The water deficit of evapotranspiration covers on potash tailing piles using cropwat

Carolina Bilibio*, Oliver Hensel

(Department of Agricultural and Biosystems Engineering, University of Kassel, Nordbahnhofstraße 1a, D-37213 Witzenhausen, Germany)

Abstract: Evapotranspiration covers are key to minimizing water percolation in waste systems. On potash tailings piles, evapotranspiration covers are important because they may decrease the leaching of brines generated from precipitation erosion. Considering this, the water deficit of four different potash tailings piles covering materials were evaluated using the CropWat model. This study was based on a lysimeter experiment carried out in Heringen, Germany. The experiment consisted of four different technogenic substrates made of municipal incineration wastes and coal combustion residues covered with a mixture of perennial grasses. By using the FAO CropWat model, the effective precipitation, crop evapotranspiration, actual evapotranspiration and the water deficit were estimated from 2014 to 2016. Further simulations determined the water deficit under different precipitation probabilities, 20%, 50% and 80%, and crop coefficients, varying from 0.4 to 1.0. CropWat estimated a crop evapotranspiration of 641.9 mm year^{-1} and an actual evapotranspiration of 448.3 mm year^{-1} or 68.5% of the annual ground-level precipitation. Over three calendar years there was a mean estimated water deficit of 28.7%. Higher levels of water deficit were estimated in spring and summer months. Further simulations revealed the water deficit might range from 55.0 mm (8.7%) for high precipitation levels to 157.4 mm (24.9%) for low precipitation depths. Additionally, water deficit is associated with the crop coefficient, ranging from 0.0 mm using a constant crop coefficient of 0.4 to 105.3 mm using a constant crop coefficient of 1.0 for an average precipitation. Overall, the CropWat model agreed with the observed measurements and no large differences among the substrates were verified.

Keywords: effective precipitation, drought, perennial ryegrass, lysimeters, crop coefficient

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1 Introduction

Evapotranspiration covers minimize the percolation of water through waste systems (Zhang and Sun, 2014; Barnswell and Dwyer, 2012; Zhang et al., 2009). An evapotranspiration cover consists of a water soil reservoir and a vegetated surface which transports the soil moisture back to the atmosphere (Hauser, 2009; Schnabel et al., 2012). The crops on evapotranspiration covers transpire the moisture, reduce erosion, decrease percolation and stabilize the surface of the soil or soil substitute (Rock et al., 2012; Hauser, 2009).

Several factors affect crop growth, such as air temperature, soil temperature and nutrition (Gill et al., 2016). However, water is the most important abiotic stress associated with aboveground and root biomass production (Staniak and Kocoń, 2015; Vries et al., 2016; Dodd and Ryan, 2016).

The moisture needed to meet the atmospheric and crop demand represents the potential crop evapotranspiration (Doorenbos and Kassam, 1979). Crop evapotranspiration is

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* **Corresponding author: Carolina Bilibio, Ph.D**, Department of Agricultural and Biosystems Engineering, 37213 Witzenhausen, Germany. Email: carolina.bilibio@uni-kassel.de. Tel: +49 5542 98-1224, Fax: +49 5542 98-1520.

generally covered by precipitation or irrigation (Smith, 1992). When the crop water requirement is not met, there is a water deficit and the actual evapotranspiration is lower than the potential crop evapotranspiration (Doorenbos and Kassam, 1979). The effects of water stress vary with crop species and the stage of crop growth (Doorenbos and Kassam, 1979).

Crop water deficit is predicted to increase due to the changes in temperature and precipitation patterns caused by global climate change (Leitinger et al., 2015; Staniak and Kocoń, 2015). Researchers predicted an increase of 1.4^{o}C to 5.8^{o}C in the global air temperature by 2100 (Staniak and Kocoń, 2015). Moreover, a decrease in the rain and snow levels is forecasted (Staniak and Kocoń, 2015; German Federal Government, 2008). In Germany, an increase of up to 3.5^{o}C by 2100 is expected (German Federal Government, 2008). This increase in temperature may intensify the evapotranspiration and the soil water depletion (Riediger et al., 2016). With regards to precipitation, an increase of winter rain and a decrease in summer precipitation is estimated in Germany (German Federal Government, 2008).

Many studies have evaluated the effects of water deficit in agricultural and bioenergy crops (Ings et al., 2013; Müller et al., 2014; López-López et al., 2018). However, in non-agricultural fields, water deficit may compromise ecological services, such as the purification of water and the regulation of the water cycle (Barnswell and Dwyer, 2012; Leitinger et al., 2015). Regarding this, the present study was aimed to evaluate the magnitude of the water deficit of four evapotranspiration covers for potash tailings piles using CropWat and compare these results with a lysimeter experimental study. In addition, we aimed to verify the impact of different precipitation probabilities, 20%, 50%, and 80%; and crop coefficients, from 0.4-1.0, on the water deficit of the potash tailings covers. We hypothesize that the extreme weather in potash pile areas will likely increase crop evapotranspiration, actual evapotranspiration and water deficit for the crops.

2 Material and methods

2.1 Experimental site and design

The experiment was carried out at the Wintershal site which belongs to the integrated Werra potash plant from K+S KALI GmbH. The potash tailings pile known as “Monte Kali”, is located at 50° 53' 160" North and 9° 59' 12" East, 409 m altitude, in the outskirts of the Hessian city of Heringen, Germany (Figure 1).

Heringen is located at 221 meters’ altitude and the climate is classified as Cfb (cold with no dry season, summer is temperate and there are at least four months with temperatures over 10°C) under the Köppen-Geiger classification (Schwarz, 2016; Peel et al., 2007; Kottek et al., 2006). According to the historical records for 1961-1990, the average annual temperature in Heringen is 8.4^{o}C (Lamprecht, 2017) and the average annual precipitation is 684 mm (Deutsche Wetterdienst, 2017a).

Figure 1 (a) Monte Kali in the outskirts of the Hessian city of Heringen, (b) Germany

Inside the confines of the experimental area, 544 m² (27.2 x 20 m), 8 three meter-deep percolation lysimeters covering an area of 2 m², were installed. The lysimeters were filled with four different substrates. Substrate 1 was 80% household waste incineration slags, and 20% coal combustion residues. Substrate 2 contained 70% household waste incineration slags, and 30% coal combustion residues. Substrate 3 included 60% household waste incineration slags, 10% of washed sand from gravel extraction, and 30% coal combustion residues. Substrate 4 had 50% household waste incineration slags, 30% coal combustion residues, 10% furnace bottom ashes with particle sizes between 0.2 and 2 mm, labelled “Kesselsand”, and 10% original bottom ashes with particle sizes from 0 to 6.3 mm, labelled “Feinasche”. Kesselsand and Feinasche are from waste-to-energy power plants. Kesselsand is collected in a water-filled hopper at the end of a boiler, Feinasche are obtained from sieving coarse ashes (Schmeisky and Papke, 2013).

After filling the lysimeters, a mixture of each substrate with organic compost, 0 - 20 mm sieve, was applied, totaling 200 tons of compost per hectare 0.3 m from the surface. In addition, different fractions of gravel were used on the bottom of the lysimeters to avoid washing-out substrates and to facilitate the drainage of percolated water.

The experimental area was isolated from the stock pile with a 2 mm thick canvas. Moreover, the lysimeters were installed 1 m above a potash tailings layer with 3% slope to facilitate the outflow of seepage water.

2.2 Meteorological data

Precipitation in the experimental field was assessed with an automatic weather station, equipped with a Datalogger DLx mET, Thies Clima (Göttingen). The weather station had a precipitation sensor with a collection area of 200 cm^2 and collected precipitation every 10 minutes. Precipitation was also evaluated using four rain gauges installed at ground level, and five precipitation gauges installed at 1 meter height (Bilibio et al., 2017).

Additional micrometeorological parameters were registered by the Thies-Clima weather station, such as wind speed ($m\ s^{-1}$, 3 m height), air temperature (2 m height), soil temperature (0.3 m depth), relative air humidity (2 m height) and solar radiation (2 m height).

Due to technical problems with the weather station from 05.08.2016 to 18.08.2016, the weather values available for Eichhof (Bad Hersfeld) were incorporated for this interval. Eichhof (Bad Hersfeld) is located at 50^o 50' 51.7" North and 9° 41' 8.1" East, and at circa 202 m altitude (Landesbetrieb Landwirtschaft Hessen, 2017).

