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Full Length Research Paper

Simulation of water uptake and redistribution in growing media during ebb-and-flow irrigation

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To optimize ebb-and-flow irrigation on concrete floors, the relative importance of substrate type, flooding depth and flooding time on water uptake of growing media in containers is important information for the grower. Describing water uptake and distribution in the container with a dynamic simulation model may overcome the disadvantages of the static parameters such as container capacity and air capacity. Water uptake and redistribution was investigated for two different growing media, a coarse white peat and a fine seedling substrate, two flooding depths (1 and 4 cm) and three flooding durations (5, 10 and 15 min). The results were used to evaluate the use of the simulation model HYDRUS1D to describe water uptake and redistribution. The hydraulic functions water retention curve and hydraulic conductivity needed for the simulation model were determined in the laboratory. The results show that substrate properties and flooding height are the main parameters determining water uptake during ebb-and-flow irrigation while flooding time has a minor effect only. Therefore, the slope of concrete floors should be at a minimum to ensure an even flooding depth for all containers. The longer flooding times and the longer drainage durations have a very small effect on water uptake. The simulation model HYDRUS1D is able to describe water uptake and redistribution in containers filled with the two growing media sufficiently well only if the hysteresis of the water retention curve is taken into account.

Key words: Horticultural substrate, hysteresis, water retention curve, HYDRUS1D, simulation model.

INTRODUCTION

Ebb-and-Flow irrigation (also called flood and drain irrigation) is often used in horticultural practice to irrigate plant containers on concrete floors. Often, this irrigation method is more economic compared to flooded tables.

The depth of water during irrigation is usually 1 to 2 cm but can be as much as 5 cm (Aendekerk, 1997; Raviv and Lieth, 2008). It is very important that the irrigation water is distributed quickly and evenly to realize a rather uniform water level for all containers on the floor. The water is drained after about 10 to 20 min and collected in a storage tank (Raviv and Lieth, 2008).

It is known from practical experience that uneven water distribution in containers at different positions on a concrete floor happens frequently. One of the main reasons is the necessary slope of the concrete floor (0.2 to 0.4%) to realize quick drainage of water (Raviv and Lieth, 2008). Containers on a lower position will receive a higher irrigation depth and a longer irrigation time compared to containers at higher positions. This may result in either drought stress for the plants in some positions or too much moisture at others which may cause aeration and disease problems.

Other factors influencing water uptake and redistribution in plant containers are the shape of the container bottom, the type of plant and the physical properties of the growing media. The variability of the container bottom and that of the plant species on a concrete floor will be very low. Therefore, the influence of the physical properties of the growing media and that of different irrigation depths and irrigation durations will be investigated in this study.

The physical properties of growing media describing

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the quality of the substrate for different horticultural uses are usually measured at standard conditions, such as the container capacity and the air capacity, both measured at a matric potential of -10 hPa. These methods are standardized (DIN EN 13041, 2010) and are widely accepted. However, horticultural practice shows that in some situations producers have big problems related to low oxygen supply even with growing media with a high air and container capacity, while in other cases plants with good growth and quality are produced with substrates of minor quality. This is not surprising because the standard parameters describe a static condition whereas in horticultural practice we have a dynamic system where the actual water and air content fluctuates considerably with time mainly due to irrigation practices. Therefore, the use of methods to describe the dynamic behavior of water and air in growing media, such as simulation models, seem to be a promising tool to describe the actual situation in a container more realistically (Fonteno, 1993; Heinen and de Willigen, 1995; Palla et al., 2008).

The use of simulation models to calculate water uptake and redistribution in plant containers depending on irrigation depth, time and type of material could be a cost effective method. Computer models are frequently and effectively used to simulate water movement in mineral soils. Model applications for growing media are much less frequent and the quality of the simulation is usually less good compared to mineral soils. Possible reasons are shrinking and swelling processes and the hysteretic behavior of the hydraulic functions. Both processes are of much higher significance in growing media compared to mineral soils.

The objectives of this study were (1) to measure the water content and water uptake during ebb-and-flow irrigation for two different growing media depending on flooding depth and flooding duration, (2) to deduct proposals to optimize the shape of concrete floors used for ebb-and-flow irrigation, and (3) to test the application of the frequently used HYDRUS1D simulation model (Simunek et al., 2008) to describe water content and water uptake and redistribution in the two materials.

THEORETICAL BACKGROUND

Water retention curve

The physical properties of growing media are described with different specific values. However, the use of these values is not always consistently used in literature. In this study, we used the following definitions (De Boodt and Verdonck, 1972; Raviv and Lieth, 2008): total porosity (TP) (combined volume of the liquid and gaseous phase of the medium), air capacity (AC) (volumetric percentage of the medium filled with air at a matric potential of 10 hPa, that is, the difference of the water content at 10 hPa and the total porosity), container capacity (CC) (volumetric water content at 10 hPa), easily available water (EAW) (difference of the volumetric water content at 10 and 50 hPa) and the water buffering capacity (WBC) (difference of the volumetric water content at 50 and 100 hPa).

Basis for modeling the behavior of water in porous media is the media's pore structure, which is reflected in the water retention curve and the unsaturated hydraulic conductivity function. Both functions are necessary to simulate changes in the content and fluxes of water.

A commonly used parametric model to relate volumetric water content to the matric potential was proposed by van Genuchten (1980) and has been used in several studies on growing media (Fonteno, 1989; Jones and Or, 1998; Raviv et al., 2001; Caron and Nkongolo, 2004). This formulation is also implemented in the HYDRUS1D model:

$$\theta_\psi = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha \cdot \psi|^n\right)^m}$$

where θ_ψ is the water content at matric potential ψ, θ_r is a minimum residual water content, which is either fitted (Simunek et al., 2008) or used as the water content at 300 hPa (Raviv and Lieth, 2008), θ_s is the saturation water content (that is, the total porosity), α, n and m are parameters without a physical meaning describing the shape of the function where m is usually fixed as m=1-1/n (Simunek et al., 2008).

The parametric formulation of van Genuchten (1980) for the water retention curve can be used in combination with an equation of Mualem (1976) to describe the unsaturated hydraulic conductivity function (Simunek et al., 2008). This formulation is also implemented in the HYDRUS1D model:

$$K_\psi = K_s \cdot S_e^{\,l} \cdot \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2$$

where K_ψ is the hydraulic conductivity at matric potential ψ, K_s is the saturated hydraulic conductivity, S_e is the effective water content $((\theta-\theta_r)/(\theta_s-\theta_r))$, l is a parameter describing the pore structure of the soil, usually set to 0.5, and m is fixed as m=1-1/n (Simunek et al., 2008; Raviv and Lieth, 2008).

