Chapter 7

Irrigation Control in Hydroponics

Fritz-Gerald Schröder\(^1\) and J. Heinrich Lieth\(^2\)

\(^1\) Department of Horticulture, University of Applied Science (HTW)
Pillnitzer Platz 2, D - 01326 Dresden, Germany

\(^2\) Department of Environmental Horticulture, University of California
One Shields Avenue, Davis, CA, 95616-8587 USA

Contents

Abstract .................................................................................................................. 265
7.1. Introduction .................................................................................................. 266
7.2. Irrigation in hydroponics ........................................................................... 268
7.3. Water quality and quantity ....................................................................... 269
  7.3.1. Water quality ......................................................................................... 270
  7.3.2. Water quantity ...................................................................................... 270
7.4. Root environment in hydroponics ............................................................... 272
  7.4.1. Dissolved oxygen .................................................................................. 272
  7.4.2. Oxygen gradient ................................................................................... 273
  7.4.3. Gas exchange ....................................................................................... 274
7.5. Irrigation systems ....................................................................................... 276
  7.5.1. Design criteria and characteristics ....................................................... 276
    7.5.1.1. Capacity .......................................................................................... 276
    7.5.1.2. Uniformity ....................................................................................... 277
  7.5.2. Type of systems ..................................................................................... 279
    7.5.2.1. Overhead systems .......................................................................... 279
    7.5.2.2. Surface systems - Drip irrigation .................................................. 280
    7.5.2.2. Subsurface or sub-irrigation systems ............................................. 282
7.5.3. Layout of irrigation systems in hydroponics ....................................... 282
  7.5.3.1. Open system ...................................................................................... 282
  7.5.3.2. Closed system .................................................................................. 283

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263
7.6. Irrigation control ................................................................. 284
  7.6.1. Irrigation scheduling ...................................................... 284
    7.6.1.1. Current standards ................................................. 285
    7.6.1.2. Uptake of nutrient solution ..................................... 286
    7.6.1.3. Interaction between irrigation schedules and plant growth .... 287
    7.6.1.4. Example for schedule ............................................ 289
  7.6.2. Sensor based irrigation control ...................................... 291
  7.6.3. Model based irrigation control ...................................... 293
  7.6.4. Modeling nutrient solution uptake ................................ 295
7.7. Future irrigation perspectives .......................................... 295
References ................................................................................. 296
Abstract

This chapter focuses on irrigation in soilless (hydroponic) production systems. The function of an irrigation system is to ensure that the plant has adequate or, ideally, optimal amounts of water, nutrients and oxygen in the root zone, which acts both as a reservoir and a conduit for these three materials. In this chapter we discuss the principles and basic components of irrigation systems and how these interact. The operation and control of such systems is described with respect to crop growth and production. Design criteria and various types of open and closed irrigation systems are presented, and the role of irrigation uniformity is discussed. Various types of irrigation systems are described, including overhead, surface, and sub-irrigation systems.

Irrigation control is the process of deciding when and how much nutrient solution to apply. In hydroponic systems, irrigation can occur much more frequently since the root zone is specifically designed for this. Sensor-based irrigation has been shown to be an effective way to irrigate in soilless production systems. Mathematical models for water and nutrient use have also proved helpful.
7.1. Introduction

Modern greenhouse production systems can be characterized as either soilless or soil-based, the latter typically being found in older operations. The trend is for growers to optimize root conditions for crops by designing and implementing systems that allow greater control of the vital root zone variables than is possible in the soil.

Hydroponic systems are soilless production systems and in this chapter the two terms are used interchangeably. The public generally considers hydroponic systems to be water culture systems with no solid media. However, most hydroponic systems in commercial production use some sort of substrate to create a matrix that forms the root zone (e.g. rockwool or coconut coir). The only thing that all hydroponic systems have in common is that no field soil is used. In addition, all containerized production systems (e.g., the production of potted flowering plants) can be regarded as hydroponic since such systems consist of an artificial root zone aimed at optimizing water and nutrient availability.

Hydroponic production systems consist of the following components: (1) the root zone, (2) the aerial organs of the plants, (3) an irrigation system to supply nutrient solution to the root zone, and (4) a drainage system for dealing with run-off. While this chapter focuses on the third component, it should be noted that all of them are intimately linked with each other and the operation of the system is dictated by the physical and chemical characteristics of the root zone.