2.3 Drainage and evapotranspiration assessment

Discharge lines connected to the lysimeters drained percolated water. These lines were linked to 60L barrels placed in a nearby shelter. The amount of drained water was first recorded on 26 July 2013, just after the lysimeter´s saturation, and was registered weekly since then, on Thursdays, 9am-10am.

$$ET_a = P - D \quad (1)$$

The actual evapotranspiration was determined using the simplified water balance expression (Aboukhaled et al., 1982; Bilibio et al., 2011; Bethune et al., 2008), Equation 1:

Where ET_a = actual evapotranspiration (mm), P = ground-level precipitation (mm), and D = drainage (mm).

2.4 Seeding and fertilization

A seed mixture containing 65% perennial ryegrass (*Lolium perenne* L.), 25% red fescue (*Festuca rubra* L.) and 10% Kentucky bluegrass (*Poa pratensis* L.) were used from 5 August to 26 September 2013, totaling 70 g m^{-2} (Schmeisky and Papke, 2013). In addition, the annual amount of fertilizer was 83 g m^{-2} in 2013, 193 g m^{-2} in 2014, 94 g m^{-2} in 2015, and 158 g m^{-2} in 2016, consisting of 61 g m^{-2} of nitrogen, 80 g m^{-2} of phosphorus, 79 g m^{-2} of potassium and 9 g m^{-2} of magnesium (Schmeisky and Papke, 2013; Papke and Schmeisky, 2017).

2.5 CropWat configuration

The crop water requirements were assessed using CropWat, version 8.0 (Smith, 1992; FAO, 2017) according to the following configuration:

2.5.1 Climate

The monthly weather data registered at the Heringen experimental site from 2014 to 2016, used were the mean maximum and minimum air temperature, solar radiation, relative air humidity and wind speed. The solar radiation ($W\ m^{-2}$) was converted to sun hours using the ET_o calculator, version 3.2 (FAO, 2014).

2.5.2 Rain

Although the precipitation was measured in three different gauges, the CropWat model was performed using the precipitation depths registered in ground-level gauges. For the 10-days water balance intervals, the actual rainfall was corrected due to runoff loss and percolation or evaporation, which normally ranges from 10%-30% (Smith, 1992). Thus, the 10-days interval effective rain, was 80% of the actual rainfall measurements, as suggested by Smith (1992).

For the daily water balance, CropWat interpolated the monthly precipitation to 10-day intervals and later distributed it in two applications within the 10-days interval, which is on the third and seventh day of the 10 day interval (Smith, 1992).

2.5.3 Crop

The green cover was assumed to have a constant height of 0.30 m; and a root depth of 0.10 m in 2014, 0.18 m in 2015 and 0.25 m in 2016 (Papke and Schmeisky, 2017). Moreover, a constant crop coefficient of 1.0 (Allen et al., 1998; Bethune et al., 2008) was settled over four 90-day crop development stages. However, during the initial establishment of the green cover in 2014, the crop coefficient was settled at 0.40. This crop coefficient is recommended for the initial stage of alfalfa (Smith, 1992). The crop coefficient adjusts the reference evapotranspiration to the actual crop characteristics (Pereira and Alves, 2013).

The maximum soil moisture depletion fraction, p, was 0.6 as suggested by ryegrass hay (Allen et al., 1998). This value represents the maximum reduction of the total available water (TAW) without causing crop water stress (Allen et al., 1998). By using the soil water depletion fraction, the ready water available (RAW) was determined.

The total available water (TAW) excludes the unavailable water due to drainage or very low matric potentials (Allen et al., 1998).

$$TAW = 1000\,.(\theta_{FC} - \theta_{WP}).Z_r \qquad (2)$$

Where TAW is the total available water in the root zone (mm); θ_{FC} is the water content at field capacity (m³ m^{-3}); θ_{PM} is the water content at the permanent wilting point (m³ m^{-3}); Z_r is the root depth (m).

$$RAW = TAW\,.p \qquad (3)$$

Where RAW is the ready water available (mm); and p is the soil water depletion fraction.

2.5.4 Substrates

The hydraulic parameters needed as inputs in the CropWat model are presented in Table 1.

Table 1 Observed hydraulic parameters of the substrates 1-4 from 0.0 to 0.64 m depth

Substrates	Bd	θs	α	n	K_s	R^2	θ_{fc}	θ_{pwp}	Δ θ_{fc}-θ_{pwp}
	g cm^{-3}	cm³ cm^{-3}	cm^{-1}		cm d^{-1}	-	cm³ cm^{-3}	cm³ cm^{-3}	mm m^{-1}
Substrate 1	1.20	0.5038	0.0777	1.2103	687.4	0.9933	0.355	0.114	241.3
Substrate 2	1.21	0.4879	0.0696	1.1913	574.0	0.9910	0.361	0.129	232.3
Substrate 3	1.25	0.4736	0.0660	1.1850	463.0	0.9867	0.357	0.132	224.8
Substrate 4	1.17	0.4913	0.1025	1.1946	697.0	0.9896	0.339	0.118	221.2
Average	1.21	0.49	0.08	1.20	605.4	0.99	0.35	0.12	229.9
SD	0.03	0.01	0.02	0.01	110.1	0.00	0.01	0.01	8.9
CV	2.7	2.5	20.8	0.9	18.2	0.3	2.7	7.0	3.9

Note: SD is the standard deviation; CV is the coefficient of variation; Bd is the bulk density; θ_s is the water content at soil saturation (cm³ cm^{-3}); α and n are fitting parameters of the van Genuchten model (van Genuchten, 1980); K_s is the saturated hydraulic conductivity; θ_{fc} is the water content at the field capacity (cm³ cm^{-3}); θ_{pwp} is the water content at permanent wilting point (cm³ cm^{-3}).

The dry bulk density ranged from 1.17 g cm^{-3} in substrate 4 to 1.25 g cm^{-3} in substrate 3. These values are considered low, according to Boden (2005), comprising a mean of 1.21 g cm^{-3} and a low coefficient of variation among the substrates, 2.7%.

A coefficient of variation lower than 10% was also found for substrates' hydraulic parameters, except for the inverse of the air entry value, α (alpha), from the water retention curve parameters, Table 1. The volumetric water content at saturation showed a mean value of 0.49 cm³ cm^{-3} whereas the water content at field capacity was on average 0.35 cm³ cm^{-3} and the water content at the permanent wilting point was 0.12 cm³ cm^{-3}. The water retention curves of substrates 1-4 are presented in Figure 2. This figure shows that the substrates presented a similar desaturation process.

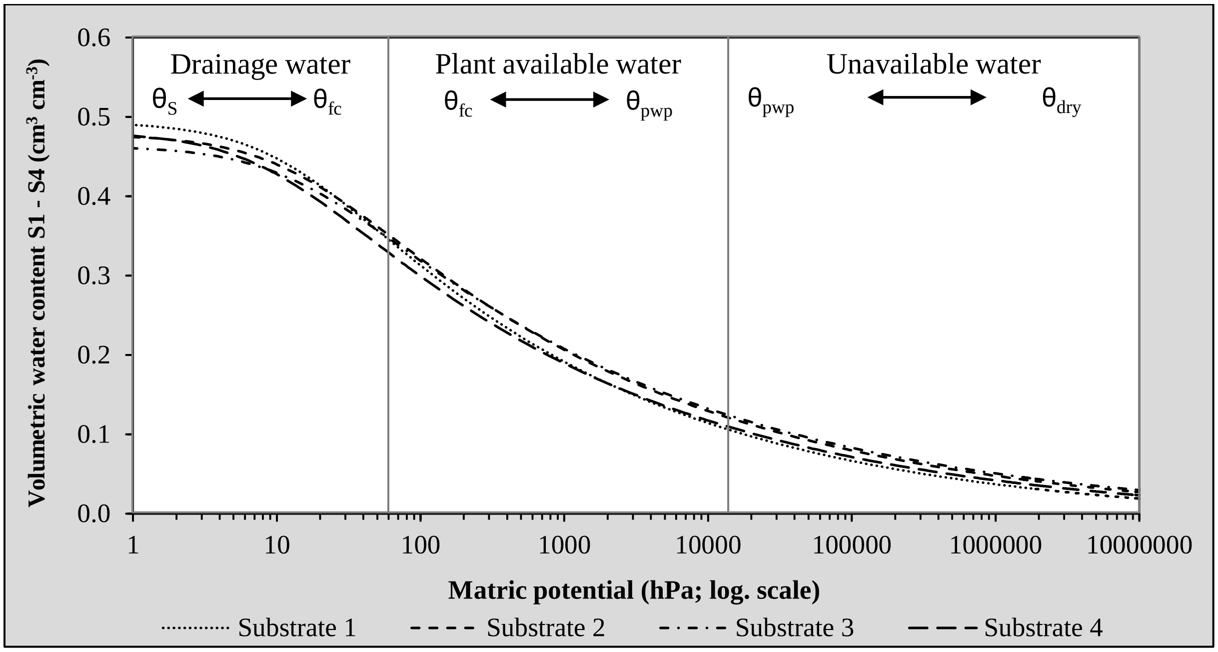


Figure 2 Water retention curve of substrates 1-4 from 0.0 to 0.64 m depth

With the volumetric water content at field capacity and at the permanent wilting point the plant-available water of the substrates was estimated which ranged from 221.2 mm m^{-1} in substrate 4 to 241.3 mm m^{-1} in substrate 1 (mean 229.9 mm m^{-1}; CV 3.9%). These values are considered high, when compared with mineral soils. Clay soils have120 mm m^{-1} of plant available water, silt soils 200 mm m^{-1}, and coarse sand soils 50 mm m^{-1} (Blume et al., 2016).

