (ET_{Lys}-$ET_{EnvSCAN}$). The difference is close to 0 (or even negative) only along dry periods. The arrows indicates the days where no or low divergence was observed. On the other hand, in response to relevant water inputs, the difference increases.

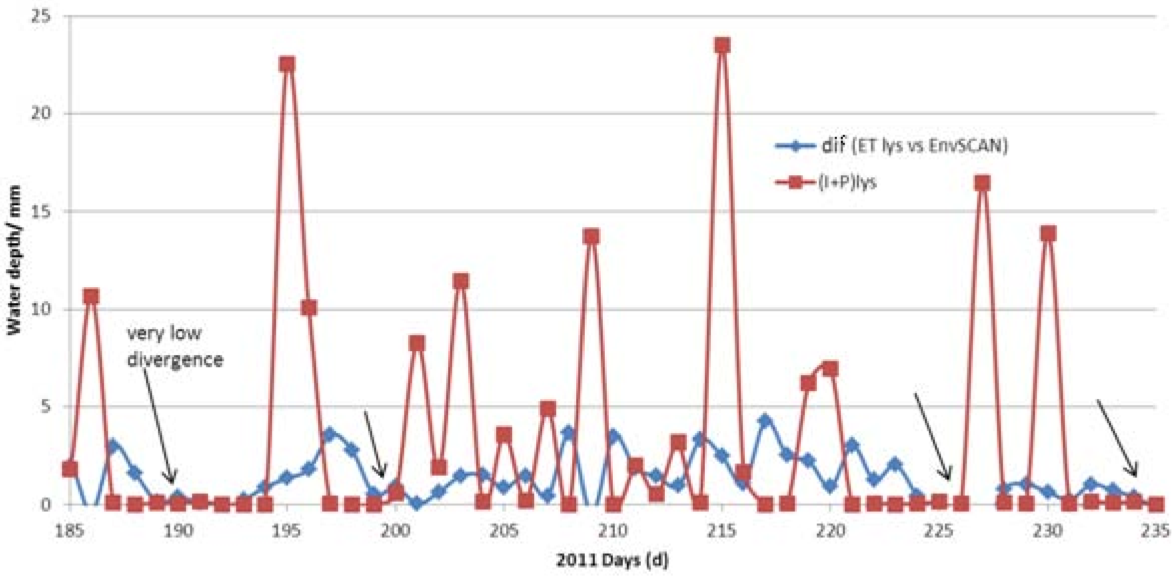


Figure 52: Daily (I+P) as measured by lysimeter vs daily difference (ET).

If the period between the 1st of April and the 30th of September is considered, the average difference (ET_{lys}-$ET_{EnvSCAN}$) is 1.48 mm (183 days). Considering only the days involved in rain or irrigation events and the successive two days after the water input (133 days) the mean error is 1.76 mm. During the other "dry days", that are not or barely affected by relevant water input (<0.5 mm), the average difference reduces to 0.7 mm and better correlation between ET_{lys} and $ET_{EnvSCAN}$ is observed.

The daily water input has no effect on the magnitude of the daily difference (ET_{lys}–$ET_{EnvSCAN}$). The coefficient of correlation (the difference time series was considered with a 2 days delay) is 0.36.

The daily ET difference (lysimeter vs soil sensors) were compared as well with the daily ET measured by means of the lysimeter (Fig. 55). Also, in this case, the differences and the daily potential evapotranspiration have a similar evolution. The picks seem to be well timed and if ET is low, the divergence is accordingly lower.