The root zone consists of solid, liquid and gases. Many different substrates, such as gravel, rockwool, sand, perlite, expanded clay or various synthetic materials are used to make up the solid matter. The liquid consists of water in which ions and gases are dissolved. It is the primary function of the irrigation system to manage this solution in an optimal manner. The practice of delivering fertiliser ions along with water is termed fertigation, and the formulation of nutrient solutions is presented in Chapter 5.

The term “nutrient solution” refers to the irrigation solution that is applied; once this liquid reaches the root zone and mingles with liquids that are already present, the “substrate solution” forms. This solution continually changes as the plants and microbes use certain portions and discharge other compounds into it. This dynamically changing liquid must be managed and optimized through various horticultural practices.

Hydroponic systems tend to have greater fluctuations in the key variables that affect crop growth. Compared with soil-based systems, hydroponic systems typically have a significantly smaller root zone volume, greater water-holding capacity, a higher percentage of available water, lower moisture tension, and greater hydraulic conductivity. In some hydroponic systems the volume of the root zone is very small, e.g. 14 l m⁻² in rockwool compared with 500 l m⁻² in soil (Sonneveld, 1981). Thus, the total amounts of available water and nutrients are
smaller in hydroponics, despite a greater water-holding capacity of most substrates. Consequently, frequent and accurate fertigation is needed to maximize crop productivity (Schröder, 1994; Bar-Yosef, 1999; Wever et al., 2001). Furthermore, while the soil and soil solution in soil-based systems act as a buffer to chemical changes, in hydroponics this buffering capacity is significantly less, making accurate dynamic control a necessity.

The frequency and rate of irrigation in commercial hydroponic systems is dictated primarily by the demand of the crop for water. Plant water requirements can be determined directly or indirectly. Sensors, such as stem flow sensors, can be used to monitor plants directly, while indirect assessment of plant status involves the use of models that correlate environmental variables (temperature, humidity, radiation, etc) with water use. While direct measurements of plant water consumption are primarily used for diagnostic purposes, they are not widely used in irrigation control because reduced water uptake can be caused by factors other than inadequate water availability in the root zone. Indirect calculation of water use is used in various irrigation control systems, but this type of control should be continually checked and calibrated to avoid excessive or inadequate irrigation. Future plant monitoring and control systems will combine plant features and its environment to provide closed-loop control (Giacomelli, 1998).

In addition to controlling the amount of nutrients and water, irrigation systems also affect the level of oxygen in the root zone. Controlling all these factors simultaneously is very difficult and generally the substrate and/or physical system must be designed to facilitate this. For example, media used for pot plant production should normally have a high cation exchange capacity in order to increase the reservoirs of nutrients and to provide a more balanced nutrient status in the root zone, even when the supply of nutrients via fertilization is not optimal. Such media should also provide a high degree of aeration to minimize problems of oxygen deficiency.

Another facet of irrigation system design and control is that such a system needs to operate efficiently and reliably, and deliver a uniform amount of liquid to all plants so as to obtain uniform, high-quality produce. Growers typically have a wide range of objectives for their irrigation systems: some focus primarily on maintaining an adequate moisture availability in the root zone, thereby avoiding water stress or nutrient deficiency, while others attempt to maximize plant performance by optimizing the air/water balance in the root zone to. In countries, where emphasis is placed on environmental concerns, growers are faced with the additional task of minimizing run-off. Full optimization that also results in minimal run-off is very difficult, as many factors need to be managed dynamically. In this chapter, we discuss the principles and basic components of irrigation systems and how these interact. Furthermore, the operation and control of such systems with respect to crop growth and production are also described.
7.2. Irrigation in hydroponics

There are two specific functional features of the root zone that are essential to understanding irrigation management. One is that the root zone acts as a reservoir that must be refilled each time a certain level of depletion has occurred. The other is that the root zone forms a conduit for materials to reach the root surface. It is important to understand both of these aspects in order to optimize irrigation.

As a reservoir, the root zone is stores a variety of important ingredients for plant growth and survival. Once any of these ingredients becomes depleted, it must be re-supplied by irrigation. It is also possible (and, in fact, likely) that some particular element may become excessive; then irrigation is needed to flush out or dilute this element.