Hysteretic properties of the water retention curve

After drying usually a poor rewetting of growing media can be observed. Thus, the water content in the substrate by rewetting at a given matric potential will not reach its value measured during drying. This is due to air

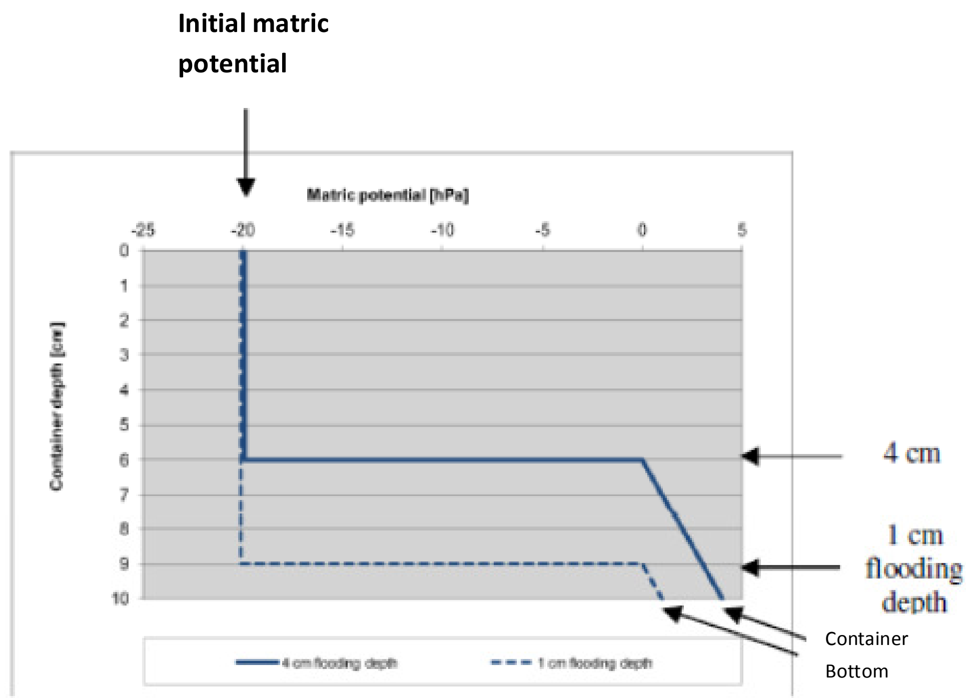


Figure 1. Initial conditions for the simulation (example for the seedling substrate).

inclusions or wetting problems of the organic material and is called hysteresis of the water retention curve (Raviv and Lieth, 2008). Hysteresis becomes especially important in irrigation systems where the water is applied from the bottom of the container, such as ebb-and-flow irrigation (Wever et al., 1997).

Applications of unsaturated flow models often assume unique, non-hysteretic functions for $\theta(\psi_m)$ and $K(\psi_m)$ to characterize the hydraulic properties of a material. Such a simplification may be acceptable for flow simulations in mineral soils; growing media usually require a more realistic description involving hysteresis in the soil hydraulic properties (Heinen and Raats, 1999; Naasz et al., 2005; Raviv and Lieth, 2008)

The procedure for modeling hysteresis in the retention function in the HYDRUS model requires that both the main drying and main wetting curves are known. θ_r, θ_s and n are assumed constant for the drying and wetting curves (Simunek et al., 2008). Thus, α is the only parameter to change when describing the main wetting and drying curves.

Simulation model, initial and boundary conditions

HYDRUS-1D is a software package for simulating water, heat and solute movement in one-dimensional variably saturated media (Simunek et al., 2008). The HYDRUS-1D program numerically solves the Richards' equation for variably-saturated water flow and convection-dispersion type equations for heat and solute transport. The program may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media.

The initial water content (or the matric potential) for all depths must be specified at the start of the simulation. For the flooding cycle, a matric potential corresponding to the measured initial water content was specified for the depths above the water surface (-20 hPa or 32 %vol and -5.000 hPa or 18.7 % vol for the seedling substrate and white peat, respectively). At the water surface during the flooding cycle (4 and 1 cm above the container bottom), a matric potential of 0 hPa was specified and at the container bottom a matric potential of +4 and +1 hPa respectively. Between the container bottom and the water surface, a linear interpolation of the matric potential was carried out (Figure 1).

For the drainage cycle, the simulated water content at the end of the flooding cycle was used as initial condition. For both, flooding and drainage cycle, a constant zero flux was used as upper boundary condition that is the assumption that there is no evaporation from the surface of the growing media:

$$q = 0 \qquad \text{at } h = 0 \text{ cm}$$

where q is the water flux and h is the height of the container counted positively downward. The lower boundary condition during the flooding cycle is a constant matric potential of zero at the water surface and of +4 hPa or +1 hPa at the bottom of the container for a flooding depth of 4 and 1 cm, respectively:

ψ_m = +4 hPa at h= 10 cm (for 4 cm flooding depth)

ψ_m = +1 hPa at h= 10 cm (for 1 cm flooding depth)

During the drainage cycle, the lower boundary condition changes to seepage face boundary condition: as long as the lower end of the container is saturated, the pressure head becomes zero and water may leave the container. If the matric potential becomes negative (unsaturated conditions), no more water may leave the container and the flux becomes zero. Thus, the boundary condition changes from a constant zero potential to a constant zero flux (Simunek et al., 2008).

ψ_m = 0 hPa at h= 10 cm (if $\theta \geq \theta_s$)

q = 0 at h= 10 cm (if $\psi_m < 0$)

Model quality evaluation

To evaluate the quality of the simulations with HYDRUS-1D different quality measures were applied: for a quick overview of the modeling quality, graphs measured against the simulated values were drawn together with the linear regression, the correlation coefficient and the 1:1 line. Without any model error, the measured and simulated values are identical and all points should lie on the 1:1 line. The points of good quality simulations should lie close to the 1:1 line, the slope of the linear regression should be close to one and the correlation coefficient should be close to one.

Numerical measures of agreement between the measured and simulated values were used as follows: a simple method to quantify the average difference between the measured and simulated values is the bias (Wallach, 2006):

$$bias = \frac{1}{N}\sum_{i=1}^{N}\left(X_i - P_i\right)$$

where N is the number of observations, X_i are the measured values and P_i the simulated (predicted) values. There should be no bias that is no over- or under-prediction of the values on an average. However, a bias close to zero is not sufficient to quantify model quality, because this could be also a result of a good prediction, or large over- and under-prediction may simply cancel each other.