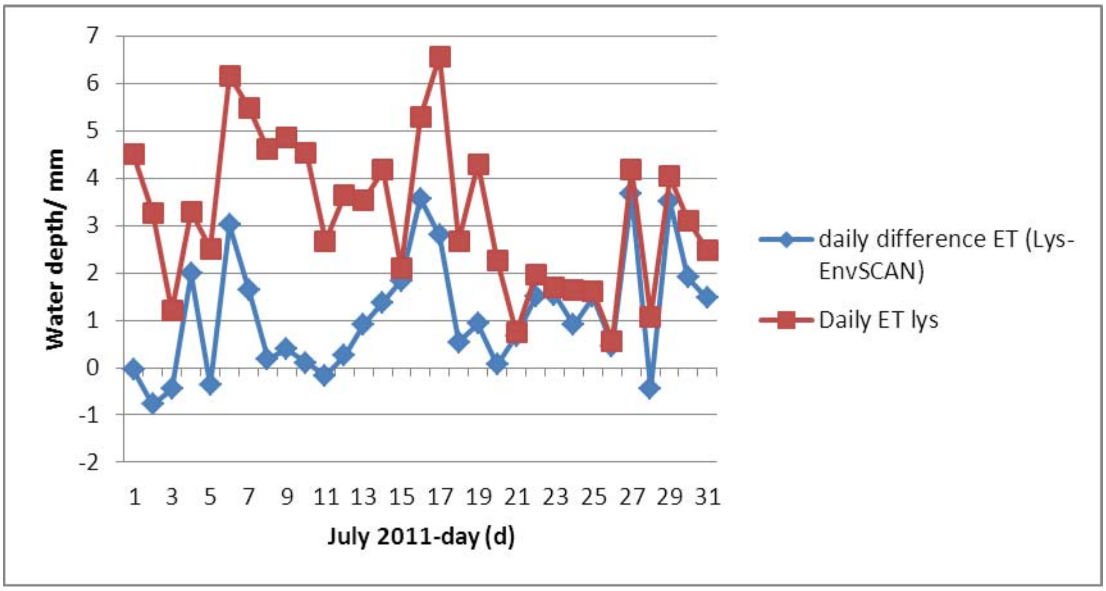


Figure 53: Daily ET as measured by lysimeter vs daily difference (ET).

Anyway, the magnitude of the difference is variable and does not depend directly on the amount of potential evapotranspiration. The coefficient of correlation is significant but low (0.55).

The evolution of the differences is not affected by extreme temperatures. According to scientific literature, high temperatures (>30°C) could lead to malfunctions of the EnviroSCAN® sensors and thus, to underestimation or overestimation of soil water changes. During the present master thesis, the maximal divergences (ET and P+I) do not coincide with the highest temperature, as figure 56 shows. The hottest period of 2011 (July) was selected in order to illustrate the evolution of the differences and its relationship with temperatures. The picks of the daily differences never correspond to the hottest days.

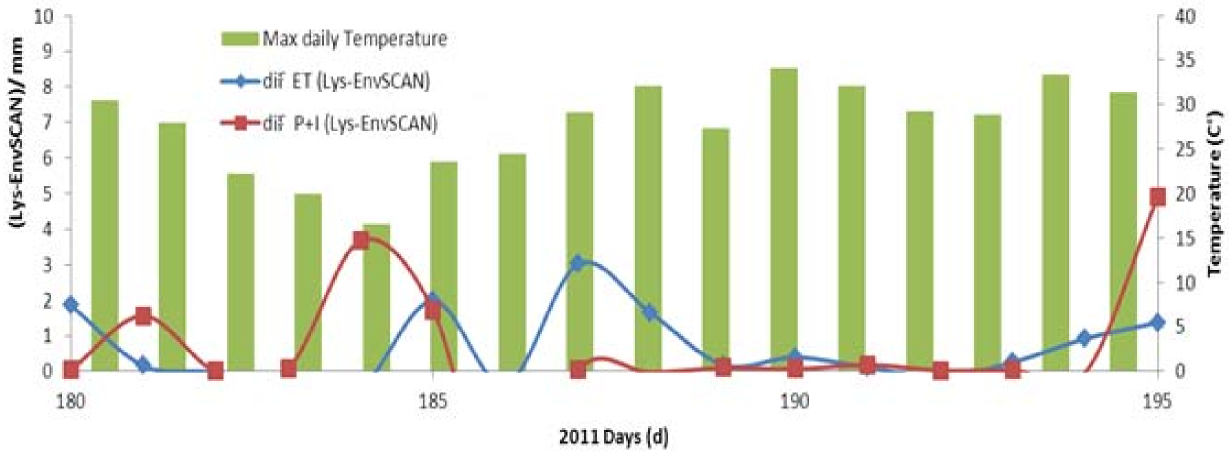


Figure 54: Evolution of daily highest temperature vs daily differences ET and (P+I).