The saturated hydraulic conductivity of the substrates ranged from 463.0 cm d^{-1} in substrate 3 to 697.0 cm d^{-1} in substrate 4 (mean 605.4 mm m^{-1}; CV 18.2%). These hydraulic conductivity values are considered very high (Blume et al., 2016) and are out of the CropWat model's range. The maximum fixed infiltration rate in the CropWat model is 300 mm d^{-1} (30 cm d^{-1}), which was used for all substrates.

2.5.5 Crop evapotranspiration

The potential crop evapotranspiration (ET_c) is estimated using the FAO Penman Monteith reference evapotranspiration (ET_o) and crop coefficients (Allen et al., 1998). The reference evapotranspiration is written as (Allen et al., 1998):

$$ET_o = \frac{0.408\,.\Delta\,.(R_n - G) + \gamma\,.\frac{900}{T+273}\,.u_2\,.(e_s - e_a)}{\Delta + \gamma\,.(1 + 0.34\,.u_2)} \quad (4)$$

Where ET_o is the reference evapotranspiration (mm day^{-1}), Rn is net radiation on the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), e_s-e_a is saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

After estimating the reference evapotranspiration, the crop evapotranspiration under standard conditions (ET_c) is estimated using the following expression (Allen et al., 1998):

$$ET_c = ET_o\,.K_c \quad (5)$$

Where K_c is the crop coefficient (dimensionless).

2.5.6 Actual evapotranspiration

The actual evapotranspiration is equal to the crop evapotranspiration up to the soil water depletion limit, p, afterwards the crop evapotranspiration will be reduced according to the expression:

$$ET_{c\,adj} = K_s\,K_c\,ET_o \quad (6)$$

Where $ET_{c\,adj}$ is the adjusted crop evapotranspiration or actual evapotranspiration (mm), ET_o is the reference evapotranspiration (mm), K_c refers to the crop coefficient,

K_s is the water stress coefficient (Allen et al., 1998). For water stress conditions, K_s <1, for non-water stress conditions, $K_s = 1$ (Allen et al., 1998)

The water stress coefficient can be estimated using the expression (Allen et al., 1998):

$$K_s = \frac{TAW - SMD}{TAW - RAW} = \frac{TAW - SMD}{(1-p)\,TAW} \tag{7}$$

Where K_s is the transpiration reduction dependent on available soil moisture, which ranges from 0 to 1, SMD is the soil moisture depletion (mm), TAW is the total available soil moisture in the root zone (mm), p is the fraction of TAW that a crop can extract without suffering water stress (-) (Allen et al., 1998). The minimum root zone moisture depletion value is registered at field capacity and the maximum is equal to the total available water (Allen et al., 1998). The moisture content above field capacity is considered as drainage and the moisture content below the permanent wilting point is unavailable to the crops' extraction (Allen et al., 1998).

The CropWater model performs a daily water balance to determine the soil moisture depletion according to the expression:

$$SMD_i = SMD_{i-1} + ET_a - P_{tot} - Irrig.Appl. + RO + DP \tag{8}$$

Where SMDi is the soil moisture depletion at the day "i"; ET_a is the actual evapotranspiration; P_{total} is the total precipitation; Irr. Appl. is the irrigation depth; RO is the surface runoff; DP is the deep percolation, in mm.

From the ground-level precipitation and actual evapotranspiration estimated with CropWat, the CropWat substrates´ drainage was estimated using the simplified water balance expression (Equation 1).

2.7 Further simulations

Additional simulations were performed considering different precipitation regimes, such as high, normal and low precipitation levels. A normal year corresponds to a precipitation with 50% exceedance probability; a high precipitation level has 20% exceedance probability; and a low precipitation level shows 80% exceedance probability (Smith, 1992). Precipitation with an 80% probability of exceedance is used for designing irrigation systems whereas precipitation with a 50% probability exceedance is considered for irrigation planning (Smith, 1992).

High, normal and low precipitation levels were estimated using 30 years (1987-2016) of precipitation registered in Bad Hersfeld. The Bad Hersfeld weather station (identification number 2171) is located at 50° 51' 6.84" North, 9° 44' 16.08" East, 272 m above sea level (Deutsche Wetterdienst, 2017a) and circa 20 km from Heringen, Werra (Deutsche Wetterdienst, 2017b).

From this data, (1) the annual rainfall was tabulated; (2) the annual rain by descending magnitude was arranged; (3) a plotting position was organized using the expression (Smith, 1992):

$$F_a = 100\frac{m}{N+1} \tag{9}$$

Where N is the number of records; m is the rank number and Fa is the plotting position.

Afterwards the accumulated precipitation was estimated according to the different precipitation regimes using linear regression.

In this sequence, the monthly precipitation was estimated according to the different degrees of probability using the following expression:

$$P_{i_{(80).}} = P_{i_{(50)}} \cdot \frac{P_{(80)}}{P_{(50)}} \tag{10}$$

Where $P_{i(80)}$ is the monthly low precipitation level for month i; $P_{i(50)}$ is the normal average precipitation for month i. $P_{(80)}$ is the accumulated precipitation with an 80% probability of exceedance. $P_{(50)}$ is the accumulated precipitation in a normal precipitation year (Smith, 1992).

These additional simulations were performed using substrate 1 at a root depth of 30 cm. This depth generally concentrates most of the grasslands' roots and perennial grasses (Hendrickson et al., 2013; Leitinger et al., 2015). Simulations were also performed using different crop coefficients 0.4 – 1.0. These crop coefficients represent the changes in the vegetation cover owing to the integration of native species, fertilization and pest control.

2.8 Statistical analyses

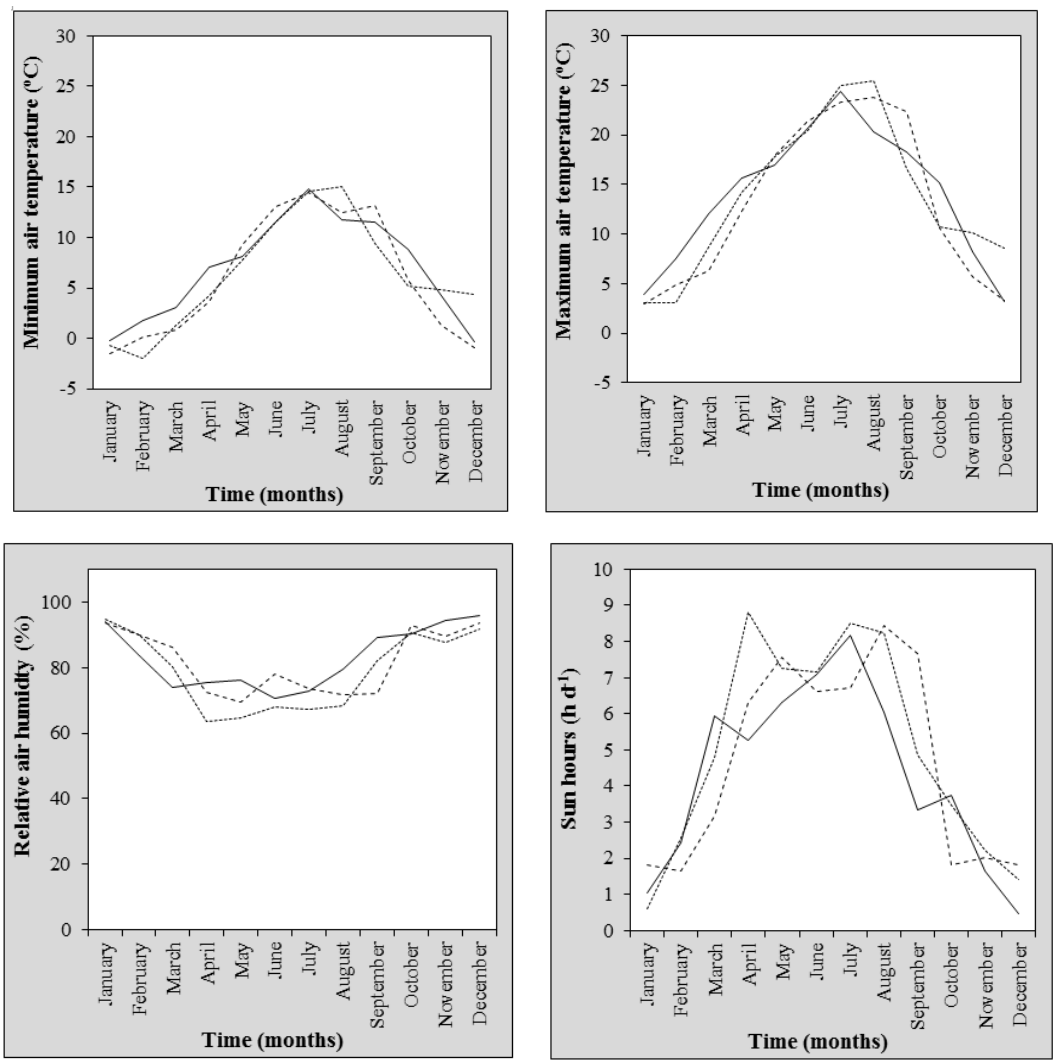
Descriptive statistics including the mean, standard deviation and coefficient of variation were used to describe the data set (Crawley, 2014; Field et al., 2012; Couto et al., 2013). A coefficient of variation lower than 10% was considered low (Couto et al., 2013). Whereas a medium coefficient of variation is between 10 and 20%, a high coefficient of variation between 20 and 30% and a very high variation is higher than 30% (Couto et al., 2013).