A measure which avoids compensation between over- and under-prediction is the mean absolute error (MAE) (Wallach, 2006):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|\left(X_i - P_i\right)\right|$$

The MAE should be close to zero. Both bias and MAE have the same units as the measured and simulated data. A widely used measure of agreement between measured and simulated values is the root mean squared error (Wallach, 2006):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - P_i\right)^2}$$

The root mean square error (RMSE) also has the same units as the measured and simulated values. However, large differences are weighed much higher than small differences between measured and simulated values. A variant of the RMSE is the relative roots mean squared error (RRMSE), which is the RMSE divided by the average of the observed values (Wallach, 2006):

$$RRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - P_i\right)^2}}{X_{av}}$$

where X_{av} is the average of the measured X_i values. It is a meaningful measure to compare simulation quality of data with highly different averages and it is independent of the units used (for example, water content in $cm^3\,cm^{-3}$ or in %vol). To compare completely different data or different models, a widely used measure is the modeling efficiency (EF) (Wallach, 2006):

$$EF = 1 - \frac{\sum_{i=1}^{n}\left(X_i - P_i\right)^2}{\sum_{i=1}^{n}\left(X_i - X_{av}\right)^2}$$

EF calculates the advantage of model results compared to using one average value. If the model gives perfect results, the predicted values P_i will be equal to the measured values X_i and, thus, EF = 1. If the average of the measured values is used as a predictor for every case, EF = 0. A model which is a worse predictor than the average may result in EF < 0. A model with acceptable quality should have EF > 0.5.

MATERIALS AND METHODS

Experimental setup

The experimental container (Figure 2) is made of plastic with an inner diameter of 10 cm and is similar to a commercial 10 cm container. It is made up of six elements that can be put together

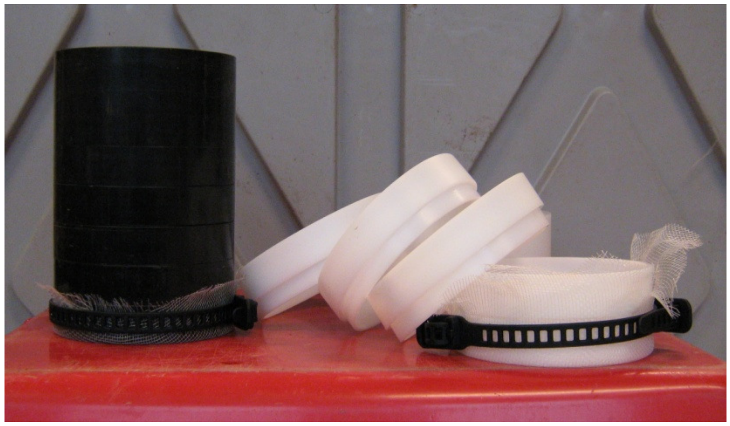


Figure 2. Experimental container with 10 cm inner diameter and 15 cm height.

Figure 3. Flooding tub with experimental containers.

similar to those used by Kritz and Khaled (1995). The total height is 15 cm, so that the shrinking of the substrate during irrigation and drying can be considered. The topmost ring is 5 cm high; the following five rings have a height of 2 cm each. The bottom of the container is replaced by a piece of gauze, which is stretched around the lower ring. The volume of the experimental container is 1.178 L. Three flooding times, two flooding depths and 3 drainage durations were used. This results in 36 treatments:

Flooding time: 1 = 5 min, 2 = 10 min, 3 = 15 min
Irrigation depth: 1 = 1 cm, 2 = 4 cm
Drainage duration: 1 = 10 min, 2 = 30 min, 3 = 90 min

The flooding depths and durations are selected according to usual practice. Each treatment is carried out in four replications. To replace for the greenhouse floor, a specially made flooding tub is used (Figure 3).

Growing media used in the study

Two types of substrate typically used in horticultural practice were chosen to carry out this investigation: Lithuanian white peat and a commercially available seedling substrate. The seedling substrate contains white peat, black peat and finely sieved cocos fiber. It is a substrate which is used specially for salinity sensitive ornamental seedlings in trays.

The properties of growing media also depend on the substrate charge and on storage conditions and duration. Therefore, the material was mixed from different original bags and stored airtight until the measurements.

The chemical properties of the substrates used in this study (EC, pH) were determined after DIN EN 13037 (2009) and DIN EN 13038 (2009). Organic matter was determined as ignition loss (DIN EN 13039, 2009): air dried and ground substrate samples are burnt at 550°C for 24 h in a muffle furnace. The residue is con-sidered as mineral material and the ignition loss as organic matter. Both are expressed as weight percent and related to dry matter content.

The particle size distribution of each substrate was determined using three 100 g oven dry samples. Each sample was placed on a series of 5 sieves (ranging from 4 to 0.5 mm) and shaken for 5 min at 160 shakes per min. Portions of substrate samples remaining on each screen were weighed and expressed as the percentage of total sample weight. The mean weight diameter (MWD) was calculated as;

Table 1. Some chemical properties of the studied materials and its mixes.

	pH	EC (mS/m)	DB (g/cm³)	DP (g/cm³)	OM (g/g)
White peat	3.9	10	0.130	1.57	0.969
Seedling substrate	5.5	25	0.139	1.63	0.886

pH (1:10); EC (1:10); DB, bulk density; DP, particle density; OM, organic matter.

Table 2. Particle size distribution of the two materials (mass fraction; g/g).

Material	> 40 (mm)	40-20 (mm)	20-10 (mm)	10-3.15 (mm)	3.15-2 (mm)	2-1 (mm)	1-0.063 (mm)	< 0.063 (mm)	MWD* (mm)
Seedling	0.0	0.0	0.5	3.8	7.5	18.9	67.3	2.0	1.15
Peat	0.0	3.3	16.4	25.0	8.9	11.0	33.5	2.0	5.65

*MWD, Mean weight diameter.

$$MWD=\sum_{i=1}^{n} x_i f_i$$

where x_i is the mass retained on the sieve divided by the total medium mass, f_i is the average particle size, and n is the number of classes (Kemper and Rosenau, 1986). Bulk density was determined after VDLUFA (1991). Particle density (DP) was estimated from the gravimetric organic matter content and the gravimetric mineral matter content (DIN EN 13041, 2010). The saturated hydraulic conductivity was determined with an Eijkelkamp constant head permeameter (DIN 19683, 1998).

Water retention drying curves were determined using an Eijkelkamp standard sand box apparatus (Gabriels and Verdonck, 1991; DIN EN 13041, 2010) to measure the water content at pF 0.7, 1.0, 1.5 and 2.0. The TP was calculated as TP = (1 – DB/DP), where DB is bulk density (g cm^{-3}) and DP is the particle density (g cm^{-3}). The water retention curve was parameterized after van Genuchten (1980) from total porosity and the volumetric water content at the measured pF values.

As growing media are known to show intensive hysteretic behavior, water retention wetting curves were determined with the above mentioned experimental container made up of six elements. The rings were filled with growing media with the same initial water content as in the experiments (-20 hPa or 32%vol and -5.000 hPa or 18.7%vol for the seedling substrate and white peat respectively) and the same bulk density, and a flooding depth of 1 cm was installed. Under the assumption that the water content at equilibrium is analogous to the water retention curve (Raviv and Lieth, 2008), the water content of the media in the rings 2, 4, 6, and 8 cm above the water surface will correspond to pF log(2) [pF 0.3], pF log(4) [pF 0.6], pF log(6) [pF 0.78], and pF log (8) [pF 0.9]. The water retention wetting curve was parameterized by adjusting the parameter α (Simunek et al., 2008). The other van-Genuchten parameters were the same as in the drying curve.