The root zone also functions as a conduit for the above materials. Elements that are near the root surface are available to the plant, and the roots use active processes to move them into the plant. This depletes these elements in the immediate surrounding of the roots. Thus concentration gradients are set up and diffusion causes replacement elements to travel towards the roots from sites of greater concentration. If conduction does not occur at a suitable rate, the plant will be starved of particular nutrients or water, even though adequate overall total amounts may be present in the reservoir. This situation can be overcome by initiating irrigation so as to displace spent nutrient solution from around the roots and replace it with fresh, optimally formulated solution.

It should be noted that the plant removes water and ions selectively at different rates. As a result, the nutrient to water ratios may be lower than the corresponding nutrient concentrations (and vice versa), thus resulting in salt build up in the root zone. This build-up of salts must be avoided, as it is deleterious to plant growth. However, if low concentrations of ions are provided, it is possible for the plants to run out of particular nutrients while there is still an adequate supply of water in the root zone.

Thus irrigation systems in hydroponics perform two tasks: (1) they replenish various elements that are stored in the root zone and (2) they provide mass flow of such materials through the conduit. Since mass flow is much faster at moving materials than diffusion processes, frequent irrigation can be used to move essential elements to the root surface. In hydroponic systems this type of control is feasible since all variables are actively controlled. In soil-based systems, frequent irrigation may not be feasible because the roots might become water logged and starved of oxygen. In systems where the drainage water is re-circulated, the reservoir is effectively extended into the tank where such water is collected.

The yields obtained from hydroponic systems are generally higher than those from soil-grown crops (Ho and Adams, 1995). In part, this is due to the intense irrigation management that creates a root zone that is optimal for plant growth.
Moreover, the water use efficiency is higher in hydroponics, because the nutrient solution is applied nearly directly to the roots, which gives the plant improved access to the materials required for optimal growth.

Plant growth in hydroponics is related to water, nutrient and oxygen supply. Water and nutrient supply can be regulated by providing an efficient irrigation system and controlling the irrigation frequency. Similarly, differences in $O_2$, $CO_2$ and ethylene in the root zone have been shown to be influenced by the growth medium and irrigation (Schwarz, 1995; Strojny et al., 1998). Adequate aeration of the root zone is vital to the plant because the roots require oxygen for respiration, which in turn is essential for adequate nutrient and water uptake. Well aerated porous substrates enable good gas exchange within the root zone. Furthermore, a nutrient solution enriched with dissolved oxygen can improve plant growth and the stability of the system.

Hydroponic systems can be either closed (recirculating) or open systems, where leachate is allowed to run off from the root zone. If the system is not closed, the irrigation system should be capable of generating some leachate and reduce the build-up of salts. In practice this leaching fraction ranges from 10 to 30 % depending on water quality and/or crop sensitivity to salts. In closed systems the build-up of salts is managed by dynamically reducing the fertilisers that are dissolved in the water added to replenish the drainage solution. In this way, the nutrient solution is recirculated until one or more ion concentrations become suboptimal to an extent that cannot be corrected. At that point the entire nutrient solution must be discarded.

Many authors suggest a surplus of nutrient solution ranging between 20 - 50% of the total supply in commercial hydroponics. In an open irrigation system, each surplus leads to a loss of water and nutrients via the run-off solution. Closed irrigation systems reduce the run-off, but require expensive equipment to disinfect the drainage solution prior to reusing.

### 7.3. Water quantity and quality

In virtually all plant production systems, access to clean water is essential for the production of high quality horticultural produce. High water quality is generally associated with the absence of dissolved materials, particularly salts. The higher the quality of water, the easier it is for growers to formulate an optimal nutrient solution. The lower the quality, the more water needs to be leached (in open systems) or discarded (in the case of closed systems). Thus, low quality can be offset, to some extent, by a greater quantity of water.
7.3.1. Water quantity

The quantity of water needed is generally dictated by the climatic conditions surrounding the aerial part of the plants and the amount of foliage present. Under high humidity, low light and low temperature, the rate of water consumption can be very low. Production systems must have irrigation systems scaled to accommodate the greatest rate of water usage; this occurs when the canopy is fully grown, the air is dry and hot (e.g. in summer), and there is considerable air-movement (as in a ventilated greenhouse). It is very important to be able to estimate the maximum rate of water use when an irrigation system is designed and installed, since an inadequately-scaled system will not be able to meet the demands of the plants, resulting in reduced yields during the summer.

