Dynamics of water and nutrients for potted plants induced by flooded bench fertigation: experiments and simulation.

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Dynamics of water and nutrients for potted plants induced by flooded bench fertigation: experiments and simulation

Proefschrift
ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
dr. C. M. Karssen,
in het openbaar te verdedigen
op dinsdag 22 november 1994
des namiddags te vier uur in de Aula
van de Landbouwuniversiteit te Wageningen

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Otten, Wilfred

Dynamics of water and nutrients for potted plants induced
by flooded bench fertigation : experiments and simulation
/ Wilfred Otten. - [S.1]. - I11.
Thesis Wageningen. - With ref. - With summary in Dutch.
ISBN 90-5485-304-2
Subject headings: potted plants ; fertigation.

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STELLINGEN.

1. Een waterretentiekarakteristiek bepaald door uitdroging na verzadiging, zoals bij karakterisering van substraten meestal plaatsvindt, geeft geen goede weergave van de relatie tussen drukhoogte en volumetrisch vochtgehalte zoals die zich bij een eb/vloed-teeltsysteem voordoet.
Dit proefschrift

2. De huidige bemestingsadviesbasis houdt onvoldoende rekening met de dynamiek en ruimtelijke verdeling van voedingsstoffen in substraten.
I.K.C. 1991 Bemestingsadviesbasis Glastuinbouw.
Dit proefschrift

3. Gezien de beperkte beheersbaarheid van de voedingstoestand van potplanten met een eb/vloed-fertigatiesysteem, is dit, vanuit bemestingsoptiek, niet het meest geschikte teeltsysteem.
Dit proefschrift

4. Bij eb/vloed-fertigatie zeggen frequentie, vloedduur en EC van de voedingsoplossing op zich weinig over de hoeveelheid water en voedingsstoffen die aan de plant worden toegediend.
Dit proefschrift

5. A model user should have enough experience to tell when model simulations are nonsense and when they are reasonable. Thus models are not substitutes for experience, but rather a tool to use with experience.
R. J. Hanks and J. T. Ritchie (eds.) 1991. Modeling plant and soil systems. Agronomy no. 31.

6. Simulatie van lokale accumulatie van zouten wordt in sterke mate bepaald door een accumulatie van fouten.
Dit proefschrift

7. Gaten in een nutriëntenbalans lijken dermate geaccepteerd dat een verklaring gegeven moet worden voor een sluitende balans.

8. Diverse onderzoeksinstellingen zien elkaar te veel als concurrent waardoor de opzet van projecten veeleer wordt beperkt door de mogelijkheden van de betreffende instelling dan door die van het onderzoekapparaat als geheel.

9. Automatisering van gegevens van uitkerende instanties leidt er helaas veelal toe dat fouten sneller worden gemaakt en hardnekkiger worden ontkend.

10. Veel sensoren in de tuinbouw worden gebruikt om het gevoel van de tuinder te digitaliseren.

11. Projecten worden steeds vaker goed afgerond dankzij de inzet van vrije tijd van de onderzoekers.

12. Gecomprimeerd werken ter reductie van het woon-werk verkeer leidt tot meer files richting Zandvoort.

13. Een goede spreker heeft meer toehoorders dan sheets.

Stellingen behorende bij het proefschrift 'Dynamics of water and nutrients for potted plants induced by flooded bench fertigation: experiments and simulation' van Wilfred Otten, 22 november 1994, Wageningen.

Abstract

Otten, W., 1994. Dynamics of water and nutrients for potted plants induced by a flooded bench fertigation system: experiments and simulation. Doctoral thesis, Agricultural University Wageningen, Wageningen, The Netherlands, 115 p.; English and Dutch summaries.

Dynamics of water and nutrients as affected by physical and chemical characteristics of a substrate, fertigation method and schedule, and plant uptake were studied for a flooded bench fertigation system for potted plants, through a detailed experimental study of the root environment and a simulation model.

Based on analogy with soils, a summary is given of the theory which describes the dynamics of water and nutrients in horticultural substrates. Existing simulation models based on this theory, so far mainly tested for field soils, were adapted to the flooded bench fertigation system. The model comprises three submodels: 1) one-dimensional vertical water transport, accounting for hysteresis, allocation of water uptake over depth, and conical shape of the pot, 2) solute transport, and 3) chemical equilibration accounting for cation adsorption and precipitation. The model requires evapotranspiration as a forcing function.

For a potting medium consisting of peat and perlite, physical characterization is discussed. Characterization dealt with the water retention characteristic, including hysteresis and the effect of repeated wetting and drying, and the hydraulic conductivity characteristic. Mathematical equations, frequently applied for description of physical characteristics of soils, were used to describe the physical characteristics of the potting medium. Cation adsorption of the potting medium was found to be affected by pH. A cation adsorption model is presented to calculate the composition of the adsorption complex in relation to the composition of the liquid phase.

Transpiration of *Ficus benjamina* and evaporation from the potting medium are discussed with respect to fertigation schedule. Using tensiometers, dynamics of water induced by fertigation of given frequencies and durations and by evapotranspiration were measured. Nutrient balances and vertical distributions were studied for different fertigation schedules. These data were mainly used for validation of the simulation model.

The simulation model gave a fair description of the measured data. The volumetric water content in relation to fertigation schedule and measured matric head profiles between fertigations could be understood by studying the dynamic behaviour of the model. Hysteresis in the water retention characteristic significantly influenced the dynamics of water. Vertical distribution of cations was strongly affected by cation adsorption. The combined use of the experiments and the model deepened the understanding of the complicated interactions between evapotranspiration, fertigation schedule, physical and chemical characteristics of the potting medium, and geometry of the pot, in particular the height. It was concluded that considering one of these factors separate from the others is not advisable, since they are all important.

Additional index words: simulation, water transport, water retention, hydraulic conductivity, hysteresis, solute transport, tensiometer, matric head, cation adsorption, EC, accumulation of nutrients, nutrient balance, potted plant, flooded bench fertigation, evaporation, transpiration, peat, perlite, *Ficus benjamina*.

Voorwoord

Het doet mij een genoegen dit voorwoord te schrijven. Niet het minst omdat aan het schrijfwerk van dit proefschrift hiermee een einde is gekomen, maar zeker ook omdat het mij de gelegenheid geeft om de vele mensen te bedanken die een bijdrage hebben geleverd aan het tot stand komen daarvan. Een aantal wil ik met name noemen.

In het bijzonder wil ik Hugo Challa (LUW, tuinbouwplantenteelt) en Pieter Raats (AB-DLO) bedanken voor hun bereidheid als promotoren op te treden. Ik dank hen voor de vele gesprekken over voortgang, moeilijkheden, en resultaten van het onderzoek, en de kritische en opbouwende opmerkingen bij het concept-proefschrift. Het enthousiasme van met name Pieter Raats voor dit werk is voor mij een enorme stimulans geweest.

Daarnaast hebben nog twee leden van de begeleidingscommissie een zeer belangrijke bijdrage geleverd aan dit proefschrift. Pavel Kabat van het SC-DLO, wil ik bedanken voor zijn kritische beschouwingen van het proefschrift, en voor de vele discussies omtrent karakterisering van substraten en modellering van transport processen. Rob Baas wil ik bedanken voor de begeleiding van vooral het experimentele werk op het Proefstation voor de Bloemisterij. Zijn vele suggesties bij de proefopzet, bij de interpretatie van de gegevens, en zijn opmerkingen bij het concept-proefschrift waren een waardevolle bijdrage.

Bij de werkzaamheden van dit proefschrift is samengewerkt met collega's van een viertal instituten. Bestuur en directie van het AB-DLO, voorheen IB, wil ik bedanken voor mijn aanstelling als DLO-AIO voor een periode van vier jaar, en voor de verlenging van drie maanden na afloop van deze periode. Daarnaast hebben medewerkers van het AB-DLO een belangrijke bijdrage geleverd aan dit proefschrift. Gedurende mijn stationering op het AB-DLO in de beginfase van dit project, vormden discussies met vele collega's de basis voor dit proefschrift. Met name wil ik danken Marius Heinen en Bram de Vos voor hun waardevolle suggesties. Jan Zwiers voerde veel van de fysische karakteriseringen uit. Medewerkers van het analytisch laboratorium wil ik bedanken voor de vele grondmonsters die zij hebben geanalyseerd, en ook Derk Blaauw voor zijn ondersteuning bij het verkrijgen van het bodemvocht uit de potgrondmonsters.

Van de medewerkers van het SC-DLO ben ik veel dank verschuldigd aan Jan Elbers. Vele uren werk heeft hij gestoken in de constructie en ijking van de tensiometers welke onmisbaar waren bij dit onderzoek. Rob Hendriks, Piet Veerman, en Junt Halbertsma wil ik met name bedanken voor hun ondersteuning bij de fysische karakterisering van de potgrond. Daarnaast wil ik de vele (anonieme) medewerkers bedanken die een bijdrage hebben geleverd aan de modellen waarvan ik bij deze studie dankbaar gebruik heb gemaakt.

Het grootste deel van de tijd ben ik gestationeerd geweest op het Proefstation voor de Bloemisterij, waar een belangrijk deel van het experimentele werk werd uitgevoerd. Medewerkers van de Technische Dienst wil ik bedanken voor de vele meters kabels die zij in de kassen aanbrachten voor het aansluiten van een meetnet. De Teelttechnische Dienst wil ik bedanken voor de verzorging van de proeven en de ondersteuning bij het verrichten van de waarnemingen. Met name geldt dit voor Klaas van Dam, voor gewasverzorging gedurende de eerste proeven, voor Jacques van Zoest, voor de gewasverzorging gedurende het laatste experiment, en voor Ton van der Wurff voor de vele wegingen en gewasmetingen. Mary Warmenhoven en Nico Straver ben ik dankbaar voor de vele analyses van voedingsoplossingen, bodemvocht en gewas. Frits Steinbuch en René de Koster dank

ik voor de automatisering van de metingen en de ondersteuning bij het werken op de VAX-computer en PC. De medewerkers van de afdeling Algemene Zaken dank ik voor hun vaak onzichtbare, maar belangrijke bijdrage aan dit werk. Alle overige medewerkers worden bedankt voor hun bijdrage aan dit werk en voor de plezierige werksfeer die ik gedurende dit onderzoek heb ondervonden. De sociale contacten gedurende de koffiepauzes waren een welkome onderbreking van het "kluizenaarsbestaan" aan de Kastanjelaan gedurende het schrijfwerk van dit proefschrift.

Medewerkers van de vakgroep Tuinbouwplantenteelt wil ik bedanken voor hun steun bij het tot stand komen van dit proefschrift. Met name de leden van het "OMO-clubje" onder leiding van Hugo Challa voor hun suggesties, en voor de bereidheid om het onderzoek, dat vaak ver van hun eigen specialisme af lag, te volgen.

Mijn ouders wil ik bedanken voor de gelegenheid die zij mij gaven om te studeren, en voor de interesse die zij altijd hebben getoond. Het is een enorme steun geweest te weten dat je bij problemen altijd op hen terug kon vallen.

Tenslotte wil ik Els bedanken voor het geduld en het vertrouwen in een goede afloop in de periode waarin het onderzoek werd uitgevoerd en in de daarop volgende periode waarin het proefschrift werd geschreven. Els, en onze beide kinderen Lucienne en Lesley, hebben mij onevenredig moeten delen met mijn werk, met als dieptepunt het missen van de geboorte van Lucienne.

Zonder de steun van al deze mensen, en de velen die hier niet met naam genoemd zijn, was ik misschien nog wel aan dit proefschrift begonnen, maar had ik het zeker niet afgemaakt. Bedankt.

Contents

1. General introduction

Composition of horticultural media and fertilization techniques went through enormous changes recently. Forced by more stringent environmental regulations, there is an increasing interest in growing systems in which there is no leaching of nutrients into subsoil and in which the leaching to surface water is minimalized (van Os et al., 1991; Bot, 1992). To maintain a less polluting, sustainable and competitive horticultural sector, new growing systems are still under investigation. Along with the developments in growing systems, many crops shift from mineral soils to new growing media. Manufacturers bring many new media and mixtures on the market. Peat is a frequently used component of substrates, but also anorganic substrates like rockwool or perlite are often used. These substrates differ considerably in their hydraulic behaviour and chemical characteristics.

With cultivations on substrate it is important to control conditions in the root zone. For effective management of irrigation and fertilization of horticultural plants, a complete understanding of the hydraulic and chemical behaviour of the substrates is essential. Although physical characterization, and to a somewhat less extent chemical characterization, received considerable attention during the past years, there is still limited knowledge on the dynamics of water and nutrients in the root environment of horticultural systems. Nevertheless, such knowledge may help to design and optimize growing systems, and to define suitability of substrates.

This thesis deals with the dynamics of water and nutrients in the root environment induced by evapotranspiration, physical and chemical characteristics of the substrate, fertigation method and fertigation schedule. As a case study, the flooded bench fertigation system for potted plants is worked out into detail.

Although this thesis in particular focusses on this system, the theory presented is also valid for other fertigation systems, while the conclusions may be directly applicable to other growing systems using sub-irrigation.

1.1 Flooded bench fertigation system

There is a still growing interest in the ebb-flood fertigation system, mostly in combination with concrete floors or benches. In 1990 such systems comprised about 19% of the potted plant area in Dutch horticulture (Ploeger, 1992). In particular in combination with benches, this system, often referred to as flooded bench fertigation system, seems most promising for the future, since it is a closed system allowing for reuse of surplus water and nutrients. Additionally, the flooded bench fertigation system allows for further automation in the growing techniques by using transportable benches and separate spaces for growing and handling.

With the flooded bench fertigation system, water and nutrients are added to the pot by flooding benches on which the plants are standing (figure 1.1). Water containing nutrients is supplied once, or several times a week. During flooding, pots are standing in a nutrient solution, usually to a height of 0.02 m, and are allowed to take up water and nutrients for a short period, e. g. about five minutes. After this period the surplus water is pumped away and reused. Optimizing the fertigation schedule requires knowledge of capillary rise and the capacity of the growing medium to hold water against gravity, of air/water ratios in the potting medium, of plant water and nutrient uptake, and of redistribution of water and nutrients in the medium, since nutrients are added with the fertigation water during cultivation. These factors are briefly summarized below.

1.1.1 Potting medium characteristics

Potting media vary widely with respect to physical characteristics. These characteristics have mostly been determined for wet conditions, which are believed to be in particluar important for plant growth. Matric heads below -1.0 m in horticultural media were reported to reduce plant growth (De Boodt and Verdonck, 1971). According to Puustjarvi and Robertson (1975) most of the water used by greenhouse plants is held at matric heads between -0.10 and -1.0 m. Different systems have been developed to classify growing media with respect to suitability for plant growth. Bragg et al. (1988) proposed a system based on air filled porosity at -0.1 m matric head, plant characteristics, and fertigation system. In Dutch horticultural industry classification of potting media is based on porosity, air content at -0.10 m matric head, and shrinkage (Wever 1991a, b).

As recognized by Bilderback and Fonteno (1987), the water retention characteristic cannot be judged separately from container geometry. Also, it was shown by Chen et al. (1980) that various media can be used successfully for growing crops, although considerably different in physical characteristics, provided a proper irrigation method and schedule is used. They concluded that irrigation is the dominant factor controlling air/water ratios in media, rather than the physical characteristics. It is therefore unlikely that optimal growing media can be defined even for groups of plants, without considering the fertigation technique (Fonteno et al., 1981; Verdonck and Gabriëls, 1988).

Effects of growing conditions and physical characteristics of the potting medium on plant growth have been studied intensively by many researchers. Conclusions, however, are often contradicting and specific for plant species. No differences in growth of Poinsettia for three different media were reported by Fonteno et al. (1981). Small effects of five different media on Azalea growth were reported by Bilderback et al. (1982), but high irrigation frequency was applied to all media to minimize an effect of water stress. Effect of substrate compaction, which reduced air content, had little effect on growth of *Pilea pubescens* 'Silver Tree', although root growth was restricted with increasing compaction of the medium (Conover and Poole, 1981). In Dutch horticulture values are recommended, based on experience and physical characterization, and advise on suitability of potting media is given in relation to growing system and plant species (Wever, 1991b).

Not much attention has been given to the chemical characteristics and composition of substrates. Generally, an adequate available nutrient level, low salinity, minimal decomposition, and high cation exchange capacity are believed to be important (Raviv et al., 1986). For potting media used in Dutch horticulture, there are recommendations for chemical composition, electrical conductivity measured in a 1:1.5 volume extract, and pH (Stichting Regeling HandelsPotgronden, 1990). Inadequate natural levels of a medium are adjusted by adding fertilizer. Growers try to maintain desired levels during growth by adding nutrients with the fertigation water.

1.1.2 Fertigation schedule

Some efforts have been made in automating scheduling of irrigations by using tensiometers, mostly in combination with drip irrigation (Dickob, 1991; Frenz et al., 1988; Lieth et al., 1989; Makroth et al., 1988; and Makroth et al., 1990). These methods were successful in research if plants were grown under relatively dry conditions at low matric heads in small greenhouses. However, in practice, the fertigation schedule is still based on experience. There have been many efforts to relate fertigation schedule in combination with the physical characteristics to plant growth. On flooded bench growing systems optimal plant growth is generally obtained for media having a high air content at high matric heads, in combination with a high fertigation frequency (de Kreij et al., 1987; de Kreij et al., 1988; de Kreij and Straver, 1988; and de Kreij, 1989). On the other hand, drier growing conditions sometimes are more favourable, e.g. if more compact plants are required (Grantzau, 1986). Control of water status in the potting medium is relatively complicated with the flooded bench fertigation system, since the supply of water to the potted plant cannot be controlled directly. For a given fertigation duration and height, this supply is determined by physical characteristics and initial wetness of the potting medium. Knowledge on movement of water in potting media may help to optimize the fertigation schedule.

1.1.3 Plant nutrition

Plant nutrition is affected by fertigation schedule, fertigation method, and by physical and chemical characteristics of the potting medium. Nutrients accumulate generally in the substrate of a flooded bench fertigation system, in particular in the top layer (de Kreij and Straver, 1988). Although often no negative effects are found on production and quality of plants as a result of salt accumulation in the top layer (de Kreij and Straver, 1988; Vogelezang, 1991), this may occur for more salt sensitive plants if they are watered from above after cultivation (Verberkt and van den Berg, 1993). Nutrition levels for optimal plant growth and quality differ among plants species. In the Netherlands, recommendations are given for different groups of potted plants (I.K.C., 1991). High nutrition levels had a positive effect on growth of hortensia (van Leeuwen, 1991a). Best quality and production for *Cymbidium*, however, was reported for low nutrition levels (van Os, 1991). Van Leeuwen (1991b) suggested that the positive effect of high fertigation frequency on *Ficus benjamina* can be explained by a lower nutrition level in wet potting media, rather than a direct effect of the water/air content. Sometimes, specific elements affect plant growth and quality (Baas and Brands, 1991; van Leeuwen, 1991a; Straver, 1994). In particular, if control of specific element concentrations in the root environment is required, chemical characteristics of the potting medium become more important.

1.2 Conclusion for the present research

All experiments summarized above have in common that they relate a fertigation schedule in combination with characteristics of the potting medium to plant response. Extrapolation of these results to other plants, other growing media, other fertigation methods, or even other seasons is difficult since no information is available on conditions created in the root environment or within the plant. Conditions in the root environment may vary in particular with respect to height and in time. Sensors to measure water and nutrient contents are available at this moment, e. g. time domain reflectometry (TDR) and capacitive sensors, but their use in potting media still needs further investigation. The absence of knowledge on conditions in the root environment complicates optimalization of the growing system. On the one hand, there is limited information on plant requirements for optimal growth, while, on the other hand, there is insufficient knowledge on how to control conditions in the root environment once desired levels are defined. Of course, increased knowledge on how to control the root environment by potting medium characteristics and fertigation method and schedule will help to obtain information on optimal growing conditions for plants.

The literature referred to above suggests some specific questions about dynamics of water and nutrients in a flooded bench fertigation system. These questions concern (1) vertical and temporal distribution of water and nutrients in the root environment affected by plant uptake, potting medium, and fertigation schedule, (2) buffer capacity of a potting medium with respect to water and nutrients in relation to variation in plant uptake within days and over longer periods, (3) the relevance of physical and chemical characteristics of the potting medium, and (4) options for water and nutrient control with the flooded bench fertigation system.

1.3 Objectives and approach for this thesis

Related to the problems indicated above, the objective of this thesis is to gain a deeper understanding into the dynamic behaviour of water and nutrients for potted plants with a flooded bench fertigation system.

Dynamics of water and nutrients induced by flooded bench fertigation will be analyzed in this thesis through experiments and computer simulations. The simulation model will be based on knowledge of movement of water and solutes in porous media, as summarized in chapter 2. Existing models for transport processes in soils are adapted for potted plants on a flooded bench fertigation system. For the dynamics of water the model SWATRE is used (Belmans et al., 1983; Feddes et al., 1988). Solute transport and chemical equilibria are described according to the model CHEM (Robbins, 1991). Adaptation of these models for the flooded bench fertigation system is discussed in chapter 7.

The research described in this thesis is subject to the following restrictions:
- Validation and parameterization is performed for one potting medium and one plant species. The potting medium consists of 75% peat and 25% perlite, which is frequently used in flooded bench fertigation systems in Dutch horticulture. *Ficus benjamina* is used in the experiments since it does not flower, has a high green mass production and is of high economic importance.
- Actual evapotranspiration and plant nutrient uptake are considered to be known in the model. This implies that interaction between plant uptake and the conditions in the root environment, e. g. reduced transpiration under dry conditions, are not considered by the model.
- A standard size pot is used and the spacings of the pots on the benches is not changed during the cultivation period.
- Only the macro-nutrients are considered; micro-nutrients like Fe, Cu, etc. are not considered in this research.

The study considers the dynamics of water and nutrients for a single pot in an actual growing situation. Parameterization of the model is performed by obtaining data as much as possible from plants grown in modern greenhouses on a flooded bench fertigation system. Much attention is therefore paid to physical (time dependent) and chemical characteristics of the medium under natural growing conditions (chapters 3 and 4), to actual evaporation, and to actual transpiration of the plant on a flooded bench fertigation system (chapter 5). The dynamics of water under natural conditions are discussed in chapter 5, the dynamics of nutrients in chapter 6. The simulation model and experiments are used together to discuss the dynamics of water and nutrients in particular with respect to fertigation schedule, with respect to physical and chemical characteristics of the substrate, and with respect to plant uptake (chapter 8).

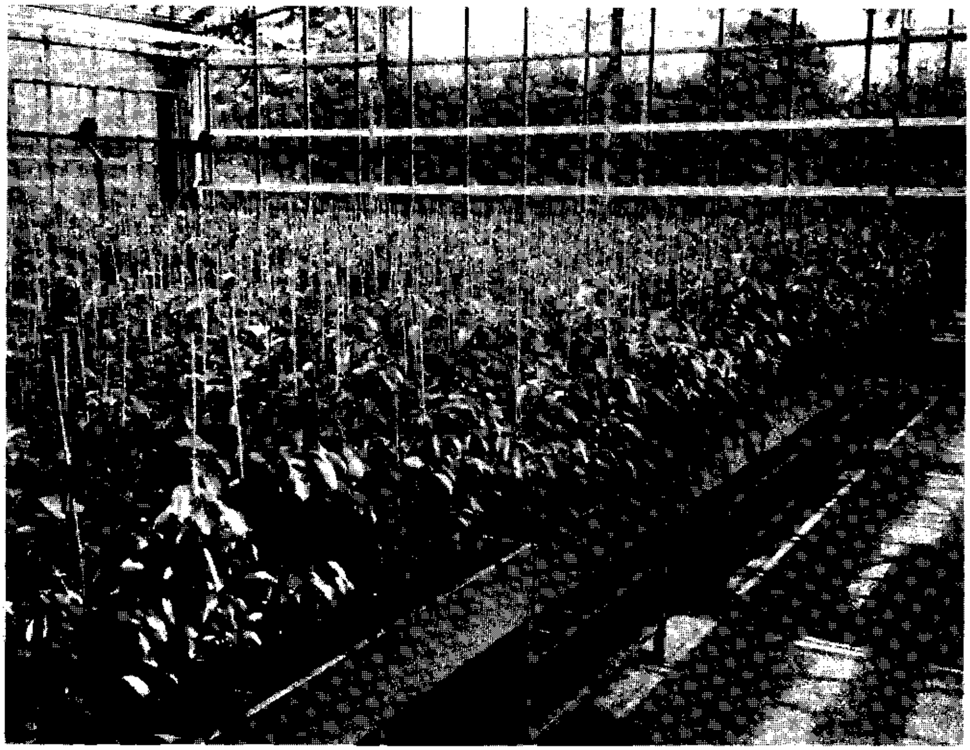


Figure 1.1. Cultivation of *Ficus benjamina* with a flooded bench fertigation system. In this greenhouse used for this research separate fertigation schedules were established for 18 benches.

2. Dynamics of water and solutes in the root zone: principles and terminology

The processes in the root environment of plants growing in artificial substrates are similar to those for plants growing in soil. Processes concerning dynamics of water and nutrients have been a major research interest for many years in soil science. In this study, a macroscopic view of substrates and processes occurring in them is pursued. In this macroscopic approach a volume of the substrate is considered which is large in comparison with microscopic dimensions, such as pores, but also small enough to be representative for a certain position in the medium. On this level behaviour can be described and measurements are made (Raats and Klute, 1968). Following definitions related to occurrence and behaviour of phases in soils, the theory is summarized with respect to substrates, and terminology and symbols used in this thesis are introduced. When the term porous medium is used in this chapter, this can refer either to a natural soil or to an artificial substrate. For soils, the theory can be found in textbooks of soil physics or soil chemistry, e. g. Bolt and Bruggenwert (ed., 1978) "Soil chemistry: A. Basic Elements"; Bolt (ed., 1982) "Soil chemistry: B. Physico-chemical models"; Koorevaar et al. (1983) "Elements of soil physics"; and Hillel (1980) "Fundamentals of soil physics". The theory is the basis of the simulation model which will be used to study the dynamics of water and nutrients in the substrate of potted plants grown on a flooded bench fertigation system.

2.1 Dynamics of the liquid phase in porous media

2.1.1 The composition of a porous medium

Within a soil or substrate based root zone, three phases can be recognized: the solid phase, the liquid phase and the gaseous phase. The solid phase forms the matrix of the medium. Considering a representative elementary volume V, this volume is partitioned according to:

$$V = V_{solids} + V_{liquid} + V_{gas} \ . \qquad 2.1$$

The sum of the volume of the liquid phase, V_{liquid}, and the volume of the gaseous phase, V_{gas}, equals the volume of the pore space. The porosity of a medium, ϕ, is defined as:

$$\phi = (V_{liquid} + V_{gas}) \ / \ V \ . \qquad 2.2$$

Among 200 potting media used in Dutch horticulture, the porosity varied from 0.83 to 0.94 (Wever, 1991b).

The water content can be expressed as a volume fraction. The volumetric water content, θ, is defined as:

$$\theta = V_{liquid} \ / \ V \ . \qquad 2.3$$

In case the volumetric water content equals the porosity, this volumetric water content is called the water content at saturation, θ_s. Although technology is available to measure volumetric water content, this still needs considerable attention before it becomes widely available for horticultural substrates. Water content on mass basis on the other hand is often more easy to determine, but this method is destructive. Water content as a mass fraction, the wetness w, is defined as:

$$w = \rho_l / \rho_s \, . \qquad 2.4$$

The bulk densities of the solid phase, ρ_s, and of the liquid phase, ρ_l, are defined as the masses per unit volume:

$$\rho_s = M_{solids} / V \; ; \; \rho_l = M_{liquid} / V \, , \qquad 2.5$$

where

M_{liquid}	= mass of the liquid phase	kg
M_{solids}	= mass of the dry solids	kg

The wetness, w, and the volumetric water content, θ, are related to each other through the bulk density, ρ_s, and the phase density of the liquid phase, γ_l, according to:

$$\theta = w \times \rho_s / \gamma_l \, . \qquad 2.6$$

The density of the liquid phase, γ_l, is often taken to be 1000 kg m^{-3}. The bulk density varied from 91 to 378 kg m^{-3} among 200 potting media (Wever, 1991b). Whether or not artificial pressure is used when filling the pots, strongly affects bulk density of the potting medium (de Kreij and Bes, 1989).

Bulk density should not be confused with the phase density of the solid particles, γ_s, which is defined as the mass of solids per unit volume of solids. If bulk density and density of the solid particles are known, the porosity can be calculated according to:

$$\phi = 1 - (\rho_s / \gamma_s) \, . \qquad 2.7$$

2.1.2 The energy concept of the liquid phase

Different forces act upon the water in a porous medium. The liquid phase is subject to the action of the gravitational field, the influences of dissolved salts and of the solid phase in its given geometry of packing, and to the action of local pressure in the gaseous phase (Bolt et al., 1976). These factors together determine the value of the potential of the liquid phase relative to a chosen standard state. The potential of the liquid phase expresses the capacity of water to do work as compared to the same mass of pure water, at atmospheric pressure and a reference elevation, defined as having a potential of zero. The total potential of the liquid phase in a rigid porous medium, ψ_t, can be divided into four components according to:

$$\psi_t = \psi_m + \psi_g + \psi_o + \psi_a \, , \qquad 2.8$$

where:

ψ_m =	the matric potential arising from interactions between the solid and the liquid phase	J kg^{-1}
ψ_g =	the gravitational potential, arising from the position of the	

liquid phase with respect to a reference level $J\ kg^{-1}$

ψ_o = the osmotic potential arising from the presence of solutes $J\ kg^{-1}$

ψ_a = the pneumatic potential due to soil gas pressure in excess to reference atmospheric pressure $J\ kg^{-1}$

Although the unit of potential is $J\ kg^{-1}$, more often the potential on a weight basis, head, is preferred in studies involving transport problems. The convenience of this form is immediately apparent from the gravitational head, h_g, which is defined as:

$$h_g = \psi_g / g = (g \times z) / g = z \ , \qquad 2.9$$

where:

g	= gravitational field strength	$N\ kg^{-1}$
z	= distance in vertical direction, taken positive upward	m

Similar to the definitions above we can introduce the total head, h_t, the matric head, h_m, and the osmotic head, h_o, by dividing the corresponding potentials by the gravitational field strength. Since matric head generally has a negative value, a high matric head refers to a lowly negative value, while a low matric head refers to a highly negative value. With reference to other units frequently used in literature, it is, as a reminder, pointed out that 1 m (expression on weight basis) is equivalent to 10 $J\ kg^{-1}$ (expression on mass basis), and is equivalent to 10^4 Pa, or 1 $N\ m^{-2}$ (expression on volume basis). In transport studies of the liquid phase in porous media under atmospheric conditions, only the gravitational and matric head are taken into account. The sum of the matric head and the gravitational head is called the hydraulic head, H (m).

$$H = h_m + h_g = h_m + z \ . \qquad 2.10$$

2.1.3 Movement of the liquid phase: governing equations

Flow of water in a substrate must obey the law of conservation which is expressed in the equation of continuity. This equation states that the difference between the flow rate into and out of a certain volume equals the sum of the time rate of change of storage and the rate of uptake by plant roots:

$$\frac{\delta\theta}{\delta t} = - \frac{\delta q}{\delta z} - S \ , \qquad 2.11$$

where:

q	= flux density of liquid phase	$m^3\ m^{-2}\ s^{-1}$
S	= sink term of the liquid phase (e.g. extraction by roots)	$m^3\ m^{-3}\ s^{-1}$
t	= time	s

The flux density of the liquid phase is the product of the volume fraction θ and the velocity of the liquid phase relative to the solid phase ($m\ s^{-1}$), and is described by Darcy's law, which states that the water flux density is proportional to, and in the direction opposite to, the potential gradient. Under atmospheric conditions the equation, expressed in terms of head, is given by:

$$q = -K(h_m) \times \delta(h_m + h_g)/\, \delta z = -K(h_m) \times \delta H/\delta z \,. \qquad 2.12$$

The hydraulic conductivity, either $K(h_m)$ or $K(\theta)$, represents the proportionality between flux and driving force. The hydraulic conductivity and the matric head both depend on the volumetric water content, which means that the conductivity is related to the matric head as well.

If we choose the level of reference for the gravitational head at z=0, combination of equations 2.11 and 2.12 leads to the partial differential equation for one dimensional flow. Written in terms of matric head, the resulting equation is:

$$\frac{\delta h_m}{\delta t} = \frac{1}{C(h_m)} \frac{\delta}{\delta z} \left[K(h_m) \left[\frac{\delta h_m}{\delta z} + 1 \right] \right] - \frac{S}{C(h_m)}, \qquad 2.13$$

where the differential water capacity, $C(h_m)$, is defined as $\delta\theta/\delta h_m$.

Solution of this equation, either analytically or an approximation by numerical methods, requires a description of the initial and boundary conditions of the system. Boundary conditions can be either defined fluxes, e. g. evaporation via the potting medium surface, or defined heads, e. g. zero matric head at a known depth as a result of the presence of a water table. For convenience and with regard to experimental and available theoretical models, the boundary conditions are often so chosen that plant uptake of water is described by a sink term. This sink term is plant specific and generally believed to be functionally dependent on climatic conditions, root density, volumetric water content, and matric and osmotic heads. Besides a specification of the boundaries and the sink term, solving equation 2.13 requires a description of the relation between matric head and volumetric water content, and the relation between hydraulic conductivity and matric head or volumetric water content. Some aspects of these characteristics are described in the following sections.

2.1.4. Water retention characteristic

The water retention characteristic describes the relation between matric head and volumetric water content of a medium. Traditionally it is determined by establishing a series of equilibria between the liquid phase in the medium and a body of water with a known potential (Klute, 1986). At each equilibrium, volumetric water content, θ, is determined and related with the value of the matric head, h_m. In practice this relation is often obtained from measurements of changes in w/γ_l rather than changes in θ, and θ is calculated from equation 2.6, assuming that bulk density, ρ_s, does not change during the characterization. The water retention characteristic is hysteretic. This means that the water content at a given matric head for a wetting medium is less than for a drying medium. A drying curve is determined by establishing a series of equilibria by drainage from a zero matric head (saturation). A wetting curve is obtained by wetting a sample from a low water content. The main wetting curve, MWC, is obtained by wetting the medium starting from the residual water content, θ_r, which is the limit of water content to which water content approaches at low (strongly negative) matric heads. As the matric head following the MWC approaches zero, the water content approaches a value called the water content at satiation. The water content at satiation may be lower than the water content at saturation due to entrapped air. The drying curve starting from the water content at satiation is called the main drying curve, MDC. Inside the MWC and MDC lies an infinite set of curves of which the exact form depends on the history of wetting and drying (Klute, 1986). These curves are referred to as scanning curves. It depends on the processes to be studied which curves have to be determined, but for most transport studies the full hysteretic nature of the medium has to be known, especially when frequent changes from wetting to drying occur (Hopmans and Dane, 1986).

The water retention characteristic can be determined either in the laboratory or in situ. An advantage of laboratory methods is that they allow for complete control of the characterization method. For instance, wetting of the samples in the laboratory can be fully controlled and described. On the other hand, an advantage of in situ measurements is that samples have the natural structure. Methods for in situ characterization are discussed by Bruce and Luxmoore (1986). Several methods for characterization in the laboratory are discussed by Klute (1986). Which method is most useful depends mainly on the range of matric heads for which the water retention characteristic must be determined. For horticultural media characterization in the laboratory is normally used.