Not even the soil water content (W) is connected with the evolution of the divergences between the two methods. The correlation coefficient between soil water content and the daily differences is close to zero (-0.0937 for P+I and 0.0428 for ET, respectively). Thus, the magnitude of the differences is independent from the soil moisture status of the profile.

6 CONCLUSION

The study was set out to explore the possibility to solve the soil water balance by means of lysimeters and EnviroSCAN® soil sensors and to determine the single components of the soil water balance equation. Furthermore, the study aimed to determine whether lysimeter and soil sensors delivered similar estimation of soil water content changes. Another task was to determine possible sources of errors and misinterpretation of lysimeter and soil sensors readings. According to previous scientific literature, lysimeters are reliable instruments in order to accomplish studies on soil water components but they are susceptible to a range of factors, such as oasis effects and environmental effects (E.g. wind, snow).

Soil capacitance sensors measure water content in the soil at different depth but they cannot detect water beyond their electrical field. Moreover, if the length of the probe is shorter than the depth of the soil profile, the whole soil profile cannot be considered.

Soil water balance components were assessed in the experimental farm of Gross-Enzersdorf during a four-year experiment under optimal water condition (2008-2011), using two weighing lysimeters and EnviroSCAN® sensors. Soil water changes, evapotranspiration and precipitation were determined on different time scales, solving a simplified soil water equation. Soil water content measured by means of lysimeter and soil water probes, showed meaningful differences. Even if the sensors had generally a synchronized reaction to precipitation, irrigation and intense solar radiation, they delivered underestimated measurements compared to the lysimeters.

Reference and spring barley evapotranspiration, determined as a consequence of lysimeters data, were reasonable on a yearly and monthly basis, even if generally slightly underestimated, probably because the water content within the soil profile was suboptimal during some period of the experiment. On a daily basis, simulation and lysimeters showed good accordance. In the east-lysimeter, the biggest RMSE coefficient (0.74 mm), as well as the lowest R^2 (0.8548), were calculated for 2009.

Precipitation determined by the lysimeters was generally higher on a yearly, monthly and daily basis (especially in wintertime) than the rain-gauge values because of the different operation modes of the two methods. Through lysimeters it is possible to detect all forms of precipitation such as snow and fog condensation while rain gauges, on the other hand, generally underestimate these phenomena. For this reason it was possible to observe a better correlation in summertime between the two instruments.

It was not possible to achieve good estimations of soil water balance components by means of the EnviroSCAN® sensors, installed in the lysimeters facility.

Reference evapotranspiration and crop evapotranspiration were generally lower and showed no accordance with simulation results. The difference between sensors and simulation was relevant and of the same magnitude over the entire period of the experiment (e.g. on a yearly basis at the east-lysimeter: 317 mm, 289 mm, 350 mm, 378 mm in 2008, 2009, 2010 and 2011 respectively). The biggest differences were recorded in summertime.

The analysis of the soil sensors data at different depth and the comparison to lysimeters data indicated that part of the water entering the lysimeter facility is not able to reach the zone of influence of the sensors.

Hence, the impossibility to detect the first centimeters of the soil profile could generate underestimations. Furthermore, the effects of superficial phenomena, such as interception, surface storage and delayed infiltration led to misinterpretation of both precipitation and evapotranspiration. Additionally, the differences between the methods showed a certain temporal accordance with the amount of water entering the soil system and with the evapotranspiration rate. Moreover, the occurrence and the magnitude of the differences did not depend on other external factors, such as temperature and soil moisture conditions.

In order to improve the results delivered by means of EnviroSCAN® sensors, it may be worth to find a way to consider the soil water dynamics of the first layer. Integrate the soil water content variations of the first centimeters would be the next logical step to provide a more precise assessment of soil water components by means of EnviroSCAN® soil sensors.

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