RESULTS

Properties of the growing media

Table 1 shows some basic properties of the studied materials. According to the particle size distribution of the studied materials (Table 2) the seedling substrate had a lower percentage of macro particles (> 2 mm; 11.8%), while the white peat had 53.6%. The mean weighted diameter was 1.15 mm for the seedling substrate and 5.65 for the white peat. Consequently, one can expect a higher percentage of small pores, more easily available water and lower air capacity of the seedling substrate compared to the white peat. This should also be reflected in the water retention curve.

Water retention curves

Major differences were observed in the water holding parameters of the two substrates (Table 3). The total porosity and the water buffering capacity were nearly equal. CC (0.88 and 0.71 cm^3 cm^{-3}) at 10 hPa and EAW (0.44 and 0.26 cm^3 cm^{-3}) was significantly higher in the seedling substrate compared to the peat, while the AC (0.03 and 0.21 cm^3 cm^{-3}) was significantly lower for the seedling substrate compared to the white peat. This agrees well with the particle size distribution which showed a high percentage of small particles in the seedling substrate compared to the peat. The measured saturated hydraulic conductivity was slightly lower in the seedling substrate compared to the peat which also agrees

Table 3. Physical properties of the two materials.

Material	Total porosity (TP) $cm^3\ cm^{-3}$	Container capacity (CC) $cm^3\ cm^{-3}$	Air capacity (AC) $cm^3\ cm^{-3}$	Easily avail. water (EAW) $cm^3\ cm^{-3}$	Water buffering capacity (WBC) $cm^3\ cm^{-3}$	Sat. hydraulic conductivity (Ks) $cm\ s^{-1}$
Seedling substr.	0.91	0.88	0.03	0.44	0.05	0.097
White peat	0.92	0.71	0.21	0.26	0.06	0.121

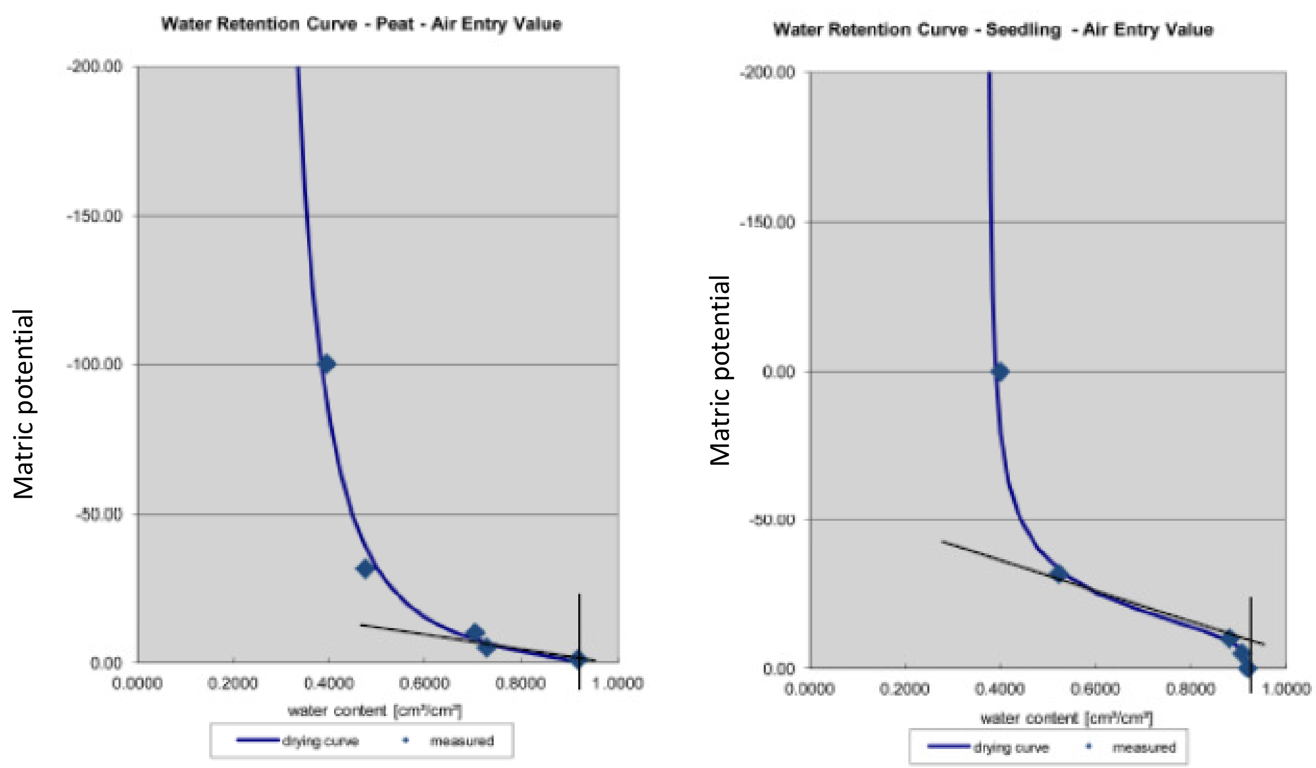


Figure 4. Drying water retention curves for the peat and the seedling substrate and the graphical determination of the air entry value.

with the smaller particle size.

Figure 4 shows the drying water retention curves for both media and the graphical determination of the air entry value (Konyai et al., 2009). The van-Genuchten parameters θ_r, α_w and n were fitted to the measured data by least square regression whereas θ_s was fixed as the water content at saturation. The van-Genuchten parameters and the air entry values are given in Table 3.