3 Results and discussions

3.1 Weather data

Figure 3 shows the monthly values of weather parameters from 2014 to 2016. The precipitation ranged from 576.5 mm in 2015 to 753.3 mm in 2014. The total precipitation in 2016 was 654.0 mm. The higher precipitation in 2014 was due to the precipitation volume registered in July, circa 237.6 mm. This value was 295% higher than the historical average for July, 60.1 mm (Deutsche Wetterdienst, 2017a).

The additional weather parameters showed a low variation among the years, totaling a mean annual minimum air temperature of 6.4°C; a mean maximum air temperature of 13.5°C; a mean relative air humidity of 81.3%; a mean sun hours of 4.6 hours day^{-1}; and a mean wind speed at 2 m height of 2.7 m s^{-1}. Higher sun hours, maximum and minimum air temperature were verified in summer months, whereas the relative air humidity and wind speed decreased in the summer (June, July and August), Figure 3.



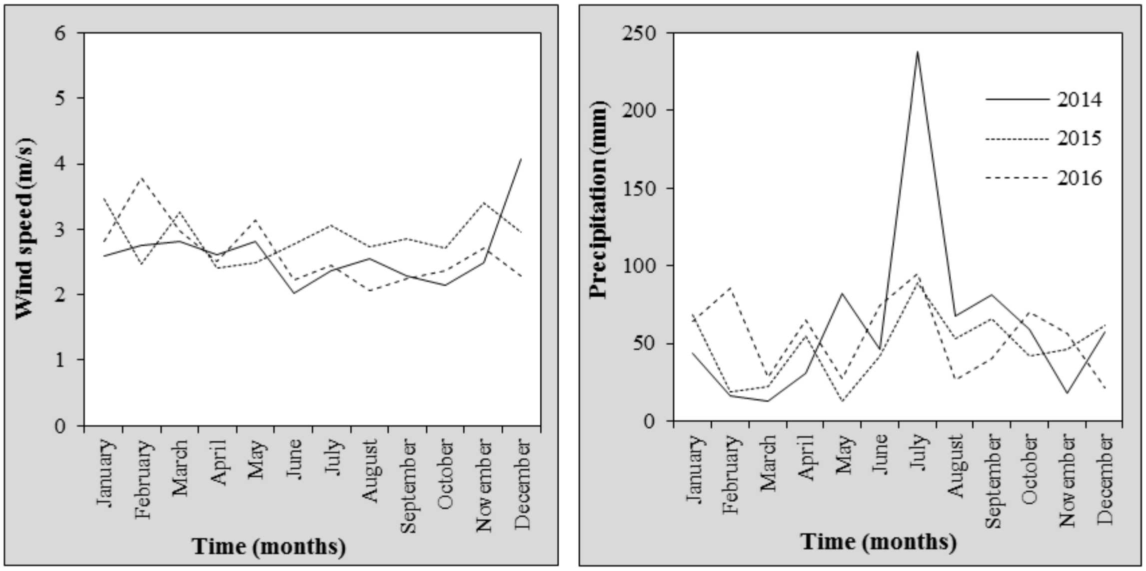


Figure 3 Minimum and maximum air temperature, relative air humidity, sun hours, wind speed and precipitation in the lysimeter experimental site during three calendar years

3.2 Crop evapotranspiration and water deficit

Table 2 shows the precipitation, effective precipitation, reference evapotranspiration, crop evapotranspiration, and water deficit for 2014, 2015 and 2016. These parameters were equal among the substrates because the same crop and weather parameters for substrates 1-4 were considered. Figure 4 presents the monthly values of effective precipitation, water deficit and crop evapotranspiration.

Table 2 Total precipitation, effective precipitation, reference evapotranspiration, crop evapotranspiration and water deficit of substrates 1 - 4 from 2014 to 2016 using CropWat at 10-day interval

©	P	P_{eff}	ET_o	ET_c	Water deficit	
	mm	mm	mm	mm	mm	%
2014	753.3	602.7	651.3	528.0	112.9	21.4
2015	576.5	461.2	735.9	734.1	387.6	52.8
2016	654.1	523.3	670.8	663.6	312.7	47.1
Mean	661.3	529.1	686.0	641.9	271.1	40.4
SD	88.6	70.9	44.3	104.7	142.0	16.7
CV	13.4	13.4	6.5	16.3	52.4	41.4

Note: P is the precipitation; P_{eff} is the effective precipitation; ET_o is the reference evapotranspiration; ET_c is the crop evapotranspiration; Water deficit is the P_{eff} - ET_c (10-days interval)©

The effective rain, consisting of 80% from the total precipitation was 602.7 mm in 2014, 461.2 mm in 2015 and 523.3 mm in 2016. The FAO reference evapotranspiration accounted for 651.3 mm in 2014, 735.9 mm in 2015 and 670.8 mm in 2016. Whereas the crop evapotranspiration estimated using the FAO two step approach, ET_o x K_c (Allen et al., 1998) was 528.0 mm in 2014, 734.1 mm in 2015, and 663.6 mm in 2016. The lower crop evapotranspiration in 2014 in relation to the reference evapotranspiration is due to the initial crop coefficient, 0.4, fixed to the initial growth of the vegetation, from January to March.

For the 10-day interval analyses, the water deficit was determined by the difference between effective precipitation and crop evapotranspiration (Harmsen et al., 2009; Bos et al., 2009). As these parameters changed according to the years, the water deficit consequently varied from 2014 to 2016, showing a minimum value in 2014, 112.9 mm (21.4% of crop evapotranspiration), and a maximum value in 2015 of 387.6 mm (52.8% of the ET_c). The highest water deficit was found in the spring and summer months, Figure 4. The water deficit in spring 2014 was 22.7 mm, whereas 146.4 mm was estimated in 2015 and 99.8 mm for the spring season in 2016. Summer months showed the highest water deficits, 88.0 mm in 2014, 229.5 mm in 2015 and 163.3 mm in 2016.