The water consumption of plants is linked to the stage of plant growth (size), solar radiation, relative humidity, and air movement. An example of the water requirements of cucumber is shown in Table 1.

Maximum water-use figures have been reported for various crops. At the low end are cool-climate cropping systems with annual water consumption as low as 8,600 m³ ha⁻¹. In systems where harvesting occurs year round from a fully developed crop canopy under warm conditions, the annual rate of water use can be as high as 11,400 m³ ha⁻¹. Other crops grown at low temperatures, and mixed crops may use 10,000 m³ ha⁻¹ per year. These figures are based on average transpiration rates, increased by ca. 30% for drainage. The drip irrigation system must have the capacity to supply the plants under conditions that represent the highest water application rate.

7.3.2. Water quality

Water quality must always be considered when starting a new greenhouse operation because water of poor quality is unusable and expensive to convert into high-quality water. Thus a grower who must continually invest resources to improve water quality will have a competitive disadvantage over growers that do not. Quality depends mainly on the water source that is available. This can be municipal tap water, well water, surface water or collected rainwater. Before the water can be used it must be analyzed to determine the base-line presence of all minerals and ions, as well as the pH and alkalinity. Without this information it will be difficult to prepare the optimal nutrient solution. Water quality depends on the concentration of each dissolved material, the presence of biotic organisms (algae, fungi, bacteria, etc.) and particulate residues. A complete analysis should be performed for anions and cations, paying particular attention to salinity, alkalinity and specific ion toxicity due to excessive concentrations of sodium, sulphate and chloride. Optimal values of water quality for open and closed systems are shown in Table 2.
### Table 1. Water consumption by cucumber (1.4 plants m$^{-2}$) in hydroponics (Göhler and Drews, 1989).

<table>
<thead>
<tr>
<th>Month</th>
<th>Water consumption (l m$^{-2}$ day$^{-1}$)</th>
<th>Water requirement (l m$^{-2}$ month$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February</td>
<td>1.8 - 2.3</td>
<td>50 - 65</td>
</tr>
<tr>
<td>March</td>
<td>2.5 - 3.0</td>
<td>75 - 90</td>
</tr>
<tr>
<td>April</td>
<td>3.5 - 4.0</td>
<td>100 - 120</td>
</tr>
<tr>
<td>May</td>
<td>5.1 - 5.6</td>
<td>155 - 170</td>
</tr>
<tr>
<td>June</td>
<td>6.0 - 6.5</td>
<td>180 - 200</td>
</tr>
<tr>
<td>July</td>
<td>5.3 - 5.8</td>
<td>160 - 175</td>
</tr>
<tr>
<td>August</td>
<td>4.0 - 4.5</td>
<td>120 - 135</td>
</tr>
<tr>
<td>September</td>
<td>2.5 - 3.0</td>
<td>75 - 90</td>
</tr>
<tr>
<td>October</td>
<td>2.0 - 2.5</td>
<td>60 - 75</td>
</tr>
<tr>
<td>November</td>
<td>1.5 - 2.0</td>
<td>45 - 60</td>
</tr>
</tbody>
</table>

### Table 2. Optimal values for water quality for open and closed systems (Göhler and Drews, 1989; Anonymous, 1992).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Open system</th>
<th>Closed system</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>dS m$^{-1}$</td>
<td>&lt; 1.0</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>5-6</td>
<td>5-6</td>
</tr>
<tr>
<td>Total salt content</td>
<td>mg l$^{-1}$</td>
<td>&lt; 500</td>
<td>&lt;250</td>
</tr>
<tr>
<td>HCO$^3$</td>
<td>mmol l$^{-1}$</td>
<td>&lt; 10</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Na</td>
<td>mmol l$^{-1}$</td>
<td>&lt; 3</td>
<td>&lt; 1.3</td>
</tr>
<tr>
<td>Cl</td>
<td>mmol l$^{-1}$</td>
<td>&lt; 2.8</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>SO$_4$-S</td>
<td>mmol l$^{-1}$</td>
<td>&lt; 4.65</td>
<td>&lt; 1.55</td>
</tr>
<tr>
<td>Zn</td>
<td>µmol l$^{-1}$</td>
<td>&lt; 10</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Fe</td>
<td>µmol l$^{-1}$</td>
<td>&lt; 17.9</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>Cu</td>
<td>µmol l$^{-1}$</td>
<td>-</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>Mn</td>
<td>µmol l$^{-1}$</td>
<td>&lt; 20</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>B</td>
<td>µmol l$^{-1}$</td>
<td>&lt; 40</td>
<td>&lt; 23</td>
</tr>
<tr>
<td>Br$^*$</td>
<td>µmol l$^{-1}$</td>
<td>&lt; 15</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