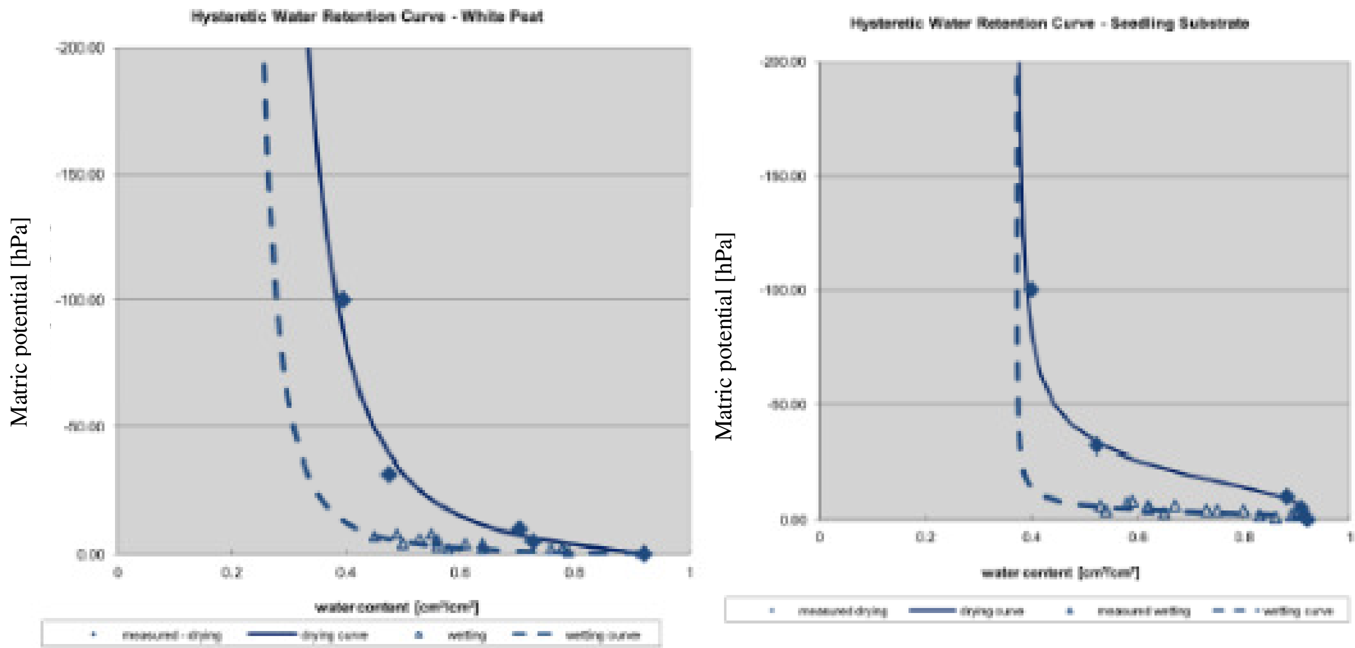


Figure 5. Water retention curves (drying and wetting curves) for the white peat and the seedling substrate.

Table 4. van-Genuchten parameters for the water retention drying and wetting curves for the peat and the seedling substrate.

Parameter	White Peat	Seedling substrate
θ_s [cm³ cm⁻³]	0.920	0.910
θ_r [cm³ cm⁻³]	0.187	0.373
α_d	0.232	0.055
α_w	1.600	0.320
α_d/α_w	6.90	5.82
n	1.411	3.022
Air entry value [hPa]	-1	-8

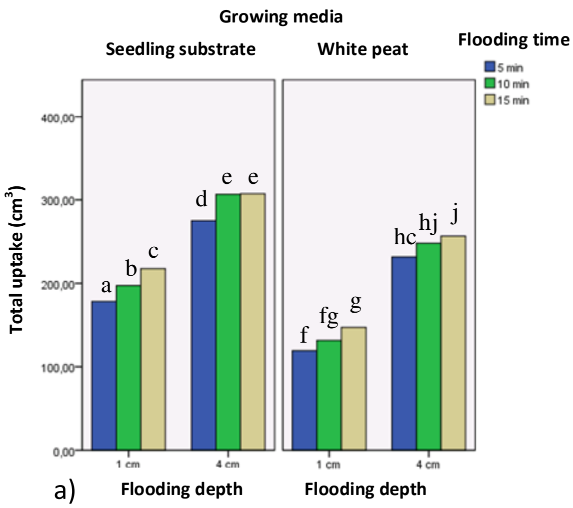
The air entry value characterizes the matric potential at which the largest pores drain during drying and air starts entering the material. The air entry value of the peat (-1 hPa) corresponds to a maximum pore size of approximate 3 mm (Hillel, 1998). The air entry value of the much finer seedling substrate (-8 hPa) corresponds to a maximum pore size of approximate 0.375 mm.

The residual water content θ_r of the van-Genuchten parameterization (0.37 and 0.19 cm^3 cm^{-3} for the seedling substrate and the peat respectively) also characterizes a much higher water content at low matric potentials and, thus, lower air content.

The wetting curves show a distinct hysteresis for both substrates (Figure 5). To describe hysteresis, the α values were fitted to the measured data by least square regression (Table 4). The parameter α_w describing the shape of the wetting curve was about 6 times larger than the parameter α_d describing the drying curve. The measured water content at high matric potentials (-5 to -10 hPa), where hysteresis shows its main effect, was about 20% higher for both growing media for the drying curve compared to the wetting curve. This corresponds well with investigations of hysteresis in peat substrates of other authors (Wever et al., 1997; Aendekerk, 1997).

Water uptake and redistribution

Figure 6a shows the measured water uptake for the two substrates, two flooding depths and the three flooding times. All factors have a statistically highly significant effect ($p < 0.01$) on the water uptake. The largest difference can be observed for the different flooding depths. The average water uptake is 198 and 132 cm³ for a flooding depth of 1 cm for the seedling substrate and the white peat, respectively, while the average water



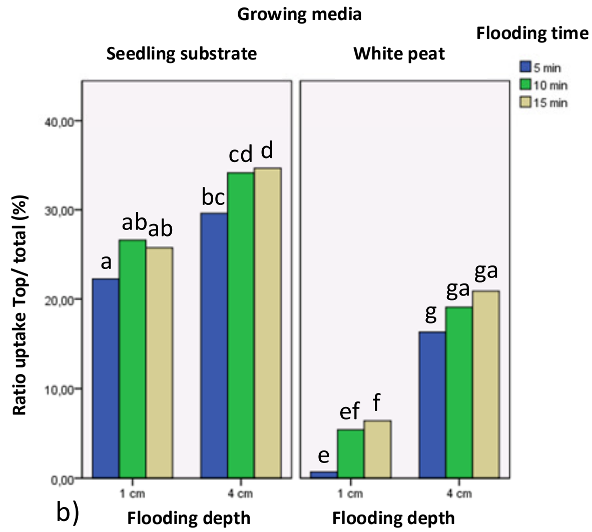


Figure 6. a) Total Water Uptake (cm³ per container) for flooding depth 1 and 4 cm and flooding time 5, 10 and 15 min for the two growing media; b) Ratio Water Uptake of the top half of the container to the total water uptake for flooding depth 1 and 4 cm and flooding time 5, 10 and 15 min for the two growing media. Different letters denote statistically significant differences.

uptake is 296 and 246 cm³ for a flooding depth of 4 cm. The influence of the substrate is high as well (average water uptake is 246 cm³ for the seedling substrate and 189 cm³ for the white peat respectively) while the effect of the different flooding times is much less pronounced (average water uptake is 201, 221 and 232 cm³ for 5, 10 and 15 min flooding time respectively). The differences of the water uptake after 10 and 15 min are statistically not significant (with the exception of seedling substrate, 1 cm flooding depth) indicating that the water uptake is a relatively fast process taking place mainly in the first 10 min.

The water uptake of the white peat at 4 cm flooding depth (246 cm³) is between that of the seedling substrate at 1 and 4 cm flooding depth (198 and 296 cm³ respectively). A similar water uptake as the white peat at 4 cm flooding depth can be expected at a depth of somewhere between 1 and 4 cm for the seedling substrate.