2.1.5. Hydraulic conductivity characteristic

The hydraulic conductivity characteristic describes the relation between hydraulic conductivity and volumetric water content or matric head. In conducting water, larger pores are most effective, since velocity of a liquid phase in a pore is proportional to the square of its radius. Since larger pores drain first as water content decreases from saturation, conductivity decreases over many orders of magnitude with decreasing water content. Although a few investigators report $K(\theta)$ being hysteretic (Staple, 1966), this relation is generally believed to be non-hysteretic. Of course, $K(h_m)$, which is used in equation 2.13, is hysteretic if hysteresis is found in the water retention characteristic.

Methods for determination of the hydraulic conductivity are given by Green et al. (1986) for use in the field and by Klute and Dirksen (1986) for use in the laboratory. Most methods are costly and time consuming and cannot cover the full water content range of interest, since values of the conductivity may vary over many orders of magnitude within this range.

2.2 Dynamics of solutes in porous media

2.2.1 Terms relating to solutes in the liquid phase

The liquid phase is usually a dilute aqueous solution of common salts from the ions Na, K, Mg, Ca, Cl, NO_3, SO_4, HCO_3, etc. The amount of an element present in a solution is often expressed as a concentration, c_i, in mol m^{-3} (= 10^{-3} mol l^{-1}), were subscript i denotes the element under consideration. The concentration is related to the mass per unit volume according to:

$$c_i = m_{i,V} / (M_i \times V_{liquid}) \ , \qquad 2.14$$

where

$m_{i,V}$ = mass of chemical species i kg

M_i = molecular mass of chemical species i   kg mol^{-1}

Chemical species in a aqueous solution often have a positive or negative charge. Although there is an infinite number of possible compositions of the liquid phase, electroneutrality is always maintained. Therefore the electrolyte concentration is often used rather than the molar concentration. The electrolyte concentration of solute i, C_i, expressed in eq m^{-3}, equals the product of the absolute value of the valence, v_i (eq mol^{-1}), and the concentration:

$$C_i = |v_i| \times c_i \ . \qquad 2.15$$

The expression 10^3 eq m^{-3} (= 1 eq l^{-1}) is often referred to as a "one normal solution".

The total content of solutes is often characterized by the electrical conductivity, measured either in the liquid phase or in a diluted extract. The electrical conductivity or specific electrical conductance of a solution is the reciprocal value of its specific electrical resistance. The latter is the resistance of a 'column' of the liquid phase with a cross section of 1 cm^2 and a length of 1 cm. EC-values are given in millimhos cm^{-1} or mS cm^{-1}. Since the mobilities of different solutes are only approximately equal, the salt concentration is only approximately defined by the EC-value. The electrical conductivity can be estimated from individual ion concentrations according to:

$$EC = \sum_i K_0 \times C_i^b \ , \qquad 2.16$$

where K_0 and b are coefficients for each of the solutes (McNeal et al., 1970). As a rough estimate an EC value of 0.1 mS cm^{-1} for a 10^{-3} normal solution is valid.

According to equation 2.8, the total salt concentration contributes to the total potential of the liquid phase by its osmotic potential component. This osmotic potential component directly affects processes like water uptake by plants. The osmotic potential is related to the total sum of ionic concentration in the liquid phase according to:

$$\psi_o = - 1/\gamma_l \times R \times T \times \sum_{a,c} c \ ,$$

or $\qquad 2.17$

$$h_0 = - 1/(\gamma_l \times g) \times R \times T \times \sum_{a,c} c \ ,$$

with $\gamma_l \times g \approx 10^4$ (N m^{-3}) and $R \times T \approx 2.4\ 10^3$ (J mol^{-1}) at 15 °C. For a solution with a salt concentration of 50 mol m^{-3} NaCl (EC≈5 mS cm^{-1}) an osmotic head, h_o, of -24 m is calculated.

2.2.2. Chemical equilibria

Conditions may arise under which certain elements will react with each other to form chemical components. Most of these reactions are reversible equilibrium reactions. At equilibrium, the reaction rates in forward and backward direction just compensate each other and the composition of the solution remains constant in time. In a general form, an equilibrium reaction can be written as:

$$aA + bB \rightleftharpoons cC + dD \,, \tag{2.18}$$

with the equilibrium condition defined as:

$$K_{eq} = ([C]^c\,[D]^d) \,/\, ([A]^a\,[B]^b) \,, \tag{2.19}$$

where brackets denote the activity of the solute. The activity of a solute is proportional to its concentration, c_i, according to:

$$a_i = f_i \times c_i \,, \tag{2.20}$$

where a_i represents the activity, and f_i the activity coefficient of solute i. The mono- and divalent ionic activity coefficients (f_1 and f_2) can be calculated from the Davies relationship:

$$\mathrm{LOG}\ f_i = -0.509 \times v^2 \times (\sqrt{I}/(\sqrt{I} + 1) - 0.3 \times I) \,, \tag{2.21}$$

where I is the ionic strength of the solution ($I=0.5\ \sum_i c_i \times v_i^2$).

A special case of reactions occurs when a liquid phase is in contact with a solid phase. In particular, naturally occurring solid phases, like clay minerals and organic material, often carry primarily negative, but also some positive surface charges. These charges are compensated by an excess of cations or anions in close proximity of the solid surface maintaining electroneutrality. This excess of ions cannot be removed from the solid phase. It is possible, however, to exchange these ions against others. Cations adsorbed by the solid phase are thus available to plants, e.g. by exchange against H-ions released from plant roots. The solid phase components that contribute to the adsorption are often referred to as the adsorption complex (for cations).

The ability of the solid phase to adsorb cations is dependent on its surface charge density and the specific surface area. The total amount of cations held exchangeable by a unit mass of soil is termed the cation exchange capacity of the soil, CEC, and will be indicated with the symbol γ. CEC is normally expressed in meq per 100 grams of dry material. The adsorbed ions are in equilibrium with the liquid phase, and equilibrium reactions can be written in a form similar to equation 2.18. The condition of electroneutrality implies that the exchange must be equivalent, e.g. two monovalent cations are replaced by one divalent cation.

The adsorption complex gives the medium a buffering capacity with respect to changes in cationic composition of the liquid phase caused by addition of fertilizer, leaching, uptake by plants or any other process affecting the composition of the solution. It also serves as a storage for nutrient ions. In horticultural substrates, a significant CEC occurs if organic matter (peat) or clay is an important constituent of the solid phase. Many other horticultural substrates like volcanic tuffs and perlite, however, have a low adsorption capacity (Bech et al., 1983).

2.2.3. Movement of solutes: governing equations

Transport of components in a porous medium occurs in the gaseous and in the liquid phase. Recognizing the liquid phase as the main carrier for most components, the mathematical formulation describing the transport as determined by the liquid flow and relevant physical characteristics is given below. For the flow of the liquid phase one is referred to section 2.1.3.

Similar to the formulation of transport of water in porous media we start with the continuity equation. Considering only one dimensional vertical transport, the mass balance at any point in a medium is given by:

$$\frac{\delta A_i}{\delta t} = - \frac{\delta j_i}{\delta z} - S_i \,, \qquad 2.22$$

where

A_i	= total amount stored of species i in the medium	$mol\ m^{-3}$
j_i	= total flux of species i	$mol\ m^{-2}\ s^{-1}$
S_i	= total source/sink term of species i	$mol\ m^{-3}\ s^{-1}$

The sink/source term, S_i, is possitive in case of a sink, e.g. as a result of plant uptake, decay and precipitation, or is negative in case of a source, e. g. dissolution of other components. The total mass of species i, A_i, can be divided over three phases discussed in the previous section according to:

$$A_i = L_i + Q_i + P_i \,,$$

$$= \theta \times c_i + (\gamma_i \times \rho_s)/(100 \times |v_i|) + \sigma_i \times \rho_s \,, \qquad 2.23$$

where

L_i	= total amount of species i in the liquid phase	$mol\ m^{-3}soil$
Q_i	= total amount of species i adsorbed	$mol\ m^{-3}soil$
P_i	= total amount of species i precipitated	$mol\ m^{-3}soil$
σ_i	= amount precipitated	$mol\ kg^{-1}$

The flux of the solute (j_i in equation 2.22) is, for non-volatile components, limited to the liquid phase and consists of at least two terms: the convective flux, $(j_i)_{con}$, and a flux resulting from diffusion and dispersion, $(j_i)_{diff}$:

$$j_i = (j_i)_{con} + (j_i)_{diff} \,,$$
$$(j_i)_{con} = q \times c_i \,, \qquad 2.24$$
$$(j_i)_{diff} = - D_i \times (\delta c_i/\delta z) \,,$$

where q represents the water flux density as given in equation 2.12, and D_i is the apparent diffusion/dispersion coefficient of a solute in the medium. The apparent diffusion/dispersion coefficient is dependent on flux density and volumetric water content:

$$D_i(\theta,q) = D_p(\theta) + \theta \times D_m(q) \,, \qquad 2.25$$

in which the first term represents the coefficient for diffusive transport according Fick's law, and the second term a coefficient for dispersion. Since the liquid phase occupies only a fraction of the medium, and pores generally do not run parallel to the flux direction, a reduction of the diffusion coefficient in porous media as compared to that of free water is found according to:

$$D_p(\theta) = D_0 \times \theta \times \tau \,, \qquad 2.26$$

where a tortuosity factor, τ, is introduced to account for the increased path length ($\tau \approx 0.5$, although in principle not independent of the volumetric water content). The convective dispersion coefficient, D_m, is generally assumed to be a function of the flow velocity:

$$D_m = \mid (q/\theta) \mid \times L_r \,. \qquad 2.27$$

For most laboratory experiments involving repacked media and for certain uniform media this dispersion length may be estimated on the order of about 0.01 m or less.

Equations 2.22 through 2.27 are the basis for many transport studies. Similar to water transport, solution of a flow problem requires complete description of the initial and boundary conditions of the system with respect to solutes. Analytical solutions can be given for some systems (Bolt, 1985; Harmsen and Bolt, 1982). Often the equations have been used in simulation studies. A review of solute transport models is given by Engesgaard and Christensen (1988). In some models the chemical equilibrium equations are directly integrated into the transport equation. Most models, including the model used in this study, calculate transport of solutes and chemical equilibria separately. These models first calculate the transport of solutes, assuming they are non-reactive, and then calculate the new chemical equilibrium, assuming local equilibrium, which implies that all reactions proceed instantaneously to equilibrium.

3. Physical characteristics of the potting medium

The properties of a medium that determine its hydraulic behaviour, are the water retention and the hydraulic conductivity characteristics (chapter 2). Both characteristics can be determined in the laboratory. The water retention characteristic is the easier one to determine experimentally. However, if hysteresis has to be considered, sufficient data on water retention are rarely available. Additionally, several researchers observed that the water retention characteristic changes as a result of root growth, mineralization of organic matter or repeated wetting and drying (Klougart, 1983; de Kreij et al., 1987; Nelson and Fonteno, 1991). The hydraulic conductivity characteristic of potting media has also been measured rarely. As a result, characterization of horticultural media is based almost exclusively on the main drying curve (MDC) of the water retention characteristic. Nevertheless, hydraulic conductivity is an important characteristic since it varies several orders of magnitude within a narrow range of matric heads occurring between successive irrigations (Wallach et al., 1992b). Since water transport to plant roots strongly depends on hydraulic conductivity, this wide range should not be overlooked.

It is the objective of this study to obtain the water retention characteristic, including hysteresis, and the hydraulic conductivity characteristic of a peat based potting medium (75% peat, 25% perlite), and to give mathematical descriptions. Mathematical descriptions provide a tool for describing physical characteristics with a minimum set of parameters. It is the objective to measure these characteristics on the potting medium with a similar density as occurs under growing conditions on a flooded bench fertigation system, and to investigate the change in water retention characteristic as a result of root growth and repeated wetting and drying.

3.1 Theory

3.1.1 Water retention characteristic: mathematical function

Several mathematical functions have been proposed to describe water retention characteristics of soils (Raats, 1992) and of potting media (Fonteno et al., 1981). For soils, van Genuchten proposed an empirical function to relate matric head h_m (in cm) to volumetric water content θ (van Genuchten, 1980; van Genuchten and Nielsen, 1985):

$$\theta = \theta_r + (\theta_s - \theta_r) / (1 + (\alpha \times |h_m|)^n)^m , \qquad 3.1$$

or

$$Se(h_m) = (\theta - \theta_r) / (\theta_s - \theta_r) = (1 + (\alpha \times |h_m|)^n)^{-m} , \qquad 3.2$$

where

θ_s = water content at saturation
θ_r = residual water content
Se = relative saturation, $0 \le Se \le 1$

The parameters α, n and m determine the *S*-shape of the water retention characteristic. Parameter n determines the steepness of the curve while α is approximately equal to the inverse of the matric head at the inflection point. Equation 3.1 adequately describes retention data for a large number of soils (Wösten and van Genuchten, 1988). Milks et al. (1989) used equation 3.1 to describe the water retention characteristics of three peat based horticultural media and concluded that it provided a better fit than a polynomial function. Successful description of the water retention characteristic of horticultural media with this equation was also demonstrated by Wallach et al. (1992a, 1992b). Parameter values for a few horticultural media are given in table 3.1.

Table 3.1. Parameters, gathered from literature, of the van Genuchten description of physical characteristics for several horticultural media. If *m* is restricted to 1-1/n, the value of *m* is presented by a - sign. Measured values are indicated with an asterisk.

medium	θ_s	θ_r	α (cm^{-1})	*n*	*m*	reference	remark
peat + vermiculite 1:1	0.869*	0.319*	0.9	3.3	1.2	Fonteno, 1988	drying curve 0 to -3.0 m
bark + peat + sand 3:1:1	0.705*	0.227*	3.4	1.1	1.0	Fonteno, 1988	drying curve 0 to -3.0 m
peat soil + peat + sand 1:1:1	0.546*	0.154*	5.2	0.8	1.0	Fonteno, 1988	drying curve 0 to -3.0 m
Cecil clay loam	0.615*	0.250*	0.3	1.8	8.2	Milks et al., 1989	drying curve 0 to -3.0 m
phenolic foam (oasis)	0.983*	0.03*	6.3	0.7	4.7	Milks et al., 1989	drying curve 0 to -3.0 m
coarse red tuff, RTB 0-1 mm, crushed	0.440*	0.078	0.019	2.195	-	Wallach et al., 1992a	drying curve 0 to -1.2 m
coarse red tuff, RTB 1-2 mm, crushed	0.646*	0.130	0.254	3.022	-	Wallach et al., 1992a	drying curve 0 to -1.2 m
coarse red tuff RTB 2-4 mm, crushed	0.710*	0.060	0.501	2.263	-	Wallach et al., 1992a	drying curve 0 to -1.2 m
red tuff 0-8 mm, RTM not crushed	0.454*	0.063	0.346	1.529	-	Wallach et al., 1992a	drying curve 0 to -1.2 m
red tuff 0-8 mm, RTM not crushed	0.400*	0.063	1.000	1.455	-	Wallach et al., 1992a	wetting curve -1.2 to 0 m
composted grape marc CGM	0.794*	0.0	1.296	1.133	-	Wallach et al., 1992b	drying curve 0 to -1.2 m
composted grape marc CGM	0.695*	0.0	12.84	1.072	-	Wallach et al., 1992b	wetting curve -1.2 to 0 m
red tuff, RTB	0.548*	0.079	0.324	2.186	-	Wallach et al., 1992b	drying curve 0 to -1.2 m
red tuff, RTB	0.450*	0.079	0.387	2.534	-	Wallach et al., 1992b	wetting curve -1.2 to 0 m
CGM (80%) + RTB (20%)	0.604*	0.105	0.410	1.852	-	Wallach et al., 1992b	drying curve 0 to -1.2 m
CGM (80%) + RTB (20%)	0.430*	0.105	0.325	1.539	-	Wallach et al., 1992b	wetting curve -1.2 to 0 m
CGM (60%) + RTB (40%)	0.640*	0.207	0.514	2.025	-	Wallach et al., 1992b	drying curve 0 to -1.2 m
CGM (60% + RTB (40%)	0.450*	0.207	1.115	2.075	-	Wallach et al., 1992b	wetting curve -1.2 to 0 m

3.1.2 Hysteresis in the water retention characteristic

Equation 3.1 can be used to describe the MDC and the MWC, leading to a different set of parameters for each. Kool and Parker (1987) showed that minimizing the number of parameters by assuming the MDC and MWC only differ in parameter α did not lead to an unacceptable loss of accuracy. Since there is an infinite number of scanning curves in between the MDC and the MWC, description of only these two is not sufficient. The complexity in describing an infinite number of scanning curves has led to simplifications. Kool and Parker (1987) developed an empirical hysteresis model, based on equation 3.1 for the MDC and MWC. Comparison of computed with experimentally determined scanning curves for eight soils revealed only one case in which predictions were poor. Drying scanning curves were obtained by using the parameter vector (θ_s^*, θ_r, α_d, *n*, *m*), where θ_s^* replaces θ_s in equation 3.1. This has the effect of scaling the drying curve to pass through the reversal point. θ_s^* can be calculated with:

$$\theta_s^* = \theta_r + \frac{(\theta_{rev} - \theta_r)}{(\theta_{y,d} - \theta_r)} \times (\theta_s - \theta_r) , \qquad 3.3$$

where

θ_{rev} = water content at reversal point

$\theta_{y,d}$ = water content at matric head of the reversal point according to the MDC

In a similar way a scanning wetting curve is obtained by replacing θ_r by θ_r^* and using α_w in equation 3.1, with

$$\theta_r^* = \theta_s - \frac{(\theta_s - \theta_{rev})}{(\theta_s - \theta_{y,w})} \times (\theta_s - \theta_r) , \qquad 3.4$$

where $\theta_{y,w}$ equals the water content corresponding with the matric head of the reversal point according to the MWC.

The model generates scanning loops which close at either the water content at saturation (wetting curve), or at the residual water content (drying curve). Under cyclical reversals between wetting and drying this leads to significant errors, which is the so-called water pumping effect. This water pumping effect means that predicted water contents tend to decrease during initial fluctuations in h_m until some stable water contents are reached (Jaynes, 1984; Klute and Heermann, 1974). Since cyclical wetting and drying frequently occurs on a flooded bench system, the procedure to calculate scanning curves is such that after two reversals, a scanning curve is closed at the starting point (h_m, θ) of the first reversal (Dirksen et al., 1993). This means that to generate a scanning curve, two points need to be known: the reversal point (h_{rev}, θ_{rev}) from which the curve departs, and a closure point (h_{clos}, θ_{clos}) to which the curve develops. Following Dirksen et al. (1993), this leads to a description with the parameter vector (θ_s^*, θ_r^*, α_w, *n*, *m*) for a wetting scanning curve, and (θ_s^*, θ_r^*, α_d, *n*, *m*) for a drying scanning curve. Substitution of the known values h_{clos}, θ_{clos}, h_{rev}, θ_{rev}, α_d or α_w, *n*, and *m* into equation 3.1, leads after rewriting to the following relations for θ_s^* and θ_r^*:

$$\theta_r^* = (-B\ \theta_{rev} + A\ \theta_{clos}) / (A - B)\ , \tag{3.5}$$

$$\theta_s^* = (\ (1 - B)\ \theta_{rev} + (A - 1)\ \theta_{clos}\ ) / (A - B)\ , \tag{3.6}$$

where A equals $(1 + (\alpha \times |h_{rev}|)^n)^{-m}$, and B equals $(1 + (\alpha \times |h_{clos}|)^n)^{-m}$, with $\alpha=\alpha_w$ for a wetting, and $\alpha=\alpha_d$ for a drying scanning curve. The shape of the scanning curve is given by equation 3.1, using θ_s^* for θ_s, and θ_r^* for θ_r. However, this curve is only valid in between the defined reversal and closure points. If drying proceeds beyond a closure point, a new scanning curve is generated starting from this closure point, and assuming closure at the residual water content. From here, equations 3.5 and 3.6 reduce to the original Kool and Parker model, and the drying curve beyond the closure point is calculated according equation 3.3. Similar a wetting scanning curve proceeding beyond its closure point, is assumed to close at the water content at saturation, and calculated according equation 3.1 and 3.4. This means that only the last opened scanning loop is closed. A FORTRAN subroutine which updates the parameters in equation 3.1 if a reversal or closure of a scanning curve occurs, is listed in appendix 2.

Equations 3.1 through 3.6 describe the full hysteretic nature of the water retention characteristic with a set of 6 parameters (θ_s, θ_r, α_d, α_w, n, m). The parameters α_d, α_w, n and m have to be obtained by fitting to experimental data. This requires an experimental MDC and at least one scanning wetting curve. The parameters θ_r and θ_s can be either measured or be determined by fitting as well.

3.1.3 Hydraulic conductivity characteristic: mathematical function

Since data of hydraulic conductivity are sometimes not available over the full range of interest or even completely absent, relations haven been developed to predict the conductivity (Mualem, 1986). None of these relationships is valid for all types of media. Therefore, they have to be used judiciously. Mualem proposed a relation to predict the hydraulic conductivity characteristic, based on the pore size distribution derived from the MDC of the water retention characteristic. For discussion one is referred to Mualem (1976, 1986), and Raats (1992). The relation is given by:

$$K(h_m) = K_s \times Se^{\ell} \times [\ ({}_0\int^{Se} h_m(x)^{-1}\ dx\ /\ {}_0\int^{1} h_m(x)^{-1}\ dx\ ]^2\ , \tag{3.7}$$

where K_s equals the hydraulic conductivity at saturation, ℓ is an empirical constant, and x an integration variable. Mualem (1986) concluded from analysis of 45 soils that ℓ should be on the average about 0.5, but Leij et al. (1992) reported that ℓ may deviate significantly from this value. Restricting permissible values for m and n to m=1-1/n leads after substitution of equation 3.1 into equation 3.7 to (van Genuchten, 1980; Mualem, 1986):

$$K(Se) = K_s \times Se^{\ell}\ (1 - (1 - Se^{1/m})^m\ )^2\ , \tag{3.8}$$

or as a function of matric head, h_m:

$$K(h_m) = K_s \times \frac{[(1 + (\alpha \times |h_m|)^n)^m - (\alpha \times |h_m|)^{n-1}]^2}{(1 + (\alpha \times |h_m|)^n)^{m(\ell+2)}} . \qquad 3.9$$

Equations 3.8 and 3.9 give a description of the hydraulic conductivity based on the water retention characteristic and the additional parameters ℓ and K_s (in cm day^{-1}). Determination of K_s is much less complicated than determination of the hydraulic conductivity. If data of the water retention characteristic are available and some data of the hydraulic conductivity characteristic are known as well, both data sets can be used to estimate the values of the parameters K_s, ℓ, θ_r, θ_s, n, α according to equations 3.1 and 3.9.

3.2 Materials and methods

3.2.1 Sample preparation

To obtain samples for characterization, rings with a diameter and height of 0.05 m were placed in pots. These pots were filled with the potting medium (75% peat + 25% perlite) without artificial pressure, using a potting machine. After filling, the pots were placed on the flooded bench system. Subsequently, they were wetted from above. In this way the samples followed the same procedure as potted plants usually do. They were left on the flooded bench system for two flooding periods before characterization in the laboratory. For larger rings (0.11 m diameter, 0.08 m height for the evaporation method) the same procedure was followed, only a larger pot was used. For rings with diameter and height of 0.2 m, used to measure hydraulic conductivity at saturation, no pots were used, but further the procedure was identical.

A few pots with rings remained on benches in a greenhouse for one or three months before characterization. In half of these pots a *Ficus benjamina* was planted. This was done to determine the change of the characteristics in time as induced by repeated drying and wetting or by plant roots. The benches were flooded either continuously, twice, or four times a week. Layout of the experiment and fertigation schedule is described in chapter 5.

After carefully removing the rings from the pots, the samples were saturated in the laboratory by slowly raising a water table from below, and leaving the samples submerged for at least five days. Soaking the sample in water till a level just at the top is a convenient method to determine the MDC (Klute, 1986).

3.2.2 Methods used for characterization

The MDC and the hydraulic conductivity characteristic were determined by the evaporation method (Boels et al., 1978; Wind, 1969). Samples were prepared as described above using the larger rings. Four tensiometers were installed horizontally in the samples and the rings were placed on balances. The loss of water was registered by the balance. Simultaneously, the matric head was measured by a pressure transducer. A measuring interval of 1 hour was used. A computer model was used to analyse the data and to calculate the water retention and the hydraulic conductivity characteristic (Fyslab. I.C.W., 1988). The measurements were done in quadruplicate. Hysteresis in the water retention characteristic and effects of repeated flooding and root growth were measured on suction tables (Klute, 1986; Stolte and

Veerman, 1990). A drying curve and a wetting curve, with a reversal point at h_m = -2 m, were determined in duplicate. The effect of repeated flooding was measured in triplicate. The hydraulic conductivity at saturation was measured in triplicate by the constant head method (Klute and Dirksen, 1986).

3.2.3 Parameter estimation

Equations 3.1 and 3.9 are used in this study. Van Genuchten et al. (1991) and Leij et al. (1992) developed a nonlinear least square fitting procedure (RETC) to estimate the parameters K_s, ℓ, α_d, n (and m), θ_s and θ_r. The procedure can be used to fit retention data and conductivity data separately or simultaneously. Options of the procedure are discussed by Leij et al. (1992). A simultaneous fit of the MDC and hydraulic conductivity data is used in this study. Since the precision of the conductivity data is supposed to be an order of magnitude less than that of the retention data, a weighing factor, expressing this difference, was set at 0.1. This is consistent with the studies of Wösten and van Genuchten (1988) and de Vos et al. (1992). The saturated hydraulic conductivity is not included in the fitting procedure but fixed at the measured value.

Since the MWC is not determined, a scanning wetting curve is used to estimate the value of α_w, as suggested by Kool and Parker (1987). The residual water content, θ_r^* for the scanning wetting curve with a reversal point at h_m=-2 m, is calculated according to equation 3.4. To fit the scanning wetting curve, the parameters n, m and θ_s are fixed at their values as determined for the MDC. This way the model RETC is run with α_w as the only unknown variable.

3.3 Results

3.3.1 Water retention characteristic

Sample preparation without artificial pressure resulted in a bulk density of 100 kg m^{-3}. There was no difference in bulk density ρ_s between rings used with the evaporation method and smaller rings that were placed in the pots. Using a potting medium density γ_s equal to 1040 kg m^{-3} (measured data Bakker and Kabat, 1990), total porosity is calculated to be 0.90 (equation 2.7). Figure 3.1 shows the MDC, measured according the evaporation method. Even at high matric heads, a large part of the pores was filled with air. The volumetric water content at h_m = -0.10 m was 0.7, and already half of the absorbed water was released at h_m = -0.40 m. The fitted relation according to the van Genuchten model is also presented in figure 3.1. The parameters leading to the best fit are given in table 3.2.

Table 3.2 Estimated parameters obtained by fitting the van Genuchten model (equation 3.1) to the measured water retention data.

Parameter	θ_r	θ_s	n	m	α_d	α_w	ℓ
Value	0.0	0.92	1.42	0.30	0.13	0.90	2.35

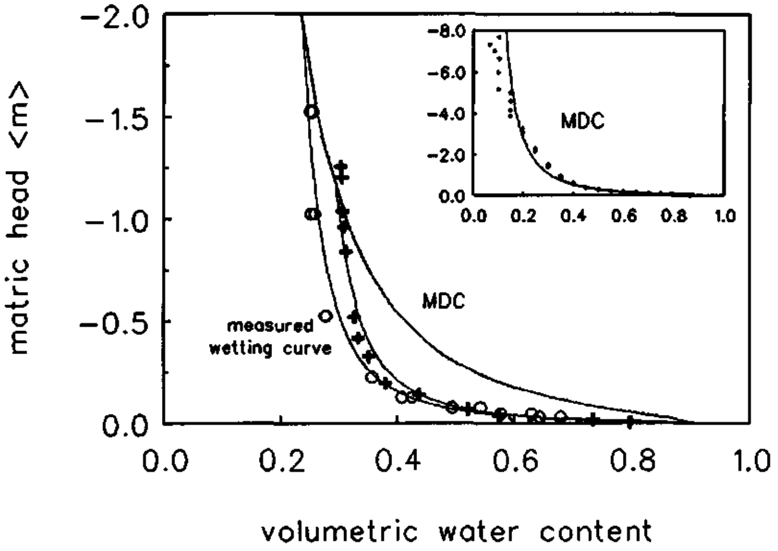


Figure 3.1. The measured MDC and two measured scanning curves. The measured wetting curve indicated by the plus signs are data obtained from Bakker and Kabat (1990). The lines are obtained by fitting according the models proposed by van Genuchten (1980) and Kool and Parker (1987).

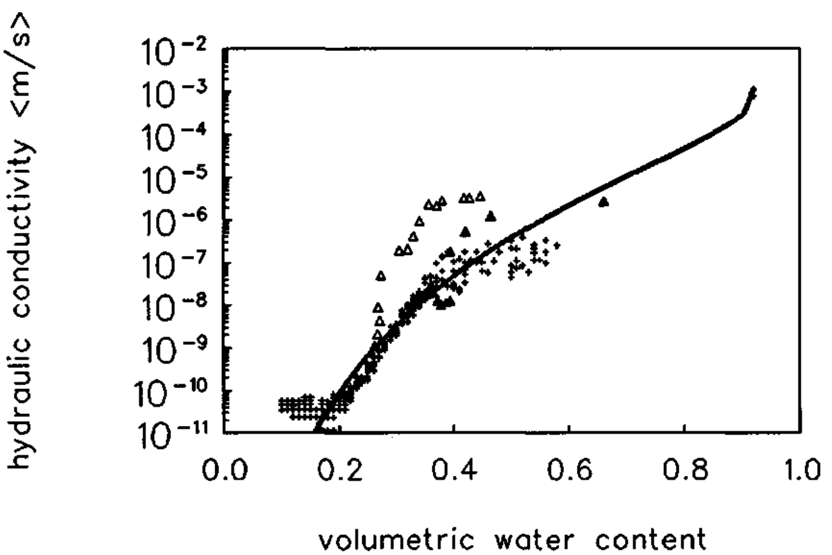


Figure 3.2. Measured and fitted hydraulic conductivity characteristic. The plus signs refer to the evaporation method; data obtained from Bakker and Kabat (1990) are presented by open triangles (sample 1), or closed triangles (sample 2).

Measured data of a wetting curve starting from h_m = -2 m to saturation were used to fit parameter α_w. Best fit was obtained with $\alpha_w = 0.9$ (cm^{-1}). Using this parameter value and equations 3.1 and 3.4, a wetting curve starting from -1.2 m was calculated. This curve is in close agreement with a wetting curve measured by Bakker and Kabat (1990). Both fitted and measured wetting curves are presented also in figure 3.1.

3.3.2 Hydraulic conductivity characteristic

The conductivity at saturation equaled 1.00 10^{-3} m s^{-1} (s.d. 1.46 10^{-4}). The hydraulic conductivity decreased several orders of magnitude from 10^{-3} m s^{-1} near saturation, to less than 10^{-10} m s^{-1} at volumetric water contents below 0.2 (figure 3.2). Since the hydraulic conductivity at high volumetric water contents is very high, the matric head gradient in the sample was very small during the initial stage of evaporation. Therefore, calculation of the hydraulic conductivity at volumetric water contents above 0.4 became less accurate and was even impossible at volumetric water contents above 0.6, with the evaporation method. Additional data from two samples, obtained with a special apparatus for measurements at higher water contents, were taken from Bakker and Kabat (1990) (figure 3.2). Only sample 2 of their data agreed well with the data obtained with the evaporation method. They found higher conductivities for their first sample, but sample preparation before characterization was not identical to that used for the second sample, and to the method used in this research. Since there were no data available in between θ=0.6 and saturation, the conductivity at saturation was fixed at the measured value of 1.00 10^{-3} m s^{-1} (86.7 m day^{-1}), and the conductivity data at θ<0.6 were fitted simultaneously with the retention data. Best fit was obtained with the parameters given in table 3.2.

3.3.3 Effect of plant roots and repeated wetting and drying

An effect of fertigation schedule and plant roots on the water retention characteristic is shown in figure 3.3. The fertigation schedule and the dynamics of water in the potting medium as affected by the fertigation schedule are being discussed in chapter 5. Samples that were left on the flooded bench system for one or three months had a water retention characteristic slightly different from the original material. Even samples from pots without plants showed an increased water retention in time (figure 3.3 a-c). This increase was for samples that did not contain roots not affected by the fertigation schedule. After one month on a flooded bench fertigation system, all samples showed an increased water retention. At high matric heads, the difference was hardly significant, but at -1 m head θ increased from 0.32 to 0.40.

For samples with roots, on the other hand, water retention was different among the fertigation schedules. An increase in θ at all matric heads was found for the pots that were continuously flooded (figure 3.3 d). An increase at matric heads below -0.3 m was found for samples that were flooded four times a week, but no effect was found at higher matric heads (figure 3.3 e). This increase was less pronounced than for plants that were flooded continuously. A decrease in water retention, on the other hand, was found for plants that were flooded twice a week (figure 3.3 f). The volumetric water content of these samples decreased on the flooded bench system sometimes to values as low as 0.05, which may have contributed to this exceptional change in the water retention characteristic. Organic material becomes somewhat more hydrophobic once it becomes dry (Beardsell and Nichols, 1982).

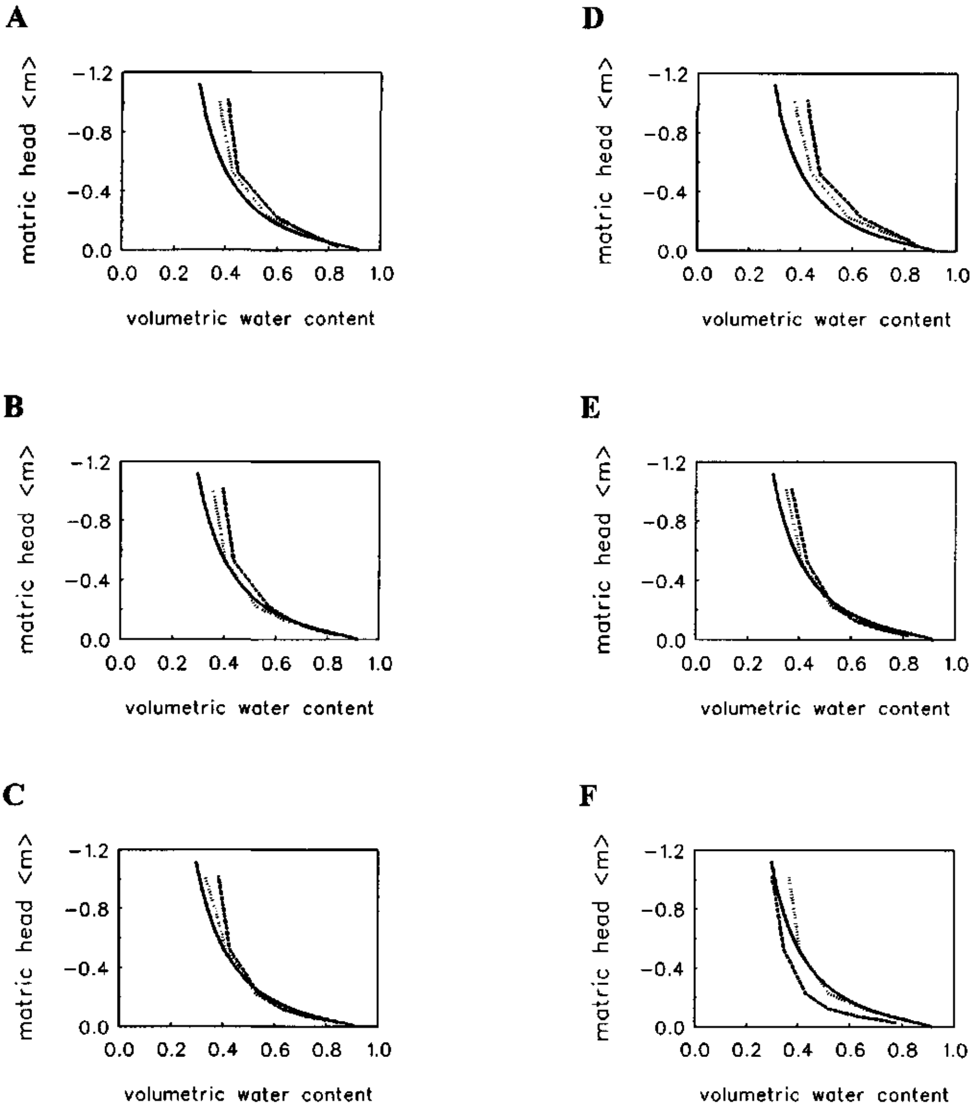


Figure 3.3. The change of the water retention characteristic in relation to fertigation schedule, measured in the presence or absence of plant roots. The original material (MDC) is presented by the continuous line, the characteristic after 1 month by the dotted line, and the characteristic after three months by the dashed line.
continuously flooded: without (A) and with (D) plant roots.
flooded four times a week: without (B) and with (E) plant roots.
flooded twice a week: without (C) and with (F) plant roots.