* Bromide sources from former use of methyl bromide
In irrigation systems with small orifices for the emission of the irrigation solution to the plants, high water quality is required to avoid clogging. If the water quality needs improvement, treatments such as filtration and/or reverse osmosis may be necessary.

Salinity is a key characteristic in conjunction with water quality. It is a measure of all the salts that are present and is quantified as the electrical conductivity (EC) of the water. The general recommendation for source water is that the EC should be below 1.0 dS m$^{-1}$. In some instances the use of water with a higher EC is feasible, as long as the ions which cause the high EC can be used as nutrients by the plants. Even then, the concentrations of these ions should not be excessive, with respect to the corresponding uptake concentrations (Sonneveld, 2000). The use of saline water in hydroponics has shown some promise under certain conditions in arid climates, like Israel, where water is scarce and expensive (Schwarz, 1995). While it may be possible to grow certain salt-tolerant plants under saline conditions, such production is generally at the expense of yield. The utilization of wastewater (sewage) that is rich in nutrients has shown some promise (Schwarz, 1995). However, problems arise from the presence of organic solids, which pose a potential risk for human health when such water is used for the production of edible produce.

7.4. Root environment in hydroponics

The root environment is dictated by the substrate that is used. This results in a matrix of solids, liquids, and gases. Generally the substrate is designed to be optimal with regard to its water and nutrient holding capacity, as well as to deal with gaseous variables. However, virtually all substrates undergo slow physical and chemical changes during use. In addition, the substrate parameters change as a result of the crop itself. For instance, the porosity may decrease as a result of the decomposition of organic substrates and increasing root mass. Some variables that are of particular importance to irrigation and the relationship of the root environment to various irrigation and hydroponic systems are discussed below.

7.4.1. Dissolved oxygen (DO)

Oxygen deficiency in the root zone may induce a number of plant reactions, such as wilting, poor root growth or even root death. In closed hydroponic systems with a low water or substrate volume, elevated water temperatures during summer may lead to oxygen deficiency due to reduced oxygen solubility and more rapid use by microorganisms and roots. Oxygen is the final oxidant in a series of enzymatic oxidations of sugars, which release most of the chemical energy needed
for root growth. The dissolved oxygen in the nutrient solution has a direct influence on root function, particularly respiration. Oxygen must be present in the water around the roots and its deficiency will depress root growth and nutrient uptake. Reduction of the dissolved oxygen to a level of below 60% saturation will inhibit the root growth of most plants, while oxygen levels of less than 2.5% saturation kill root tips and stop growth (Jackson, 1980).

With increasing temperature, the solubility and hence the availability of oxygen in the water will be reduced whereas the plant’s demand for oxygen will increase. The saturation levels of dissolved oxygen at 10, 20, and 30 °C are 10.93, 8.84, and 7.53 mg l⁻¹ O₂, respectively. Over the same temperature range, the plant’s demand for oxygen will increase by about 4. In addition, oxygen is consumed by microorganisms inhabiting the soil and soil solution (Vestergaard, 1984). Depending on the water source, the dissolved oxygen level is approximately between 20 and 40% of total capacity at saturation. The oxygen content of the solution is directly influenced by the hydroponic irrigation system and substrate. For example, if water passes through the nutrient unit and emitters, the dissolved oxygen level will increase by about 50% due to mechanical water movement (Schröder, 1994; Wever et al., 2001).

Generally, the only way for oxygen to enter the water is virtually by surface diffusion. The amount of oxygen diffusion into the water depends on the ratio of water or substrate surface to air, the partial oxygen pressure, the barometric pressure and the temperature (Vestergaard, 1984). Other ways of increasing oxygen diffusion are to increase the surface of the solution by spraying, dropping, turbulence or bubbling of air. It is also possible to oxygenate the solution by adding chemicals or pure oxygen under pressure. One of the objectives of irrigation is to stabilize the dissolved oxygen concentration within the hydroponic system.