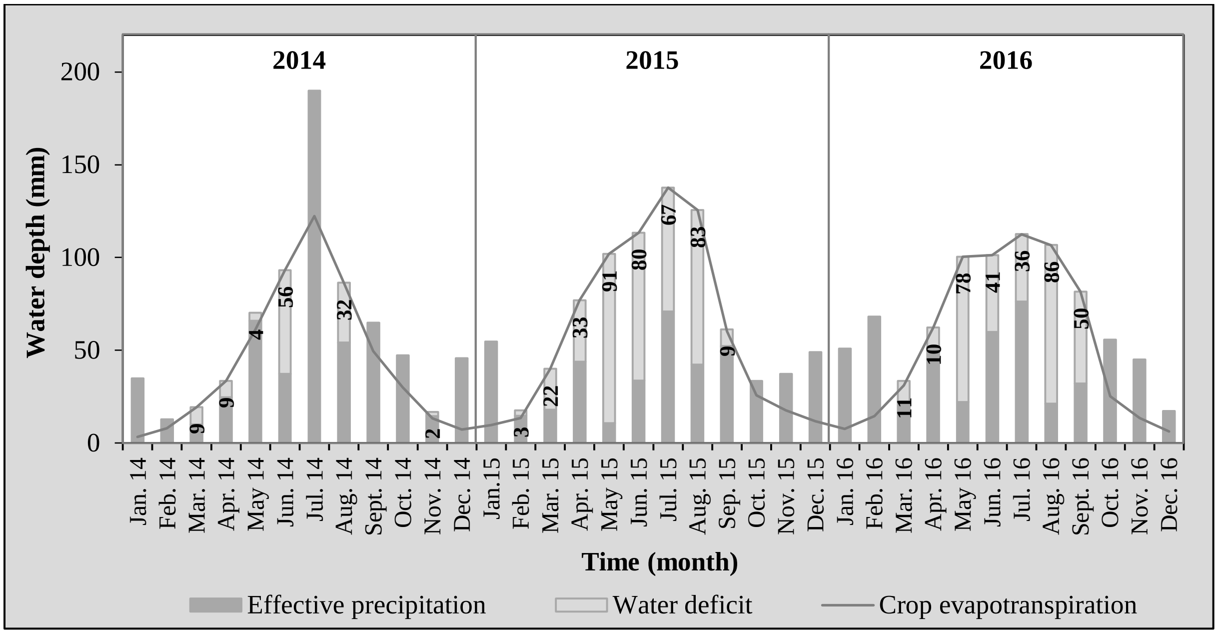
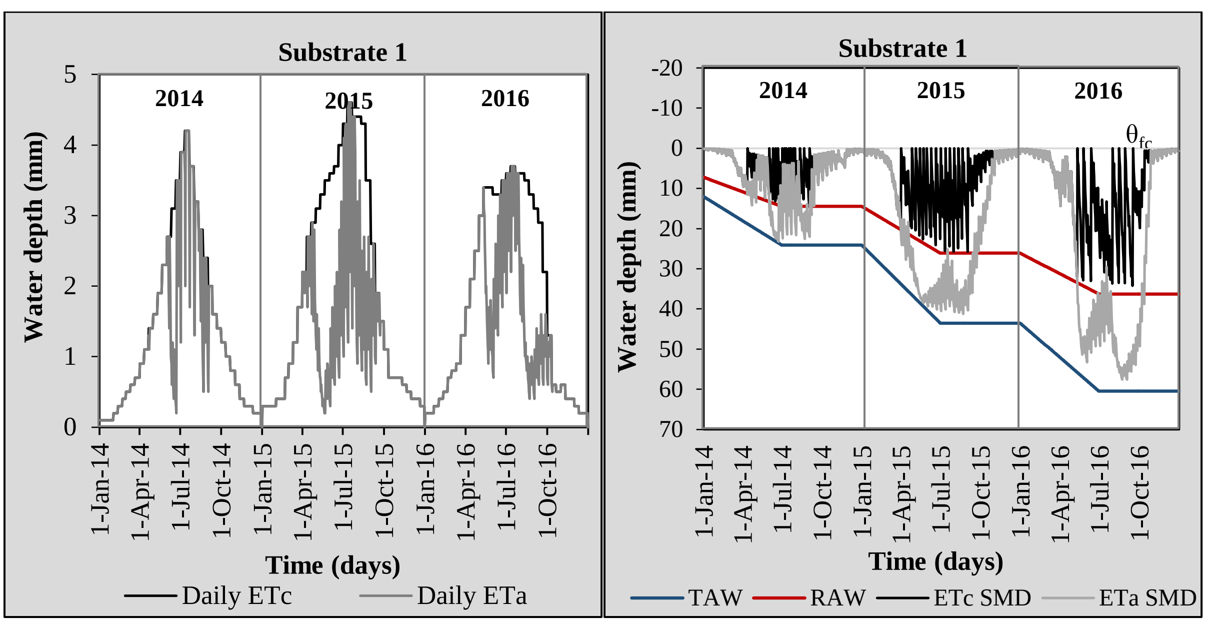


Figure 4 Effective precipitation, crop evapotranspiration and water deficit for substrates 1 - 4 during 2014, 2015 and 2016

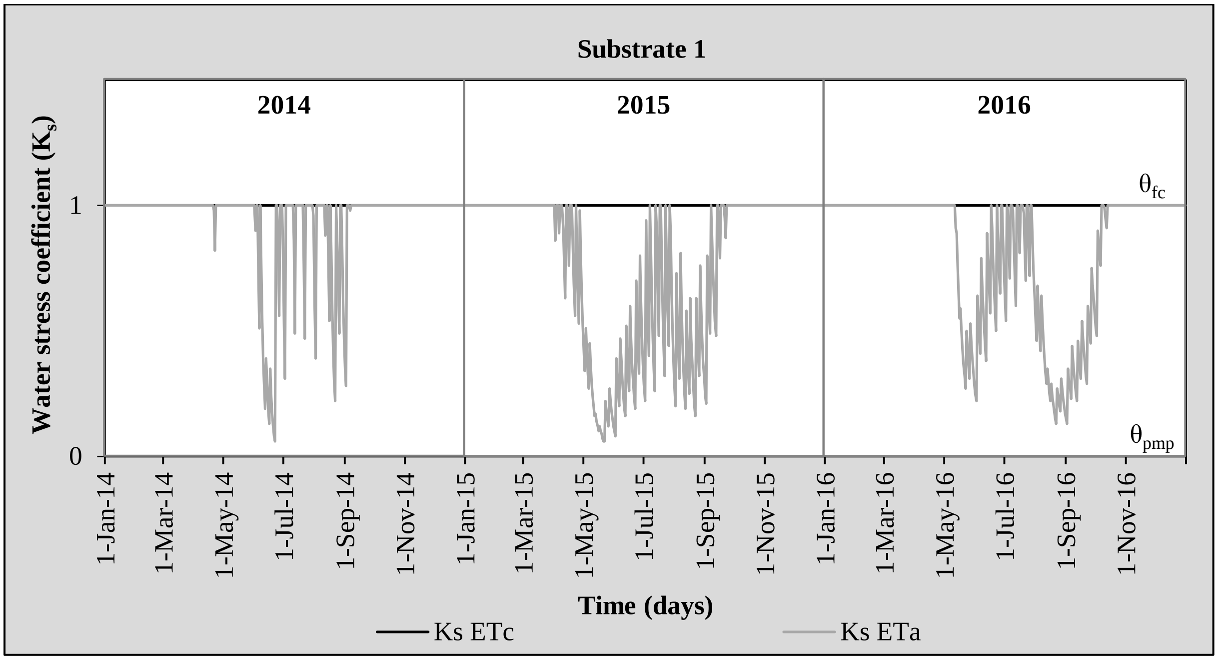
Note: Values within the columns refer to the water deficit of the respective month (mm). Water deficit = $P_{eff.}$ - ET_c (10-days interval)

Figure 5a shows the daily crop and the actual evapotranspiration of substrates 1-4 from 2014 to 2016. From Figure 5a, one can observe the crop and actual evapotranspiration were similar in November, December, January and February. However, during the growing season of the perennial grasses, approximately from March to October (Mueller et al., 2005) the actual evapotranspiration was lower than the crop evapotranspiration because the water consumption of the crops was below the ready available water (Figure 5b).

Figure 5b shows that under rainfed conditions (gray line) water depletion reached the lowest limit of the total available water (TAW) in the summer months. The lowest limit of TAW is the permanent wilting point (Ks = 0) and the highest is at field capacity (Ks = 1). Figure 5c presents the water stress coefficient, Ks, for substrate 1. The water stress coefficient of substrates 2-4 were similar to substrate 1.



(a) (b)



(c)

Figure 5 Different parameters under rainfed conditions for substrate 1 in 2014, 2015 and 2016

(a) Crop evapotranspiration and actual evapotranspiration under rainfed conditions for substrate 1 in 2014, 2015 and 2016. (b) Soil moisture depletion under optimum (ETc) and rainfed (ETa) conditions for substrate 1 during 2014, 2015 and 2016. (c) Water stress coefficient under optimum (Ks ETc) and rainfed (Ks ETa) conditions for substrate 1 in 2014, 2015 and 2016.

Note: θ_{fc}: Field capacity. θ_{pmp}: Permanent wilting point.