3.4 Discussion

Sample preparation has a strong influence on the physical characteristics. In particular bulk density affects the physical characteristics of the potting medium (Bakker and Kabat, 1990). De Kreij and de Bes (1989) compared several methods for physical characterization of horticultural media. These methods differ in the way of filling the cylinders (with or without compaction), and in method of wetting the medium. They preferred a method in which densities are found to be comparable with those under practical horticultural conditions and concluded that a good method includes filling the cylinders without artificial pressure and achieving an appropriate setting by flooding from beneath. Bragg and Chambers (1988) used three cycles of wetting and drying from beneath to obtain the final bulk density. In this experiment samples were treated the same way as the potted plants. It is therefore expected that the samples reflect the natural conditions as much as possible, which is necessary to obtain meaningful data.

The fitted water retention characteristic is in good agreement with the measured data (R^2=0.974). Volumetric water content is slightly underestimated between -1 and -3 m head, and at lower heads the fitted curve tends to overestimate volumetric water content. At heads above -1 m head the fitting is in close agreement with the measurements. Other researchers (Milks et al., 1989; and Nelson and Fonteno, 1991; Wallach et al., 1992a, 1992b) who successfully used this fitting procedure for different substrates, only reported data at high matric heads, since those are of most practical importance. The fitted water content at saturation was equal to 0.92. This is in close agreement with the calculated porosity of 0.9. Nevertheless, this may be an overestimate since generally, a value of θ_s is found to be lower than the total porosity due to entrapped air (Klute, 1986). The best fit was obtained with a residual water content θ_r=0. This may be due to the absence of data in the drier region (Wösten and van Genuchten, 1988). The steepness of the curve is mainly determined by parameter α, which for the MDC was fitted at 0.13. This value is high compared to that of soils (Wösten, 1987), but higher values are also reported for other horticultural media (table 3.1). A higher value results in a steeper curve and higher air contents at high matric heads. A sufficiently high air content at -0.10 m matric head is considered an important characteristic of horticultural media (De Boodt and Verdonck, 1972; Verdonck and Gabriëls, 1988). Opinions with regard to this air content are different among investigators: Bunt (1974) required air contents above 10% by volume; Puustjarvi (1974) 45%; and Verdonck et al. (1974) found that container grown plants require a minimum air content of 15%. The air content of the medium used in this study is 22% at -0.10 m head. This air content is probably sufficient, since this medium gave in earlier studies excellent plant growth with high irrigation frequency (de Kreij and Straver, 1988).

It is shown by Bilderback and Fonteno (1987) that the container geometry and water retention must be considered together rather then discussing physical properties alone, since air content in potted plants is affected by container geometry, especially by its height. They introduced the container capacity, CC, defined as the amount of water held by the potting medium after drainage from saturation. CC can be determined experimentally (Bragg and Chambers, 1988), or calculated from the water retention characteristic and the known container geometry (Fonteno, 1988). For the potting medium, described in this chapter, combined with a pot as used in the experiments and described in chapter 5 (0.12 m height,

10^{-3} m^3 volume), the CC equals 0.82 10^{-3} m^3, which means that the volumetric air content is 10%.

Hysteresis has a large effect on θ at a given matric head. Both wetting scanning curves were described properly with equation 3.1 using $\alpha_w = 0.90$. This gives a ratio α_w/α_d equal to 7.5, which is much higher than the approximation $\alpha_w/\alpha_d \approx 2$ suggested by Kool and Parker (1987) for soils, but is consistent with Wallach et al. (1992a), who also found that organic material used in horticultural media shows strong hysteresis (table 3.1). To obtain wetting scanning curves, reversals from the MDC were done at -2.0 and at -1.2 m matric head. Within this range the water retention characteristic is easier to determine and it covers the range which is of most practical importance (Wallach et al., 1992a). The MWC is not measured but calculated, using α_w and equation 3.1. The calculated MDC and MWC are shown in figure 3.4. Some experimental data of in situ measurements of θ and h_m for periodically flooded plants are also shown in this figure. The method to obtain these data is described in chapter 5. As expected, all data points are in the domain bounded by the MDC and the MWC.

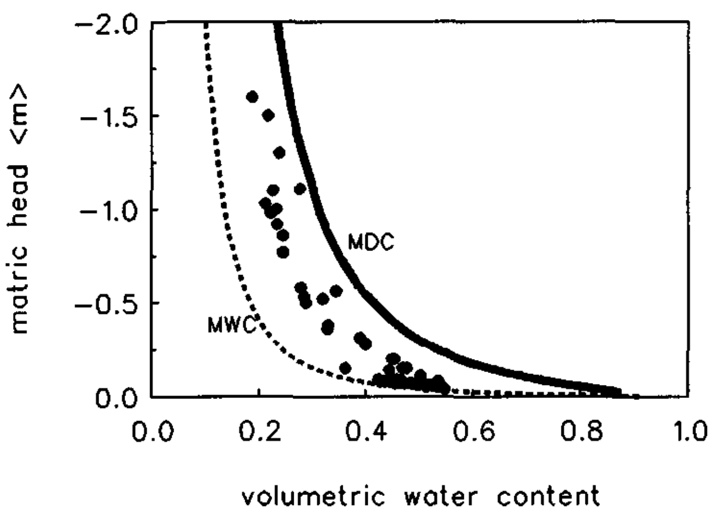


Figure 3.4. The calculated MDC and MWC and experimental data of in situ measured volumetric water content and matric head for periodically flooded plants.

Water retention increased during plant growth for most samples, a phenomenon observed also by others (de Kreij, 1989; Nelson and Fonteno, 1991). This cannot be explained by a change in density, since density was not affected significantly by irrigation schedule. Nevertheless water retention increased in time for all samples without roots. This may partly be due to rearranging particles after repeated wetting and drying although Bragg and Chambers (1988) and White and Mastalerz (1966) reported that the final setting of the potting medium is achieved after three cycles of wetting and drying. Decomposition of organic material may be an additional cause of increasing water retention (Klougart, 1983). Organic matter content decreased from 0.707 to 0.684 g/g in two months. The presence of roots affected the water retention characteristic. Roots may reduce overall pore space and increase water retention at lower matric heads (Nelson and Fonteno, 1991). In the presence of roots, the change in water retention in time was strongly affected by the irrigation schedule, which makes it difficult to predict. Nevertheless, the water retention does change in time, the importance of which will be discussed in chapter 7.

The hydraulic conductivity at saturation is high compared to soils, but is within the range reported for several horticultural media (table 3.3). With decreasing water content the hydraulic conductivity decreased rapidly (figure 3.2). As a result, the hydraulic conductivity is considerably less than the conductivity at saturation, even at high matric heads, often found in horticultural media. The hydraulic conductivity is fitted with the combined van Genuchten Mualem equation (3.6). Since there are no data at θ higher than 0.60, the model is used to interpolate in between the data at lower θ, and the conductivity at saturation. Best fit was obtained with parameter ℓ=2.35. This value is quite different from the value 0.5 suggested by Mualem (1986). Fitting with ℓ=0.5, however, resulted in an overestimation of the hydraulic conductivity compared with the measurements. Wösten and van Genuchten (1988) suggest to consider ℓ as a variable and found ℓ-values varying from -16 to 2.2 for different soils. Although ℓ for the medium used in this study is higher than 0.5, this does not mean that ℓ deviates from 0.5 also for other horticultural media. Wallach et al. (1992a, 1992b) found good agreement between calculated and measured conductivity in several horticultural media with parameter ℓ fixed at 0.5. However, the measurements do show that it is not possible to estimate the hydraulic conductivity based only on the water retention characteristic and the conductivity at saturation, assuming ℓ equal to 0.5.

3.5 Conclusions

The results support the use of existing models frequently applied to soils, for describing the physical characteristics of the potting medium used in this study. The water retention model proposed by van Genuchten (1980) provides a useful tool to describe water retention. Others demonstrated its use for other horticultural media (Milks et al., 1989; Wallach et al., 1992a, 1992b). An empirical model to describe hysteresis proposed by Kool and Parker (1987) can successfully describe scanning wetting curves in the range of matric heads of -2.0 m up to saturation, which is in practice the most important range of the water retention characteristic. Combined with the hydraulic conductivity model of Mualem (1976), a useful model is obtained to describe hydraulic conductivity of the potting medium, using only two unknown additional parameters. With these models it is possible to describe the physical characteristics of the potting medium, including hysteresis in the water retention characteristic, by a set of eight parameters.

Table 3.3. The saturated hydraulic conductivity for several horticultural media.

medium	K_s cm day^{-1}	reference
composted grape marc (CGM)	749	Wallach et al. 1992b
'red' tuff (0-8 mm) (RTB)	6048	Wallach et al. 1992b
80% RTB + 20% CGM	5342	Wallach et al. 1992b
60% RTB + 40% CGM	10540	Wallach et al. 1992b
'red' tuff (0-1 mm, sieved)	662	Wallach et al. 1992a
'red' tuff (1-2 mm, sieved)	12068	Wallach et al. 1992a
'red' tuff (2-4 mm, sieved)	14962	Wallach et al. 1992a
brown reddish sandy soil	150	Chen et al. 1980
coarse sand	780	Chen et al. 1980
heavy clay soil (Terra rossa)	15	Chen et al. 1980
heavy clay soil (alluvial)	0.05	Chen et al. 1980
black tuff (2 - 4 mm)	9288	Chen et al. 1980
red tuff (2 - 4 mm)	10224	Chen et al. 1980
fine perlite (0 - 2 mm)	307	Chen et al. 1980
coarse perlite (0.2 - 2 mm)	780	Chen et al. 1980
poplar leaves	204	Ünver et al. 1983
Creek sand	172	Ünver et al. 1983
volcanic tuff	368	Ünver et al. 1983
silvabark	136	Ünver et al. 1983
raw turf	66	Ünver et al. 1983
v. coarse perlite (0.5-4 mm)	56	Ünver et al. 1983
coarse perlite (0.4-2 mm)	22	Ünver et al. 1983
vulcanic tuffs	>50000	Bech et al. 1983
silty gravel	288	Klougart 1983
coarse peat	1152	Klougart 1983
fine peat	1728	Klougart 1983
peat + gran. stonewool 1:1	4272	Klougart 1983
granulated stonewool	16632	Klougart 1983
coarse polyphenol foam	39120	Klougart 1983
stonewool-plates	49056	Klougart 1983
black tuff, in use for 1 to 13 years	760 to 4128	Galin and Singer 1988
red tuff, in use for 1 to 13 years	1032 to 3888	Galin and Singer 1988
red yellow tuff, in use for 1 to 13 years	1032	Galin and Singer 1988
peat-sand-sawdust mix (1:1:1)	16128	Chen et al. 1992

4. Cation adsorption by the potting medium

One of the most important mechanisms which regulates the availability of nutrients in the root zone is the exchange of cations. Negative sites present at organic material are able to adsorb cations such as K^+, Na^+, Mg^{2+} and Ca^{2+} at ratios determined by affinity with the adsorbing sites and the concentrations in the liquid phase. Adsorption of cations strongly affects their spatial distribution within the root zone, e.g. K was found to accumulate in lower layers of a potting medium containing clay on a flooded bench system as a result of strong adsorption of K at the clay minerals (Reischmann, 1985). The cation exchange capacity (CEC) is defined as the amount of cations that can adsorb per unit weight and is usually expressed as milli-equivalents per 100 g. CEC varies among horticultural media from almost zero for perlite to more than 100 meq $100g^{-1}$ for peat and vermiculite (Bunt, 1976). Since peat is the major component of the potting medium in this study (75% peat, 25% perlite), the CEC of the potting medium is expected to be dominated by the CEC of peat. Organic matter, especially humic substances, contain carboxylic and phenolic groups which are capable of releasing and adsorbing hydrogen ions. CEC of organic matter depends on dissociation of these weak acids, which increases as the pH rises (Raviv et al., 1986). Peat exhibits a low initial pH and CEC level. In order to increase pH, lime ($CaCO_3$ + $MgCO_3$) is added to the medium, and thus Ca and Mg replace H-ions. As a result not only pH but also CEC increases. CEC of peat ranges from 80 to 300 meq/100g (Bolt and Bruggenwert, 1978; Bunt, 1976; Puustjarvi and Robertson, 1975). CEC generally increases with increasing degree of decomposition of peat (Harada and Inoko, 1975; Puustjarvi and Robertson, 1975), and with increasing pH (Raviv et al. 1986). CEC values are usually reported at pH 7.0. Since optimum pH for nutrient availability of a peat based potting medium ranges from 5.0 to 5.5 (Bunt, 1976), the CEC under normal growing conditions may be lower.

In this chapter, the cation adsorption capacity of the peat based potting medium and the affinity of the adsorption complex for macro elements like Na, K, Ca and Mg is described. The partitioning of cations between liquid and adsorbed phases is determined in samples obtained from the potting medium in which plants were grown on a flooded bench fertigation system. A numerical equilibrium model, derived from the exchange model of Robbins et al. (1980), is used to simulate partitioning of total amount of cations among soluble and adsorbed phases. This model is used to discuss the relevance of the cation adsorption of the potting medium for nutrient availability and for fertigation of potted plants. The model will be incorporated into a solute transport model to study the dynamic behaviour of nutrients in potted plants grown on a flooded bench fertigation system.

4.1 Principles of a cation exchange model

Partitioning the total amount of cations between the liquid and adsorbed phase is accomplished following the cation exchange model of Robbins et al. (1980). The model assumes that the CEC is constant, which in case of organic matter is only valid if pH and ionic strength of the liquid phase are constant. Further, it is assumed that cation exchange is a reversible process and that the sum of Ca, Mg, K and Na is equal to the CEC:

$$CEC = \gamma_{Ca} + \gamma_{Mg} + \gamma_{K} + \gamma_{Na} , \qquad 4.1$$

where γ is the exchangeable cation (meq $100g^{-1}$) and the subscripts denote the cations under consideration. The exchange equilibrium is presented by selectivity coefficients, which are defined as:

$$\frac{[A] \times N_B}{[B] \times N_A} = K_{A,B} , \qquad 4.2$$

for homovalent exchange (mono-mono- or di-divalent), and as

$$\frac{[A] \times N_B}{[B]^{0.5} \times N_A} = K_{A,B} , \qquad 4.3$$

for mono(A)-divalent(B) exchange, respectively. The brackets denote the activity of the cations, and N is defined as the fraction of the adsorption complex occupied with the cation. The coefficient for homovalent exchange is known as the Kerr-constant, only the activity of the cations is used rather than the concentration. The selectivity coefficient for mono-divalent exchange equals the reciprocal of the constant known as the Gapon exchange constant (Bolt and Bruggenwert, 1978). The composition of the liquid and of the adsorbed phases can be calculated with six selectivity coefficients, $K_{Ca,Mg}$, $K_{Na,Ca}$, $K_{K,Ca}$, $K_{K,Mg}$, $K_{Na,Mg}$, and $K_{Na,K}$ and six corresponding equilibrium conditions as presented in equations 4.2 and 4.3. The compositions are calculated following the solution scheme proposed by Robbins et al. (1980). The model requires CEC, six selectivity coefficients for exchange reactions, total amounts of cations present, volumetric water content, and bulk density as an input. It gives for all cations the amount adsorbed and concentrations in the liquid phase as output. A FORTRAN listing of the submodel, incorporated in a solute transport model, is given by Robbins (1991).

4.2 Materials and methods

A method proposed by Bascomb (1964) was modified so that cation exchange capacity could be determined under restricted pH and ionic strength conditions (Rhoades, 1982). CEC of the peat component of the potting medium is determined at three values of pH, and at two values of ionic strength. The CEC of the perlite component is determined at two values of pH and at two values of ionic strength. The pH and ionic strength values are presented in table 4.1. An ionic strength of 0.006 corresponds with an EC value approximately equal to 0.5 mS cm^{-1}, and ionic strength of 0.06 corresponds with an EC value approximately equal to 5 mS cm^{-1}. Eight gram of the peat was put into six percolation columns (0.4 m long). The columns were saturated from below followed by percolation with 40 ml water. Subsequently, the adsorption sites were saturated with Ba, by percolation with 40 ml $BaCl_2$ (0.2M), and by percolation with 80 ml $BaCl_2$ (0.05M). This was followed by a percolation with a $BaCl_2$ solution about equivalent to the desired ionic strength and acidified with HCl to the desired pH. For an ionic strength of 0.006M this concentration was 0.002M $BaCl_2$, and for an ionic strength of 0.06 this concentration was 0.02M $BaCl_2$. Three pH values were realized by adding respectively 0, 0.5, or 5 ml HCl (0.05n) to the percolation solution. This procedure was also used for two columns with eight grams of perlite, but for the perlite columns only two pH values were used by adding respectively 0 and 1 ml HCl to the percolation solution. After this procedure, the samples were removed from the columns and dried. The dry material (0.5 g) was equilibrated with 20 ml $MgSO_4$ (0.02M), to replace Ba with Mg. The resulting $MgSO_4$ solution was adjusted to the proper pH and ionic strength according the procedure outlined by Gillman and Sumpter (1986) and Kalisz (1986). CEC was calculated from the Mg lost in the solution according to the procedure given by Rhoades (1982).

Selectivity coefficients for the equilibrium between cations in the liquid phase and exchangeable cations were determined by bringing the sample in equilibrium with a solution of a known composition, followed by determination of the composition of the adsorption complex. Eight gram of perlite, or peat, or the potting medium were put into 0.40 m long percolation columns. The columns were percolated with 0.3 liter of a solution that was 100 times more concentrated than the desired solution. This was followed by a percolation with 0.5 liter with the desired solution. Two different solutions were used, the composition of which is presented in table 4.2. After this procedure, the composition of the percolate was identical to that of the solution. Samples were removed from the columns and gravimetric water content was determined. Adsorbed cations were exchanged by adding 40 ml 0.1M $BaCl_2$ to 0.5 gram dry sample and K, Na, Ca and Mg were determined in the solution after filtration. The adsorbed amount of cations was calculated from the measured concentrations in the filtrate and corrected for the amount present in the liquid phase retained after the percolation procedure. The latter was assumed to be equal to the product of the gravimetric water content and the concentration of the cation in the percolate.

Twenty-four samples of potting medium from potted plants grown on a flooded bench fertigation system were analyzed to determine adsorption equilibria occurring in the potting medium under natural conditions. All samples were taken from the lower half of the potting medium after one month of growth. Each of the samples was split in two. One subsample was centrifuged in a special type of tube ("Sissingh tube"). In these tubes the sample is separated from a cup underneath by a paper filter. The tubes were placed in a centrifuge and the liquid phase was collected in the cup (5 minutes centrifuged followed by 15 minutes with 3000 rpm). The solution was analyzed for pH, Ca, Mg, Na and K. The second subsample was used for determination of the organic matter content, and for total analyses of Ca and Mg. Adsorbed and soluble K and Na in this sample were determined after extraction by hydrochloric (0.1n) and oxalic (0.4n) acid (1:10 w/v extract). Exchangeable cations were calculated as the difference between the total amount (subsample 2) and the amount in the liquid phase (subsample 1). The latter was obtained as the product of the concentration in the liquid phase and the gravimetric water content.

4.3 Results

The cation exchange capacity of the peat component of the potting medium was strongly affected by pH (table 4.1). The pH of the original material was 3.9 and the corresponding CEC was slightly below 40 meq $100g^{-1}$. Addition of $Ba(OH)_2$ to increase the pH, significantly increased CEC, especially when raising the pH from 3.9 to 5.4. The effect of ionic strength on CEC was less significant. The largest increase was found at pH of 5.4, and was 8 percent when increasing ionic strength from 0.006 to 0.06. The CEC of perlite was in the order of 5 meq $100g^{-1}$ or less for all samples. The pH was difficult to control for these samples, but the data suggest that there was no significant effect of either pH or ionic strength on CEC of perlite.

Table 4.1. CEC (meq $100g^{-1}$) of peat and perlite components of the potting medium in relation to pH and ionic strength (I) (n=2).

component	peat						perlite			
I	0.006			0.06			0.006		0.06	
pH	3.9	5.4	6.8	3.9	5.4	6.8	5.1	5.2	4.7	5.3
CEC	38	106	119	39	115	126	3	5	5	1

Table 4.2. CEC and composition of the adsorption sites (ads, meq $100g^{-1}$) for peat, perlite and the potting medium, after equilibration with a solution containing K, Na, Ca and Mg (sol, meq l^{-1}).

component	K		Na		Ca		Mg		total CEC
	ads	sol	ads	sol	ads	sol	ads	sol	
peat pH=3.6	< 0	1	2.1	3	32.6	4	8.5	2	43.2
	1.6	1	1.2	1	30.1	2	15.9	2	48.8
perlite pH=6.2	< 0	1	0.7	3	0.1	4	0.1	2	0.9
	0.1	1	0.8	1	0.2	2	0.1	2	1.2
potting medium pH=6.5	0.1	1	1.8	3	58.2	4	14.5	2	74.6
	1.2	1	2.7	1	49.3	2	23.3	2	76.5

There was a considerable difference in adsorption of K, Ca, Mg and Na on peat. Ca and Mg together occupied more than 95% of the adsorption sites (table 4.2), and among these, Ca was adsorbed at most. The total amount of cations adsorbed on peat (which had a pH of 3.6) was about 46 meq $100g^{-1}$, which was slightly higher than the measured CEC of peat at pH 3.9. Both perlite samples indicated that Na was adsorbed more strongly than the other cations by perlite. The selectivity for cation adsorption by the potting medium, which is a mixture of the peat and perlite, was dominated by that of peat. The total adsorption was higher for the potting medium which was a result of the higher pH (pH=6.5).

Table 4.3 shows the composition of the adsorption complex and the liquid phase for the 24 samples of potting medium that had been used to grow plants on a flooded bench fertigation system. The adsorbed amount and the amount in the liquid phase are both given per 100 g dry potting medium. For all samples, Ca was the major component adsorbed by the potting medium followed by Mg. Only small amounts of Na and K were adsorbed. The amount of Ca adsorbed was 12 to 22 times higher than the amount present in the liquid phase. For Mg this ratio ranged from 5 to 10. For both Na and K, the ratio was below 1.0, indicating that the quantity in the liquid phase exceeded the quantity adsorbed. Selectivity coefficients as defined by equations 4.2 and 4.3 were calculated for all samples and are presented in table 4.4.

Table 4.3. CEC, EC of the liquid phase, percentage organic matter (OM), gravimetric water content (w), pH and amount of K, Na, Ca and Mg retained by 100 g potting medium divided between adsorbed and liquid phase (respectively ads and sol, both expressed as meq per 100 g potting medium).

no	K		Na		Ca		Mg		CEC	EC	w	% OM	pH
	ads	sol	ads	sol	ads	sol	ads	sol					
1	3.2	4.6	0.4	0.4	57.1	4.2	16.5	2.3	77.2	2.3	5.4	70.5	5.4
2	2.9	3.3	0.3	0.4	57.1	2.9	18.2	2.0	78.5	1.8	5.6	70.1	5.5
3	2.9	4.9	0.3	0.5	57.2	4.5	17.2	2.8	77.6	2.5	5.8	70.8	5.5
4	1.7	4.7	0.1	0.7	53.8	4.5	18.2	2.8	73.8	2.0	7.3	70.1	5.6
5	2.5	3.4	0.3	0.5	54.0	3.4	18.3	2.2	75.1	1.8	5.6	70.6	5.7
6	2.9	5.1	0.4	0.8	56.6	4.8	16.2	3.0	76.1	2.6	5.9	70.2	5.5
7	2.0	3.9	n.d	0.5	49.0	3.0	23.8	3.3	74.8	2.4	4.4	71.6	5.4
8	2.6	2.9	n.d	0.5	47.1	2.3	24.1	2.7	73.8	2.0	4.7	69.9	5.5
9	3.3	3.8	n.d	0.5	48.7	3.1	24.1	3.2	76.1	2.6	4.4	70.2	5.4
10	1.6	3.1	n.d	0.6	47.2	2.8	23.9	3.0	72.7	2.2	5.0	70.0	5.5
11	0.8	2.9	n.d	0.5	48.1	2.5	22.6	2.8	71.5	2.0	4.7	70.2	5.5
12	1.8	4.0	n.d	0.8	47.1	3.4	22.7	3.4	71.6	2.6	4.7	70.9	5.3
13	2.1	3.5	n.d	0.7	47.9	2.8	23.3	3.0	73.3	2.6	4.3	70.5	5.4
14	2.0	4.5	n.d	0.8	55.7	4.3	16.2	2.6	73.9	2.2	5.6	65.8	5.5
15	1.5	2.8	n.d	0.7	48.9	2.5	22.8	2.7	73.2	2.0	4.8	72.1	5.5
16	1.6	3.6	n.d	0.8	57.1	3.5	18.2	2.2	76.9	1.8	6.2	71.6	5.7
17	1.9	3.7	n.d	0.8	49.3	3.1	22.9	3.1	74.1	2.5	4.4	72.3	5.4
18	2.7	4.8	n.d	0.8	58.9	4.5	16.8	2.6	78.4	2.2	5.9	70.5	5.5
19	0.8	3.1	n.d	1.0	45.2	3.9	22.4	3.0	68.4	2.4	4.7	70.6	5.5
20	1.8	3.6	n.d	0.9	54.9	3.4	16.5	2.4	73.2	2.1	6.0	69.8	5.6
21	2.2	3.9	n.d	1.3	45.4	3.3	21.3	3.5	68.9	2.6	4.7	70.6	5.3
22	2.6	4.7	n.d	1.2	53.4	4.5	14.4	2.8	70.4	2.6	5.5	68.8	5.4
23	1.1	2.7	n.d	0.8	47.6	2.2	22.9	2.6	71.6	2.2	4.5	71.4	5.5
24	1.6	3.1	n.d	0.8	57.1	2.7	18.6	1.9	77.3	1.8	5.6	70.6	5.7

Table 4.4. Calculated selectivity coefficients for cation adsorption by both peat, both perlite, and both potting medium samples from table 4.2, and the average value for 24 samples from potted plants occurring under natural conditions (table 4.3).

sample	$K_{Ca,Mg}$	$K_{Na,Ca}$	$K_{K,Ca}$	$K_{K,Mg}$	$K_{Na,Mg}$	$K_{Na/K}$
peat	0.52	1.04	n.d.	n.d.	0.38	n.d.
peat	0.53	0.79	0.59	0.31	0.42	1.33
perlite	2.0	0.01	n.d.	n.d.	0.013	n.d.
perlite	0.5	0.008	0.06	0.03	0.004	0.13
pot. med.	0.50	2.17	13.0	4.6	0.76	0.17
pot. med.	0.47	0.57	1.30	0.61	0.27	0.44
samples	0.47 n=24, s.d.=0.05	4.3 n=6, s.d.=2.9	3.78 n=24, s.d.=1.39	1.65 n=24, s.d.=0.74	1.73 n=6, s.d.=1.30	1.32 n=6, s.d.=0.58

4.4 Discussion

CEC of peat strongly increased with increasing pH at both electrolyte levels. The average CEC increase was 28 meq per unit pH increase which is close to the reported value of 30 meq by Helling et al. (1964), although CEC of the potting medium did not increase linearly with pH. As the pH was raised from 3.9 to 5.4, the CEC increased more compared to an increase in pH from 5.4 to 6.8. This result agrees with those of Harada and Inoko (1975). Increasing the ionic strength of the solution only slightly increased the CEC. The maximum increase was 8 percent as ionic strength increased by a factor 10. Reported effects of ionic strength on CEC of organic matter vary among investigators. No effect was reported by Harada and Inoko (1975) for salt concentrations of 0.005N, 0.05N and 0.2N. Kalisz (1986) however reported CEC to increase with the square root of the ionic strength over the experimental range of 0.006 to 0.096 M. Since an increase of the ionic strength by a factor 10 or more will only be found in the upper few centimeters of pots placed on a flooded bench fertigation system, and since organic matter highly buffers against changes in pH, the CEC of potting medium is assumed to be relatively constant throughout the cultivation period.

CEC of perlite was very low, which agrees with data reported by others (Bunt, 1976; Raviv et al., 1986). As a result, addition of perlite will reduce the CEC of the potting medium almost in accordance with the fraction of perlite present in the potting medium. The pH of the potting medium in table 4.2 was 6.5. If the medium would have consisted of peat only, a CEC of 116 would be expected at this pH (table 4.1). The actual CEC was 75.6 (table 4.2), which is only 65% of 116. This is close to an expected decrease based on the organic matter content of 68% for these samples. For samples obtained from potted plants grown on a flooded bench system, CEC varied from 68.6 to 79.3. This agrees with the expected values, based on pH and organic matter content. At all pH and ionic strength levels, the CEC of the potting medium and peat was much higher than the reported lower boundary for an optimal substrate of 20 meq $100g^{-1}$ (Abad et al. 1989).

Both divalent cations Ca and Mg were adsorbed more strongly than Na and K by peat and potting medium. Perlite showed a somewhat greater adsorption of Na, but since

CEC of perlite is very low, this adsorption will be insignificant. The data in table 4.3 show that after one month with a crop, the adsorption complex of the potting medium was mainly occupied by Ca, and to a somewhat lesser extent by Mg. Compared to soils, the potting medium was more selective for adsorption of Ca and less selective for adsorption of K. Adsorption of K and Na by the potting medium was very low. This means that most of the Na which is added to potted plants, remains in the liquid phase. It also means that the availability of K for plant uptake is mainly determined by the concentration in the liquid phase. For Ca and Mg, however, a high buffering is expected since large amounts are adsorbed. The calculated selectivity coefficients varied significantly between samples from potted plants grown on a flooded bench fertigation system (table 4.4). There was no relation between variation of the selectivity coefficients and the occupation of the adsorption complex. The selectivity coefficients seemed to increase with decreasing pH, but the number of data was too small to determine a relation accurately. For Ca-Mg exchange the average selectivity coefficient was 0.47, which means that Ca is preferred over Mg by a factor of 2.1. This is higher than the average factor of 1.2 found for mineral soils (Bolt and Bruggenwert, 1978). A greater selectivity for Ca by organic soils as compared to mineral soils was also reported by Naylor and Overstreet (1969). K was preferred over Na by a factor of 1.3, which is smaller than the average factor of 5 found for mineral soils. Higher selectivity for K in soils is often a result of the presence of clays of the mica type (e.g. illites) or vermiculite (Bolt and Bruggenwert, 1978). For the potting medium, the presence of perlite may have reduced the selectivity for K as compared to peat, since perlite favoured adsorption of Na.

The adsorption of cations is an important mechanism which influences the concentration of cations in the solution surrounding plant roots. The concentration of Ca and Mg in the liquid phase is, unlike that of Na and K, highly buffered against factors that might change the composition of the solution, e.g. plant uptake or fertilization. Buffering of the potting medium can be illustrated by the following examples. Consider a potting medium with a volumetric water content of 0.25 and concentrations in the liquid phase of 4, 2, and 7 mmol/l of Ca, Mg and K respectively. Assume that with fertigation the volumetric water content is increased to 0.5. The optimal concentrations are assumed to be 3.5, 2, and 7 mmol/l for Ca, Mg, and K respectively. If cation adsorption is absent, irrigation water with a composition of 3, 2, and 7 mmol/l of Ca, Mg and K respectively would be adequate. However, irrigation water of this composition will hardly change the concentrations in the liquid phase, if the medium adsorbs cations to an extent as presented in this study. To decrease the Ca concentration in the liquid phase with 0.5 mmol/l, the composition of the irrigation water must contain no Ca, 5 mmol/l Mg, and 7 mmol/l K. The extra Mg is needed to replace the Ca liberated from the adsorption complex. This example assumes a perfect mixed system in equilibrium with the adsorbed phase. If the system is not mixed, like the potted plant system in which irrigation water enters the pot at the bottom, the situation becomes more complicated. Adsorption of cations may then be one of the factors which contributes to the spatial distribution of cations within the root zone of potted plants.

As a second example illustrating the important role of the buffer capacity of the potting medium as a result of adsorption, the effect of dilution of the liquid phase is discussed. Dilution occurs if the EC of the irrigation water is lower than the EC of the liquid phase, but also in analysis of the medium when extracts are used. In Dutch horticulture nutrients are often determined by a 1:1.5 volume extract. Divalent cations are more diluted than monovalent cations as a result of equilibration with the adsorption complex. Assuming a liquid phase with an average composition as given in table 4.3, the divalent cations are underestimated by 10 percent at least, while the monovalent cations are overestimated by more than 15 percent. Of course, other processes like dissolving of Ca and Mg precipitates may have an even stronger influence on the measured concentrations in the 1:1.5 volume extract (Sonneveld et al., 1990).

4.5 Conclusions

This study shows that a considerable amount of cations in a peat based potting medium is adsorbed by the solid phase. For samples from potted plants, an average CEC of 75 meq/100 g was found, while total sum of cations was only 12 meq in the liquid phase. CEC of the potting medium was mainly determined by organic matter content. CEC increased with increasing pH and increasing salt concentration of the liquid phase. For this reason, pH and ionic strength should be within the range occurring under normal growing conditions if CEC of a peat based potting medium is determined. Compared to organic matter, perlite has a negligible CEC. Addition of perlite therefore reduces the CEC of the potting medium. Under normal growing conditions, Ca and Mg occupy more than 95% of the adsorption sites, with Ca favoured over Mg by a factor of 2.1. Since adsorbed cations can become available for plant uptake, the adsorption complex of the potting medium considerably increases the available amount of Ca and Mg. On the other hand, the adsorption of cations strongly buffers the potting medium against changes induced by fertigation. This complicates the control of the cation composition of the liquid phase. Cation exchange models may help adjusting the fertigation schedule, since they can predict the changes of a system as a result of an external factor, e.g. the composition of the solution used for subirrigation.