7.4.2. Oxygen gradient

The level of dissolved oxygen in hydroponic solutions varies with the flow technique and flow rate. Depending on the design of the hydroponic system, there are 3 different flow techniques: longitudinal, horizontal and vertical.

In one specialized hydroponic system known as “aeroponics”, the nutrient solution is continually sprayed on the roots, thereby enabling a dissolved oxygen level of almost 100% to be attained. Deep flow technique (DFT) is based upon the oxygen dissolved in the nutrient solution, whose level is enhanced by continuous recirculation. The root system becomes loose, so that solution exchange can take place easily. Combining DFT with vertical flow gives excellent control of the root zone, not only for oxygen, but also for the transport of waste products (CO₂) away from the roots. The nutrient film technique (NFT) involves continuous solution recirculation and establishment of very thin nutrient films in the root environment.
by solution flow along channels. As the roots grow in the channel, they form a mat, which functions as a barrier to force the solution to flow over the roots. A dramatic oxygen gradient along NFT channels has been observed, with dissolved oxygen concentrations dropping from 100 to less than 60 % of saturation by the end of each channel. (Gislerød and Kempton, 1983; Vestergaard, 1984; Goto et al., 1996; Yoshida et al., 1997). A modified NFT system, called “Super NFT”, uses nozzles to spray the solution along the channel and thus reduce this problem.

The oxygen supply changes substantially with the water holding capacity and porosity of the substrate in hydroponic systems involving substrates. Baas et al. (1997) propagated roses in 6.5 cm-high rockwool cubes and found that oxygen stress was minimal and rooting optimal at a volumetric air content of 20 to 25% in the lower 2.75 cm of the substrate, corresponding to a volumetric air content of 37 to 42% in the whole cube.

Rose cuttings rooted and grown in aerated water culture and rockwool under various oxygen conditions did not show significant differences regarding the shoot growth in short term experiments. Low oxygen conditions increased root porosity and alcohol dehydrogenase (ADH) activity. Changing plants from aerated to non-aerated solutions, caused an increase in ADH activity, but after 9 days, the ADH activity of these plants was still lower than in those which had been maintained continually in non-aerated solution. In the non-aerated solutions, the root growth was reduced by 50% while the shoot growth was unaffected. Plants formed more primary roots and fewer seminal roots under oxygen deficiency. These results indicate that roses are able to adapt to unfavourable oxygen conditions for a short time (Gislerød et al., 1997). Although the uptake of N, K and Ca has been shown to be significantly lower in crops grown under oxygen stress, in an experiment with cucumber grown for 10 days under low oxygen conditions (0.01 and 0.1 mM O₂) the plants did not exhibit a difference in shoot growth (Yoshida et al., 1997). Nevertheless, it can be presumed that suboptimal irrigation or irrigation control, with high irrigation frequencies and almost complete water saturation of substrates over a long time, will directly influence root and shoot development and growth. The only practical way to achieve a steady supply of oxygen is to find a balance by vertical oxygen diffusion in a system with a large surface area and horizontal flow. Schröder (1994) described plant plane hydroponics (PPH) as a thin layer system with fleece mats as a substrate. The oxygen level solution increased by up to 95% (on average 80%) along the horizontal flow due to good surface diffusion.

7.4.3. Gas exchange

Weyer et al. (2001) measured gas composition in growth media, focussing mainly on oxygen, carbon dioxide and ethylene. The model system consisted of a cylinder of 0.2m height filled with ca. 3.5 l medium. Oxygen levels as low as 5.4 %,
CO$_2$ as high as 8.7 % and C$_2$H$_4$ as high as 8.3X10$^{-5}$ % were measured. The O$_2$ concentration decreased from the top to the bottom of the cylinder, while the CO$_2$ and C$_2$H$_4$ concentrations increased. The gradients for O$_2$ and CO$_2$ concentrations over the height of the cylinder were less than 0.6% for most media except rockwool, where an average difference of 4% O$_2$ was found. For C$_2$H$_4$, the differences between top and bottom were relatively more profound (up to 0.9X10$^{-5}$ % C$_2$H$_4$), and even higher in rockwool (2.5 to 0.9X10$^{-5}$ % C$_2$H$_4$). Oxygen contents were lowest and CO$_2$ and C$_2$H$_4$ were highest in peat and in the bottom layer of rockwool. There appears to be a relationship between O$_2$ concentration and the physical characteristics, since peat and the bottom of rockwool have a low air content and show low O$_2$ concentrations.