Table 3 Observed and estimated actual evapotranspiration (ET_a) and drainage (D) of substrates 1-4 from 2014 to 2016 at the lysimeter experimental site

Year	Observed				Estimated			
	ET_a		D		ET_a		D	
	mm	%	mm	%	mm	%	mm	%
2014	556.8 ± 11.5	73.9 ± 1.5	196.6 ± 11.5	26.1 ± 1.5	452.7 ± 3.1	60.1 ± 0.4	300.6 ± 3.1	39.9 ± 0.4
2015	360.7 ± 10.4	62.6 ± 1.8	215.8 ± 10.4	37.5 ± 1.8	435.1 ± 1.2	74.0 ± 3.0	141.4 ± 1.2	24.5 ± 0.2
2016	466.7 ± 11.5	71.4 ± 1.8	187.4 ± 11.5	28.6 ± 1.8	457.1 ± 1.8	69.9 ± 0.3	197.0 ± 1.8	30.4 ± 0.4
Mean	461.4	69.3	199.9	30.7	448.3	68.0	213.0	31.6
SD	98.1	6.0	14.5	6.0	11.7	7.2	80.8	7.8
CV	21.3	8.6	7.3	19.4	2.6	10.5	37.9	24.5

Table 4 Observed and estimated water deficit of substrates 1-4 from 2014 to 2016 at the lysimeter experimental site

Year	Water deficit			
	Observed		Estimated	
	mm	%	mm	%
2014	0.0 ± 0.0	0.0 ± 0.0	73.5 ± 3.1	14.0 ± 0.6
2015	373.0 ± 10.4	50.8 ± 1.4	298.6 ± 1.2	40.7 ± 0.2
2016	199.3 ± 11.5	29.3 ± 2.9	208.9 ± 1.8	31.4 ± 0.3
Mean	190.8	26.7	193.7	28.7
SD	186.6	25.5	113.3	13.6
CV	97.8	95.5	58.5	47.3

Under daily estimations, the crop evapotranspiration was 526.2 mm in 2014, 733.7 mm in 2015 and 666.0 in 2016. These values are similar to the crop evapotranspiration estimated using 10-day intervals (Table 2). The estimated actual evapotranspiration for substrates 1-4 was on average 452.7 mm in 2014, 435.1 mm in 2015 and 457.1 mm in 2016 (Table 3). The estimated actual evapotranspiration showed a low variation among the years (2.6%). The ratio estimated actual evapotranspiration to ground-level precipitation was 60.1% in 2014, 74.0% in

2015 and 69.9% in 2016 (Table 3). A low variation among the years (10.5%) was found for the estimated actual evapotranspiration to ground-level precipitation ratio.

With regards to the drainage, a mean value of 213.0 mm year^{-1} was estimated for substrates 1-4 (Table 3). This mean drainage represents circa 31.6% of the ground level precipitation over three calendar years (Table 3). Regarding the water deficit, a mean value of 73.5 mm was estimated in 2014 (14.0% of the crop evapotranspiration), 298.6 mm in 2015 (40.7% of the crop evapotranspiration) and 208.9 mm in 2016 (31.4% of the crop evapotranspiration). As expected, the lowest water deficit was estimated for the year with the highest amount of precipitation (2014) and the highest water deficit was projected for the year with the lowest precipitation level (2015). The mean water deficit over the three experimental years estimated using CropWat was 193.7 mm or 28.7% of the theoretical crop evapotranspiration (Table 4). The water deficit was estimated by the difference between the crop evapotranspiration and actual evapotranspiration (Doorenbos and Kassam, 1979).

A comparison between the observed and estimated actual evapotranspiration, drainage and water deficit considering the four different substrates is shown in Table 3 and Table 4.

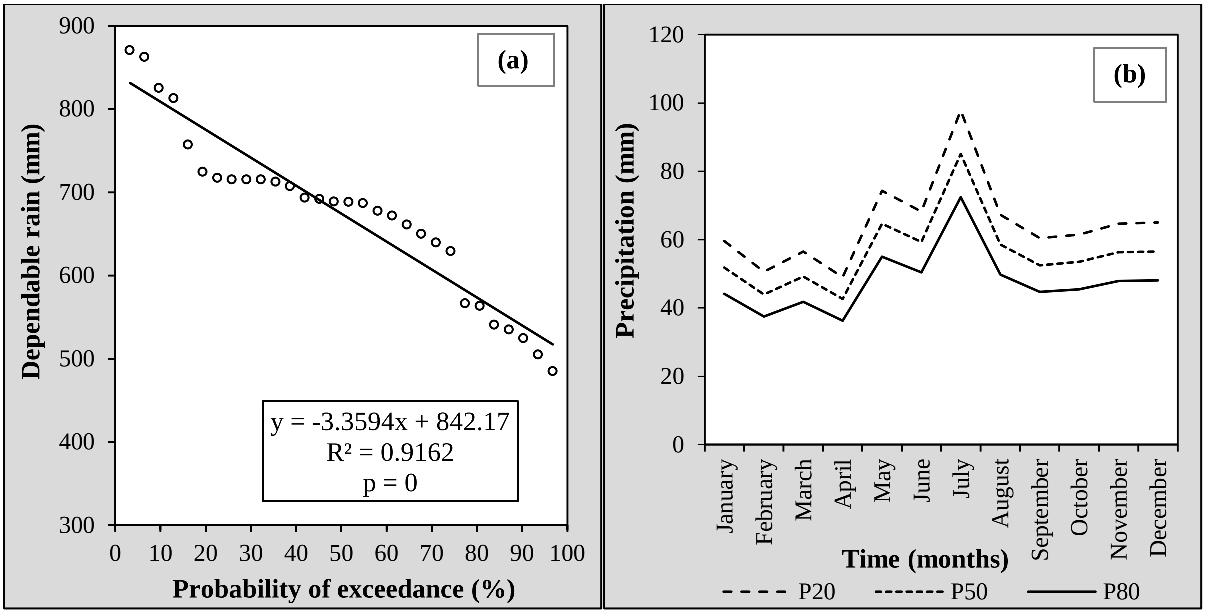
When studying the differences between CropWat and lysimeter actual evapotranspiration, the model underestimated the values under high precipitation values (2014) and overestimated under low precipitation depths (2015) in Table 3. However, for average precipitation (2016) the model precisely estimated the actual evapotranspiration. In dry years, the differences between predicted and indirect measurements of actual evapotranspiration can be associated with additional abiotic stresses beyond the water deficit. These additional factors are, for instance, the electrical conductivity or pH of the substrates. In years with high precipitation levels, the differences between predicted and indirect measurements of actual evapotranspiration may be related to the evapotranspiration capacity of the vegetation cover. The evapotranspiration of well-watered crops may exceed the unity crop coefficient fixed in the simulation using the CropWat model. The evaluation depth can also contribute for the differences between CropWat's estimated actual evapotranspiration and the lysimeters' assessments. The CropWat performed a daily water balance in the root zone and the lysimeters' measurements were carried out at 3.0 m depth. Overall, the mean drainage and water deficit were similar between the estimated and observed values from 2014 to 2016 (Table 3 and Table 4). The mean observed drainage was 199.9 mm year^{-1} (30.7% of the ground-level precipitation) and the mean observed water deficit was 190.8 mm year^{-1} (26.7% of the crop evapotranspiration).

3.3 Further simulations

Further simulations were performed to study the water deficit under different precipitation probabilities and crop coefficients. Figure 6 presents the precipitation depths of three precipitation probabilities considering a precipitation series of 30 years from Bad Hersfeld, located circa 20 km from the lysimeter experimental site.

For high precipitation levels with an exceedance probability of 20% (P20), the precipitation depth was 775 mm; whereas for a normal year (P50) the precipitation depth was circa 674.2 mm; and for a low precipitation level (P80), the precipitation depth was 573.4 mm. It is therefore possible to note the precipitation levels measured in 2014 (753.3 mm), 2015 (576.5 mm) and 2016 (654.1 mm) in Heringen, were close to high, low and normal precipitation levels respectively. Hence, in the three years of evaluation, the main water balance components of the evapotranspiration covers were evaluated under three different precipitation regimes. Even so the present simulations are valid because it considers the historical values of temperature, sun hours, wind speed and relative air humidity.

Regarding the weather conditions, an annual mean value for the minimum air temperature of 4.7^{o}C was found, 13.7^{o}C for the maximum air temperature, 4.0 h d^{-1} for the sun hours, 1.9 m s^{-1} for the wind speed, and 79.4% for the relative air humidity. These values are similar to those found in Heringen, except for the wind speed (mean 2.7 m s^{-1} in the lysimeter experiment), which can be a result of the differences in altitude.