5. Water content and matric head induced by evapotranspiration and flooded bench fertigation

The water content in the root environment of potted plants is closely related to loss and supply of water. Loss of water from the potting medium occurs through uptake by plant roots, or directly from the surface of the potting medium, both processes together defined as evapotranspiration, ET. Supply of water occurs as a result of flooding the benches the plants are standing on. Capillary rise of water during this flooding period is mainly determined by a one-dimensional vertical transport (chapter 2). Since ET is a continuous process and fertigation normally is intermittent, the water content of the potting medium will fluctuate. Levels between which the water content will fluctuate are determined by the amount of water added to the medium in relation to ET and pot volume. As pointed out in chapter 2, it requires knowledge of ET of potted plants to simulate the dynamics of water in the root environment. ET data and data describing dynamics of water in the root zone are only rarely available for potted plants grown on a flooded bench fertigation system.

The objective of this chapter is to describe the evapotranspiration of a *Ficus benjamina* grown on a flooded bench fertigation system in a greenhouse, and to describe the resulting dynamics of water in the root zone, as affected by fertigation schedule. The evaporation and transpiration data will be used as input data for a simulation model describing dynamics of water in the root zone. The measured dynamics of water in this chapter will be used to validate this model.

5.1 Materials and methods

5.1.1 Experimental setup

Evapotranspiration by potted plants and water content of the potting medium were investigated in three successive experiments. The first and second experiment were conducted in a small greenhouse in the spring and winter of 1990, respectively. The third experiment was conducted in a larger, more modern, greenhouse in the spring of 1992. Average air temperature was maintained at 23 ^{0}C in all experiments. During the third experiment, air humidity was controlled at 70%. *Ficus benjamina exotica* plants were potted in plastic pots (0.12 m height, 10^{-3} m^3 volume) filled with an "flooded bench mix" consisting of 25% perlite and 75% peat, and a basal fertilizer of 3.0 kg m^{-3} lime and 0.75 kg m^{-3} 13N-11P-23K. Physical characteristics of the potting medium are described in chapter 3, chemical characteristics in chapter 4. Plants were placed on benches with a density of 25 plants m^{-2}. The plants were fertigated by flooding the benches with a 0.02 m level of nutrient solution, each time of watering. In the first two experiments the EC of the nutrient solution was controlled manually; for the third experiment EC was controlled by computer. A detailed layout of the experiments, including the fertigation schedule, is given in table 5.1. The fertigation schedule in the third experiment was designed to include both dry and wet conditions, to allow for wider comparison with model calculations. The schedule was not altered during the cultivation period, even if conditions became less favourable for plant growth. Between continuously flooded pots the bench was covered with white plastic to prevent evaporation from the bench and growth of algae.

Table 5.1. Layout of the experiments.

experiment	1
period	April to June 1990 days of the year 103 to 180
surface	4 tables 3.8 m^2 each
fertigation schedule	continuously flooded with EC 2.2
experiment	2
period	October 1990 to April 1991 days of the year 280 (1990) to 100 (1991)
surface	8 tables 3.8 m^2 each (4 tables * 2 treatments)
fertigation schedule	1: continuously flooded with EC 1.8 2: twice a week flooded with EC 1.8
experiment	3
period	March to May 1992 days of the year 110 to 180
surface	18 tables 14 m^2 each (3 tables * 6 treatments)
fertigation schedule	1: continuously flooded with EC 1.7 2: four times a week for 30 minutes with EC 1.7 3: four times a week for 30 minutes with EC 2.2 4: four times a week for 5 minutes with EC 1.7 5: twice a week for 30 minutes with EC 1.7 6: twice a week for 30 minutes with EC 2.2

5.1.2 Plant growth and light interception

Shoot length, shoot fresh mass, shoot and root dry mass, and leaf area were measured monthly (n=6). Number of leaves was counted and leaf size was measured with a DELTA-T (Mk2) area measurement system. Light interception was periodically measured on cloudy days with a 0.80 m long tube PAR (= photosynthetically active radiation, 400 - 700 nanometer) sunfleck ceptometer (Decagon). PAR radiation was measured above and below plants (n=10). Assuming an exponential relation between light interception and LAI (Goudriaan, 1985), the measured interception data were fitted with:

$$I / I_o = (1 - \sigma) \times e^{(-k \times LAI)} , \qquad 5.1$$

where:

I	= PAR measured below plants	$W\ m^{-2}$
I_0	= PAR measured above plants	$W\ m^{-2}$
LAI	= leaf area index	$m^2\ m^{-2}$
σ	= canopy reflection coefficient	
k	= extinction coefficient obtained by fitting	

The canopy reflection coefficient, σ, is fixed at 0.056 (1-0.944) and is calculated as $(1-\sqrt{(1-SCV)})/(1+\sqrt{(1-SCV)})$, assuming the scattering coefficient of green leaves (SCV) to be 0.2 for visible light (Goudriaan, 1985).

5.1.3 Evapotranspiration

Evapotranspiration, ET, by continuously flooded plants was studied using 4 balances (Sauter-kom) attached to a computer (Hewlett Packard 85). On each balance a tray ($h \times w \times l$=0.04 × 0.5 × 0.6 m) was placed with a water reservoir (1.2 10^{-3} m^3) above it to maintain a water level of 0.02 m. On each tray 9 plants were grown with a plant density identical to plants grown on benches (25 plants m^{-2}). Plants on the balances were frequently exchanged with other plants from the benches. Balances were placed near the benches and surrounded by other plants to create conditions similar to those of plants grown on benches. On two balances, the potting medium of the plants was covered in order to determine transpiration (T) alone. Evaporation (E) was calculated as the difference between T and ET measured simultaneously on the other two balances. For periodically flooded plants, ET was measured by weighing 8 plants from each bench after flooding, and before the next flooding. ET was calculated from the difference of both masses.

Unless mentioned otherwise, ET rates are expressed per m^2 bench surface. The potting medium surface, however, only partly covers the benches. To convert the rates expressed per m^2 bench to rates expressed per m^2 potting medium surface, they are multiplied by 3.5.

5.1.4 Water absorption by the potting medium

For periodically flooded plants, absorption of water by the potting medium was determined by weighing plants before and after flooding. The amount of water absorbed while flooding, was calculated as the difference between both masses. After correction for mass of the pot, dry mass of the potting medium and plant mass, the mass of water retained by the potting medium was obtained. Plant mass data were derived from monthly measurements and interpolated for days in between. With the known total volume of the potting medium and density of water, the average volumetric water content was calculated.

5.1.5 Matric head of the potting medium

Tensiometers were used to measure the matric head of the potting medium. The relation between matric head and volumetric water content was discussed in chapter 3. Continuous measurements were made by a specially developed tensiometer system. The system consisted of 30 ceramic cups with a length of 65 mm and a diameter of 6 mm (Soil Moisture Equipment Corp, type 652X01-B1M1), each of them connected by a copper tube and a three-way stop-cock to a pressure transducer (type Honeywell 141PC15D). Details are given by van den Elsen and Bakker (1992). The transducers were divided over six waterproof boxes (CITO Benelux B.V, type 02.163609). Each box contained a power source (10 V) controlled by a trigger input (made by DLO Technical and Physical Engineering Research Service, TFDL-DLO). The trigger was activated by and voltage from the pressure transducers was registered on a HP3852A data acquisition and control unit. Tensiometers and pressure transducers were filled with deaerated water and each of them calibrated with an accuracy of 0.002 m.

In the second experiment the tensiometers were mainly used to measure local differences of matric head within the root environment. Five tensiometer cups were installed horizontally in the potting medium at heights of resp. 0.015, 0.035, 0.06, 0.085 and 0.105 m. Local extraction of water from the potting medium by plant roots may induce a vertical gradient in total head if redistribution of water cannot keep up with ET.

During the third experiment tensiometers were used to compare matric heads induced by the fertigation schedules. Only the schedules with an EC of 1.7 were used (table 5.1). For each of these schedules, a tensiometer was installed horizontally in the potting medium at a height of 0.06 m (n=8).

Periodically, one plant was used to measure matric head profile and ET for the same plant simultaneously. Therefore, five tensiometers were installed horizontally, at the heights mentioned earlier. This plant and tensiometer system were both placed on a balance to measure ET. A measuring interval of one hour was used for mass and matric head readings.

In a similar way matric head profiles induced by flooding were measured. A pot with five tensiometers installed horizontally was flooded for a period long enough to allow for maximal capillary rise. During flooding, matric head was measured at intervals of one minute.

5.2 Results and discussion

5.2.1 Plant development

Plant size and biomass partitioning were affected by fertigation schedule. Shoot mass, shoot-root ratio, shoot length, leaf size and leaf number all decreased with decreasing fertigation frequency (table 5.2). These are normal effects of water deficit on plant growth (Kramer, 1983b). A flooding duration of 5 minutes did not affect plant growth compared to a flooding duration of 30 minutes. Root mass was not significantly affected by fertigation schedule. Visually there was no effect of fertigation schedule on root development, except for continuously flooded plants, where roots with a larger diameter grew outside the pot directly into the solution. This suggests that aeration was sufficient for root growth under these wet conditions. Most of the roots were in lower regions of the pot and were absent in the uppermost centimeter, probably due to high salinity. The nutrient level (EC) hardly affected plant growth. Only in combination with high fertigation frequency, shoot-root ratio decreased with increasing EC. Plant height, leaf area, and plant mass were not significantly affected by EC under these conditions. This is not in agreement with Ceulemans and Impens (1983), who found that plant height, leaf area, and dry matter of *Ficus benjamina* were affected by EC. Two explanations for the absence of an effect of EC on plant growth in this experiment can be given. Firstly, both EC levels used in this experiment are close to the optimum EC of 1.75 mS, reported by Ceulemans and Impens. Secondly, the EC in the root environment of potted plants on a flooded bench fertigation system does not reflect the EC of the water used for fertigation, but varies with height of the potting medium and in time (Baas et al., 1992). Variation of EC within the root environment will be further discussed in chapter 6.

Table 5.2. Realized plant growth at day 178 in relation to fertigation schedule. Fertigation schedule numbers refer to the third experiment in table 5.1. LSD = least significant difference.

parameter		fertigation schedule						LSD
		1	2	3	4	5	6	
shoot fresh mass	g	88.5	86.1	86.0	80.9	63.3	60.1	11.6
length	cm	68.8	68.0	65.9	65.5	57.3	59.4	2.5
leaf area	cm^2	2416	2336	2361	2231	1742	1627	313
leaf number		165	153	158	152	124	116	24
shoot dry mass	g	19.4	17.7	18.6	16.9	13.9	13.4	3.5
root dry mass	g	4.58	4.05	5.04	4.58	4.64	4.34	1.22
total dry mass	g	23.9	21.8	23.7	21.4	18.6	17.7	4.7
shoot/root ratio		4.27	4.40	3.71	3.69	3.01	3.08	0.45

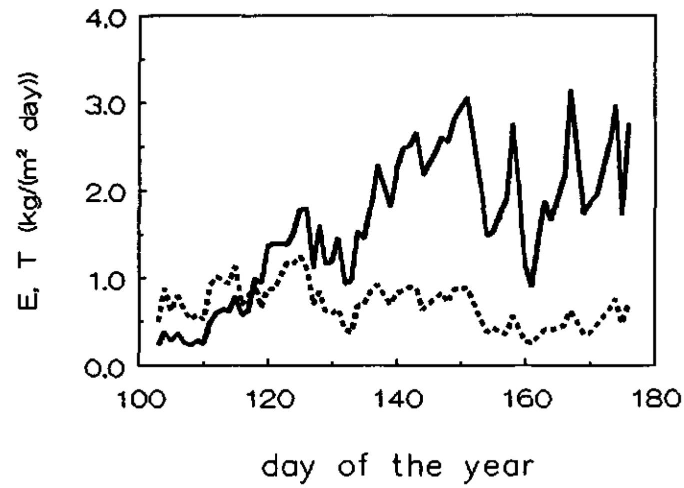


Figure 5.1. Transpiration (T, continuous line) and evaporation (E, dashed line) for continuously flooded plants.

5.2.2 Evapotranspiration

Evapotranspiration, ET, accounts for loss of water from the potting medium. Measured from April to June 1990, ET varied from 0.75 kg m^{-2} day^{-1} at the start to 3.70 kg m^{-2} day^{-1} at the end, with large variations between successive days (figure 5.1). Average ET over the three experiments was 1.7 kg m^{-2} day^{-1} (0.066 kg $plant^{-1}$ day^{-1}) with a minimum of 0.4 and a maximum of 4.1 kg m^{-2} day^{-1}. These rates are comparable with those reported by others, e.g. Morgan et al. (1981) reported average rates varying from 0.037 to 0.100 kg $plant^{-1}$ day^{-1} for *Nephrolepis* grown at different matric heads in the root environment, and de Kreij et al. (1987, 1988) reported average ET of 0.6 to 1.6 kg m^{-2} day^{-1} for *Croton* grown on a flooded bench fertigation system in different seasons with different fertigation schedules. Since radiation usually represents the major energy source for evaporation of water, there often is a close relation between ET and radiation (de Graaf and van den Ende, 1981). For LAI larger than 4, ET fitted well with radiation measured outside the greenhouse, but for smaller plants this relation was only poor since less radiation was intercepted by plants. Fitting significantly improved if interception of radiation by the plant was included in the regression model, leading to:

$$ET = K1 + K2 \times I_s \times (1 - e^{(-k \times LAI)}) + K3 \times I_s , \qquad 5.2$$

which after rewriting leads to

$$ET = K1 - K2 \times I_s \times e^{(-k \times LAI)} + K4 \times I_s , \qquad 5.3$$

where:

I_s	= daily radiation, outside greenhouse	$J\ m^{-2}\ day^{-1}$
K1	= coefficient obtained by fitting	$kg\ m^{-2}\ day^{-1}$
K2,K3	= coefficients obtained by fitting	$kg\ J^{-1}$
K4	= K2+K3	

The second term in equation 5.2 represents an increased ET as a result of increasing light interception. The extinction coefficient, k, was obtained from fitting light interception measurements with LAI according to equation 5.1. Values for LAI were obtained from monthly measurements and interpolated for days in between. Best fit of the light interception measurements was obtained with an extinction coefficient, k, of 0.84. This light interception, however, was an average value measured for PAR light on cloudy days, when most of the radiation is diffuse. Varying this extinction coefficient in equation 5.3 hardly affected the correlation. Best fit of ET was performed with the coefficients presented in table 5.3. ET was fitted according equation 5.3 with 97 percent of variance accounted for, which is accurate enough to describe the boundary conditions of a simulation model used in this study. The coefficients K2 and K4 were different for the three experiments (table 5.3), which may be due to different conditions for the experiments. The third experiment, was conducted in a larger, more modern greenhouse. Light transmission into this greenhouse was different from the greenhouse used for the other two experiments, and humidity was maintained at a higher level. In the second experiment there was additional heating during the winter period, which promotes ET (de Graaf and van den Ende, 1981).

Table 5.3. Regression coefficients K1,K2 and K4 in equation 5.3 for three experiments.

period	year	K1	K2	K3	K4
April-June	1990	0.431	-10.34	24.32	13.98
October-April	1990/1991	0.530	-20.00	33.69	13.69
March-May	1992	0.471	-11.88	24.56	12.68

5.2.3 Fraction evaporated

Evaporation, E, from the potting medium was not predicted accurately by a regression model including radiation and leaf area, as the one presented in equation 5.3. Including air temperature, air humidity and soil temperature in the regression formula increased the number of coefficients but hardly improved fitting. However, E as a fraction of ET could be predicted. The fraction of ET which evaporated from the potting medium reduced from

0.90 down to 0.15 with increasing LAI (figure 5.2). Following other researchers (Belmans, 1983; Ritchie, 1972), who described partitioning of ET over E and T as a function of LAI, the fraction evaporated was fitted according to:

$$E / ET = C1 + C2 \times e^{-C3 \times LAI} . \qquad 5.4$$

The fitted coefficients C1, C2 and C3 are given in table 5.4.

Table 5.4. Regression coefficients C1,C2 and C3 in equation 5.4.

period	year	C1	C2	C3	R^2
April-June	1990	0.19	0.65	-1.58	97.8
October-April	1990/1991	0.16	0.72	-0.91	79.3
March-May	1992	0.11	0.85	-1.68	97.0

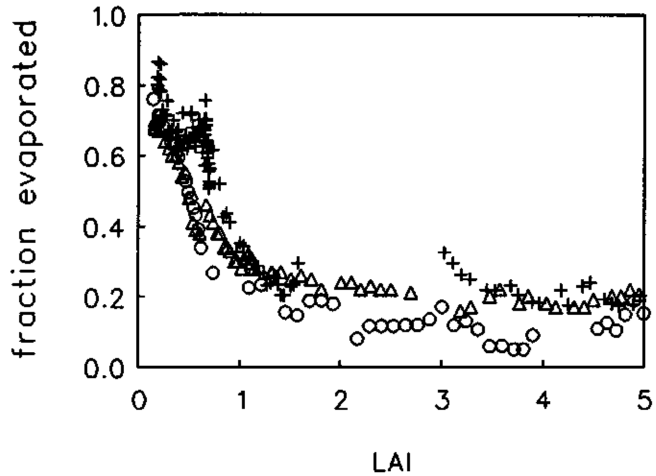


Figure 5.2. Fraction of total evapotranspiration evaporated from the potting medium for continuously flooded plants in relation to LAI. The symbols △, + and ○ refer respectively to experiment number 1, 2 or 3.

Table 5.5. Cumulative T (kg m^{-2}), E (kg m^{-2}), and fraction lost by evaporation (100×E/(T+E) for *Ficus benjamina* grown on a flooded bench fertigation system.

period	year	T	E	perc.
April-June	1990	97.0	44.6	31 %
October-April	1990/1991	94.8	66.4	41 %
March-May	1992	97.5	23.6	19 %

Although LAI was the most important factor in partitioning ET over E and T, partitioning obviously was affected also by other factors. Higher fractions of E are normally found for wet soil as compared to dry soil (Kabat et. al., 1992), but since the pots were continuously flooded in all three experiments, it is more likely that this partitioning was affected by climatic factors, like humidity, air temperature, light entrance into the greenhouse, and additional heating, or by the EC in the root environment.

The cumulative amount of water lost by E varied largely among the three experiments, but cumulative amount of water lost by T was almost the same (table 5.5). In particular in the experiment conducted in the winter period, where LAI was less than 1 for several weeks, the cumulative amount of water lost by evaporation was a large part of total water use.

5.2.4 Diurnal pattern in evaporation and transpiration

ET rates showed a diurnal pattern with higher rates during midday and lower rates during night. The maximum T and E rates were respectively 3.1 (SE= 0.3) and 2.5 (SE= 0.35) times higher than the daily average. Three examples of a diurnal pattern of E and T rates for different plant sizes are shown in figure 5.3. At day 109, LAI was about 0.17, and total ET was 0.662 kg m^{-2}, of which 69% evaporated from the potting medium. At day 124, LAI was about 0.55, and total ET was 1.435 kg m^{-2}, of which 45% evaporated from the potting medium, while at day 145, LAI was 2.77, and total ET 3.830 kg m^{-2}, of which 12% was accounted for by the potting medium. During night, where T became almost zero, E surpassed T.

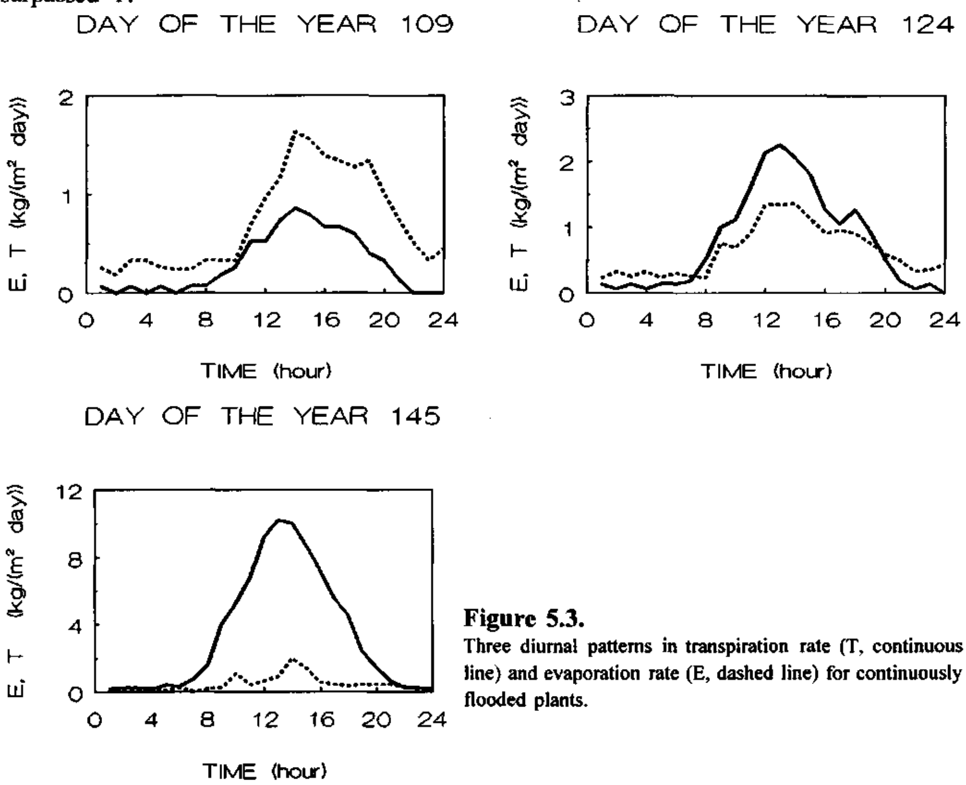


Figure 5.3.
Three diurnal patterns in transpiration rate (T, continuous line) and evaporation rate (E, dashed line) for continuously flooded plants.

5.2.5 Evapotranspiration by periodically flooded plants

ET was significantly affected by the fertigation schedule. Decreasing fertigation frequency or duration, and increasing EC reduced ET (table 5.6). ET causes a reduction in matric head which eventually may lead to a reduction in T (Kramer, 1983a). Since more water was lost from non-covered plants as a result of additional E from the potting medium, the matric head in the potting medium reduced more quickly for these plants. This resulted into a stronger reduction of T for non-covered compared to covered plants. Since E is calculated as the difference between water loss from covered and non-covered plants, E is underestimated in these cases. This was in particular found for drier treatments under high evapotranspirative demand. These values in table 5.6 are therefore marked with an * and considered to be non-representative. For the other treatments E and T were believed to have occurred independently.

No reduction was found in E for plants that were flooded 4 times a week for 30 minutes as compared to continuously flooded plants. Obviously, the potting medium remained sufficiently wet to maintain maximum evaporation. For the other treatments a reduction was found in E (table 5.6). In particular during the last weeks of the experiment the potting medium in these treatments was very dry, which lead to a reduction of the E. Transpiration by the plant reduced with decreasing frequency, with decreasing flood duration, and also with increasing EC. As a result, reduction in total ET with decreasing frequency and increasing EC, was mainly caused by this reduction in T. The fraction of water lost by E was therefore higher for periodically than for continuously flooded plants (table 5.6).

Table 5.6. Cumulative ET (kg plant^{-1}), T (kg plant^{-1}), and calculated E (kg plant^{-1}) in relation to fertigation schedule. Values indicated by an asterisk are believed to be less accurate.

schedule	EC	ET	T	E	perc.
continuous	1.7	5.67	4.68	0.99	17.5
4*30 min	1.7	4.94	3.79	0.97	19.6
4*30 min	2.2	4.51	3.38	1.13	25.1
4* 5 min	1.7	4.20	3.65*	0.54*	12.8*
2*30 min	1.7	3.84	3.41*	0.44*	11.5*
2*30 min	2.2	3.74	2.96*	0.78*	20.8*
LSD		0.37	0.34	0.39	7.3

5.2.6 Volumetric water content of the potting medium

Volumetric water content of the potting medium after flooding was affected by fertigation schedule (figure 5.4). Highest volumetric water content was found for continuously flooded plants, where average volumetric water content in 60 days gradually increased from 0.63 to 0.71. Although these plants were flooded continuously, this volumetric water content was still lower than container capacity. For the potting medium and pot used in this experiment container capacity is 0.82 10^{-3} m^3 (chapter 3).

Volumetric water content reached after fertigation gradually decreased in three months from 0.54 to 0.45 for plants that were flooded four times a week for 30 minutes. Since highest ET was 0.16 kg plant^{-1} day^{-1}, and since the longest time between two flooding periods was two days, this volumetric water content is expected to be sufficient to cover evapotranspirative demand, assuming that all water is easily available for the plant.

When flooding time was reduced to 5 minutes, volumetric water content after flooding decreased in time as a result of increased ET. Obviously, a flooding period of 5 minutes, in combination with this frequency, was only sufficient in the beginning, resulting in volumetric water contents identical to those of plants that were flooded for 30 minutes (figure 5.4). If plants were flooded twice a week for 30 minutes, water content after flooding also decreased after day 130. In combination with this frequency a flooding period of 30 minutes was not long enough under high evapotranspirative demand.

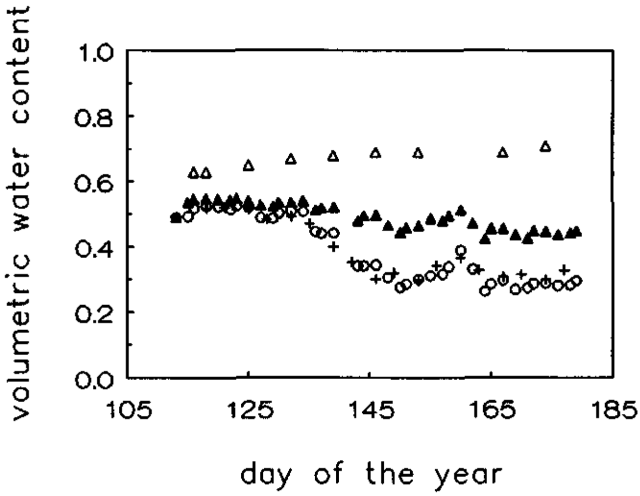


Figure 5.4. The average volumetric water content measured after flooding. The plants were flooded continuously (▵), 4 times a week for 30 minutes (▴) 4 times a week for 5 minutes (○) or twice a week for 30 minutes (+).

5.2.7 Matric head of the potting medium

For periodically flooded plants, the hourly measured matric head reflected not only a drying and wetting cycle, but also a diurnal ET pattern (figure 5.5). At a height in the pot of 0.06 m, the lowest matric head for periodically flooded plants in the third experiment was measured at day 150, when ET reached its maximum value. For plants that were flooded four times a week for 30 minutes the lowest matric head was -1.53 m (SE=0.60, n=9), for plants that were flooded four times a week for 5 minutes the lowest matric head was -7.18 m (SE=1.73, n=9), and for plants flooded twice a week it dropped below -8.0 m, which is about the lowest value that can be measured with these tensiometers. Among pots within the same treatment matric heads varied largely, in particular at lower matric heads just before flooding. A number of explanations can be given for this variation. The first explanation is differences in ET. From day 148 to day 150, ET varied from 0.214 kg plant^{-1} to 0.277 kg plant^{-1} (mean=0.249, SE=0.0214, n=11) for plants that were flooded four times a week for 30 minutes. Since at lower matric head the differential capacity $C(h_m)$ increases, which means that at lower values the matric head becomes more sensitive to changes in volumetric water content, this variation in ET will contribute to a variation in the matric head in the potting medium. Additionally, hysteresis and variation in physical characteristics of the potting medium may contribute to this variation in matric heads.

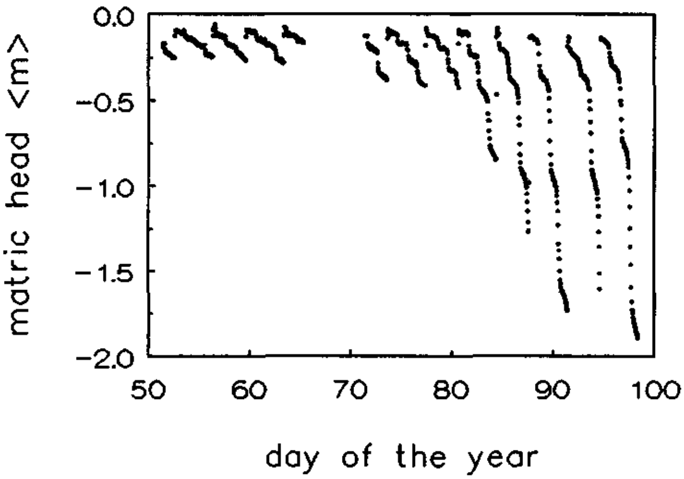


Figure 5.5. The matric head measured at 0.085 m height in a potting medium as a result of evapotranspiration and irrigation on a flooded bench system. The plants were flooded twice a week.

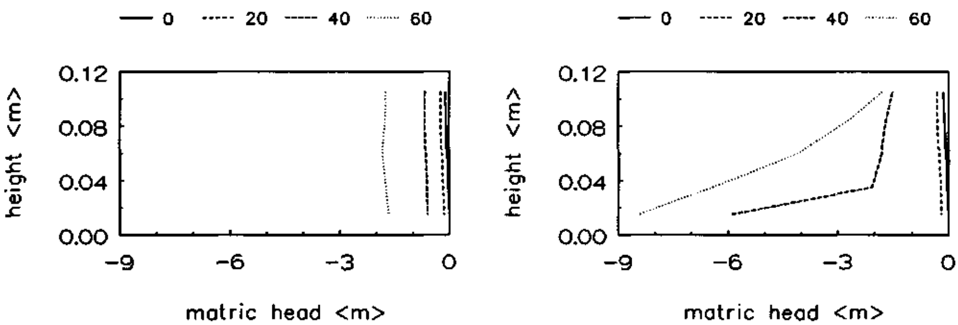


Figure 5.6. Matric head as a function of height after 0, 20, 40 and 60 hours of transpiration without supply of water. During the period previous to this measurement the plant was continuously (left graph) or periodically flooded (right graph).

Five tensiometers were installed horizontally in the potting medium to determine vertical gradients of the matric head. The continuously flooded plants were almost at hydrostatic equilibrium, which indicates that all water lost by ET was immediately replaced by capillary rise from the nutrient solution on the benches. Once flooding was stopped, the matric head decreased equally at all depths for these plants (figure 5.6, left graph). This means that the potting medium almost remained at a hydrostatic equilibrium during ET. For periodically flooded plants a hydrostatic equilibrium was only found at high matric heads (figure 5.6, right graph). However, as the matric head decreased, its value decreased more rapidly in lower layers than in higher layers of the potting medium. It can therefore be concluded that most of the water was extracted from lower layers, which is consistent with the majority of roots found there and with the increase of salinity with height, and that redistribution of water within the medium could not keep up with ET if the medium became drier. Although ET for both plants presented in graph 5.6 was almost the same, and the matric head profiles were identical at the start, the decrease of the matric head in time and height differed considerable for both plants. Hysteresis in the water retention characteristic, which reduces the volumetric water content and as a result also the hydraulic conductivity at the same matric head, may cause this phenomena. This explanation will be verified by model calculations in chapter 7. The measurements, however, did indicate that if the plants were kept sufficiently wet at matric heads above -1.50 m, local drought did not occur under these circumstances.

5.2.8 Water absorption during fertigation

If after a period of evapotranspiration plants were flooded, matric head immediately increased to zero in the layer of the potting medium that was flooded, indicating a quick saturation. The matric head of higher layers in the potting medium, however, increased more slowly in time. Higher layers were wetted by vertical transport of water within the potting medium. When flooding started after the potting medium had dried to a matric head of -1.10 m, it took over 40 minutes of flooding to reach a hydrostatic equilibrium (figure 5.7). In practice, however, flooding periods of 5 minutes are more common.

Absorption of water as affected by fertigation frequency, flooding duration and EC was measured in the third experiment. Volumetric absorption of water, defined as the supply during flooding resulting from capillary rise (m^3) divided by pot volume (m^3), was strongly related to the average volumetric water content of the potting medium before flooding (figure 5.8). If the average volumetric water content was smaller than 0.45, capillary rise increased with increasing flooding duration. With decreasing volumetric water content the differences between flooding periods of 5 and 30 minutes increased, but, even at low volumetric water contents, the majority of capillary rise took place within 5 minutes. There was no effect of fertigation frequency, neither from EC of the solution on the amount of water absorbed while flooding. Of course, if frequency was reduced the volumetric water content before flooding was lower, so indirectly affected frequency capillary rise significantly.

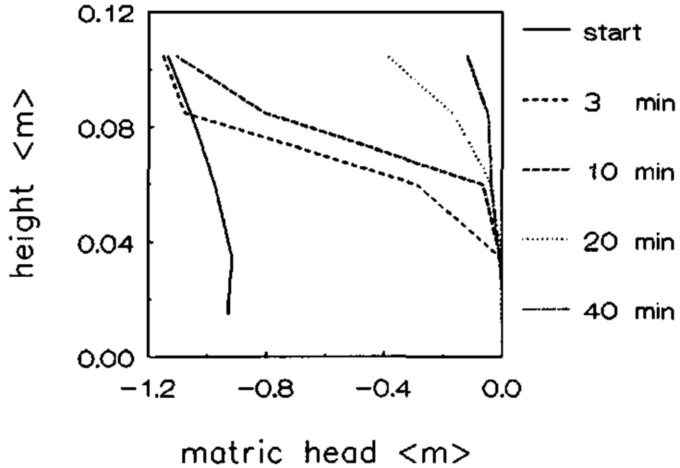


Figure 5.7. Matric head in relation to height, measured before and after 3, 10, 20 and 40 minutes of flooding.

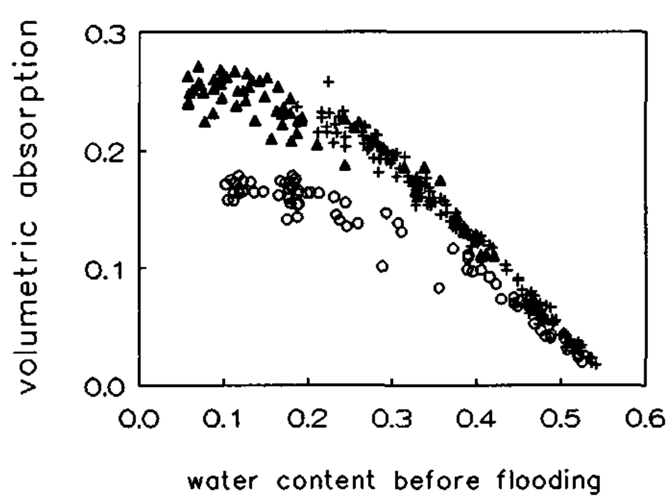


Figure 5.8. The volumetric absorption of water by the potting medium during the flooding period in relation to the volumetric water content before flooding. The plants were flooded twice a week for 30 minutes (▲), four times a week for 30 minutes (+) or four times a week for 5 minutes (○).