Figure 6b shows the ratio of the water uptake of the topmost 5 cm of growing media in relation to the total water uptake (10 cm height). 22 to 35% of the total water uptake goes to the upper half of the container filled with the seedling substrate whereas, this ratio is only 1 and 21% for the white peat. The effect of the different influence factors substrate, flooding depth and flooding time is similar to that for the total water uptake: all factors are statistically highly significant ($p < 0.01$); substrate and flooding depths show the highest effect whereas the influence of flooding time is less pronounced. There is no significant difference in the percentage of the water uptake of the topmost 5 cm in relation to the total water uptake after 10 and 15 min of flooding. This agrees well with the results of the total water uptake (water uptake occurs mainly in the first 10 minutes).

After the end of an irrigation cycle the redistribution of water through capillary rise from the bottom to the top of the container is expected. There is a slight but not significant tendency that the total water uptake will increase with time after the end of the irrigation (Figure 7a).

The ratio of the water uptake of the upper part of the container to the total water uptake is shown in Figure 7b. The increase of this ratio is negligible in the time period from 10 to 30 min, whereas there is a, however not significant, tendency, that this ratio will increase between 30 and 90 min after irrigation ends.

Simulation results

In a first step the water uptake and redistribution was simulated without taking hysteresis into account. Figure 8a and b show as an example the results of the simulation for 15 min flooding duration, flooding depth of 1 cm and a drainage time of 90 min. Obviously, the simulated water content is much higher than the measured one. In the bottommost layer, the simulated water content exceeds the measured by 10 to 20%vol. In the topmost layer, the simulated water content is about 40 to 50%vol higher than the simulated one. Thus, the model highly over-estimates the amount of water entering the substrate by capillary forces. This fact is also reflected in the drying and wetting water retention curves which differ significantly (Figure 5). To describe water content and water uptake correctly with the model, the hysteresis of the water retention curve must be taken into account.

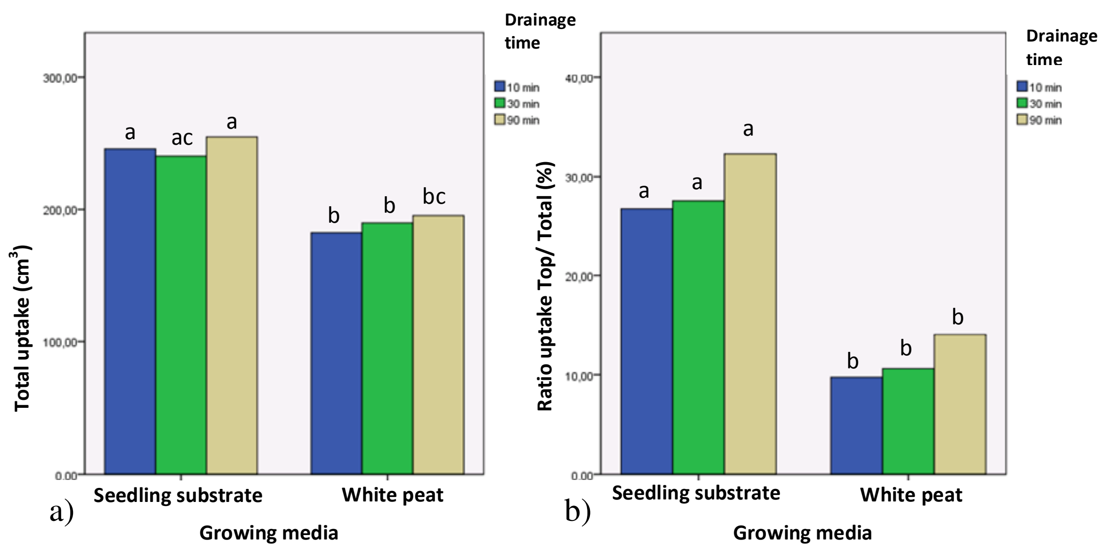


Figure 7. a) Total Water Uptake (cm³ per container) at 10, 30 and 90 min after the end of the irrigation cycle for the two growing media; b) ratio Water Uptake of the top half of the container to the total water uptake at 10, 30 and 90 min after the end of the irrigation cycle for the two growing media. Different letters denote statistically significant differences.