(a) (b)

Figure 6 Precipitation depths and precipitation series of 30 years from Bad Hersfeld

(a) Probability of exceedance of the annual precipitation, points are the annual precipitations registered in Bad Hersfeld from 1987 to 2016 (30 calendar years). (b) Monthly precipitation according to different degrees of probability

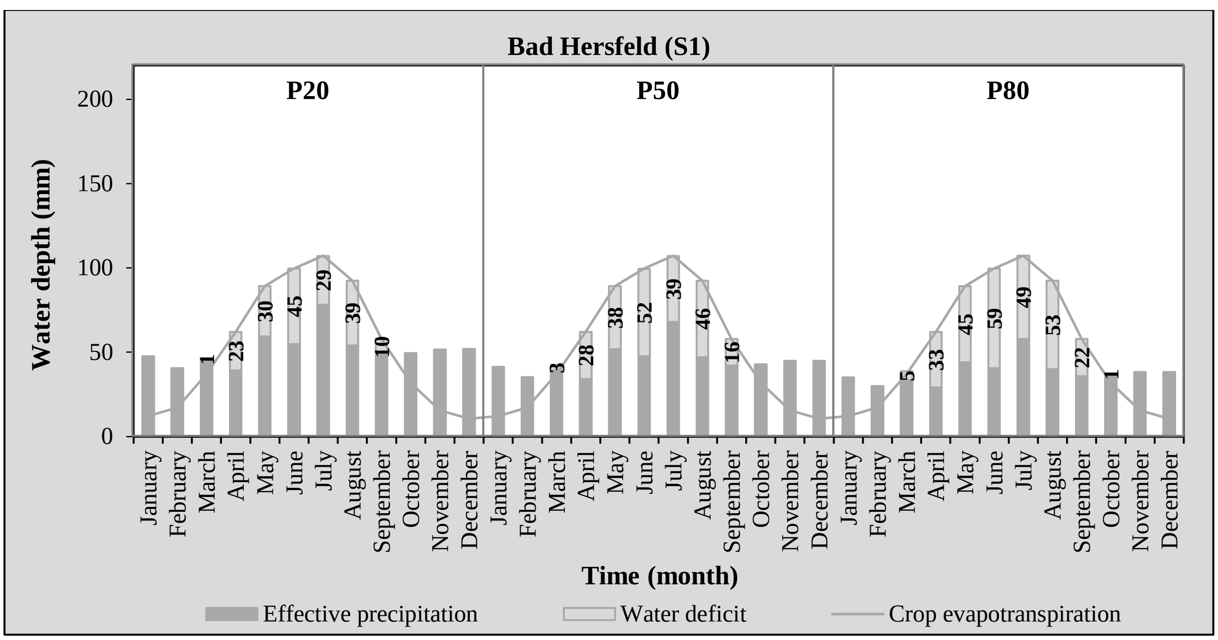
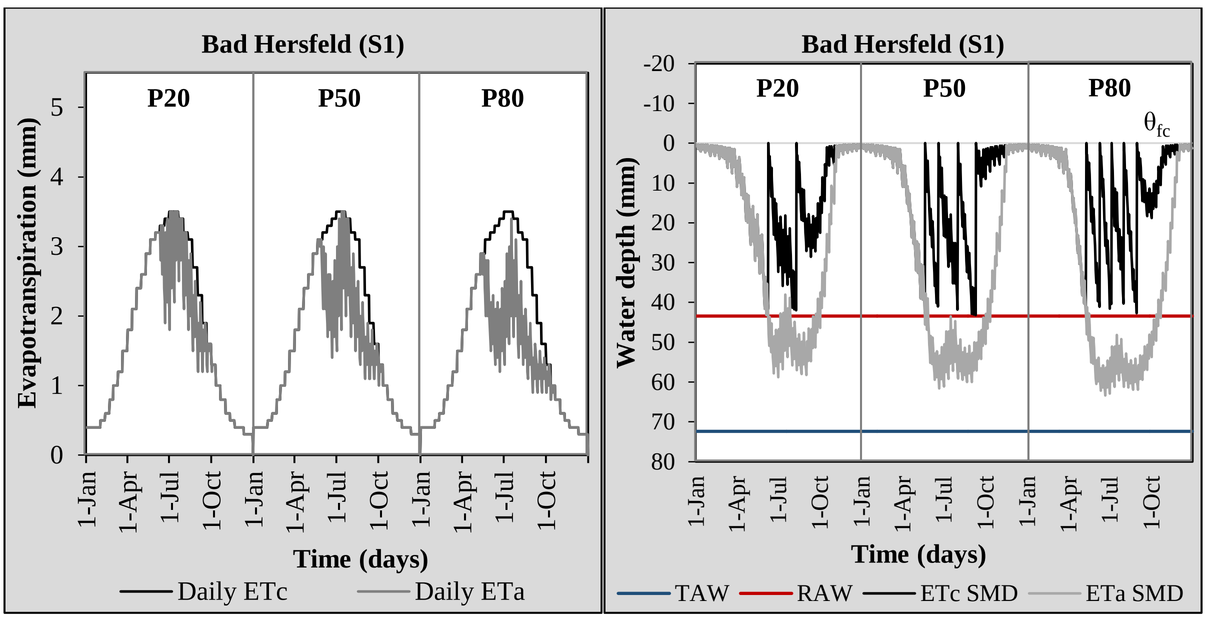


Figure 7 Effective precipitation, crop evapotranspiration and water deficit for a green cover under different precipitation probabilities, 20%, 50% and 80%, in substrate 1

Figure 7 shows the effective precipitation, crop evapotranspiration and water deficit considering different exceedance probabilities of the precipitation in Bad Hersfeld. The effective precipitation was 619.9 mm for a high precipitation depth (P20), 539.3 mm for a normal year (P50) and 458.8 mm for a low precipitation depth (P80). The crop evapotranspiration was equal among the years, 632.5 mm $year^{-1}$, because it is independent of the precipitation depths. Whereas the water deficit was 175.9 mm for P20, 221.3 mm for P50 and 276.5 mm P80. The water deficits occurred in the spring and summer. For P20, the spring water deficit was 54.0 mm, for P50 it was 68.8 mm and for P80 the spring water deficit was 83.3 mm. The summer water deficit for P20 was 112.4 mm, for a normal year 136.7 mm and for P80 the summer water deficit was 161.1 mm (Figure 7). Much like the observations in the lysimeter experimental field in Heringen, the water deficit increased from high annual precipitation depths to low precipitation depths.

Figure 8 shows that the daily actual evapotranspiration under rainfed conditions decreased when the precipitation decreased from high (P20) to low (P80) precipitation levels. Higher differences between crop evapotranspiration and actual evapotranspiration were found from June to October (Figure 8). The differences between crop and actual evapotranspiration resulted in an estimated water deficit of 8.7% for high precipitation levels, 16.6% for an average precipitation depth and 24.9% for low precipitation amounts.

With regards to the drainage, 198.9 mm of seepage was estimated under high precipitation depths (P20), 148.1 mm under a normal precipitation year and 99.8 mm under low precipitation levels. Totaling an actual evapotranspiration to precipitation ratio of 74.3% for P20, 78.0% for P50 and 82.6% for P80. These actual evapotranspiration rates represent the water consumption of a well-established crop (root depth 30 cm, crop height 30 cm) under high, normal and low precipitation levels.



(a) (b)

Figure 8 Crop evapotranspiration and water depth under different time

(a) Daily crop evapotranspiration and actual evapotranspiration for a green cover under different exceedance probabilities of the precipitation, 20%, 50% and 80% and substrate 1. (b) Soil moisture depletion for a green cover under optimum (ETc SMD) and rainfed conditions (ETa SMD) considering different exceedance probabilities of the precipitation and substrate 1

Note: θ_{fc}: Field capacity.

Figure 9 shows the effective precipitation, crop evapotranspiration and water deficit for a green cover under normal precipitation depths and different crop coefficients (K_c). As expected, it was observed that when using a constant precipitation (674.1 mm), effective precipitation (539.3 mm), reference evapotranspiration (641.0 mm), and different crop coefficients (0.4, 0.6, 0.8 and 1.0), different crop evapotranspiration depths were obtained, comprising 249.6 mm for a K_c of 0.4; 376.3 mm for a K_c of 0.6; 504.4 mm for a K_c 0.8; and 632.5 mm for a K_c of 1.0. This resulted in different water deficits ($P_{eff.} - ET_c$), 0.0 mm for a Kc of 0.4; 26.2 mm for a Kc of 0.6; 116.3 mm for a Kc of 0.8; and 221.3 mm for a Kc of 1.0. As previously observed, the water deficits were concentrated in the spring and summer months.