6. Nutrient balances and vertical distribution

On a flooded bench fertigation system nutrients are added to potted plants with each fertigation. In practice, the frequency of fertigation is tuned to the need of plants for sufficient water. Supply of nutrients is controlled by the nutrient concentration in the fertigation solution. In commercial horticulture, samples from potting media are analysed during cultivation to check if nutrient contents remain constant. A 1:1.5 volume extraction method is most commonly used for peat based potting media (Sonneveld et al., 1974). For all nutrients, but in particular for Na and Cl, concentrations in the fertigation water are often higher than uptake concentrations. In a closed recirculating system this causes excess of nutrients to accumulate in the substrate, in the drainage water or both. Excess of nutrients is not removed from the potting medium when flooded bench fertigation is used. As a result, they accumulate in the potting medium, causing EC to increase in time, in particular in the top layer (de Kreij and Straver, 1988). Once in the potting medium, redistribution of nutrients is mainly determined by the dynamics of water. Since fertigation schedule did affect dynamics of water on a flooded bench fertigation system (chapter 5), it is likely that the dynamics of nutrients are related to fertigation schedule as well. There is, however, still little knowledge on how accumulation, vertical distribution, and nutrient composition of the potting medium solution are related to that of the fertigation water. There also is hardly any knowledge on how fertigation frequency affects salinity in the root zone.

The objective of this study is to determine balances and vertical distribution for nutrients added to potted plants with flooded bench fertigation in relation to the fertigation schedule. Since instruments for continuous registration of the nutrient composition in the root zone are not available at this moment, destructive measurements were made at three stages of growth to study long term accumulation of nutrients. Nutrient accumulation and vertical distribution were compared for different fertigation schedules. Additionally, the EC measured in the 1:1.5 volume extract is compared with the EC measured in the liquid phase of the potting medium, which gives a better presentation of the conditions in the root environment, since samples are not subjected to unnaturally high water contents (Rhoades, 1982). In contrast to horticultural practice, the spacing of plants was not changed during cultivation and the fertigation schedule was not altered even if accumulation of nutrients occurred and conditions became less favourable for plant growth.

6.1 Materials and methods

Ficus benjamina plants were grown on a flooded bench fertigation system during the spring of 1992, in the period from day 110 to 180 (March-May). Plastic pots (0.12 m height, 1×10^{-3} m^3) filled with a "flooded bench mix" consisting of 75% peat and 25% perlite were used. Six different fertigation schedules were used in this experiment (table 6.1). All treatments were done in triplicate. Evapotranspiration, and dynamics of water in the potting medium related to these fertigation schedules were discussed in chapter 5. Nutrient compositions of the fertigation solutions are given in table 6.2. A composition with an EC of 2.2 is generally recommended for *Ficus benjamina* (IKC, 1991). The amount of nutrients in the potting medium was determined after 3, 7 and 11 weeks. Three methods were used to determine the effect of the fertigation schedule on nutrient distribution in the potting medium. For each method samples were taken from various heights to study the vertical distribution of nutrients in the potting medium. The methods used, the number of layers, and the layer thickness of the potting medium samples were different among fertigation schedules (table 6.1).

Table 6.1. Overview of the fertigation schedules and analyses.

treatment number	1	2	3	4	5	6
fertigation frequency (per week) and duration	continuous	4 times 30 min.	4 times 30 min.	4 times 5 min.	2 times 30 min.	2 times 30 min.
EC fertigation solution	1.7	1.7	2.3	1.7	1.7	2.3
EC-1:1.5	yes	yes	yes	yes	yes	yes
EC potting medium solution (EC-PMS)	no	yes	yes	no	yes	yes
EC soil moisture samplers (EC-SMS)	yes	yes	yes	yes	yes	yes
nutrient composition PMS	no	yes	yes	no	yes	yes
total analyses of potting medium and plant	no	yes	yes	no	yes	yes
samples from layers (height m)	0.08 - 0.12 0.00 - 0.08	0.10-0.12 0.08-0.10 0.04-0.08 0.00-0.04	0.10-0.12 0.08-0.10 0.04-0.08 0.00-0.04	0.08-0.12 0.00-0.08	0.10-0.12 0.08-0.10 0.04-0.08 0.00-0.04	0.10-0.12 0.08-0.10 0.04-0.08 0.00-0.04

Table 6.2. Nutrient composition of the fertigation water (mmol/l).

EC	K	Ca	Mg	Na	NO_3	H_2PO_4	SO_4	Cl
1.7	5.4	3.1	0.82	0.55	10.6	1.30	1.37	0.26
2.3	8.0	4.4	1.18	0.61	15.5	1.85	1.83	0.27

The first method, referred to as EC-1:1.5, measured the EC in a volume extract (Sonneveld et al., 1974). With this method 60 ml sample, compressed with 1000 kg/m^2, was mixed with 90 ml water. The suspension was shaken horizontally for 20 minutes, and, following filtration, the EC of the resulting solution was measured. For the second method, referred to as EC-PMS, potting medium solution was obtained from samples by centrifuging (chapter 4), and the composition and EC were measured. For both methods, EC-1:1.5 and EC-PMS, samples from ten pots for each treatment were mixed and analysed. Samples were obtained immediately after fertigation. For the third method, referred to as EC-SMS, the EC was measured in samples obtained with soil moisture samplers (0.10 m long, 0.0025 m diameter, Eijkelkamp, The Netherlands) from five pots on each table. Samplers were installed horizontally in the potting medium at various heights (table 6.1). Each sampler was connected with a hollow needle to a vacuum tube to collect a sample. Depending on the wetness of the potting medium, it took up to 30 minutes to collect a sample. This non-destructive method was used to determine EC between successive fertigations.

Nutrient balances were determined from total analyses. Ca, K, Mg, Na, N, P, S and

Cl were determined for samples from four heights (table 6.1). Ignoring drainage and other processes, e. g. denitrification, a balance for each nutrient is given by:

$$A_{pm,t} + A_{plant,t} = A_{pm,t=0} + A_{I} \ . \qquad 6.1$$

The total amount present in the potting at time t, $A_{pm,t}$, was calculated from total analyses of samples obtained from layers in the pot, multiplied by the mass of the potting medium in each layer, assuming uniform density of the medium. Cumulative nutrient uptake by the plant, $A_{plant,t}$, was calculated from composition of shoots and roots, multiplied by their masses at time t. The amount of nutrients added to the potted plant was calculated as the sum of the amount initially present in the potting medium, $A_{pm,t=0}$, resulting from natural occurrence and initially added fertilizer, and the cumulative amount added with fertigation, A_I. The amount added by fertigation was calculated from the composition of the fertigation water multiplied with the cumulative capillary rise during flooding (chapter 5).

6.2 Results

6.2.1 Comparison of EC measurement methods

Compared to the commonly used EC-1:1.5, higher EC values were found in the potting medium solution, when using the EC-PMS method. With the 1:1.5 volume extraction method the EC decreased as a result of dilution of the potting medium solution. There was only a poor relation between the EC 1:1.5 and the EC in the potting medium solution (figure 6.1). This poor relation is likely to be caused by differences in the volumetric water content of the samples. Since water content after flooding decreased with increasing height in the potting medium, samples obtained from higher layers in the potting medium were more diluted with the EC-1:1.5 method (figure 6.1). The dilution factor was about 3.2 for the samples obtained from lower layers and 4.7 for samples obtained from higher, more dry layers. Dilution increased between successive fertigations (table 6.3). Samples from the lower part of potted plants were compared before and after flooding. The EC-PMS increased between flooding, but the EC-1:1.5 decreased in the same period. Decrease in EC-1:1.5 is a result of nutrient uptake by the plant, while the increase of EC-PMS is a net result of nutrient uptake and evapotranspiration. Average evapotranspiration from the pots between these fertigations was 0.130 kg. Since the average gravimetric water content after flooding equalled 0.500 kg, the EC-PMS in the lower half of the potting medium is expected to increase from 3.9 to 5.3, if redistribution of nutrients and plant uptake are ignored.

Table 6.3. The EC-PMS and EC-1:1.5 before and after fertigation at height 0-0.08 m (mixed samples of 2 pots; s.d. between brackets).

	after irrigation	before irrigation
EC-PMS (n=4)	3.90 (0.19)	5.00 (0.16)
EC-1:1.5 (n=4)	1.52 (0.13)	1.33 (0.15)

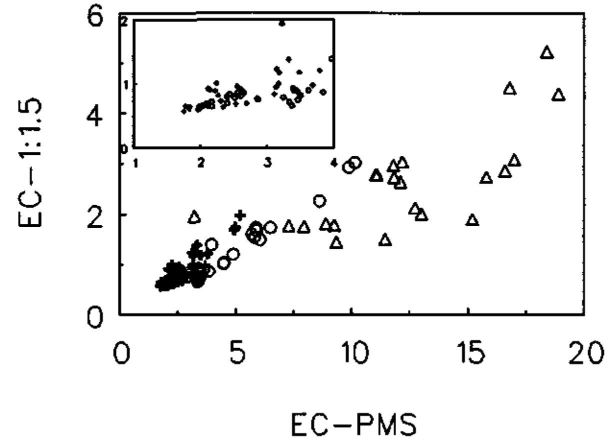


Figure 6.1. The relation between EC-1:1.5 and EC-PMS. The samples were obtained from a height of 0.08-0.10 m (▵), 0.04-0.08 m (○), or 0-0.04 m (+).

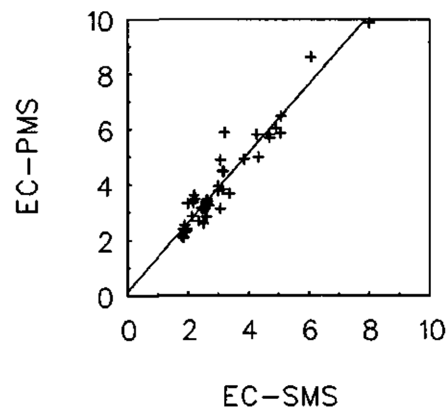


Figure 6.2. The relation between EC-PMS and EC measured in samples obtained with soil moisture samplers, EC-SMS.

EC measured in the samples obtained with the soil moisture samplers (EC-SMS) was linearly related with EC-PMS, although lower values were found for EC-SMS (figure 6.2). The regression coefficient was 1.25, and the intercept 0.15 (R^2=96.6%). Since samples were taken from the same pots at the same heights, this suggests that composition of the potting medium water obtained with both methods is not identical.

6.2.2 Nutrient balances

Even at an EC of 1.7, which is lower than recommended for *Ficus* plants, only part of the nutrients added to the pot was used for plant growth. The remainder accumulated in the potting medium. Phosphate accumulation in relation to fertigation schedule is presented in figure 6.3. The amount accumulated in the potting medium increased with increasing frequency and increasing EC of the fertigation water. Increased accumulation with increasing EC was a result of an increased nutrient transport with a given volume of water entering the pot. Increase of frequency caused more evapotranspiration, and hence also more nutrient transport into the potting medium. Nutrient uptake by the plants also increased with frequency, since plant size increased (chapter 5). Since nutrient transport into the pot increased more than uptake by the plant, P-accumulation increased with increasing frequency (figure 6.3). Plant composition was not significantly affected by the fertigation schedules used in this experiment. Only Mg uptake increased with increasing frequency (7.2%), and Ca uptake increased with increasing EC (7.2%) and increasing frequency (5.3%). Although most accumulation was found for P, other nutrients accumulated in the potting medium as well (table 6.4). Accumulation as a percentage of the amount added with fertigation was affected by fertigation schedule, but for all schedules used in this experiment, significant amounts accumulated in the potting medium, even if the EC of the fertigation was lower than 2.2, as recommended for *Ficus* plants (IKC, 1991). To prevent accumulation, the concentrations in the fertigation solution should be reduced by about these percentages, or excess of salts should be leached, which is not a realistic option for flooded bench fertigation.

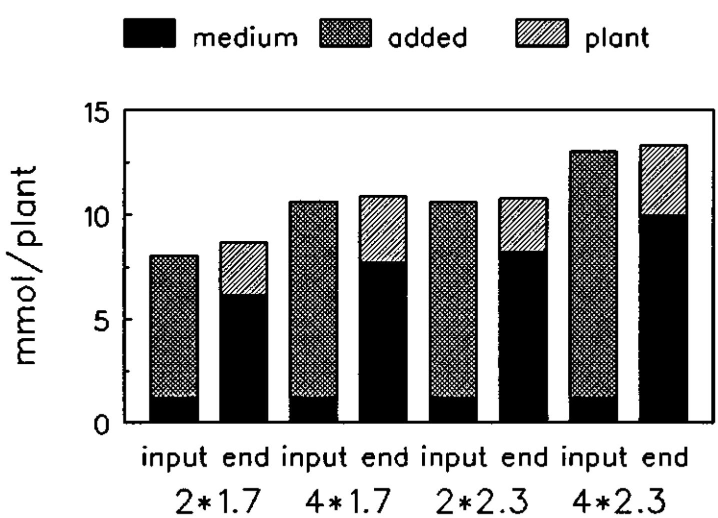


Figure 6.3. The amount of P accumulated in the potting medium, and in the plant, and the cumulative amount added to the pot, in relation to fertigation frequency (twice or four times a week), and EC of the fertigation water (1.7 or 2.3), after 11 weeks.

Table 6.4. Accumulation of nutrients as a percentage of the amount added in relation to the fertigation schedule.

EC	K	Ca	Mg	N	P	S
2*1.7	56	50.9	39.0	39.8	64.6	49.3
4*1.7	58.8	51.7	36.4	44.6	66.7	50.5
2*2.3	56.5	52.0	23.0	45.8	61.5	44.2
4*2.3	68.1	58.8	34	62.6	69.4	50.1

Table 6.5. The amount of nutrients before growth (start), and in various heights after 3, 7 and 11 weeks (mmol/100 g), and the cumulative amount in the pot (mmol/pot). The plants were flooded four times a week with an EC of 1.7.

week	height	K	Ca	Mg	Na	N	P	S	Cl	OM	pH
start	-	8.9	24.7	13.4	24.6	55.1	1.9	5.8	0.5	66.9	5.11
3	0.10-0.12	17.9	32.7	21.8	25.2	89.0	8.5	12.7	4.2	71.1	5.00
	0.08-0.10	10.6	25.3	13.4	20.3	58.7	1.9	5.8	1.0	71.8	5.26
	0.04-0.08	9.9	25.1	12.9	20.0	56.9	1.5	5.4	0.5	70.9	5.49
	0.00-0.04	11.3	29.5	10.0	20.8	55.0	1.6	5.5	0.5	70.5	5.63
	total	12.2	28.8	14.2	22.0	64.5	2.9	7.0	1.2		
7	0.10-0.12	38.8	41.5	34.6	31.4	127.1	17.7	20.7	9.0	68.8	4.92
	0.08-0.10	24.0	24.9	15.5	23.9	72.3	4.2	7.5	2.4	70.7	5.22
	0.04-0.08	15.5	28.5	10.3	21.7	61.9	2.3	6.1	0.7	69.8	5.56
	0.00-0.04	14.0	34.4	6.4	22.2	61.9	2.1	5.7	0.5	69.5	5.83
	total	21.4	32.9	14.8	24.8	77.7	5.4	9.0	2.4		
11	0.10-0.12	52.3	42.8	40.0	34.2	139.7	23.9	25.3	11.3	66.9	4.82
	0.08-0.10	35.0	25.5	16.1	24.7	83.0	5.6	8.7	3.6	68.8	5.19
	0.04-0.08	23.2	31.9	9.3	20.6	70.9	3.8	6.9	0.9	68.8	5.54
	0.00-0.04	18.5	37.9	6.4	20.4	66.2	3.7	6.1	0.4	68.0	5.95
	total	30.1	35.4	15.4	24.6	86.6	7.7	10.4	3.1		

Table 6.6. The concentrations in the potting medium solution at various heights after 3, 7 and 11 weeks, and the composition of the fertigation water (mmol/l). The plants were flooded four times a week with an EC of 1.7.

weeks	height	K	Ca	Mg	Na	NO_3	H_2PO_4	SO_4	Cl	EC
irrigation		5.4	3.1	0.82	0.55	10.6	1.30	1.37	0.26	1.7
3	0.10-0.12	24.6	17.2	24.4	14.7	70.6	>3	13.9	9.4	10.3
	0.08-0.10	9.4	3.9	4.4	3.7	19.0	2.7	3.4	2.2	3.26
	0.04-0.08	6.2	3.2	3.0	1.6	13.0	1.6	1.7	1.0	2.18
	0.00-0.04	6.1	2.9	1.9	1.2	11.8	1.4	1.3	0.8	1.98
7	0.10-0.12	80.4	36.7	33.3	38.0	207.7	27.0	20.8	26.9	26.9
	0.08-0.10	28.4	7.7	10.0	6.7	44.7	7.1	7.1	5.2	7.53
	0.04-0.08	12.5	4.5	3.4	1.5	18.8	3.4	4.0	1.4	3.33
	0.00-0.04	8.7	3.6	1.3	0.8	13.3	1.9	1.8	0.7	2.30
11	0.10-0.12	112.4	14.0	59.5	48.3	227.0	43.5	30.9	32.2	32.1
	0.08-0.10	54.4	6.0	13.8	14.4	78.9	10.1	10.1	7.5	11.6
	0.04-0.08	24.5	3.7	4.7	4.6	34.5	5.5	4.7	1.8	5.85
	0.00-0.04	12.0	2.5	1.8	2.2	15.2	2.8	2.2	0.5	3.21

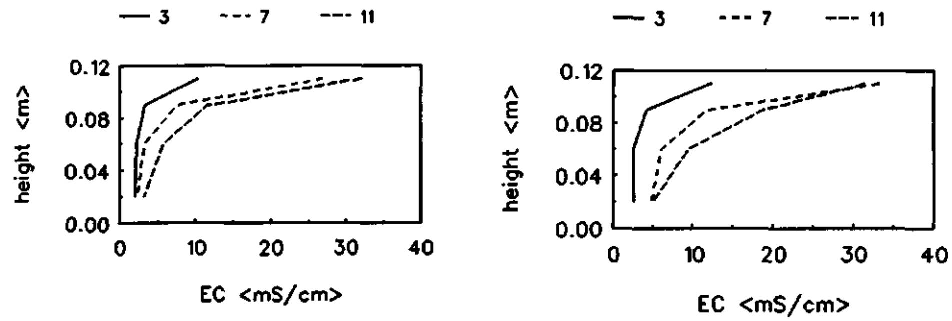


Figure 6.4. EC-PMS in relation to height for pots that were flooded four times a week with an EC of respectively 1.7 (left) and 2.3 (right).

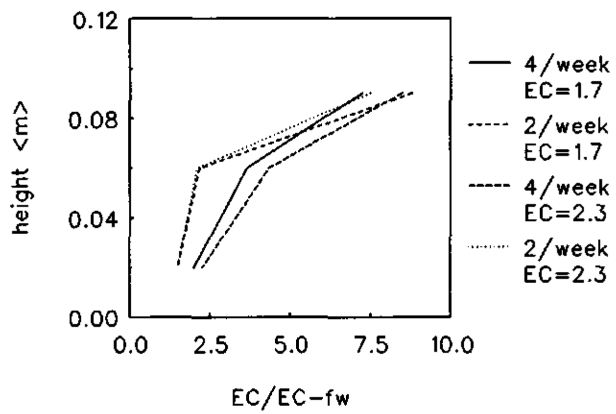


Figure 6.5. EC-PMS after 11 weeks divided by the EC of the fertigation water (EC-fw), as affected by fertigation frequency (twice or four times a week) and EC of the fertigation water (1.7 or 2.3).

6.2.3 Vertical distribution

Nutrients were not distributed homogeneously within the potting medium. Salinity build-up started in the upper layer of the potting medium (figure 6.4). The strong increase in the upper layers was caused by the relatively high contribution of the evaporation to the total evapotranspiration during the first weeks (chapter 5). Salinity was build up also in lower layers. Vertical distribution of total soluble salts was affected by flooding frequency. A build-up factor, defined as the EC measured in the potting medium solution divided by the

EC of the fertigation water, increased in lower layers of the potting medium with increasing frequency, but was almost independent of EC of the fertigation water (figure 6.5). In all layers the EC was higher than in the fertigation water, and in the top layer it was about five times higher than in lower layers.

Except for Ca, total amounts of all nutrients increased also with height in the potting medium. The total amount equals the sum of the amounts incorporated in the solid phase, adsorbed, precipitated, and in the potting medium solution. Individual nutrients present in the potting medium solution did not have the same vertical distribution as the total amounts. This was in particular the case for Ca and Mg. During cultivation, total Ca increased in particular in lower layers of the potting medium, while Mg decreased in lower layers and increased in higher layers (table 6.5). This was also found for the other fertigation schedules. Total Mg decreased during cultivation in the lower layers of the potting medium, but the concentration in the potting medium solution remained relatively constant, and was always higher than the Mg concentration in the fertigation solution (table 6.6). Ignoring the top layer of the potting medium, total Ca decreased with increasing height (table 6.5), while Ca in the potting medium solution increased (table 6.6). For anions total amount and concentrations in the potting medium solution both increased in height during cultivation (table 5.5 and 5.6).

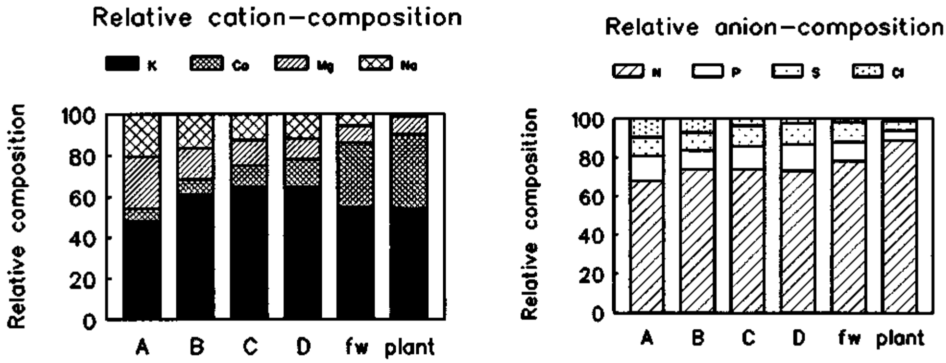


Figure 6.6. The cation and anion composition (mol) of the plant, the fertigation water (fw), and the potting medium at a height of 0.10-0.12 (A), 0.08-0.10 (B), 0.04-0.08 (C), and 0.0-0.04 (D). The plants were flooded four times a week with an EC of 1.7 for a period of 11 weeks.

The composition of the potting medium solution differed considerably from the fertigation water, and varied with height (figure 6.6). The cation composition of the fertigation water was, with the exception of Na, almost identical to that of the plants. The potting medium solution, however, contained considerably more K, Mg, and Na than the fertigation water. The increase of Na was a result of the relative low uptake by the plant. The decrease of Ca was a result of adsorption by the potting medium, and of precipitation in the upper layers of the potting medium. The anion composition of the potting medium solution was closer in agreement with that of the fertigation water than the cation composition, and showed less variation in height. Only Cl was found to accumulate relatively more than the other anions. Accumulation occurred in particular in the higher layers of the potting medium.

6.2.4 Temporal aspect of nutrient accumulation

In commercial horticulture, samples are commonly derived from the lower 0.08 m of the pot. The EC-1:1.5 in the lower 0.08 m increased in time for all treatments (table 6.7), but remained within the range 0.6 < EC-1:1.5 < 1.2, recommended for *Ficus benjamina* (IKC, 1991). During the first three weeks, there was no effect of fertigation frequency on EC. However, after eleven weeks, fertigation frequency had more effect on the EC-1:1.5 in the lower 0.08 m of the potting medium, than the EC of the fertigation water. EC-1:1.5 increased with increasing frequency and with flooding duration (table 6.7). An exception was found for pots that were flooded continuously, where highest EC-1:1.5 was found after 7 weeks, which did not increase further.

Table 6.7. The EC-1:1.5 of the lower 2/3 of the potting medium in relation to time and fertigation schedule (n=3, l.s.d.=0.18).

frequency	continuously	4*30 min	4*30 min	4*5 min	2*30 min	2*30 min
EC mS/cm	1.7	1.7	2.3	1.7	1.7	2.3
3 weeks	0.66	0.71	0.88	0.68	0.63	0.85
7 weeks	1.19	0.85	1.41	0.69	0.73	0.89
11 weeks	1.16	1.41	2.27	1.14	0.77	1.01

Table 6.8. The EC measured in potting medium water extracted with soil moisture samplers at 0.04 m height, before and after three successive fertigations with EC of the irrigation water of respectively 1.7 and 2.3. (n=6, s.d. between brackets).

	monday		wednesday		tuesday		saturday	
EC irrigation	before	after	before	after	before	after	before	after
1.7	-	3.03 (0.34)	3.69 (0.30)	3.15 (0.32)	3.54 (0.17)	3.16 (0.45)	4.53 (0.43)	3.19 (0.40)
2.3	-	5.63 (0.68)	7.16 (1.03)	5.14 (0.55)	7.21 (1.07)	4.96 (0.79)	8.17 (0.99)	4.95 (0.70)

Additionally to this slow increase in time, the fertigation schedule affected EC between successive fertigations. The EC in the potting medium solution increased between fertigations, since uptake concentration by the plant was lower than EC in the liquid phase. For plants that were flooded four times a week, the EC's before and after flooding for three successive fertigations are presented in table 6.8. The samples were obtained with soil moisture samplers at 0.04 m height. The EC-SMS after flooding was almost constant for these successive fertigations, but EC before flooding varied considerably, probably as a result of variation in evapotranspiration between the fertigations. This increase in EC between fertigations will be less if fertigation frequency is increased or evapotranspiration reduced. Potting media of plants that were flooded twice a week became too dry to collect samples before fertigation. Samples obtained 24 hours after flooding, however, from pots that were flooded twice a week with an EC of 1.7, showed a slight decrease in EC. EC decreased from 1.92 (s.d.=0.12) to 1.88 (s.d.=0.11) according the first, and from 2.22 (s.d.=0.31) to 1.95 (s.d.=0.10) according a second measurement (n=5). This may either be an indication that uptake EC by the plant was slightly above this value for these plants during this stage of cultivation, or it is a result of redistribution following fertigation, which was much slower for these drier pots (chapter 5).

6.3 Discussion

The relation between EC-1:1.5 and EC-PMS was affected by the volumetric water content of the samples. For drier samples a stronger dilution was found. Volumetric water contents of the samples were not determined, so a dilution factor for each sample cannot be calculated. As a rough estimate, based on a volumetric water content of a sample of 0.5, a dilution factor with the 1:1.5 method of 4 is calculated, which lies between the 3.2 and 4.7, as was found for respectively wet and more dry samples. The time passed between sampling and fertigation affected both methods, but in particular the EC-PMS increased between fertigations. This has of course implications for sampling, since EC is strongly determined by the time passed between sampling and fertigation. On the other hand, it also means that EC in the root environment depends on fertigation frequency. For relative comparison of potting media the extraction method therefore seems useful, since it is less affected by the moment of sampling, while EC-PMS gives more information on the actual concentration in the root environment. EC-PMS is a destructive method, and therefore not very suitable to study short term dynamics of EC in the root environment. EC withdrawn with soil moisture samplers is more suitable for that purpose. The EC-SMS was found to be lower than EC-PMS. This was not caused by a selective permeability of the tube. The location of the porous tube in the medium, however, may have contributed to this difference. For example, when a porous tube is installed such that it is in contact with both macropores and micropores, the sampler is likely to withdraw initially more mobile liquid from larger pores. Relative small pores present inside perlite (Chen et al., 1980) may act as a stagnant phase. A second explanation for lower values of EC-SMS is the vertical gradient in volumetric water content and EC of the potting medium. Location of the sampler in the center of a layer will not give a representative sample for the EC of that layer, if water is not withdrawn equally from all directions surrounding the sampling tube.

Neither the EC measured in the potting medium water, nor the EC-1:1.5 gives the exact amount of accumulation of nutrients in the potting medium. Total element analyses of the potting medium must be used to establish nutrient balances. Although the left and right hand side of the nutrient balance in equation 6.1 should be equal, this was rarely the case. The average error, defined as the difference between input (A_I) and amount recovered ($A_{plant,t} + A_{pm,t} - A_{pm,t=0}$) divided by the input times 100, was +7.4%. In particular SO_4, of which 17% of the input could not be recovered in potting medium or plant, contributed strongly to this average. At least part of this difference was caused by a flux of nutrients out of the pot during fertigation, which was ignored in this balance. During fertigation nutrients may diffuse out of the pot, since concentrations in the potting medium solution were higher than concentrations in the fertigation water. Additionally, when fertigation was stopped, water dripped out of the potting medium and, with this, nutrients got lost as well. If flooding time is kept short and flooding level is not too high, this loss is probably small, since time for diffusion is short and since water will flow upwards even when the flooding level is lowered (Molitor and Fischer, 1989). The relative small differences between input and amount recovered in this experiment also suggest that these processes only played a minor role. An earlier experiment (chapter 5, experiment 2) showed that larger differences were found for plants that were continuously flooded, which suggest that for continuously flooded plants these processes may considerably contribute to the nutrient balance. Water and nutrient fluxes out of the pot, however, are complicated to measure.

Evaporation affected both accumulation and vertical distribution of nutrients in the potting medium. Salinity in the upper layers significantly reduced for pots of which the surface was covered with plastic (table 6.9). At the same time, however, EC increased in the lower layers. As a result of covering the potting medium surface, more roots were found in the upper layers. This may have caused a different water and nutrient uptake pattern. These measurements show that, although evaporation was absent, the upper layer still became more saline than the lower layers, and that the EC in the lower layers was higher when evaporation was absent. In the absence of a cover, evaporation caused more transport of salts from lower layers into higher layers of the potting medium, where roots were absent, probably as a result of high osmotic potentials there. The fraction of water that evaporated through the potting medium surface was mainly determined by leaf area index (chapter 5). Therefore, plant density and other factors affecting evaporation, can be expected to affect build-up of salinity in the root zone. The uniform plant density scheme maintained in this research may have caused stronger salinization of the potting medium than will be found in more practical situations.

Table 6.9. EC-1:1.5 for potted plants with and without covered potting medium surface. Plants were fertigated four times a week for 5 minutes (11 weeks) with an EC of 1.7. (s.d. given between brackets).

Height (m)	non-covered (n=3)	covered (n=2)
0.08-0.12	5.43 (0.64)	3.54 (0.10)
0.00-0.08	1.12 (0.22)	1.75 (0.06)

The EC-1:1.5 in the lower part of the potting medium, which is commonly analysed in commercial horticulture, was found to be affected by fertigation schedule. With increasing wetness, the EC increased. This is consistent with data reported by Reischmann (1985), but van Leeuwen (1991a) reported EC to decrease with increasing irrigation frequency. The frequencies he used were up to four times a day, and were much higher than the frequencies used in this experiment. Accumulation of salt, however, is also affected by plant uptake. Growth and evapotranspiration were found to be affected by fertigation schedule (chapter 5). Accumulation reflects an overall reaction of plant uptake and differences in nutrient distribution induced by the fertigation schedule. Since both cannot be separated experimentally, it cannot be concluded from the experiments whether the fertigation schedule, or different plant uptake was responsible for different increase of EC.

The composition of the fertigation water was different from that of the potting medium solution. Additionally, it was found that nutrients that accumulated in the potting medium not necessarily also accumulated in the potting medium solution. K accumulated in the potting medium with a significant increase in the concentration in all layers of the potting medium. Ca accumulated also (table 6.5), but the increase in concentration was not as high as for K (table 6.6). As a result of precipitation of phosphate and sulphate salts, the Ca concentration remained relatively low in the upper layers of the potting medium. In lower layers, precipitation with Ca is not expected, since concentrations were too low. Yet the concentration of Ca decreased in these layers compared to the concentration in the fertigation water, although the total amount of Ca increased. This can be explained by a highly favourable adsorption of Ca by the potting medium (chapter 4). Ca added with the fertigation water exchanged mainly with Mg on the adsorption sites. As a result, Ca concentration decreased, while the Mg concentration increased simultaneously. Mg concentration in the lower layers increased, while the total amount of Mg decreased (tables 6.5 and 6.6). Cation adsorption therefore influenced the availability and vertical distribution of Ca and Mg considerably. For the potting medium used it this study this meant that the Mg concentration in the potting medium water remained at a higher level than the concentration in the fertigation water. Since cation adsorption played an important role in this, it also meant that Ca/Mg ratios initially present as a result of initial fertilization, remained present in the potting medium for a long time, although a solution of a different composition was used for fertigation.

Since EC and composition of the potting medium solution of potted plants grown on a flooded bench fertigation system are only partly determined by EC of the fertigation water, different plant responses can be expected with respect to fertigation schedule, potting medium, or evaporation from the potting medium surface, e.g. by increasing plant density on the benches. Vice versa, different fertigation frequencies affect plant growth not only through different water content in the potting medium, but also through different EC levels.

7. Dynamic behaviour of water and nutrients: simulation

Optimal fertigation of plants requires optimized frequency and supply of water and solutes. Optimization of frequency requires knowing the time course of the cumulative plant uptake and supply, which in turn depends on duration of flooding. Once the benches are flooded the quantity that is supplied to the plant during fertigation is determined by capillary rise. Capillary rise depends strongly on physical characteristics and on water content. As a result, the amount supplied is highly correlated with frequency. In practice, fertigation is tuned to the evapotranspiration. Because water and nutrients are supplied simultaneously to the plant, optimal supply of water may be sub-optimal with respect to plant nutrition.

Complicated dynamic interactions between plant uptake, fertigation schedule, water and solute distribution in the root zone, and chemical processes can be studied using a simulation model which includes a sufficiently detailed description of these processes. Various models have been developed to simulate dynamics of water and nutrients for different crops growing in natural soils (Engesgaard and Christensen, 1988; Feddes et al., 1988; Hanks and Ritchie (eds.), 1991; Molz, 1981). Such models, however, have only rarely been applied to potted plant systems (Chen and Lieth, 1992). In fact none of the models can be applied directly to such systems, since the geometry of the system, the boundary conditions and the physical characteristics of the potting medium differ significantly from those in field soils.

The objective of this chapter is to present a model which simulates dynamics of water and nutrients on a flooded bench fertigation system, to discuss the parameterization, and to compare simulations with experimental results reported in chapters 5 and 6. These experiments have been conducted to validate the simulation model; on the other hand the model is also needed for full interpretation of the experiments.

7.1 Simulation model for water and solutes

A model has been developed to simulate dynamics of water and solutes in the potting medium. The model refers to a pot with specified dimensions on a flooded bench fertigation system and requires daily evapotranspiration and nutrient uptake as inputs. The model simulates spatial and diurnal fluctuations in water content, matric and osmotic head, fluxes and solute contents, as induced by fertigation schedule and plant uptake.

The simulation model integrates three submodels: one for movement of water, one for transport processes of non-reactive solutes, and one for chemical equilibrium processes. It is assumed that in any horizontal plane the water and solutes are in equilibrium at all times, which is of course an approximation. Hence, non-homogeneity of the state variables in the horizontal plane is ignored, which means that only vertical distribution is considered. A basic relation of the model is the equation of continuity (chapter 2), elaborated here for one-dimensional vertical transport in a conically shaped pot:

$$\frac{\delta GA_k}{\delta t} = - \frac{\delta G\, J_k}{\delta z} - G\, S_k \,. \qquad 7.1$$

All symbols are defined in the list of symbols (appendix 1). The geometry factor, G, represents the cross sectional area as a function of height associated with the conical shape of the pot. The factor G is defined as:

$$G(z) = \pi \times r(z)^2 = \pi \times (r_{top} - z/tg\beta)^2, \qquad 7.2$$

where r_{top} is the radius at the top of the pot, and ß is the angle between the wall of the pot and a horizontal plane.