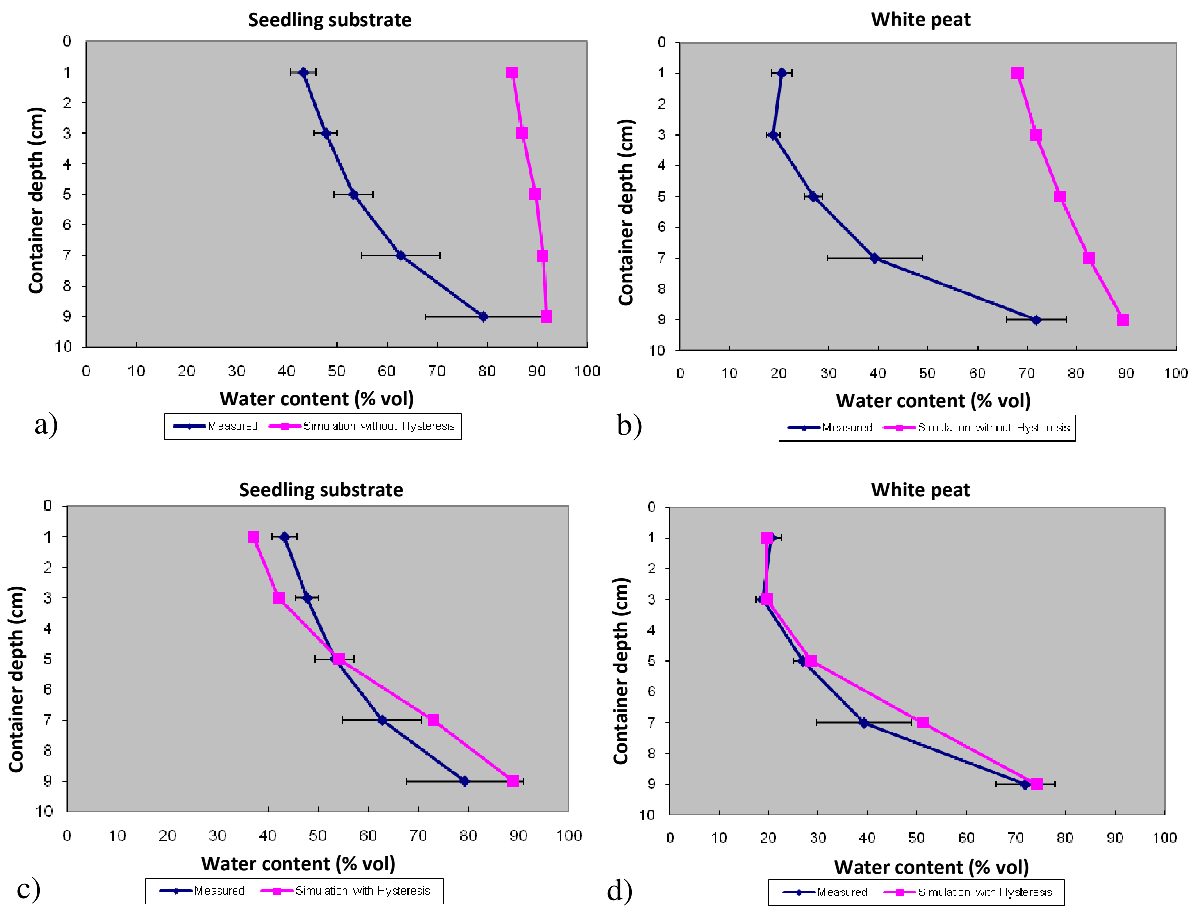


Figure 8. Water content (%vol) after 15 min of flooding, flooding depth 1 cm and after 90 min of drainage simulated without hysteresis (a, b) and with hysteresis (c, d) for the seedling substrate and the white peat.

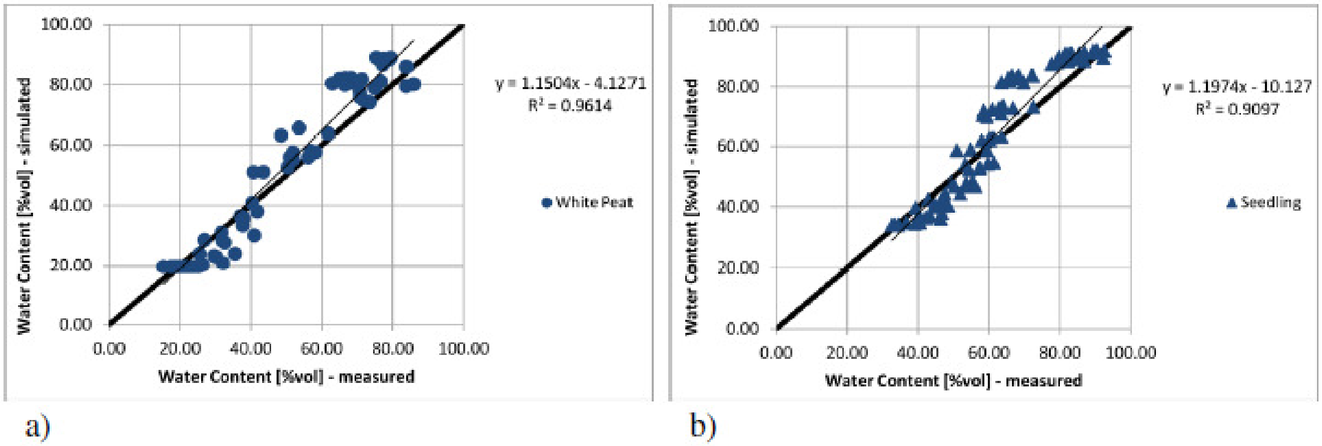


Figure 9. Measured against simulated water content (%vol) for the white peat (a) and the seedling substrate (b).

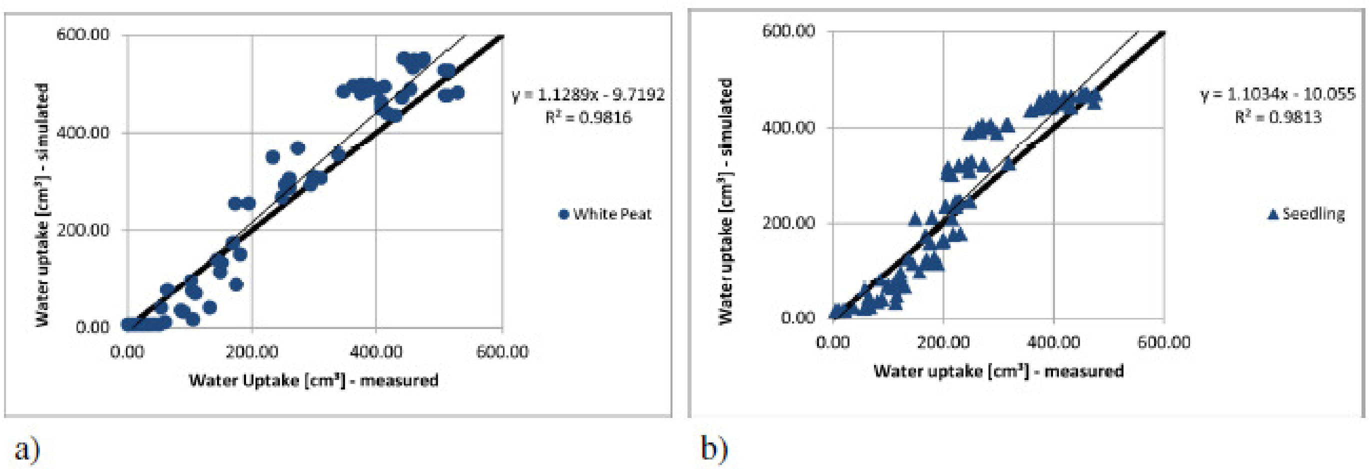


Figure 10. Measured against simulated water uptake (cm³) for the white peat (a) and the seedling substrate (b).

Considering hysteresis, the simulation yields a completely different picture (Figure 8c and d). Due to hysteresis, the water uptake into the initially relatively dry substrate during the flooding period is much smaller. The measured and simulated values agree much better. Therefore, the simulations for all cases measured were carried out using the hysteretic water retention curves.

The quality of the simulation was evaluated using the above mentioned quality measures. Figure 9 shows the measured against simulated water content for both growing media together with the 1:1 line. The correlation coefficient (0.96 and 0.91 for the white peat and seedling substrate respectively) is high. The slope of the regression line (1.15 and 1.20) however indicates that there is a tendency that the model under-estimates low values and over-estimates high values.

Similar but slightly better results can be seen for the water uptake (Figure 10), where the correlation coefficient is 0.98 and the slope is 1.13 and 1.10 for the white peat and seedling substrate, respectively.

Table 5 shows numerical quality measures for the simulation of the water content in the containers. For growing media and for flooding depths, there is a negative bias indicating that the simulated values are on an average 2.31 and 2.40 %vol higher for the seedling substrate and the white peat. This bias is less pronounced for the 1 cm flooding depth simulation compared to the 4 cm flooding depth. MAE and RMSE give similar results in that respect that the simulation quality for the 1 cm flooding depth is better than that for the 4 cm flooding depth, and that there are no big differences in the simulation quality between the two growing media investigated. The RRMSE ranges from about 10 to 17%. The modeling EF ranges from 0.70 to 0.97 indicating good to reasonable simulation quality.