Figure 10 shows the daily crop and actual evapotranspiration for a green cover under normal precipitation depths and different crop coefficients. Figure 10b presents the water depletion in the root zone for a green cover under optimum and rainfed conditions considering normal precipitation depths and different crop coefficients for substrate 1. When considering the water deficit according to the different crop coefficients under daily soil water balance, the highest water deficit was estimated using a unity crop coefficient, 1.0, consisting of 16.6% (105.3 mm) of the crop evapotranspiration and the lowest was estimated using the crop coefficient of 0.4, corresponding to 0.0% of water deficit (0.0 mm).

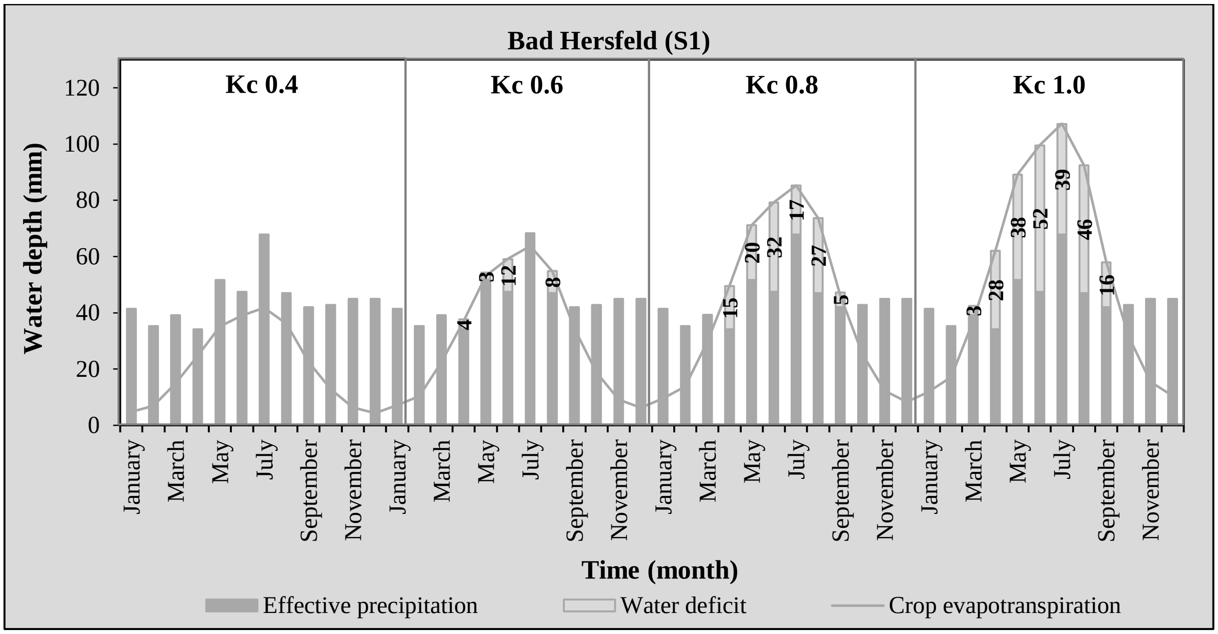
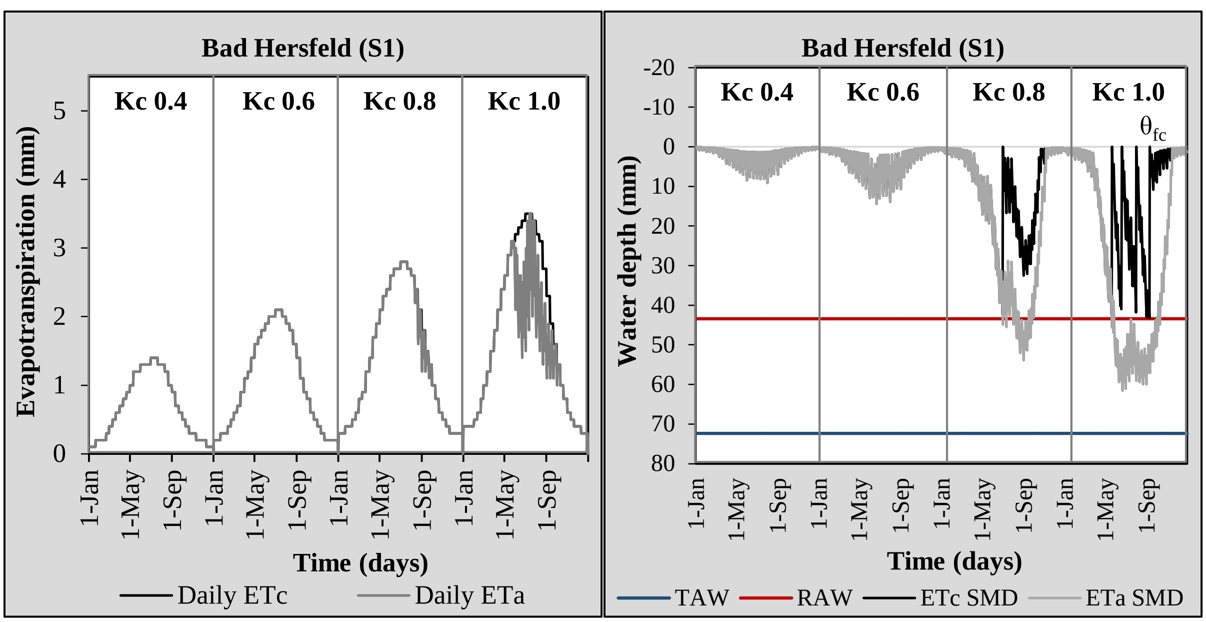


Figure 9 Effective precipitation, crop evapotranspiration and water deficit for a green cover under normal precipitation depths and different crop coefficients in substrate 1



(a) (b)

Figure 10 Crop evapotranspiration and water depth under different time

(a) Crop evapotranspiration and actual evapotranspiration of a green cover under normal precipitation depths and different crop coefficients in substrate 1. (b) Soil moisture depletion under optimum (ETc) and rainfed (ETa) condition for normal precipitation depths and different crop coefficients in substrate

Note: θ_{cc}: Field capacity.

The water deficit studied with 10-day (P_{eff}-ET_c) and daily intervals (ET_c-ET_a) provided different levels of water deficit for the evapotranspiration covers according to the year of evaluation, precipitation regimes, and crop coefficients. The values found in the present study are higher than the water deficit presented by Drastig et al. (2016) for Germany. The authors studied the irrigation requirements of different annual crops from 1902 to 2010. The authors found a mean water deficit of 112 mm year^{-1}, varying from 100 to 127 mm year^{-1}. These differences can be associated with the growing season of the perennial grasses and due to differences in weather parameters, such as precipitation, wind speed, solar radiation and temperature.

4 Conclusions

CropWat simulations were performed to study the water deficit of four evapotranspiration covers for a potash tailings pile located in Heringen, Germany, from 2014 to 2016. In addition, the results of the CropWat simulations were compared with a lysimeter experimental study. Further simulations were conducted using 30 years of historical weather data, different precipitation probabilities, 20%, 50%, and 80%; and crop coefficients, from 0.4-1.0.

Under daily estimations using CropWat model it was verified a water deficit of 14.4% of the crop evapotranspiration in 2014, 40.7% in 2015 and 31.4% in 2016. The mean water deficit over the three experimental years was 193.7 mm or 28.7% of the theoretical crop evapotranspiration. Whereas the annual water deficit observed from the lysimeters measurements was 0.0% in 2014, 50.8% in 2015 and 29.3% in 2016. On average from 2014 to 2016 the observed water deficit using lysimeter measurements was 26.7% of the crop evapotranspiration, which approximates of the CropWat results (28.7%).

When considering the different precipitations probabilities, it was found a water deficit of 8.7% for the high precipitation levels, 16.6% for an average precipitation and 24.9% for the low precipitation amount. For the water deficit according to the different crop coefficients, the highest water deficit was estimated using a unity crop coefficient, 1.0, consisting of 16.6% of the crop evapotranspiration.

Further observations of the CropWat model simulations revealed that the actual evapotranspiration and seepage depths on average approximated to the values observed in the field. The average estimated actual evapotranspiration using CropWat model from 2014 to 2016 was 448.3 mm and the measured actual evapotranspiration using lysimeters was 461.4 mm for the same period. Whereas the average estimated drainage using CropWat model was 213 mm and the observed measurement was 199.9 mm. The differences between the observed and the simulated values using CropWat can be associated with additional abiotic stresses and evaluation depths. For instance, the observed measurements of the lysimeter´s outflow were performed at 3.0 m deep, whereas the seepage estimated with CropWat was assessed on the effective root depth, 0.10 m in 2014, 0.18 in 2015 and 0.25 m depth in 2016.

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