7.1.1. Submodel describing movement of water

Movement of water is calculated by combining Darcy's law with the continuity equation (7.1). The water balance model SWATRE (Soil Water and Transpiration Rate, Extended) is used in this study to simulate the dynamics of water (Wesseling et al., 1991). A detailed description of an earlier version of this model, including validation for several agricultural applications is given by Belmans et al. (1983), Feddes et al. (1988), and Kabat et al. (1992). SWATRE is adapted for this study by including the geometry of the pot according to equations 7.1 and 7.2. The subroutine describing hysteresis, which was already included in a later version of SWATRE, has been slightly adapted to prevent "water pumping" (chapter 4, appendix 2). Selection of different lower boundary conditions is possible in SWATRE. A subroutine has been included which allows to switch between boundaries corresponding to the fertigation schedule. Actual evaporation and transpiration data are used as forcing functions. A subroutine to allocate measured transpiration over the root system as affected by conditions in the medium has been included. The boundaries and the water uptake routine are discussed below.

The lower boundary on a flooded bench system changes from flux type to matric head type and vice versa according to equations 7.3 through 7.5, which distinguish three phases for each cycle:

Phase 1: boundary condition during supply of water and nutrients:

$$t_{fs} \leq t < t_{fe},\ z = z_f,\ h_m = 0; \qquad 7.3$$

Phase 2: boundary condition during drainage of nutrient solution:

$$t_{fe} \leq t < t_{de},\ z=0,\ h_m=0,\ \delta H/\delta z > 0; \qquad 7.4$$

Phase 3: boundary condition during period with zero flux at the bottom of the pot:

$$t_{de} \leq t < t_{fs},\ z = 0,\ q = 0. \qquad 7.5$$

During flooding (phase 1), it is assumed that the water table inside the pot equals the flooding height (z_f) outside the pot. Start (t_{fs}) and end (t_{fe}) of flooding are imposed by the fertigation schedule. After flooding has stopped, water flows out of the pot for a short period, as long as $\delta H/\delta z$ at the bottom of the pot is positive (free drainage). During this period the boundary condition is described by a zero matric head at the bottom of the pot and the flux out of the pot is calculated. The time at which drainage ends and $\delta H/\delta z$

becomes zero at z=0, defined as t_{dc}, is calculated by the model. The period with zero flux at the bottom of the pot lasts till the next flooding.

Total water uptake by the entire root system, i. e. measured actual transpiration, is used as input in this model. However, as a result of non-homogeneous distribution of roots, vertical gradients in physical conditions (K, θ, and h_m), and strong osmotic gradients, the water uptake is not uniform in height. Allocation of water uptake over height is calculated according to equation 7.6:

$$S(z,t) = \frac{[\, h_{root} - h_m(z,t) - h_o(z,t) \,]}{R_s + R_r}, \qquad 7.6$$

with $R_s(z,t) = 1/(B\ K(\theta)\ L(z,t))$, and $R_r(z,t) = R_u\ /\ L(z,t)$ (Hillel, 1977). This macroscopic model treats the root system as a fixed resistance network, and disregards the microscopic aspects of matric and osmotic head in the immediate vicinity of an active root. The h_{root} for which total water uptake from all layers equals transpiration, is calculated by an iteration procedure according Hillel (1977).

7.1.2. Submodel describing movement of solutes

Transport of solutes is calculated by combining equation 7.7 for diffusive and convective transport,

$$J_i = - D_0\ \theta\ \tau\ \frac{\delta c_i}{\delta z} - L_r\,|\,q\,|\,\frac{\delta c_i}{\delta z} + q\ c_i\ , \qquad 7.7$$

with the continuity equation (7.1). All three terms in equation 7.7 are discussed in chapter 2. The upper boundary condition of the system is given by a zero solute flux (J_i=0). The lower boundary condition depends on the phase as defined in equations 7.3 through 7.5. The lower boundary is given by a zero flux (J_i=0) during ebb phase (phase 3), or by flux identical to $q \times c_i$, where c_i equals the concentration in the fertigation solution if q is upward (phase 1) and c_i equals the concentration in the soil solution at the bottom of the pot if q is downward (phase 2).

Total nutrient uptake by the plant is used as a forcing function in this model. The sink term for nutrients, S_k in equation 7.1, is calculated by dividing the total nutrient uptake over the layers in the profile according root distribution. Equations 7.1 and 7.7 are solved for eleven species (Ca, Mg, K, Na, NO_3, SO_4, Cl, H_3PO_4, H_2PO_4, HPO_4 and PO_4). Following Robbins (1991), the numerical solution is given by a 6 point implicit "Crank-Nicholson" finite difference approximation with linearization in time and space of the soil parameters (diffusion coefficients and fluxes) using the so called "Thomas tridiagonal matrix algorithm". A finite difference solution may cause considerable errors in the concentration profile owing to numerical dispersion. To minimize this effect, thin layers are chosen and a solution scheme proposed by Bresler (1973) is followed. This scheme includes a second order approximation which suppresses most of the numerical dispersion. A FORTRAN listing of this subroutine is given in appendix 3.

7.1.3 Submodel describing cation adsorption and precipitation
After each time step and for each layer in the profile, chemical equilibria are obtained with a model developed by Robbins (1991). The chemical submodel calculates EC, ionic strength, activity coefficients, osmotic head, and concentrations of solutes after equilibration with the adsorbed phase and after precipitation or dissolution of calcium phosphate and calcium sulfate, assuming instantaneous local equilibrium. Other chemical reactions, like anion adsorption (normally low in organic soils (Fox and Kamprath, 1971)), formation of ion pairs (which would increase solubility), precipitation with micro elements, and precipitation of carbonates (unlikely at pH measured in the medium), are not included in the model. Equations for calculation of EC, osmotic potential, activity coefficients and ionic strength are discussed in chapter 2. Equilibrium of cations with the adsorbed phase of the organic potting medium is calculated according the cation adsorption model proposed by Robbins (1991), which is discussed in chapter 4 for the potting medium used in this study. Based on concentrations measured in the potting medium solution, precipitation of calcium phosphate and calcium sulfate is expected to occur in particular in the top layer of the potting medium. Chemical reactions included in the chemical subroutine program are listed in table 7.1. The model requires pH, bulk density, CEC, volumetric water content, solute concentrations, amounts of precipitates, and adsorbed amounts before equilibrium as input, and gives these variables and also EC and osmotic head at equilibrium as output.

7.2. Model parameters

Not all parameters mentioned in the previous equations were determined experimentally in this study. An attempt is made to simulate the overall behaviour of the system while choosing these parameters within reasonable limits. Experimental data and data gathered from literature are summarized and discussed below.

7.2.1 Description of the pot and the fertigation schedule
The simulations refer to experiments conducted in a greenhouse with *Ficus benjamina*. Dimensions of the pot were 0.12 m height, and radius at the top and bottom, respectively, 0.058 and 0.0475 m, which gives an angle determining the conical shape, ß, of 85.0 (tgß = 11.43 in equation 7.1). Fertigation schedules and composition of the solution are described in chapters 5 and 6. Flooding height (z_f) is set at 0.015 m. This is lower than the level of 0.02 m, measured at the edge of the benches, since flooding level on the benches is lower in the center, and since pots are constructed so that the bottom is slightly above the benches to allow for free drainage. The level of 0.015 m is chosen as an average flooding level inside the pot. It takes about 2 minutes to reach this maximum flooding level, and a same period is needed for water to flow from the benches once flooding is stopped. So a flooding period of 5 minutes actually is a flooding period of about 7 minutes with a flooding level ranging from 0 to 0.015 m. In the model the profile is divided into twenty-eight layers: 20 layers of 0.005 m at the top, and 8 layers of 0.0025 m at the bottom. Number and grouping of layers reflect a compromise between the need to simulate the expected large gradients in the top and bottom layers, and increased computer time with

increasing number of layers. Increasing layer thickness reduces computer time but also significantly affects simulated capillary rise.

Table 7.1. Chemical reactions and relations included in the chemical equilibrium submodel.

Reaction/relation	constant	literature
Precipitates:		
-dicalciumfosfate:		
$Ca(HPO_4)$ <==> Ca + HPO_4	2.19E-7	Bolt and Bruggenwert, 1978
-gypsum:		(ch.6)
$CaSO_4$ <==> Ca + SO_4	2.45E-5	
		Bolt and Bruggenwert, 1978
Dissociation:		
H_3PO_4 <==> H + H_2PO_4	7.58E-3	
H_2PO_4 <==> H + HPO_4	6.31E-8	Bolt and Bruggenwert, 1978
HPO_4 <==> H + PO_4	4.68E-13	Bolt and Bruggenwert, 1978
		Bolt and Bruggenwert, 1978
Adsorption:		
Ca-ads + Mg <==> Mg-ads + Ca	0.47	
2Na-ads + Ca <==> Ca-ads + 2 Na	4.3	this thesis, chapter 4
2K-ads + Ca <==> Ca-ads + 2 K	3.78	this thesis, chapter 4
2K-ads + Mg <==> Mg-ads + 2 K	1.65	this thesis, chapter 4
2Na-ads + Mg <==> Mg-ads + 2 Na	1.73	this thesis, chapter 4
Na-ads + K <==> K-ads + Na	1.32	this thesis, chapter 4
		this thesis, chapter 4
Other relations (see chapter 2 for explanation):		
-electrical conductivity:		
$Ec = \sum_i K_0 \times C^b$		
-osmotic head:		
$h_o = -1/(\rho_l\, g)\ R\, T \sum c$		
-ionic strength		
$I = 0.5 \sum_i c_i v_i^2$		
-activity coefficients:		
$\log f_v = -0.509\ v^2 (\sqrt{I}/(\sqrt{I} + 1) - 0.3\ I)$		

Table 7.2. The parameters in the van Genuchten model regarding the water retention and conductivity characteristics of the potting medium.

parameter	θ_r	θ_s	n	m	α_d	α_w	l	K_s
value	0.0	0.92	1.42	0.30	0.13	0.90	2.35	8670

7.2.2 Hydraulic characteristics of the potting medium

Physical characterization has been performed on samples which reflected the natural growing conditions as much as possible (chapter 3). The main drying curve of the soil water retention characteristic is described with a mathematical model proposed by van Genuchten (1980), and the hydraulic conductivity with a model of Mualem (1976). Hysteresis is included in the description according to an empirical model proposed by Kool and Parker (1987), which is adapted to suppress the artificial effect of "water pumping" under cyclic fertigation, by closing the scanning loops at the previous reversal point, as pointed out in chapter 3. This leads to a set of seven parameters for complete description of the physical characteristics. Characterization and parameterization has been discussed in chapter 3. The parameters are summarized in table 7.2.

7.2.3 Solute transport characteristics of the potting medium

Diffusion coefficients of the solutes in water range from 0.7 E-9 to 2.0 E-9 $m^2 s^{-1}$ at 25 °C (Kemper, 1986). In the model an average value of 1.4 E-9 is used, and an effect of temperature is ignored. The coefficient τ in equation 7.8 is often set equal to 0.5, although it may be larger in wet soil than in dry soil (Koorevaar et al., 1983). Considering an average volumetric water content of 0.4, a diffusion coefficient ($\tau \times D_0$) of 0.7 E-9 $m^2 s^{-1}$, and an average daily flux of 1.16 E-7 m s^{-1}, an average value of the "diffusion length" of $L_{diff} = \theta D_0 \tau q^{-1}$ = 2.4 E-3 m is obtained. The dispersion length is roughly proportional to aggregate size (Bolt, 1982). In this study the dispersion length L_r is set at 0.004 m. Variation of dispersion length from 0.001 to 0.01 m does not have much effect on calculated distribution. Slightly smaller gradients are simulated with increasing dispersion length. A stagnant phase, possibly occurring from small pores inside the perlite (Chen et al., 1980), which would have contributed to dispersion, is ignored in the model.

7.2.4 Chemical characteristics of the potting medium

Constants for chemical equilibria have been obtained from literature and experimental data (table 7.1). The bulk density is set at 100 kg m^{-3} (chapter 3). During cultivation the pH decreases with height, but remains fairly constant with time (chapter 6). Cation exchange capacity is set at 76 meq 100 g^{-1} for the lower layers of the potting medium. Since pH is lower in the upper layers of the potting medium and CEC decreases with decreasing pH (chapter 4), a lower CEC is set for the higher layers in the potting medium. The lowest CEC at the top layer is set at 71 meq 100 g^{-1}.

7.2.5 Plant characteristics

Root length distribution as a function of height is estimated from literature data, and root dry mass distribution. Root mass distribution is determined according to a visual judgement of root distribution (table 7.3), and measured total root dry mass (chapter 5).

Table 7.3. Estimated percentages of total roots present in a profile layer of 0.01 m thickness after 10, 15, 25 and 50 days of cultivation. Percentages are used as input for the model and are based on visual judgement of root distribution.

height (cm)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
10 days	5.5	5.5	7.5	7.5	10	10	10	10	15	14	4.9	0.1
15 days	8	8	10	10	10	10	10	10	10	10	3.9	0.1
25 days	12	12	10	10	10	10	8	8	8	8	3.9	0.1
50 days	15	14	10	10	10	10	7.5	7.5	5.5	5.5	4.9	0.1

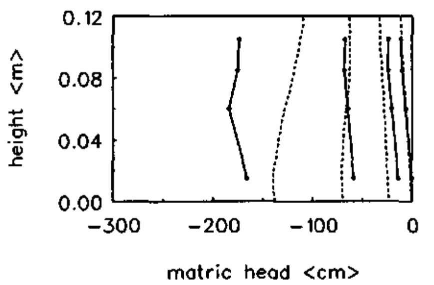
Root length is estimated from root dry mass distribution and specific root mass. Reported specific root masses for horticultural plants grown in pots range from 12 to 115 m g^{-1} (de Willigen and van Noordwijk, 1987; Chen and Lieth, 1992), from which the specific root mass is estimated to be 50 m g^{-1} in this study. Assuming root mass of 4 E-3 kg and a pot volume of 1 E-3 m^3, a root length density of 2 E5 m m^{-3} is calculated, which, as expected, is higher than values reported for crops in field soils. The root resistance per unit length, R_u, is estimated at 5 E10 s m^{-1}, based on reported range of 1 E8 to 1 E13 (Belmans et al. 1979; Hillel, 1977). Variation in the model of root length and root resistance mainly affects the calculated root pressure head, h_{root}, but has less effect on allocation of water uptake with height.

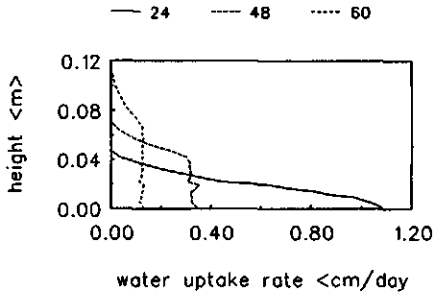
7.3 Results

Results of simulations are compared with experimental data from chapters 5 and 6. Performance of the model in simulating various aspects of water dynamics is evaluated in three separate cases: total water storage of the potting medium during cultivation with different fertigation schedules; matric head profiles while flooding; and matric head profiles between fertigations. Simulation of solute distribution is compared with EC profiles, measured in the potting medium solution. Simulated ion distribution is discussed in relation to measured distribution patterns.

7.3.1 Dynamics of water between fertigations

Matric head profiles between fertigations were highly dependent on the fertigation schedule during cultivation (chapter 5). For a plant which has been continuously flooded during cultivation (figure 7.1) the matric head between fertigations decreases less than for a plant which has been periodically flooded (figure 7.2). The volumetric water content before evapotranspiration of the plant in figure 7.1 is considerably higher than that of the plant in figure 7.2 (respectively 0.697 and 0.584 kg/pot). Since both profiles are at hydrostatic equilibrium initially, it is believed that this difference in water content results from hysteresis. Transpiration is almost identical for both plants, respectively 0.398 and 0.365 kg/pot in 60 hours. Simulations start with an EC profile as measured (chapter 6). Simulations using the main drying curve of the water retention characteristic initially show identical matric head profiles for both plants, while calculated matric head remains higher than -0.50 m for the entire height. Since this is inconsistent with the measurements, a scanning wetting curve according to which total water storage in the pot equals the measured water content, is chosen as an initial condition. The simulated matric head profiles are now more consistent with the measurements (figure 7.1 and 7.2). For the plant that has been flooded continuously during cultivation the matric head decreases to the same extent in all layers, although simulated uptake of water by roots occurs mostly from lower layers in the profile (figure 7.1), in particular in the beginning. It is therefore concluded that the hydraulic conductivity of the potting medium for these volumetric water contents is sufficiently high to cause immediate redistribution of water. For the second plant, with a much lower water content, redistribution of water cannot keep up with transpiration. Both measurements and simulation show that the profile remains fairly uniform during the first 24 hours, but as transpiration proceeds, matric head declines more in the lower half.





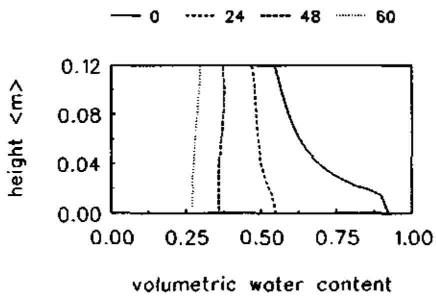
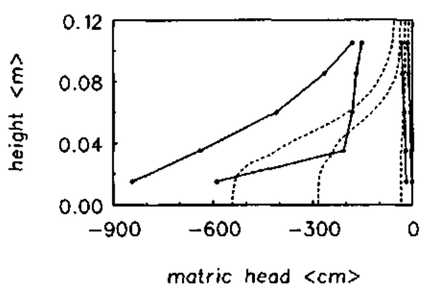
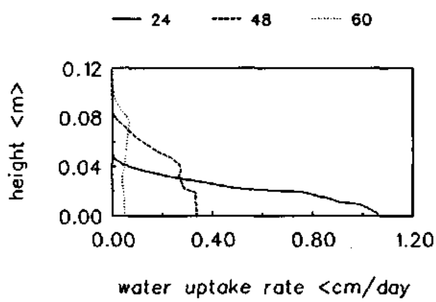


Figure 7.1. Measured (continuous line) and simulated (dotted line) matric head, simulated volumetric water content, and simulated water uptake rate, after 0, 24, 48, and 60 hours of transpiration. During cultivation the pot was continuously flooded for 3 months.





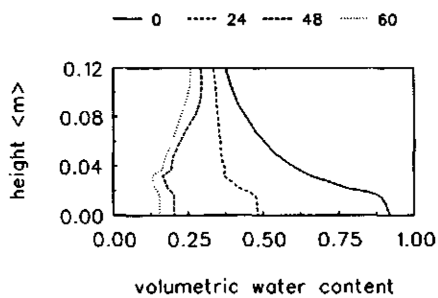


Figure 7.2. Measured (continuous line) and simulated (dotted line) matric head, simulated volumetric water content, and simulated water uptake rate, after 0, 24, 48, and 60 hours of transpiration. During cultivation the pot was periodically flooded for 3 months, and subsequently flooded for 1 day before measurements started.

Allocation of water uptake by roots is comparable with the other pot (figure 7.2). The volumetric water content for this pot, however, is lower (figures 7.1, 7.2). As a result the hydraulic conductivity becomes too low to allow for immediate redistribution of water during evapotranspiration. Largest gradients in matric head are found just before flooding, while largest gradients in water content are found immediately after flooding (figures 7.1 and 7.2).

The different dynamics between the two plants can well be understood with the model, even though simulated matric heads are higher than the measured ones. Simulations have been performed with the physical characteristics as measured in the laboratory, ignoring a change in water retention characteristic as a result of fertigation and plant roots (chapter 3). Repeated wetting and drying, and plant roots result in a more rapid decrease in matric head with decreasing water content, compared to the medium as characterized before cultivation. This can very well explain why the measured matric head is lower than simulated.

7.3.2 Dynamics of water during flooding

Measured matric head profiles for pots with a flooding level of 0.03 m are compared with simulated profiles (figure 7.3 and 7.4). Results of two simulations and measurements are discussed here. These pots differ in the volumetric water content before flooding. The simulated matric head agrees well for lower layers of a dry sample (figure 7.3), but increase in higher layers is underestimated. Matric head remains unaffected for some time, but then increases suddenly, indicating that a sharp wetting front gradually rises in the pot. For the wetter sample (figure 7.4), increase of matric head is underestimated for all layers, and, as expected, the wetting front is less sharp. For other profiles (not shown) capillary rise is underestimated also. It turns out that capillary rise in particular is very sensitive for the hydraulic conductivity. Since capillary rise is underestimated, this suggests that the hydraulic conductivity may be higher than used in these simulations. This can either be caused by an underestimation of the hydraulic conductivity, or by an underestimation of the volumetric water content related to hysteresis. According to the simulations, longer flooding than 5 minutes, which is the more common period in practice, is required for maximal capillary rise. When flooding shorter, only lower layers will be wetted initially. This is predicted well by the model. In conclusion the model may be expected to predict water capillary rise well for less extreme flooding, but simulated redistribution after flooding may be underestimated.

7.3.3 Average water content during cultivation

The fertigation schedule significantly affects total water storage in the pot (chapter 5). Using the measured evapotranspiration as forcing function, the model predicts water storage after flooding well (figure 7.5). Simulated water storage is constant with continuously flooded plants, while measured water content increases slightly (figure 7.5). This increase may indicate that the water retention characteristic changes during cultivation. In particular for continuously flooded plants the volumetric water content measured in relation to matric head increased during cultivation as a result of root growth and flooding (chapter 3). Such an increase, which is not accounted for in the model, would explain that total water storage in the pot increases in time. For the medium used in this study, this increase seems hardly relevant. However, for media with a lower air content at high matric heads, this may become important with respect to aeration.

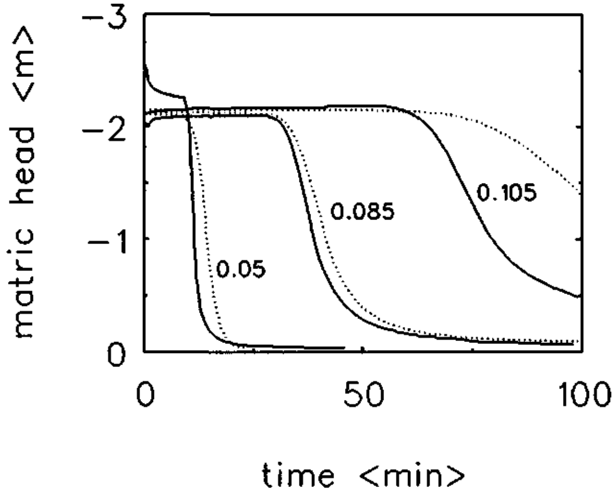


Figure 7.3. Measured (continuous line) and simulated (dotted line) dynamics of matric head induced by flooding at respectively 0.05, 0.085 and 0.105 m height. Before flooding started, the average matric head in the profile was -2.1 m.

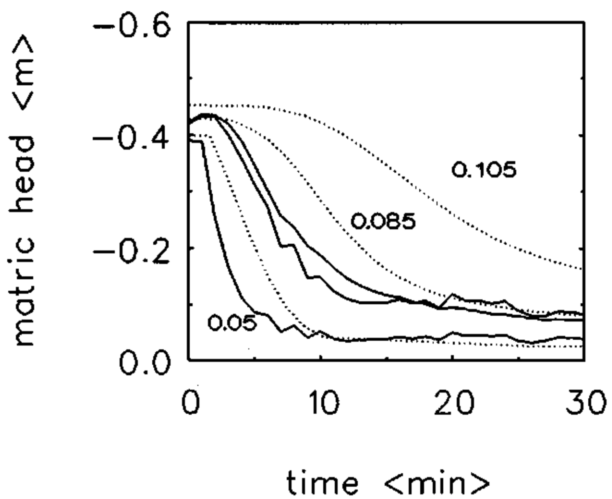


Figure 7.4. Measured (continuous line) and simulated (dotted line) dynamics of matric head induced by flooding at respectively 0.05, 0.085 and 0.105 m height. Before flooding started, the average matric head in the profile was -0.45 m.

Total water storage for pots that were flooded four times a week for 30 minutes is slightly overestimated by the model (figure 7.5). Water content of pots fertigated twice a week is underestimated, in particular during the last days of the cultivation. As a result, simulation cannot proceed beyond day 65 since measured transpiration between fertigations was higher than simulated total water storage. For both drier treatments (flooded 2×30 minutes and 4×5 minutes) total water storage after flooding decreases from about 0.55 to values below 0.30 between days 30 and 40, since capillary rise cannot keep up with increased evapotranspiration. Between those days, evapotranspiration almost doubled (chapter 5).

Simulations suggest that hysteresis in the water retention curve is a very important phenomenon, and mainly responsible for differences among fertigation schedules. If hysteresis is ignored, a volumetric water content of 0.82 is simulated for plants that are flooded either continuously or four times a week for 5 minutes (figure 7.5). Such high volumetric water contents, and the fact that this remains constant during cultivation and unaffected by fertigation schedule do not agree at all with the measurements. Including hysteresis in the water retention characteristic reduces the average volumetric water content for this fertigation schedule and this potting medium by more than 50 percent.

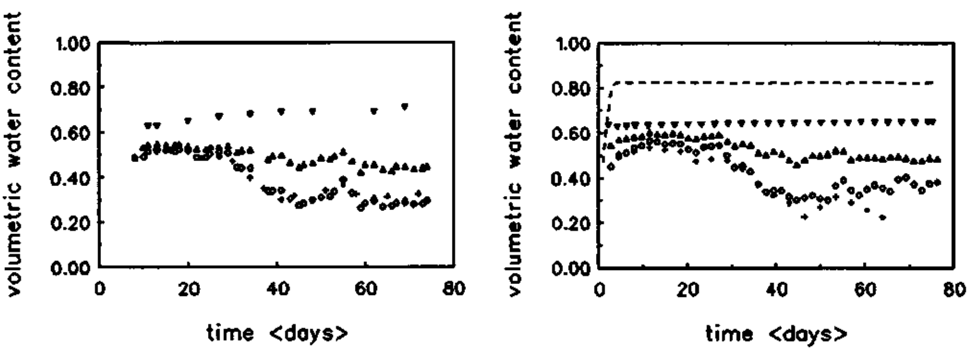


Figure 7.5. Measured (left) and simulated (right) average volumetric water content after fertigation with different fertigation schedules. Continuously flooded (▾), 4 times a week for 30 minutes (▴), 4 times a week for 5 minutes (○) and twice a week for 30 minutes (+). The dashed line refers to simulation without hysteresis, fertigation 4 times a week for 5 minutes.

7.3.4 Dynamics of nutrients during cultivation

Simulated EC profiles for plants that are flooded four times a week for 30 minutes agree reasonably well with the measured profiles (figure 7.6). However, for plants that are flooded twice a week, the simulation only agrees well for the first three weeks of cultivation. After 7 weeks, the simulated EC in the lower half of the potting medium is about 3 to 4 times higher than measured. This disagreement can be explained by an underestimation of the volumetric water content for this fertigation schedule (figure 7.5), and a slower redistribution of water after fertigation. According to the model, the upper 0.06 m remains dry between fertigations. Since this does not agree with measurements, upward redistribution of water and solutes is underestimated by the model. As a result, solutes accumulate in lower layers rather than in the top layer of the pot, which explains severe overestimation of EC in the lower half of the pot. Since differences in build-up of salinity induced by the fertigation schedule are in particular observed after a longer period than three weeks (chapter 6), the measured effect of fertigation schedule on EC build-up cannot be confirmed by the simulation model.

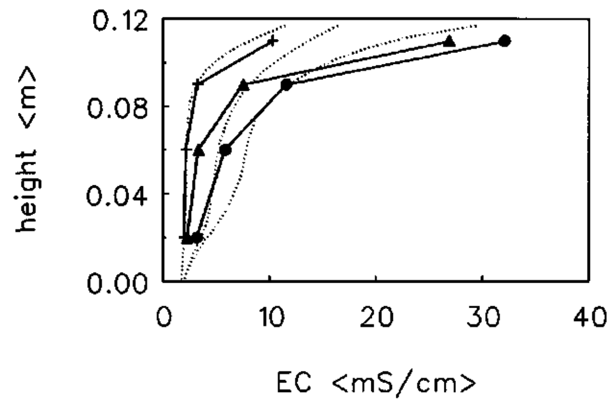


Figure 7.6. Measured EC after 3 (+), 7 (▲), and 11 (•) weeks of cultivation (continuous lines with measure points) and simulated profiles (dotted lines). During cultivation the plants were flooded 4 times a week for 30 minutes (EC = 1.7). EC refers to the EC in the potting medium solution immediately after fertigation.

Profiles with increasing EC in height are measured and simulated immediately after fertigation. Simulation shows that EC between fertigations increased in particular in the lower layers of the potting medium where most roots are located. Between fertigations, the EC profile becomes more homogeneous in height. Measuring the EC in the liquid phase of the potting medium directly after fertigation may have the advantage that volumetric water content is observed as most constant in time. On the other hand, the largest differences in height may be expected at that moment also. Measured EC in the potting medium solution is then more dependent on sampling height.

Simulated cation composition of the potting medium water shows patterns comparable with those discussed in chapter 6. The relative contribution of Na and Mg to the cation composition increases in height, while the contribution of Ca decreases. At the adsorption complex the relative composition of Mg compared to Ca decreases in lower layers, while the opposite occurs in higher layers, which supports the conclusions in chapter 6 that the cation adsorption complex plays an important role in cation composition of the liquid phase. Ca accumulates in lower layers, while the other cations accumulate mainly in the top layers. Additionally, precipitation also contributes to lower Ca concentrations in the potting medium solution. Although adsorption of K and Na is relatively low compared to Ca and Mg, still about 30% of these ions that accumulate in the potting medium are adsorbed, which reduces the concentrations in the liquid phase considerably. The majority of all cations together is adsorbed on the organic material. The adsorption complex buffers the solution in particular against changes in Ca and Mg. This buffer may be even more relevant if the concentration of one of the cations is to be changed.

7.4 Discussion

The linked water and solute model provides a useful tool for studying the dynamics of water and nutrients for the potted plant on a flooded bench fertigation system. A satisfactory description of dynamics of water is given for wet growing conditions, while less satisfactory results are obtained for drier conditions. These conditions, however, may be less relevant for practice, since growth reduces then as well.

Average volumetric water content during cultivation is predicted well by the model. Two things are essential in this simulation. The first one is hysteresis in the water retention characteristic. Simulations strongly suggest that in particular hysteresis causes the differences in volumetric water content during cultivation. Therefore, hysteresis needs more attention in characterization of horticultural substrates. Secondly, the initial condition plays an important role in the simulated volumetric water content during cultivation. Since potting media are never saturated before being placed on a flooded bench system, simulations start with a scanning curve of the water retention characteristic rather than from the main drying curve. Since this affects simulated water contents, the initial conditions, in particular the consequences of wetting from above before pots are placed on a flooded bench system, need further investigation.

Simulated allocation of water uptake in height is dominated by osmotic head distribution. The subroutine responsible for allocation (also equation 7.6) is rather arbitrary since it treats physical conditions surrounding roots identical to those between roots. However, conditions surrounding roots may differ significantly from the medium between roots. Additionally the model does not account for reducing root contact with decreasing θ (Herkelrath et al., 1979), neither for reduced water uptake resulting from poor aeration, which may be expected in the lower layers of the medium. Finally, the root length and resistances are estimated from literature. Variation of these within limits reported in literature, however, hardly affects simulated uptake patterns. These are mainly induced by the osmotic head gradients. Although the model works well for the conditions found in the potting medium in this study, detailed validation is still needed.

Several elements of the model and application could be enhanced through additional work. For example, evapotranspiration data are used as a forcing function of the model. Evapotranspiration was affected by the fertigation schedule (chapter 5). Strictly, this restricts use of the model to situations for which evapotranspiration is known beforehand. Linking this model to a crop transpiration model may remove this restriction. The model is based on basic processes of water transport. Parameters of the model have physical meanings, and can be specified independently. This suggests that the model can be applied to other media by changing the parameters. Additionally, the model may be applied to other irrigation systems, if boundary conditions of this system are specified and included in the model. It may be of particular interest to compare dynamics induced by overhead irrigation with those resulting from sub-irrigation. In its present form, the main applications of the model are to analyse dynamics of water and nutrients with respect to fertigation schedule, physical characteristics and pot geometry, since it treats these aspects of the growing system as one entity.

8. General discussion

This thesis aims to quantify dynamics of water and nutrients in the root environment of potted plants induced by flooded bench fertigation. It can be concluded from the previous chapters that these dynamics are affected by a combination of characteristics of the medium, fertigation schedule, and plant uptake. In this thesis, plant uptake is not modelled but described as a forcing function. To create an optimal root environment, one must decide upon 1) the substrate, mainly based on physical and chemical characteristics, 2) the pot geometry, and 3) the fertigation method, e. g. frequency, duration, and composition of nutrient solution. Among these, the first two will have to be selected beforehand, while fertigation method can be altered during cultivation. These choices, and their relevance for the dynamics of water and nutrients will be discussed in this chapter. Two aspects are considered of particular importance for the flooded bench fertigation system: the available amount of water, and the amount of water added by fertigation. These two aspects will first be considered for one medium and one fertigation schedule (section 8.1 and 8.2), followed by a discussion on how they are affected by hydraulic characteristics of the medium (section 8.3), by the geometry of the pot (section 8.4), and by the fertigation schedule (section 8.5) with respect to plant uptake. Dynamics of nutrients, in particular as affected by fertigation frequency and evaporation, are discussed in section 8.6.

8.1 Amount added with fertigation: volumetric absorption

The absorption of water during flooding increases with decreasing volumetric water content before flooding (chapter 5). Simulated volumetric absorption in relation to volumetric water content before flooding is presented in figure 8.1. Volumetric absorption was defined in chapter 5 as the amount added to the medium due to capillary rise divided by the volume of the potting medium. Simulations are performed with a flooding duration of 5 minutes, while it is assumed that the water retention characteristic is best described with a scanning curve between -2.0 and 0 m (chapter 3). This scanning curve gives a more realistic description of the water retention characteristic in situ than either the main drying or main wetting curve (chapter 3). Also it is assumed that the profile is in hydrostatic equilibrium before flooding, which is a reasonable approximation for wet conditions (chapter 5). The average volumetric water content equals the total water storage in the pot divided by pot volume. The local volumetric water contents in the profile decrease with height since the profile is assumed to be at hydrostatic equilibrium.