Numerical quality measures for the simulation of the water uptake are given in Table 6. The maximum total water uptake for the different measurements in the

Table 5. Quality measures for the simulation of the water content.

measure	Seedling substrate			White peat		
	1 cm flooding depth	4 cm flooding depth	All	1 cm flooding depth	4 cm flooding depth	All
Bias (%vol)	-0.32	-4.30	-2.31	-0.36	-4.44	-2.40
MAE (%vol)	2.66	7.15	4.90	5.72	6.63	6.18
RMSE (%vol)	3.56	8.96	6.81	6.67	8.36	7.56
RRMSE (%)	10.01	17.91	13.63	11.66	11.99	10.84
EF	0.973	0.844	0.905	0.827	0.698	0.766

MAE, Mean absolute error; RMSE, root mean squared error; RRMSE, relative root mean squared error; EF, modeling efficiency.

Table 6. Quality measures for the simulation of the water uptake.

Measure	Seedling substrate			White peat		
	1 cm flooding depth	4 cm flooding depth	All	1 cm flooding depth	4 cm flooding depth	All
Bias (cm^3)	-12.65	-168.67	-90.66	-13.96	-174.24	-94.10
MAE (cm^3)	25.27	168.67	96.97	38.96	174.24	106.60
RMSE (cm^3)	35.88	187.64	135.09	53.61	182.60	134.57
RRMSE (%)	16.24	45.79	32.97	16.26	36.98	27.25
EF	0.994	0.948	0.958	0.994	0.966	0.975

MAE, Mean absolute error; RMSE, root mean squared error; RRMSE, relative root mean squared error; EF, modeling efficiency.

experimental containers is approximately 550 cm^3. The negative bias ranges from -12.7 to -174 cm^3 indicating that the simulated water uptake on an average over-estimates the measured water uptake. Similar to the simulation of the water content, the bias for the water uptake is less pronounced for the 1 cm flooding depth simulation compared to the 4 cm flooding depth. MAE and RMSE give similar results as for the simulated water content: the simulation quality for 1 cm flooding depth is better than for 4 cm flooding depth, and there are no big differences in the simulation quality between the two growing media. The RRMSE for the water uptake ranges from about 16 to 46%. The modeling EF is very high ranging from 0.95 to 0.99.

DISCUSSION

Water uptake and redistribution

The high water uptake of the seedling substrate shows its good ability for a capillary upward movement of irrigation water, but also the possible disadvantage of resulting low air contents. The white peat shows a distinctively different behavior due to its different physical properties. The results also show that a lower ability for an upward water movement in case of peat may be compensated by a higher irrigation depth.

After some time of cultivation, plants in containers usually have roots throughout the whole container. Right after planting, however, the availability of water in the top half of the container is important to secure the water supply of the plants. There is a tendency that the total water uptake will increase with time after the end of the irrigation. Obviously, after the flooding phase stopped and water drained from the concrete floor, there can be no more water uptake with time. A possible reason could be the fact, that right after water is removed at the end of the irrigation cycle some water is stored by capillary forces between the lower end of the container itself and the supporting surface. By removing the container to sample and determine the water content of the different layers, this amount of water will be left on the supporting surface. With longer time until sampling the containers, part of this water may enter the substrate by the higher capillary forces of the substrate. This may result in slightly, but statistically negligible increasing water contents after longer drainage times.

There is a tendency for a slight upward movement of water by capillary forces inside of the substrate in the container. However, this seems to be of very little importance leaving the substrate properties and the flooding height as the main parameters determining water uptake during ebb-and-flow irrigation.

Because the type of growing media used by horticultural producers is often determined by the type of cultivation and the production workflow, the results indicate that the main emphasis to optimize ebb-and-flow irrigation systems should be given to the flooding depth, while flooding time is of minor importance, at least for the growing media investigated in this study.

In practice, concrete floors have a slope of 0.2 to 0.4% to realize quick drainage of water. The results show however that flooding time is not important for water uptake but, apart from the physical properties of the media themselves, flooding depth is the main factor responsible for water uptake. A practical implication from the physical point of view for water uptake is that the slope of concrete floors should be at a minimum to ensure an even flooding depth for all containers. This however will result in longer flooding times, but they will have a very small effect on water uptake, and also longer drainage durations, which also have a negligible effect on water uptake. Possible negative effects of longer flooding times on higher susceptibility to plant diseases could be minimized by either the shape of the container bottom or by rills in the concrete floor similar to those used on flooded benches.

Simulation

The model highly over-estimates the amount of water entering the substrate by capillary forces. This fact is also reflected in the drying and wetting water retention curves which differ significantly. To describe water content and water uptake correctly with the model, the hysteresis of the water retention curve must be taken into account

During the flooding period, the model mainly used the wetting water retention curve, whereas during the drainage and redistribution phase, both curves and their connections were used in the lower parts of the container, the water content mainly decreased during drainage and redistribution resulting in the use of the drying curve whereas in the upper part of the container, some capillary rise of water takes place resulting in the use of the wetting curve.

Conclusions

Water uptake and redistribution during ebb-and-flow irrigation

The results of this study show that substrate properties and the flooding height are the main parameters determining water uptake during ebb-and-flow irrigation while flooding time has a small effect only. There is no significant change of the total water content in the time period after 10 min of drainage indicating that drainage is a fast process even in the seedling substrate with more fine pores compared to the white peat. This has several implications for optimizing ebb-and-flow irrigation: The physical properties of the growing media are very important factors to influence water content in the substrate. This is not surprising and is usually considered by horticultural producers who select an appropriate substrate suitable for the respective plant needs. Because flooding depth is the main factor responsible for water uptake and flooding time is not important, the slope of concrete floors should be at a minimum to ensure an even flooding depth for all containers.

Simulation with HYDRUS1D

The simulation results show that the simulation model HYDRUS1D is able to basically describe water uptake and redistribution in containers filled with the two growing media investigated. However, as these substrates show high hysteresis of the water retention curve, it is absolutely necessary that the model takes this hysteresis into account. The regression lines of the simulated against the measured values indicate that on average the higher water contents are slightly over-estimated whereas the lower water contents are under-estimated. A possible reason is that the hysteresis of the water retention curve is not described completely correct because this hysteresis mainly governs the water uptake and distribution in the container. The description of hysteresis is simplified in two aspects: 1) the wetting curve is described only by changing the parameter α of the van-Genuchten parameterization while the other parameters are kept constant. This is done because the HYDRUS1D version used has only this option to consider hysteresis while other authors suggest that hysteresis of growing media needs a more complex formulation (Naasz et al., 2005); 2) the determination of the wetting curve was done in a very simple way to measure the water content in different layers after water uptake took place and relating these values to the theoretical matric potential at equilibrium. This method should be evaluated and optimized in future investigations. However, the use of HYDRUS1D seems to be a promising method to overcome the pure static description of physical properties of growing media, such as available water capacity and air capacity, towards a dynamic description of the water movement in containers with the ultimate goal to optimize the production of horticultural plants produced in growing media.

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