The simulated volumetric absorption curve lies between those representing, respectively, minimum and maximum absorption. Flooding for 5 minutes is insufficient for maximal capillary rise. Minimum absorption results from flooding the lower 0.015 m of the potting medium while no additional capillary rise occurs. The maximum line assumes that maximal capillary rise occurs leading to an equilibrium water content after flooding, defined as flooded bench capacity. Flooded bench capacity is determined by the water retention characteristic and the geometry of the pot. For the scanning curve of the water retention characteristic and the geometry of the pot used in this study, this flooded bench capacity

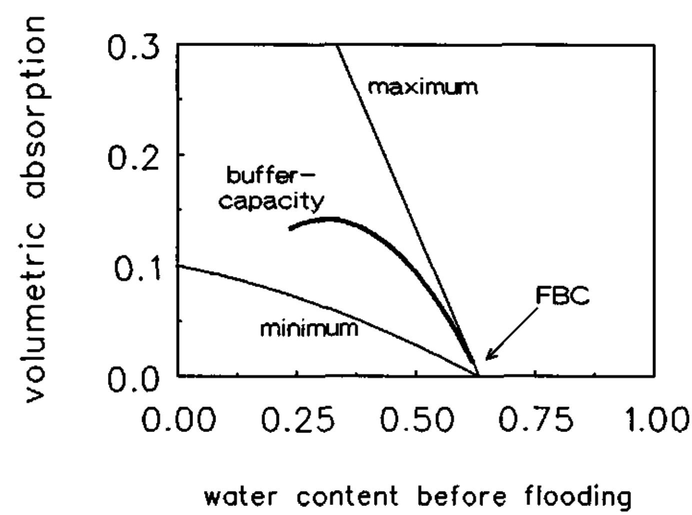


Figure 8.1. Simulated volumetric absorption after 5 minutes of flooding in relation to the volumetric water content before flooding. The curve lies between lines representing the minimum and maximum absorption. The intercept on the horizontal axis equals the flooded bench capacity (FBC); the top of the curve represents the buffer capacity.

equals 0.63. Flooded bench capacity is different from the container capacity (Fonteno, 1988; Milks et al., 1989), which equals the amount of water held by a potting medium for a defined pot resulting from drainage after saturation. Flooded bench capacity, as defined here, is the amount of water held for a defined pot and potting medium after capillary rise. If hysteresis in the water retention characteristic is absent, the flooded bench capacity may become equal to container capacity. However, flooded bench capacity becomes lower if hysteresis occurs. Flooded bench capacity will depend on the history of wetting and drying of the sample, since for hysteretic water retention characteristics the $h_m(\theta)$ relation depends thereupon (chapter 3). Regardless of flooding duration, the water storage cannot become higher than flooded bench capacity. Consequently, air content cannot become less than the difference between porosity and flooded bench capacity. However, since at flooded bench capacity the profile is at hydrostatic equilibrium, vertical gradients in water content will occur, leading to higher water and lower air contents in the lower part of the pot.

8.2 Available amount of water: buffer capacity

Capillary rise during flooding increases with decreasing initial water content (figure 8.1). However, the fertigation becomes less effective with decreasing initial water content, since capillary rise becomes much lower than the maximal capillary rise which can be achieved, e. g. by flooding longer. The highest volumetric absorption due to capillary rise after flooding for five minutes equals 0.14 (figure 8.1). To prevent desiccation of the potting medium, the amount of evapotranspiration between fertigations should not exceed this value. As shown in figure 8.1, this value is much lower than the total water storage in the pot. Therefore, this value is probably the best definition of the buffer capacity for the medium on a flooded bench fertigation system. Buffer capacity or easily available water is often considered as a medium characteristic solely (Verdonck et al., 1983; Gabriëls and Verdonck, 1991); but others relate this also to pot geometry (Milks et al., 1989; Fonteno, 1988). If flooded bench fertigation is used, the buffer capacity may be much lower than would be expected on the basis of the water retention characteristic and pot geometry solely. It is as much determined by fertigation method and hydraulic conductivity of the substrate (section 8.3). This has major implications for the fertigation schedule, since much higher fertigation frequencies are required than expected from the total water storage in the medium.

8.3 Hydraulic characteristics

Capillary rise is significantly affected by the hydraulic conductivity of the medium. Volumetric absorption increases with increasing hydraulic conductivity (figure 8.2). This effect becomes increasingly important at lower volumetric water contents. A tenfold decrease in hydraulic conductivity strongly reduces capillary rise, which makes the medium less suitable for the flooded bench system. A tenfold increase hardly affects water absorption for high initial volumetric water contents associated with high fertigation frequencies, since water absorption is close to the maximum for both curves.

Volumetric absorption during flooding is also affected by the water retention characteristic. Assuming the same hydraulic conductivity characteristic, $K(\theta)$, an effect of an increase of the parameter α of the van Genuchten description of the water retention characteristic on the volumetric absorption relation is illustrated in figure 8.3. Increasing α reduces the water content and hence increases the air content at high matric heads. As a result of increased α, two main effects occur. The flooded bench capacity, as defined in paragraph 8.1, reduces. This effect is comparable with an effect of the water retention characteristic on container capacity (Fonteno, 1988). Secondly, for a given flooding duration, capillary rise reduces, resulting in a lower buffer capacity of the medium. Parameter α may differ among media (chapter 3). But α also increases for a wetting curve compared to a drying curve, resulting from hysteresis. Hysteresis therefore reduces both the buffer capacity, which is the amount that can be withdrawn between fertigations without causing the medium to desiccate for a given flooding duration, and the flooded bench capacity, which represents the water storage in the profile for flooding duration long enough to allow maximal capillary rise. It is assumed in this discussion that $K(\theta)$ is unaffected, which automatically means that the $K(h_m)$ relation has changed. Among different media both characteristics generally will be different, which means that the combined effects shown in figures 8.2 and 8.3 can be expected.

Understanding of dynamics of water and nutrients in horticultural substrates requires more detailed characterization than is customary. Additionally, it is essential that characterizations are performed on substrates reflecting natural conditions as much as possible. Characterization should include the main drying curve of the water retention characteristic at least between saturation and -1.0 m matric head, but preferably also

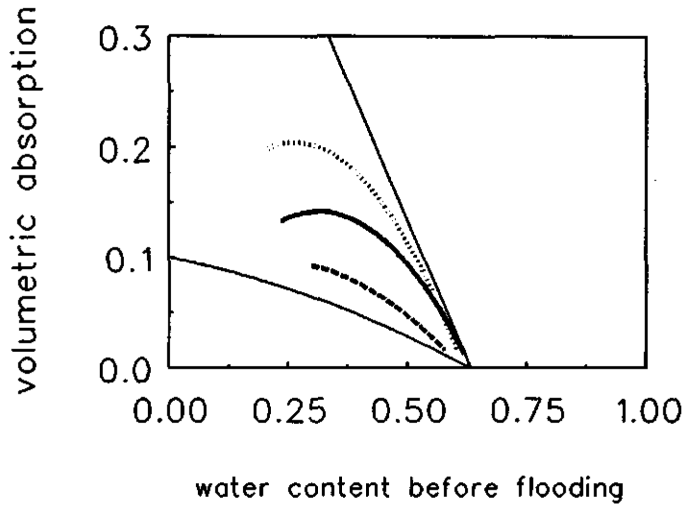


Figure 8.2.
Effect of a tenfold increase (dotted line) and tenfold decrease (dashed line) of the hydraulic conductivity on the volumetric absorption after 5 minutes of flooding in relation to volumetric water content before flooding.

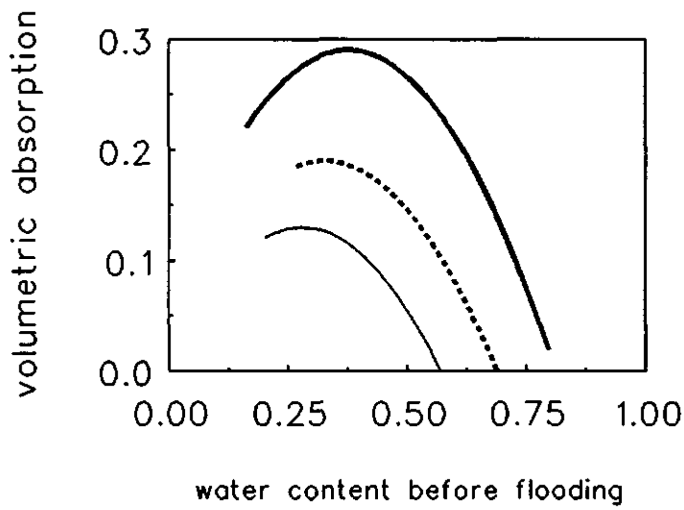


Figure 8.3. Simulated volumetric absorption after 5 minutes of flooding in relation to volumetric water content before flooding for different water retention characteristics. The curves correspond with a parameter α of 0.13 (thick continuous line), 0.3 (dashed line), and 0.6 (thin continuous line), which corresponds with volumetric air contents at -1.0 m matric head of 0.215, 0.370 and 0.500 respectively.

somewhat beyond that point. Additionally at least one wetting curve is required. A scanning curve starting from -1.0 m matric head seems most practical, since this one is easier to determine than the main wetting curve. Other scanning curves may be estimated according to the procedure outlined in chapter 3. In particular for media consisting of peat, hysteresis was significant (chapter 3). Unfortunately, hysteresis in horticultural substrates has been measured only rarely. The volumetric water and air contents at high matric head, and the way these are affected by hysteresis, are important media characteristics. Even for continuously flooded plants, the water retention characteristic in situ was closer related to a scanning wetting curve than to the main drying curve, which is determined commonly. Initial water content of the medium, and initial wetting from above, as is commonly done before placing pots on a flooded bench system, may have important effects on water contents during cultivation, and need further investigation.

Hydraulic conductivity is also very important, as shown here for sub-irrigation systems. Hydraulic conductivity as a function of the water content may be estimated from the water retention characteristic (chapter 3). This requires at least a good estimate of the hydraulic conductivity at saturation, but even then considerable errors can be made if no additional data are available (chapter 3). Since horticultural substrates differ considerably in their hydraulic conductivity, this parameter needs more consideration in characterization. It is difficult to recommend values for this parameter at this moment, but a tenfold reduction of the hydraulic conductivity of the substrate used in this study would make it unsuitable for the flooded bench fertigation system. Relations as presented in figure 8.1, which can be either simulated or measured (chapter 5), may help to develop such recommendations in the future.

8.4 Pot geometry

The choice of a pot is usually determined by plant species and plant size. Among plant species, however, pots may differ considerably in height. Container capacity is affected by pot geometry (Fonteno, 1988). The conical shape of the pot hardly affects water absorption during fertigation on a flooded bench fertigation system (figure 8.4). For a cylindrical pot, capillary rise is slightly higher, but there is almost no difference at water contents higher than 0.45. On the other hand, height of the pot has a large effect. Both buffer capacity and flooded bench capacity (paragraph 8.1 and 8.2) increase with decreasing height (figure 8.4). This is consistent with Fonteno (1988), who also concluded that height is important for the amount of water held. Of course, in practice, pot height and pot volume increase simultaneously, while at the same time larger plants leading to higher evapotranspiration are grown in higher pots. But, if two pots have the same volume and the same loss through evapotranspiration, longer flooding is required for the higher pot. Vice versa, higher volumetric water contents can be expected in lower pots. Although it is difficult to give a quantitative effect due to interactions with evapotranspiration and fertigation, the pot geometry, and in particular the height, considerably determines the available amount of water on a flooded bench fertigation system. It is, however, more common to adjust the fertigation schedule and potting medium to pot geometry.

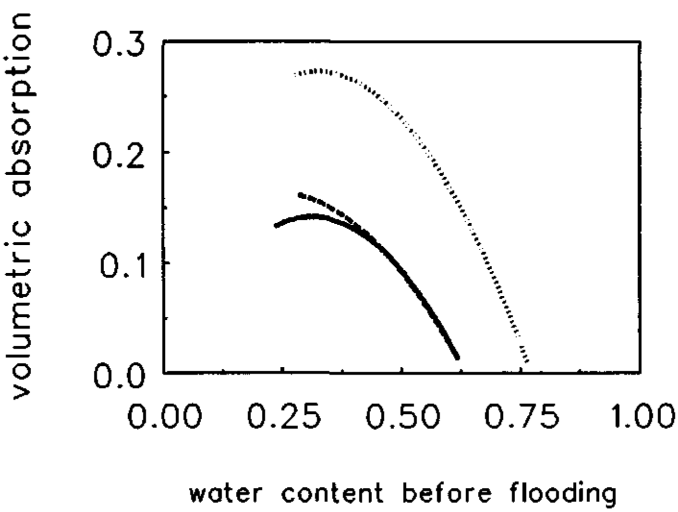


Figure 8.4. Effect of pot geometry on volumetric absorption during 5 minutes of flooding in relation to volumetric water content before flooding. The pots have a content of 1 dm^3. The pot is conical with a height of 0.12 m (continuous line) or 0.06 m (dotted line); or cylindrical with a height of 0.12 m (dashed line).

8.5 Control of the medium by fertigation schedule

Once the potting medium, the fertigation method, the pot and the plant have been selected, the conditions in the root environment can be controlled by adjusting the fertigation schedule. This requires insight into the interactions with the pot geometry, the physical characteristics, and evapotranspiration. The options for water control discussed here are flooding duration and flooding frequency. Discussion focusses on volumetric absorption with respect to evapotranspiration.

8.5.1. Flooding duration

Longer flooding increases volumetric absorption in particular at lower initial volumetric water contents (figure 8.5). Higher final volumetric water contents and higher buffer capacity may be expected when flooding longer. For a given (constant) evapotranspiration, figure 8.5 may be used to predict volumetric water content during cultivation. First we calculate the volumetric evapotranspiration, as the amount lost through evapotranspiration between fertigations divided by substrate volume. For a constant volumetric evapotranspiration, the average water content will stabilize at a value for which volumetric absorption equals volumetric evapotranspiration (figure 8.5). If during cultivation the medium becomes too dry, longer flooding seems a solution. However, it requires considerable longer flooding if the medium becomes very dry (chapter 7). The first minutes are most effective for capillary rise. If pots become too dry, it is more effective to increase frequency.

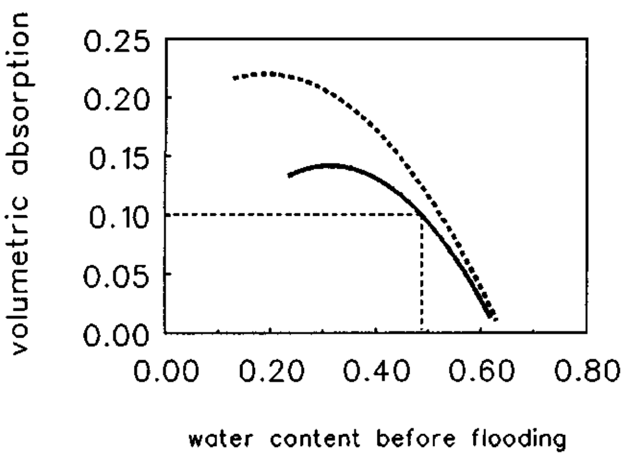


Figure 8.5. Simulated volumetric absorption in relation to volumetric water content before flooding for a flooding duration of 5 minutes (continuous line) or 30 minutes (dashed line). A volumetric water content of 0.48 corresponds with a volumetric absorption of 0.1 (dotted lines).

8.5.2 Fertigation frequency

Figure 8.5 and table 8.1 show that increase in evapotranspiration between fertigations leads to lower water contents before flooding. Of course, the water content after flooding equals the water content before flooding plus the volumetric absorption. Increase in evapotranspiration between fertigations may result from increasing irradiation, increasing plant growth, but also from a decreasing fertigation frequency. For a given volumetric evapotranspiration, a minimum fertigation frequency can be determined, which is required to prevent desiccation below a certain water content. For instance, if the desired water content equals 0.48, and the plant is flooded for 5 minutes, the maximum volumetric evapotranspiration between successive fertigations equals 0.1 (0.1 kg dm^{-3} pot volume; figure 8.5). If evapotranspiration divided by pot volume equals 0.05 kg day^{-1}, a fertigation frequency of at least once every two days is needed. However, if volumetric evapotranspiration equals 0.2 kg day^{-1}, a fertigation frequency of at least twice a day is required. ET for continuously flooded plants varied from 0.016 to 0.164 kg pot^{-1} day^{-1}, for a pot volume of 1 dm^3 (chapter 5).

Since evapotranspiration will vary not only among days, but also among plants on the same day, an effect on volumetric water content before and after flooding induced by variation of 20% in evapotranspiration is also presented (table 8.1). Variations in evapotranspiration among days or plants, cause considerable differences in water content if lower water contents are maintained. Reinforced by a stronger decreasing h_m with θ at lower θ, this explains why large differences in matric head were measured among plants in particular for drier cultivations (chapter 5). Since it may be expected that variation in water content among pots increases with decreasing water content, and since much longer flooding is required with decreasing initial θ leading to longer period during which the lower layer is saturated, the flooded bench fertigation system is less suitable for cultivation under dry conditions. High frequencies and longer flooding duration will reduce differences in volumetric water contents among pots.

Table 8.1. Simulated average volumetric water content before and after flooding (5 minutes every day) with respect to daily evapotranspiration, and an effect of variation of +/- 20% of the evapotranspiration.

ET	water content	+ 20 % ET	- 20 % ET
0.14	0.30 - 0.44	-	0.45 - 0.56
0.10	0.48 - 0.58	0.43 - 0.55	0.53 - 0.61
0.05	0.57 - 0.62	0.56 - 0.62	0.59 - 0.63
0.02	0.61 - 0.63	0.61 - 0.63	0.61 - 0.63

8.6 Dynamics of nutrients

With respect to water uptake, osmotic heads are of particular importance in the potted plant system. For wet growing conditions, the osmotic head was an order of magnitude lower (more negative) than the matric head (chapter 6). This was also found for other growing systems and other media (Charpentier, 1988). In the potted plant system the osmotic head is not uniform in the root environment. Vertical distribution and accumulation in time was affected by fertigation frequency and duration (chapter 6). Reduction of fertigation frequency causes a greater increase of EC in the root environment between fertigations, in particular in the lower layers of the potting medium (figure 8.6). As a result, the EC in the root environment is not identical to the EC of the fertigation water. This suggests that the latter is not a good parameter to relate to plant response.

It is difficult to control salinity on a flooded bench fertigation system. Since nutrients are added together with water, the factors that influence water uptake discussed before will also affect nutrition of the plant (chapter 6). Generally, selection of fertigation frequency and duration will depend on evapotranspiration rather than on nutrient content in the root environment.

Accumulation of nutrients on a flooded bench fertigation system is in particular found in the top layer. Evaporation of water from the potting medium surface largely explains this accumulation (figure 8.7). Simulation shows that strong vertical gradients can be prevented by reducing evaporation. This agrees with the reduced accumulation in the top layer resulting from covering the potting medium surface (chapter 6). Reduction of evaporation may be difficult to achieve in practice, but accumulation can be expected to increase with decreasing plant density (chapter 5), or with increasing pot temperature by bench heating (Vogelezang, 1993). Salts accumulated in the top layer will not become available again for the plant, unless they are removed by flushing from above. Therefore, reduction of EC during cultivation will reduce EC in the lower layers, where most roots are found, but will not reduce the amount of salts already accumulated in the top layer. If lower EC of the fertigation water is used right from the start, it seems possible to prevent EC increase in the lower layers of the potting medium (figure 8.8). Reduction of evaporation (for instance by increasing plant density in particular during the initial stage of cultivation), frequent fertigation, proper initial fertilization (or initial wetting with a solute concentration), and additional fertigation with lower concentrations together may improve salinity control on a flooded bench fertigation system. However, among the usual growing systems for potted plants, nutrition seems to be most difficult to control in systems using sub-irrigation.

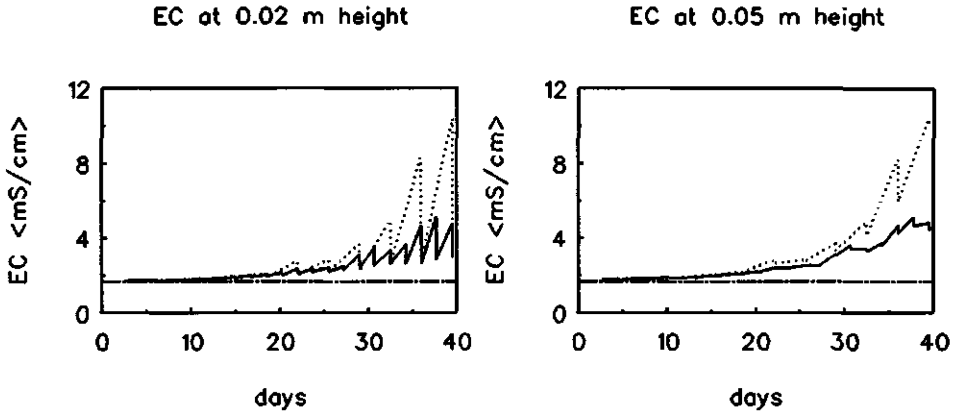


Figure 8.6. EC simulated at 0.02 and 0.05 m height in the liquid phase of the potting medium. The potting medium was fertigated 4 times a week (continuous line), or twice a week (dotted line) with EC of the fertigation water equal to 1.7 (horizontal line).

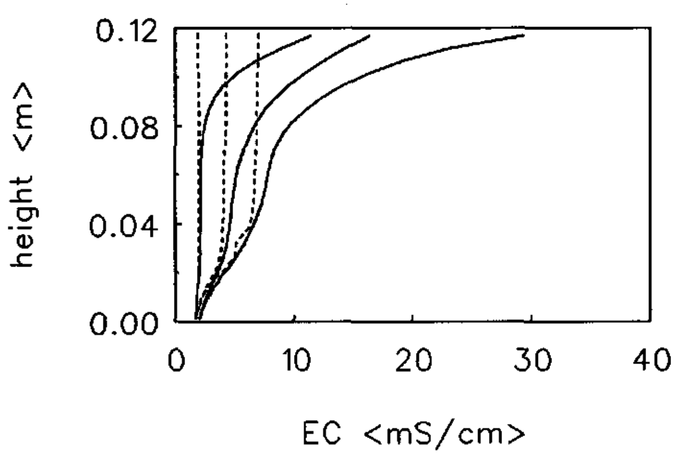


Figure 8.7. Simulated EC profiles after 3, 7 or 11 weeks of cultivation with evaporation (continuous lines) and without evaporation (dashed lines). Pots were flooded 4 times a week for 30 minutes with an EC of 1.7 (chapter 5, 6).

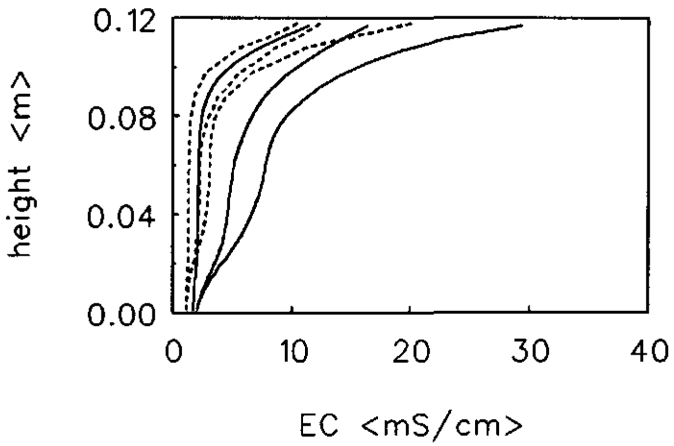


Figure 8.8. Simulated EC profiles after 3, 7, and 11 weeks of cultivation. Pots were flooded 4 times a week for 30 minutes with an EC of 1.7 (continuous lines) or with an EC equal to plant uptake (dashed lines).

8.7 Conclusions for dynamics of water and nutrients on a flooded bench fertigation system

Based on the experimental results combined with model simulations this thesis gives rise to the following conclusions for dynamics of water and nutrients on a flooded bench fertigation system with respect to physical and chemical characteristics of the potting medium, fertigation schedule, and evapotranspiration:

1) A simulation model based on theory describing movement of water and solutes in porous media can help to increase insight into complicated interactions between fertigation schedule, fertigation method, medium characteristics and plant uptake.

2) Hysteresis in water retention of the potting medium reduces total water storage in the pot during cultivation. The strong hysteretic nature of the medium used in this study caused reduction by 25 to 70 percent depending on the fertigation schedule. Secondly, hysteresis reduces capillary rise during fertigation. With more frequent fertigations and sufficiently high conductivity of the medium, the average water content is mainly determined by geometry of the pot and the water retention characteristic. This questions classification of substrates based on the main drying curve of the water retention characteristic.

3) Hysteresis in the water retention characteristic increases the air volume in the potting medium which allows high fertigation frequencies, even during periods of low evapotranspiration.

4) The hydraulic conductivity characteristic affects capillary rise during fertigation

significantly, and is in particular a determining factor under drier conditions and short fertigation duration.

5) For a given fertigation schedule and pot geometry, the buffer capacity, defined as the amount of water that can be withdrawn between two fertigations without causing the medium to desiccate, is determined by both the water retention and conductivity characteristic. This buffer capacity is much less than total water storage in the pot, and decreases with decreasing flooding duration, with decreasing conductivity, and with increasing air content at high matric heads.

6) Volumetric absorption in relation to volumetric water content, either measured or calculated, can best be used to evaluate suitability of a medium for the flooded bench system. This relation combines effects of fertigation schedule, pot geometry, water retention characteristic and hydraulic conductivity characteristic. Since these are all equally important, judgement on one of these characteristics separate from the others is not advisable.

7) Between fertigations, most water is withdrawn from lower layers in the pot. This pattern is mainly induced by the osmotic head profile. At low fertigation frequencies, this can lead to local drier conditions, but for more practical conditions water redistribution is expected to keep up with transpiration, causing a downward flux of water and solutes between fertigations.

8) Different fertigation schedules will result in different EC levels in the root environment. This affects plant growth even stronger than differences in water content.

9) A considerable percentage of evapotranspiration results from evaporation through the potting medium surface, in particular during the initial stage of cultivation. This affects spatial distribution and accumulation of nutrients in the root zone.

This thesis dealt with dynamics of water and nutrients for potted plants grown on a flooded bench fertigation system. As pointed out before, this system was selected to enable an in depth analysis. The results show that, based on the knowledge of movement of water and nutrients in porous media, it is possible to analyse a horticultural system while looking upon plant, growing system, fertigation schedule and medium characteristics as one entity. This approach elucidated some aspects which have been ignored too much in the past. Among these are hysteresis in the water retention characteristic and the hydraulic conductivity characteristic of substrates. Further, changing the irrigation schedule does not only affect the water content but also the nutrition, a factor often forgotten when studying an effect of irrigation frequency on plant growth. Many of the conclusions with respect to dynamics of water and nutrients will be valid for other growing systems using sub-irrigation. On the other hand, other growing systems may have their own specific important factors, e. g. spatial distribution of irrigation water for overhead sprinkler irrigation systems, or flow patterns towards drains. However, the dynamics for those systems may also be clarified if such systems are studied in a way similar to the case study in this thesis. Such studies may pinpoint shortcomings of growing systems and suggest directions for future research. The theory presented in chapter 2 forms the basis of such studies, although some systems may also require formulation of the transport equations in two or three dimensional form.

Information about evapotranspiration is essential for control of water and nutrients in the root environment. This information is only rarely available. The model used in this study uses evapotranspiration data as a forcing function. This choice was made to reduce misinterpretations resulting from uncertainties in evapotranspiration. However, this approach certainly limits application of the model. In future research, this limitation may be removed if simulation models describing evapotranspiration and plant growth are linked to the model presented here.

Additionally to the model approach, the dynamics in the root environment of horticultural systems can be studied through appropriate sensors. In this thesis tensiometers were used. Tensiometers have been used successfully in the past for other growing systems and other media (Dickob, 1991; Frenz et al., 1988). However, due to the shape of the water retention characteristic of many horticultural substrates, tensiometers are rather insensitive to changes in volumetric water content under wet conditions. Other options are sensors which measure the volumetric water content, such as TDR (time domain reflectometry) and capacitive sensors. Further if EC in the liquid phase is measured simultaneously, these sensors are even more useful. Although these sensors are available already for research purposes, construction of these sensors will still need considerable attention before they come widely available for horticultural systems. However, even if water content and EC are measured properly, knowledge on transport processes in porous media to select the fertigation schedule is still required. Especially for this, and for interpretation of hydraulic characteristics of horticultural media, the model presented in this thesis is essential.

Summary

Optimal plant growth requires optimal control of the root environment. Since for horticultural growing systems with artificial substrates the substrate volume is kept relatively small, water and nutrients must be added frequently. There are different ways of fertigation. Water and nutrients are added either from above, e. g. drip or sprinkler fertigation, or from below, e. g. by flooding the lower part of the substrate. Besides the direction of flow of the nutrient solution, an additional difference between both methods is that with fertigation from below by flooding it is not possible to control the amount of water and nutrients added with each fertigation. Once water and nutrients have been added to the substrate, they will redistribute. As a result, conditions in the root environment will be strongly determined by physical and chemical characteristics of the medium. There have been many efforts trying to relate physical and chemical characteristics of a substrate to plant growth. However, this has not been very successful, and often results have been contradicting. Optimal characteristics of potting media are difficult to define universally, since suitability of a given substrate also depends on fertigation schedule, fertigation method, geometry of the substrate (in particular height), and plant uptake.

The objective in this thesis is to quantify dynamics of water and nutrients in the root zone with respect to physical and chemical characteristics, fertigation schedule, fertigation method and plant uptake. As a case study, the flooded bench fertigation system for potted plants was selected. With the flooded bench fertigation system, water and nutrients are added by flooding the benches with plants once or several times a week. During flooding, pots are standing in a nutrient solution, usually to a height of 0.02 m, and are allowed to take up water and nutrients for a short period, e.g. about five minutes. For this study, *Ficus benjamina* grown in a potting medium consisting of 75% peat and 25% perlite was selected.

Following definitions related to dynamics of water and nutrients in soil, the theory is summarized, and terminology is introduced with respect to substrates in chapter 2. Transport of water through a porous medium is described with Darcy's law, which states that the water flux density is proportional to the hydraulic head gradient. It requires a relation between the volumetric water content and the matric head, called the water retention characteristic, and a relation between the hydraulic conductivity and the matric head or the volumetric water content, called the hydraulic conductivity characteristic. Both characteristics can be determined in the laboratory. Transport of nutrients is described with a convective flux and a flux resulting from diffusion and dispersion. The combination of these transport equations with equations of continuity, which state that the differences between the rates of flow into and out of an element equal the sum of the rates of storage and the rates of uptake by plant roots, leads to a partial differential equations which can be solved numerically. Besides a numerical solution scheme, solution of the equations requires implementing the appropriate initial and boundary conditions, and requires a description of plant uptake in relation to conditions in the medium. This theory forms the basis of many simulation models developed for field soil. One of these models (SWATRE) is adapted to the situation of potted plants grown on a flooded bench fertigation system.

The study of dynamics of water requires description of the water retention and hydraulic conductivity characteristics of the potting medium. Water retention characteristics often are hysteretic: different relations are found for drying or wetting conditions. Hysteresis in the water retention characteristic has been measured rarely for horticultural media. Also the hydraulic conductivity characteristic has rarely been measured. For the potting medium used in this study both characteristics were determined. To obtain samples that reflect natural conditions at the start of the growing period as much as possible, rings used for characterization were filled with the potting medium the same way as pots usually are filled, using a potting machine without artificial pressure. It was shown that water retention increased in time as a result of root growth and repeated wetting and drying.

The physical characteristics are described by mathematical relationships with a minimum set of parameters. A mathematical model proposed by Van Genuchten was successfully applied to describe the water retention characteristic of this potting medium. Others demonstrated its use for other horticultural media. In combination with an empirical model proposed by Kool and Parker, a simple model is presented to describe the water retention characteristic of the potting medium, including hysteresis, with a set of six parameters. Combined with the hydraulic conductivity model of Mualem, a model is obtained to describe the hydraulic conductivity, using only two unknown additional parameters. Parameters for both equations were obtained for the potting medium by fitting to experimental results.

One of the most important mechanisms which regulates the distribution and hence availability of nutrients in the root zone is the exchange of cations. The potting medium used in this study consisted of a mixture of two solid components. Cation adsorption on perlite was almost zero (chapter 4). On the other hand, the cation adsorption on peat was very high, and dependent on pH. Under conditions occurring in horticultural practice, this resulted in a total cation adsorption of 75 meq/100g, which was about six times higher than the amount present in the potting medium solution. Ca and Mg occupied more than 95% of these adsorption sites, with Ca favoured over Mg by a factor 2.1. Since these cations can be exchanged with other cations, cation adsorption considerably increased the available amount of Ca and Mg, and affected vertical distribution of cations as well. A cation adsorption model is proposed, which can be used to predict the changes of a system as a result of external factors, e.g. the composition of the solution used for fertigation.

Evapotranspiration (ET) and dynamics of water induced by the fertigation schedule are described in chapter 5. Daily ET by continuously flooded *Ficus benjamina* plants reflected LAI and daily radiation integral outside the greenhouse. With a plant density of 25 plant m^{-2} bench, ET varied from 0.4 kg m^{-2} day^{-1} to 4.1 kg m^{-2} day^{-1} for, respectively, crops of small plants in winter and fully grown plants in summer. With small plants most water was lost through evaporation from the potting medium. The fraction lost by evaporation decreased exponentially with increasing LAI, which is mainly a function of plant size and plant density. The total cumulative amount of water lost by evaporation varied from 19 to 41% of total ET for continuously flooded plants. If the potting medium was kept sufficiently wet, evaporation was not affected by fertigation frequency. Transpiration, on the other hand, was reduced with decreasing fertigation frequency or duration, and with increasing EC. As a result, the fraction evaporated was higher for periodically than for continuously flooded plants.

Average volumetric water content of the potting medium after flooding was strongly affected by fertigation schedule. The average volumetric water content was always smaller than container capacity (0.82 10^{-3} m^3), even when the plants were continuously flooded. Plants that were flooded four times a week for 30 minutes contained less water after flooding than continuously flooded plants. Reducing flooding duration or flooding frequency significantly further reduced the average volumetric water content of the potting medium after flooding.

Matric head in the potting medium reflected not only a drying and wetting cycle, but also the diurnal transpiration pattern. Measurements with tensiometers at different heights showed that water uptake by plants was higher in lower layers of the pot, which was consistent with the presence of the majority of roots there. Local drought in the lower layers of the potting medium occurred at matric heads below -1.50 m. Considerable variation was found in matric head among plants within the same treatment. This may be caused by variation in ET, hysteresis in water retention of the potting medium, and differences in physical characteristics among the pots.

Capillary rise of water while flooding was not only affected by the flooding duration but mainly by the volumetric water content before flooding and therefore by ET. Capillary rise increased with increasing flooding duration and decreasing volumetric water content. The effect of increased flooding duration was more pronounced with decreasing volumetric water content. While flooding, the lower part of the potting medium became immediately wet, which resulted in an increased matric head. The matric head increased more slowly in higher layers. When the matric head was reduced to -1.10 m, it took over 40 minutes to reach a hydrostatic equilibrium while flooding. Since in practice flooding periods of 5 minutes are more common, prediction of the supply of water on a flooded bench fertigation system requires a computation based on the flow equation for the nutrient solution.

Nutrient balance sheets and vertical distribution in the potting medium are discussed in chapter 6. EC and composition of the potting medium solution of plants grown on a flooded bench fertigation system varied in time and space. In the upper layers the EC was of the order of five times higher than in the lower layers. Nutrients accumulated initially in the top layer of the potting medium. This was mainly caused by evaporation from the potting medium, which was high in particular during the initial stage of cultivation. As time proceeded, EC increased in lower layers as well. Increase of EC in lower layers was affected by EC of the fertigation water, fertigation frequency, and evaporation.

Cation composition of the liquid phase in the pots was different from the composition of the fertigation water, and varied strongly in height. In particular the vertical distribution of Ca and Mg was dominated by the adsorption on the potting medium. Na and Cl accumulated in the potting medium solution, since uptake by plants and adsorption on the potting medium are negligible. Since EC and composition of the potting medium solution are only partly determined by EC and composition of the fertigation water, different plant responses may be expected with respect to fertigation schedule, potting medium, or evaporation, e.g. by increasing plant density on the benches. Vice versa, different fertigation frequencies affect plant growth not only through different water contents in the potting medium, but also through different EC levels.

An explanatory model was developed to simulate the dynamics of water and solutes in the potting medium for a flooded bench fertigation system. The model refers to a pot with specified dimensions on a flooded bench fertigation system and requires daily evapotranspiration and nutrient uptake as inputs. The model comprises three submodels: one for dynamics of water (based on the model SWATRE), one for dynamics of non-reactive solutes, and one for chemical equilibrium processes (based on CHEM). The model SWATRE was adapted with respect to geometry of the pot, description of the boundary conditions for the flooded bench fertigation system, and the allocation over the root system of the uptake of water and nutrients as affected by external conditions. Results of simulations are compared with experimental data from chapters 5 and 6. The model gave a satisfactory description of the dynamics of water on the flooded bench system for wet growing conditions. Capillary rise and redistribution of water were underestimated by the model, in particular under dry conditions. The measured average volumetric water contents in relation to fertigation schedule and measured matric head profiles between successive fertigations could be understood by studying the dynamic behaviour of the model.

Interpretation of the experiments in combination with the simulation model gave rise to the following main conclusions:

- Hysteresis in the water retention characteristic significantly reduces water content and capillary rise on a flooded bench fertigation system. Additionally, the hydraulic conductivity characteristic is a very important parameter, in particular under drier conditions and short fertigation duration. In characterization of horticultural substrates, these characteristics should not be overlooked.
- For a given fertigation schedule and pot geometry the buffer capacity, defined as the amount of water that can be withdrawn between two fertigations without causing the medium to desiccate, is determined by both the water retention and the hydraulic conductivity characteristic.
- The fertigation schedule, the pot geometry, in particular height, evapotranspiration and physical characteristics all are important with respect to dynamics of water and nutrients in the potting medium. Considering any of these factors in isolation from the others is therefore not advisable.
- Cation adsorption capacity of a substrate determines spatial distribution and hence availability of nutrients. The largest part of the amount of Ca and Mg was adsorbed on the potting medium.
- Plant nutrition and fertigation schedule are highly intertwined. Different fertigation frequencies will result in different EC's in the root environment, the effect of which on plant growth may be even stronger than the effect of differences in water content.

Samenvatting

Een van de aspecten die bij teeltoptimalisering van belang zijn, is de optimalisering van het wortelmilieu. Aangezien voor veel substraatteelten het substraatvolume relatief klein wordt gehouden, moeten water en nutriënten frequent worden toegediend. Hiervoor zijn verschillende mogelijkheden. Toediening van water en nutriënten kan plaats vinden van bovenaf, bijvoorbeeld door middel van druppelaars of sproeiers, dan wel van onderaf, bijvoorbeeld door het onderste deel van het substraat onder water te zetten (eb/vloed systemen). In de eerste plaats verschillen beide methoden in de richting waarin het toegediende water in het substraat stroomt. Daarbij is een verschil dat bij eb/vloed systemen het niet mogelijk is om de hoeveelheid die per vloedbeurt wordt toegediend exact te bepalen. Wanneer het onderste deel eenmaal onder water is gezet, wordt de verdere opname bepaald door capillaire opstijging, waardoor het wortelmilieu in sterke mate bepaald wordt door fysische en chemische eigenschappen van het substraat. Er zijn vele pogingen ondernomen om deze eigenschappen te relateren aan groei, maar de resultaten zijn veelal tegenstrijdig. Optimale eigenschappen van een substraat zijn niet eenvoudig te definiëren, aangezien verwacht mag worden dat geschiktheid van een substraat mede af zal hangen van de fertigatiemethode, het fertigatieschema, de dimensies van het substraat (in het bijzonder de hoogte) en de plantopname.

Het doel in dit proefschrift is om de dynamiek van water en nutriënten in het wortelmilieu te kwantificeren in relatie tot fertigatiemethode en -schema, plantopname en eigenschappen van het substraat. Het eb/vloed fertigatiesysteem voor potplanten is gekozen om in detail uit te werken. Bij dit teeltsysteem worden water en nutriënten van onderaf aan de pot toegediend door één of enkele malen per week een laag voedingsoplossing aan te brengen op de tafels waarop de potten staan. Gedurende deze vloedperiode staan de potten aan de onderzijde in een voedingsoplossing, meestal tot een hoogte van 0.02 m, voor een periode van ongeveer 5 minuten. Bij bestudering van dit systeem is in dit proefschrift gekozen voor de *Ficus benjamina*, geteeld in een eb/vloed potgrond bestaande uit veen (75%) en perliet (25%).

De theorie en terminologie welke in dit proefschrift gebruikt worden om de dynamiek van water en nutriënten in het wortelmilieu te beschrijven, worden geïntroduceerd in hoofdstuk 2, op analoge wijze zoals deze voor gronden zijn gedefinieerd. Transport van water wordt beschreven volgens Darcy, waarbij wordt aangenomen dat de flux evenredig is aan de gradiënt in stijghoogte in het substraat. Hiervoor is een relatie nodig die het verband weergeeft tussen volumetrisch vochtgehalte en de drukhoogte, de waterretentiekarakteristiek, en een relatie die het verband weergeeft tussen de waterdoorlatendheid en de drukhoogte of het volumetrisch vochtgehalte, de waterdoorlatendheidskarakteristiek, welke beide in het laboratorium kunnen worden bepaald. Transport van nutriënten wordt beschreven door een combinatie van convectief transport en transport ten gevolge van diffusie en dispersie. De combinatie van deze transportvergelijkingen met een continuiteitsvergelijking levert een stelsel van vergelijkingen op welke numeriek kan worden opgelost. Naast een oplossingsmethodiek is hiervoor een beschrijving nodig van de randvoorwaarden van het systeem, en voor de plantopname in relatie tot condities in het wortelmilieu. Deze theorie vormt de basis van veel simulatiemodellen, waarvan er één (SWATRE) is aangepast voor de omstandigheden zoals die zich bij een eb/vloed teeltsysteem voordoen.

De waterretentiekarakteristiek is veelal onderhevig aan hysterese: verschillende relaties worden gevonden voor uitdrogen en bevochtigen van een substraat. Zowel hysterese in de waterretentiekarakteristiek als de waterdoorlatendheidskarakteristiek zijn slechts sporadisch gemeten voor substraten. Beide karakteristieken zijn bepaald voor de potgrond in deze studie, waarbij er voor gezorgd is dat de monsters zo goed mogelijk overeen kwamen met de potgrond bij het begin van een teelt. Gedurende de teelt veranderde de waterretentiekarakteristiek van de potgrond ten gevolge van wortelgroei en herhaaldelijk uitdrogen en herbevochtigen.

Er werd gebruik gemaakt van de analytische functies van Van Genuchten en Mualem voor de beschrijving van de hydraulische eigenschappen van de potgrond. Deze relaties werden door anderen met succes toegepast voor de beschrijving van hydraulische eigenschappen van andere substraten. In combinatie met een empirisch model voor de beschrijving van hysterese levert dit een set van acht parameters op waarmee de hydraulische eigenschappen van de potgrond werden beschreven. Door fitting van de relaties met de metingen werden deze parameters verkregen.

Kationadsorptie is een van de belangrijkste processen die de verdeling en dus de beschikbaarheid van nutriënten in substraten beïnvloeden. Kationadsorptie aan perliet was verwaarloosbaar laag, maar de kationadsorptie aan de organische fractie van de potgrond was hoog en afhankelijk van de pH. Onder omstandigheden zoals die zich in een teelt voordeden, was de CEC ongeveer 75 meq/100 g, waardoor de totale hoeveelheid geadsorbeerde kationen ongeveer zes keer hoger was dan de totale hoeveelheid in de waterige fase van de potgrond. Meer dan 95% van het adsorptiecomplex werd bezet door Ca en Mg, met een sterke voorkeur voor Ca. Met behulp van een model werd de verdeling berekend van kationen over de geadsorbeerde en de waterige fase in de potgrond.

Evapotranspiratie (ET) en de dynamiek van water in relatie tot fertigatie met een eb/vloed teeltsysteem worden beschreven in hoofdstuk 5. Met een plantdichtheid van 25 planten per m^2 tafeloppervlak varieerde de dagelijkse verdamping van 0.4 kg m^{-2} tot 4.1 kg m^{-2} voor, respectievelijk, een gewas met kleine planten in de winter en volgroeide planten in de zomer. Bij kleine planten ging het merendeel van het water verloren via het potgrondoppervlak. Het deel van het water dat via het potgrondoppervlak verdampte nam exponentieel af met de LAI. Voor drie uitgevoerde teelten met continu vloed op de tafels was de cumulatieve evaporatie tussen 19% en 41% van de cumulatieve ET. De fractie verdamping via het grondoppervlak was nog iets hoger voor planten met een wisselende eb/vloed situatie, doordat de transpiratie meer daalde dan de evaporatie.

Het totale watergehalte in de pot werd in sterke mate bepaald door de fertigatie. Voor alle behandelingen was het totale watergehalte kleiner dan de containercapaciteit, ook al werden water en nutriënten continu van onderaf aangeboden. Verlagen van de frequentie of van de vloedduur had in het begin van de teelt weinig effect, maar leidde tot een aanzienlijke reductie van het watergehalte in de potgrond aan het einde van de teelt.

Drukhoogtes in de potgrond daalden bij toenemende verdamping en stegen bij iedere vloedbeurt. Registratie van drukhoogte op meerdere hoogtes in de pot liet zien dat tussen vloedbeurten in de drukhoogte onderin de pot het snelste daalde, vooral wanneer de drukhoogte lager was dan -1.50 m. Er werd een aanzienlijke variatie gevonden in drukhoogte tussen potten met dezelfde behandeling. Dit werd mogelijk veroorzaakt door variatie in ET, hysterese en verschillen in hydraulische eigenschappen van de potgrond.

Capillaire opstijging van de voedingsoplossing werd niet alleen bepaald door de vloedduur, maar in sterke mate ook door het vochtgehalte van de potgrond. De capillaire opstijging nam toe bij dalend vochtgehalte. Gedurende de vloedperiode steeg de drukhoogte het eerst onderin de pot. Uitgaande van een drukhoogte in de pot van -1.10 m vóór fertigatie, waren er ongeveer 40 minuten nodig voor maximale capillaire opstijging. Aangezien in de praktijk een kortere vloedduur meer gebruikelijk is, vergt voorspelling van toediening van water en nutriënten met een eb/vloed teeltsysteem een berekening op basis van de transportvergelijkingen gepresenteerd in hoofdstuk 2.

De nutriëntenbalans en de verticale verdeling van nutriënten in de potgrond worden gepresenteerd in hoofdstuk 6. De EC en samenstelling van de waterige fase in de potgrond varieerde in de tijd en hoogte. De EC bovenin de pot was ongeveer vijf keer hoger dan onderin. Initieel accumuleerden nutriënten vooral bovenin, ten gevolge van de relatief grote evaporatie in de beginfase van de teelt. Naarmate de teelt vorderde accumuleerden de nutriënten ook onderin de potten. Behalve door plantopname, werd accumulatie beïnvloed door de EC van de fertigatieoplossing, de fertigatiefrequentie en de evaporatie.

De kationensamenstelling van de waterige fase in de potgrond varieerde met de hoogte en was anders dan de samenstelling van de fertigatieoplossing. De verdeling van met name Ca en Mg werd in sterke mate bepaald door kationadsorptie. Na en Cl accumuleerden met name in de waterige fase van de potgrond doordat de opname van deze elementen door de plant en de adsorptie gering waren. Aangezien de EC en samenstelling van de waterige fase van de potgrond slechts ten dele afhangt van de EC en samenstelling van de fertigatie-oplossing, kunnen verschillen in toediening van nutriënten verwacht worden voor verschillende frequenties van water geven, verschillende potgronden en verschillen in evaporatie, bijvoorbeeld ten gevolge van verschillen in plantdichtheid. Vice versa kan verwacht worden dat verandering van het fertigatieschema de plant niet alleen beïnvloedt via een verandering van het vochtgehalte in de potgrond, maar evenzeer door een verandering van de bemesting.

Voor simulatie van de dynamiek van water en nutriënten is een model ontwikkeld voor een potplant met een eb/vloed fertigatiesysteem. Het model gebruikt gemeten ET als input, en bestaat uit drie submodellen: een voor de dynamiek van water (gebaseerd op SWATRE), een voor de dynamiek van nutriënten en een voor vorming en oplossen van neerslagen en voor kationadsorptie. Resultaten van simulaties werden vergeleken met de resultaten uit hoofdstukken 5 en 6. Het model geeft een goede beschrijving van de dynamiek onder natte omstandigheden. Capillaire opstijging en herverdeling in de potgrond worden onderschat voor drogere omstandigheden. De gevonden verschillen in totaal watergehalte in de pot gedurende de teelt kunnen goed worden verklaard met behulp van het model.

Interpretatie van de experimenten in combinatie met de simulaties leverde de volgende belangrijkste conclusies op:

- Hysterese in de waterretentiekarakteristiek reduceert het watergehalte in de potgrond gedurende een teelt en reduceert capillaire opstijging op een eb/vloed teeltsysteem. De waterdoorlatendheidskarakteristiek speelt daarbij een belangrijke rol, in het bijzonder onder drogere omstandigheden en bij korte vloedduur. Bij karakterisering van substraten moet derhalve meer aandacht geschonken worden aan deze eigenschappen van een substraat.
- De buffercapaciteit van een potgrond wordt op een eb/vloed teeltsysteem zowel door de waterretentie- als door de waterdoorlatendheidskarakteristiek bepaald, en kan aanzienlijk lager zijn dan de totale hoeveelheid water welke in het substraat aanwezig is.
- Het fertigatieschema, de potdimensies (in het bijzonder de hoogte), de evapotranspiratie en de hydraulische en chemische eigenschappen van de potgrond zijn alle van belang voor de dynamiek van water en nutriënten. Beschouwing van een dezer factoren afzonderlijk van de andere wordt derhalve sterk ontraden.
- Kationadsorptie bepaalt in belangrijke mate de ruimtelijke verdeling en dus ook de beschikbaarheid van nutriënten. Het merendeel van Ca en Mg was geadsorbeerd aan de potgrond.
- Bemesting en frequentie en duur van watergeven zijn nauw met elkaar verbonden. Verschillen in frequentie van watergeven of veranderen van de vloedduur zal verschillen in EC in de waterige fase van de potgrond tot gevolg hebben, waarvan de gevolgen voor de plant mogelijk groter zijn dan die welke veroorzaakt worden door verschillen in watergehalte in de potgrond.

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Appendix 1. List of symbols

a_i	= activity of chemical species i	mol m^{-3}
A_i	= total amount stored of species i in the medium	mol m^{-3}
A_k	= total amount species k in the medium	amount m^{-3}
b	= coefficient in equation 2.16	
B	= parameter representing relative root activity (eq. 7.6)	
c_i	= concentration of solute i	mol m^{-3}
C_i	= electrolyte concentration of solute i	eq m^{-1}
$C(h_m)$	= differential water capacity, defined $\delta\theta/\delta h_m$	m^{-1}
CEC	= cation exchange capacity	meq 100 g^{-1}
$D_i(\theta,q)$	= apparent diffusion/dispersion coefficient	m^2 s^{-1}
$D_m(q)$	= convective dispersion coefficient	m^2 s^{-1}
$D_p(\theta)$	= apparent diffusion coefficient	m^2 s^{-1}
$D_0(\theta)$	= diffusion coefficient	m^2 s^{-1}
E	= evaporation	kg m^{-2} day^{-1}
E_p	= potential evaporation rate	kg m^{-2} day^{-1}
EC	= electrical conductivity	mS cm^{-1}
ET	= evapotranspiration	kg m^{-2} day^{-1}
f_i	= activity coefficient of chemical species i	
f_1	= monovalent ionic activity coefficient	
f_2	= divalent ionic activity coefficient	
g	= gravitational field strength	N kg^{-1}
G(z)	= cross sectional area associated with conical shape of the pot	
H	= hydraulic head	m
h_{clos}	= matric head at closure point	m
h_g	= gravitational head	m
h_m	= matric head	m
h_o	= osmotic head	m
h_{rev}	= matric head at reversal point	m
h_{root}	= root water head	m
h_t	= total head	m
I	= ionic strenth of a solution	mol m^{-3}
j_i	= total flux of species i	mol m^{-2} s^{-1}
$(j_i)_{con}$	= convective flux of species i	mol m^{-2} s^{-1}
$(j_i)_{diff}$	= diffusive/dispersive flux of species i	mol m^{-2} s^{-1}
j_k	= flux of substance k	amount m^{-2} s^{-1}
K_0	= coefficient in equation 2.16	
$K(h_m)$	= hydraulic conductivity related to matric head	m s^{-1}
$K(\theta)$	= hydraulic conductivity related to θ	m s^{-1}
K_s	= hydraulic conductivity at saturation	m s^{-1}
ℓ	= parameter in Van Genuchten relation	
L	= root length density	m m^{-3}
L_{diff}	= diffusion length	m
L_i	= total amount of species i in the liquid phase	mol m^{-3}
L_r	= dispersion length	m
m	= parameter in van Genuchten relation	
$m_{i,V}$	= mass of chemical species i	kg
M_i	= molecular mass of chemical species i	kg mol^{-1}
M_{liquid}	= mass of the liquid phase	kg
M_{solids}	= mass of the dry solids	kg
n	= parameter in van Genuchten relation	
P_i	= total amount of species i precipitated	mol m^{-3}
q	= flux density of the liquid phase	m^3 m^{-2} s^{-1}
Q_i	= total amount of species i adsorbed	mol m^{-3}
r	= radius of the pot	m
r_{top}	= radius at top of the pot	m

R_u	= resistance of root cortex per unit length	s m^{-1}
S	= sink term, representing uptake by plant roots	m^3m^{-3} s^{-1}
Se	= relative saturation	
t	= time	s
t_{ebb}	= starting time of the ebb period	s
t_{fe}	= time at which flooding ends	s
t_{fs}	= starting time of the flooding period	s
T	= transpiration	m s^{-1} (or day^{-1})
v_i	= valence of chemical species i	eq mol^{-1}
V	= volume of the potting medium	m^{-3}
V_{gas}	= volume of the gas phase	m^{-3}
V_{liquid}	= volume of the liquid phase	m^{-3}
V_{solids}	= volume of the solid phase	m^{-3}
w	= water content on mass base	
z	= height, positively upwards	m
z_f	= height of the flooding	m
z_t	= height at top of the profile	m
α	= parameter in van Genuchten relation	cm^{-1}
β	= angle between wall of pot and horizontal asci	
γ	= amount adsorbed	meq $100g^{-1}$
γ_l	= phase density of the liquid phase	kg m^{-3}
γ_s	= phase density of the solid particles	kg m^{-3}
ϕ	= porosity of a medium	
ψ_a	= pneumatic potential	J kg^{-1}
ψ_g	= gravitational potential	J kg^{-1}
ψ_m	= matric potential	J kg^{-1}
ψ_o	= osmotic potential	J kg^{-1}
ψ_t	= total potential of the liquid phase	J kg^{-1}
θ	= volumetric water content	
θ_{clos}	= volumetric water content at closure point	
θ_r	= residual volumetric water content	
θ_{rev}	= volumetric water content at reversal point	
θ_s	= volumetric water content at saturation	
$\theta_{y,d}$	= θ at matric head of reversal point, according to the MDC	
$\theta_{y,w}$	= θ at matric head of reversal point, according to the MWC	
ρ_s	= bulk density, mass of dry soil per unit volume	kg m^{-3}
ρ_l	= density of the liquid phase	kg m^{-3}
ρ_s	= density of the solid particles	kg m^{-3}
σ_j	= amount precipitated	mol kg^{-1}
τ	= tortuosity factor	

Appendix 2

A FORTRTAN submodel to update the parameters used in the Van Genuchten description to describe the water retention characteristic including hysteresis. Parameters are updated if a closure of a scanning curve, or if a reversal occurs.

```
      subroutine upda3
c ---------------------------------------------------------------------c
c     Subroutine     : upda3                                            c
c     Author         : Wilfred Otten                                    c
c     Version        : 1.0                                              c
c     Date           : 4-April 1994                                     c
c     Purpose        : To check for hysteretic reversal                 c
c                      update model parameters                          c
c     Comment        : The model from Kool et al. was slightly          c
c                      adapted so that each scanning loop closes        c
c                      at the previous reversal point rather than       c
c                      at the residual water content or saturated       c
c                      water content. This adaptation was               c
c                      performed to reduce the effect of "water         c
c                      pumping" which might be the result of the        c
c                      calculations under cyclic variations of          c
c                      pressure head. Only the last opened              c
c                      scanning curve is closed at the reversal         c
c                      point. Behind this point the curves are          c
c                      closed at saturation or residual water           c
c                      content conform the original model.              c
c                      If the last opened curve revers too close        c
c                      to the opening point, it is neglected; closure   c
c                      occurs in that case at the previous              c
c                      closure point.                                   c
c                      If closure occurs, logical closure(node)         c
c                      must be .true.                                   c
c                      W. Otten 4-2-94.                                 c
c ---------------------------------------------------------------------c
c
      include 'common.for'
c
        integer*4 node,lay
       real*8    delp,sew,sed,sedcl,sewcl,hulp,hulpw
c       numnod - 6 since lower 6 nodes are not relevant on flooded
c      bench fertigation system.
      do 100 node=1,numnod-6
        lay = layer(node)
c       ---- check for reversal ----
        delp = hm1(node) - h(node)
        if (((delp/float(index(node))  .lt. (tau)
     &   .and.(.not.closure(node))).or.
     &    h(node) .ge. 0.)) go to 99
      if ((index(node).eq.-1).and.(h(node).ge.-2))then
        hrev(node)=0
        hrevold(node)=0
        hclos(node)=-1E12
        hclold(node)=-1E12
        wcnrev(node)=cofgen(2,lay)
        wcnrevold(node)=cofgen(2,lay)
```

```
          wcncl(node)=cofgen(1,lay)
          wcnclold(node)=cofgen(1,lay)
          thetar(node) = cofgen(1,lay)
          thetas(node)=cofgen(2,lay)
          thetsn(node) = thetas(node)
          goto 100
        end if
c         ---- wcn is water content at reversal point ----
          sew = (1.+(cofgen(8,lay)*(-h(node)))  **cofgen(6,lay))
     &         **(-cofgen(7,lay))
          sed = (1.+(cofgen(4,lay)*(-h(node)))  **cofgen(6,lay))
     &         **(-cofgen(7,lay))

        if (index(node) .eq. 1) then
           wcn = thetar(node) + (thetas(node)-thetar(node))  * sew
          else
           wcn = thetar(node) + (thetas(node)-thetar(node))  * sed
          endif

        if (delp/float(index(node)).ge.tau    )then
c         ---- change index ----
            index(node) = -1*index(node)
          if (index(node).eq.-1)then
            if ((hrev(node)-(hrev(node)/5)).ge.h(node))then
c!  only small scanning curve (proceed as if this did not occur)
               hrev(node)=hrevold(node)
               wcnrev(node)=wcnrevold(node)
               hulp=hrevold(node)
               hulpw=wcnrevold(node)
               hrevold(node)=hclold(node)
               wcnrevold(node)=wcnclold(node)
               hclos(node)=hclold(node)
               wcncl(node)=wcnclold(node)
               hclold(node)=hulp
               wcnclold(node)=hulpw
            else
c! close curve at last reversal point and update reversal and closure points
               hrevold(node)=hrev(node)
               wcnrevold(node)=wcnrev(node)
               wcnclold(node)=wcncl(node)
               hclold(node)=hclos(node)
               hclos(node)=hrev(node)
               wcncl(node)=wcnrev(node)
               hrev(node)=h(node)
               wcnrev(node)=wcn
            end if
          else
            if ((hrev(node)+(hrev(node)/5)).le.h(node))then
c!  only small scanning curve (proceed as if this did not occur)
               hrev(node)=hrevold(node)
               wcnrev(node)=wcnrevold(node)
               hulp=hrevold(node)
               hulpw=wcnrevold(node)
               hrevold(node)=hclold(node)
               wcnrevold(node)=wcnclold(node)
               hclos(node)=hclold(node)
               wcncl(node)=wcnclold(node)
               hclold(node)=hulp
```

```
              wencloId(node)=hulpw
           else
c! close curve at last reversal point and update reversal and closure points
              hrevold(node)=hrev(node)
              wenrevold(node)=wenrev(node)
              wencloId(node)=wencl(node)
              hclold(node)=hclos(node)
              hclos(node)=hrev(node)
              wencl(node)=wenrev(node)
              hrev(node)=h(node)
              wenrev(node)=wen
           end if
         end if
         sewcl = (1.+(cofgen(8,lay)*(-hclos(node)))  **cofgen(6,lay))
     &        **(-cofgen(7,lay))
         sedcl = (1.+(cofgen(4,lay)*(-hclos(node)))  **cofgen(6,lay))
     &        **(-cofgen(7,lay))

       else !****closure occurs

         if (index(node).eq.1)then
           hrev(node)=-1E12
           hrevold(node)=-1E12
           hclold(node)=0
           hclos(node)=0
           wenrev(node)=cofgen(1,lay)
           wenrevold(node)=cofgen(1,lay)
           wencl(node)=cofgen(2,lay)
           wencloId(node)=cofgen(2,lay)
         else
           hrev(node)=0
           hrevold(node)=0
           hclold(node)=-1E12
           hclos(node)=-1E12
           wenrev(node)=cofgen(2,lay)
           wenrevold(node)=cofgen(2,lay)
           wencl(node)=cofgen(1,lay)
           wencloId(node)=cofgen(1,lay)
         end if
         sewcl = (1.+(cofgen(8,lay)*(-hclos(node)))  **cofgen(6,lay))
     &        **(-cofgen(7,lay))
         sedcl = (1.+(cofgen(4,lay)*(-hclos(node)))  **cofgen(6,lay))
     &        **(-cofgen(7,lay))

       end if
c        ---- update alfa,thetar and thetas ----
         if (index(node) .eq. 1) then

c        ---- wetting branch ----
        alfa(node) = cofgen(8,lay)
c        thetas(node) = cofgen(2,lay)
        thetas(node)=((1-sewcl)*wen  + (sew-1)*wencl(node))/(sew-sewcl)
        thetar(node)=(-sewcl*wen+sew*wencl(node))/(sew-sewcl)
        thetsn(node) = cofgen(2,lay)
c           endif
       else

c        ---- drying branch ----
```

```
      alfa(node) = cofgen(4,lay)
      thetas(node)=((1-sedcl)*wcn  + (sed-1)*wcncl(node))/(sed-sedcl)
      thetar(node)=(-sedcl*wcn+sed*wcncl(node))/(sed-sedcl)
      thetsn(node) = cofgen(2,lay)
         endif

 99   if ((h(node).ge.0).and.
    $      ((hrev(node).ne.0).or.(hclos(node).ne.-1E12)))  then
c ***  Main drying curve
        hrev(node)=0
        hrevold(node)=0
        hclos(node)=-1E12
        hcloid(node)=-1E12
        wcnrev(node)=cofgen(2,lay)
        wcnrevold(node)=cofgen(2,lay)
        wcncl(node)=cofgen(1,lay)
        wcnclold(node)=cofgen(1,lay)
         alfa(node) = cofgen(4,lay)
        thetar(node) = cofgen(1,lay)
        thetas(node)=cofgen(2,lay)
        thetsn(node) = thetas(node)
        index(node)=-1
 11      format (f,x,i2,x,f,x,f,x,f)
      end if
 13   format (i2,x,f,x,g9.3e2,x,g9.3e2,x)
 100   continue
      return
      end
```

Appendix 3

A FORTRAN subprogram to calculate vertical solute transport, in a conical shaped pot. Program must be linked with a water transport model.

```
        subroutine sol4
c*****************************************************  c
c     subroutine name     : sol4                        c
c     Author              : W. Otten                    c
c     Version             : 2.1                         c
c     Date                : 09-5-1994                   c
c     Purpose             : solving the non-linear differential   c
c                           transport equation according an implicit   c
c                           finite difference "Cranck-Nicholson"   c
c                           approximation using the Thomas   c
c                           tridiagonal matrix algorithm.   c
c                           Numerical dispersion is suppressed by   c
c                           a second order approximation of the   c
c                           derivatives as proposed by Bressler(1973)   c
c                           The subroutine requires theta and fluxes   c
c                           calculated with a soil water simulation   c
c                           model as input.   c
c                           Model assumes horizontal uniformity in   c
c                           the profile, and calculates vertical   c
c                           transport in a conical shaped profile   c
c                                                       c
c*****************************************************  c
      implicit none
      include 'common.for'

      integer*4  node
      real*4   thetav(60),adif(60),ab(60),bb(60),cb(60),db(60)
      real*4   beta1,beta2,beta3,beta4
      real*4   A1(60),B1(60),C1(60),D1(60),F(60),G(60)
      real*4   thav2(60)

c ---- This line is needed in case of flooded bench system
      if (swbotb.eq.0) thetm1(numnod)=thetakeep
c ---- save old concentrations
c       if (t.gt.49)then
c         sa(numnod+1)=0.5*cgro
c       else
         sa(numnod+1)=cgro
c       end if
      do 10 node=1,numnod
         sam1(node) = sa(node)
         thav2(node)=(theta(node)+thetm1(node))/2
         if(node.gt.1)then
            thetav(node)=(theta(node)+theta(node-1)
   $                    +thetm1(node)+thetm1(node-1))/4
            adif(node)=ddif*tau1+labda1*abs(q(node))/
   $                   (thetav(node)*dt)
         end if
10    continue
c ---- Some constants in the diffusion/convection equation.
     do 30 node=2,numnod-1
       ab(node)=(1-dz(node)*0.5*gdlna(node))
```

```
$            *(adif(node)*thetav(node))/
$            (-disnod(node)*-dz(node)*2)
$          + (.5*q(node)/thav2(node)+
$         .5*q(node+1)/thav2(node))
$           * ((theta(node)-thetm1(node))/(8*2*-dz(node)))
$           * q(node)/
$             (thetav(node)*dt*-disnod(node))

      bb(node)=(1+dz(node)*0.5*gdlna(node+1))*
$            (adif(node+1)*thetav(node+1))/
$            (2*-disnod(node+1)*-dz(node))
$          +  (.5*q(node)/thav2(node)+
$         .5*q(node+1)/thav2(node))
$           * ((theta(node)-thetm1(node))/(8*2*-dz(node)))
$           * q(node+1)/
$              (thetav(node+1)*dt*-disnod(node+1))


      db(node)=(1+dz(node)*0.5*gdlna(node+1))
$            *q(node+1)/(2*-dz(node)*dt)
      cb(node)=(1-dz(node)*0.5*gdlna(node))
$            *q(node)/(2*-dz(node)*dt)
 30   continue
     ab(1)=0
     bb(1)=(1+dz(1)*0.5*gdlna(2))*
$       (adif(2)*thetav(2))/(2*-disnod(2)*-dz(1))
$      +(.5*q(1)/thav2(1)+.5*q(2)/thav2(1))
$      * ((theta(1)-thetm1(1))/(8*2*-dz(1)))*q(2)/
$        (thetav(2)*dt*-disnod(2))

     db(1)=(1+dz(1)*0.5*gdlna(2))*q(2)/(2*-dz(1)*dt)
     cb(1)=0
     ab(numnod)=(1-dz(numnod)*0.5*gdlna(numnod))
$           *(adif(numnod)*thetav(numnod))/
$            (2*-disnod(numnod)*-dz(numnod))
$         + (.5*q(numnod)/thav2(numnod)+
$            .5*q(numnod+1)/thav2(numnod))
$         * ((theta(numnod)-thetm1(numnod))/(8*2*-dz(numnod)))
$         * q(numnod)/(thetav(numnod)*dt*-disnod(numnod))

     bb(numnod)=0
     db(numnod)=(1+dz(numnod)*0.5*gdlna(numnod+1))
$           *q(numnod+1)/(2*-dz(numnod)*dt)
     cb(numnod)=(1-dz(numnod)*0.5*gdlna(numnod))
$           *q(numnod)/(2*-dz(numnod)*dt)


     do 40 node=1,numnod
c ---- Coefficients for the tridiagonal matrix
c ---- Set BETA values 0 or 1 according direction of waterflow
c ---- to calculate convective transport.q(node) is the flux through
c ---- the top the compartment node, and positive in upwards direction.
       If (q(node).gt.0)then
         beta1=-1
         beta2=0
       else
         beta2=-1
         beta1=0
```

```
          end if
          if (q(node+1).gt.0)then
             beta3=1
             beta4=0
          else
             beta4=1
             beta3=0
          end if
c ---- Coefficients for the tridiagonal matrix
          A1(node)=-ab(node)-beta2*cb(node)
          B1(node)=(theta(node)/dt)+ab(node)+bb(node)-
     $           beta1*cb(node)-beta4*db(node)
          C1(node)=-bb(node)-beta3*db(node)
          D1(node)=sa(node-1)*(ab(node)+beta2*cb(node))  +
     $         sa(node)*( (thetm1(node)/dt) - ab(node)-bb(node)+
     $                beta1*cb(node)+beta4*db(node)  ) +
     $         sa(node+1)  *  (bb(node) + beta3*db(node)) -
     $         nupt(ionnum,node)
 40    continue
c ---- Solving the tridiagonal matrix
c ---- calculate F & G coefficients from nodes 1 to numnod
        F(1)=C1(1)/B1(1)
        G(1)=D1(1)/B1(1)
        do 50 node=2,numnod
          F(node)=C1(node)/(B1(node)-F(node-1)*A1(node))
          G(node)=(D1(node)-A1(node)*G(node-1))/
     $         (B1(node)-A1(node)*F(node-1))

 50    continue
c ---- calculate new solute concentration.
        do 60 node=numnod,1,-1
          sa(node)=G(node)-F(node)*sa(node+1)
 60    continue
c      write (*,59)sa(1),sa(2),sa(3),sa(4),sa(5),sa(6),sa(7),sa(8)
 59    format (8(x,f7.2))
        if (q(numnod+1).gt.0)then
           profinp(ionnum)=profinp(ionnum)+q(numnod+1)*cgro
        else
           profinp(ionnum)=profinp(ionnum)+q(numnod+1)*sam1(numnod)
        end if

        return
        end
```

Curriculum vitae

Wilfred Otten werd op 23 april 1962 te Wageningen geboren. In 1980 behaalde hij het VWO diploma aan het Wagenings Lyceum, en werd begonnen met de studie Bodemkunde en Bemestingsleer aan de Landbouwuniversiteit te Wageningen. In het kader van deze studie heeft hij zes maanden stage gelopen bij het DLO Winand Staring Cetrum (SC-DLO). In september 1987 slaagde hij voor het doctoraalexamen in de richting Bodemkunde en Bemestingsleer met als hoofdvakken bodemscheikunde en theoretische produktie ecologie en als bijvak natuurkunde. Na voltooiing van de studie volgde in april 1988 tot april 1989 een aanstelling als programmeur (FORTRAN) bij het Biogeografisch Informatie Centrum. In april 1989 volgde de aanstelling als DLO-AIO bij het DLO Instituut voor Agrobiologisch en Bodemvruchtbaarheidsonderzoek (AB-DLO) en de vakgroep tuinbouwplantenteelt van de Landbouwuniversiteit Wageningen. In deze periode werd het onderzoek beschreven in dit proefschrift uitgevoerd. Voor het grootste deel van deze periode was hij gestationeerd op het Proefstation voor de Bloemisterij in Nederland te Aalsmeer. In de periode april 1993 tot juli 1993 volgde een aanstelling bij het AB-DLO, waarin verder werd gewerkt aan dit proefschrift. Met ingang van september 1994 is hij in dienst van de Universiteit van Cambridge.