Investigations with the thin layer PPH system have shown similar CO$_2$ concentrations in the gas of the root zone. Average CO$_2$ concentrations of 2800 ppm and 2700 ppm were measured for cucumber and tomato respectively (Schröder, 1994), with peaks of 6900 ppm and 6000 ppm CO$_2$ resulting probably from increased biological activity at periods of high temperature and light during the growth period. Since plant roots and microorganisms consume O$_2$ and produce CO$_2$, the root zone must be regarded as a living community.

Carbon dioxide concentrations in the soil atmosphere range from 1000 to 20,000 ppm (Geisler, 1963; Müller, 1980). Nonnen (1980) split up the total CO$_2$ production into root-, rhizosphere- and soil- or microbial respiration. Values reported by various investigators indicating the CO$_2$ production by microbial activity differ by 50 to 80% (Trolldendier, 1972; Martin, 1977; Schröder, 1994). Root responses to high CO$_2$ concentrations are less definitive than those observed at low O$_2$ concentrations. Carbon dioxide concentrations that have been reported to inhibit root growth vary greatly and it is difficult to compare the experimental findings with field conditions. A high CO$_2$ concentration (10,000 ppm) can partially inhibit while 1000 ppm may stimulate root growth (Geisler, 1963; Radin and Loomis, 1969).

When applying these findings, it should be taken into account that the currently available methods for determining CO$_2$ do not allow concentration measurement at the immediate root surface. In almost all cases, the reported values indicate concentrations in the air included in the substrate pores of the root environment. The CO$_2$ concentration in the water film surrounding the roots can be higher than in the bulk of the substrate. Nevertheless, some results show that high CO$_2$ concentrations can be tolerated better by roots in hydroponics if sufficient dissolved oxygen is available at the same time (Jackson, 1980).

Since O$_2$ and CO$_2$ are correlated with the water content in the root zone, they may be regarded as modifying factors. Raising the water content of soil and substrates causes increasing CO$_2$ and decreasing O$_2$ concentrations. Adequate substrate aeration is of vital importance for plants grown in media. Thus, it is important to be able to obtain quantitative information on the gas composition of the media so as to be able to relate this to plant performance. This requires the
development of a robust testing method to measure gas composition in growth media. Not only O₂, but also CO₂ and C₂H₄ concentrations have been shown to be influenced by growth media and irrigation (Stojny et al., 1998). The O₂ supply is determined mainly by the physical characteristics of the substrate, and the volumetric air content is important because it is directly related to O₂ diffusion rates (Bunt, 1991).

Effective transport of water is important to provide roots with water and nutrients. Insufficient transport of water due to unsaturated hydraulic conductivity may lead to dry areas and reduced use of the available substrate volume by the roots (Wever et al., 1997). This is particularly important when sub-irrigation is applied. Furthermore, the water capacity of the substrate must be known. When the volume of the available water in the substrate is high but the rate of water uptake by the plants is low while the supply of nutrient solution depends on the water consumption by the crop, the solution in the root zone cannot be renewed as frequently as desired with detrimental effects on the supply of oxygen to the roots.

7.5. Irrigation systems

In general, irrigation systems deliver water to the plants. In hydroponics, the irrigation systems deliver nutrient solution to the growth medium, if used, or direct to the roots of the plants, if no substrate. Various types of irrigation system are used in greenhouse production.

7.5.1. Design criteria and characteristics

Irrigation systems are hydraulic systems that move liquids from a source to a destination, where some sort of emitter is used to transmit the liquid to the root zone. All irrigation systems require pressure to move the liquid through pipes or tubing. The further the liquid moves through such tubing the more the pressure declines.

Irrigation systems typically involve a number of separate circuits, which are grouped so that all plants within each group are irrigated at the same time. Each circuit must be designed to meet certain criteria as outlined below.

7.5.1.1. Capacity

A fundamental criterion for an irrigation circuit is its capacity which should be sufficient to handle the demand placed upon it. Typically, each emitter has a particular flow rate that it is designed to deliver at a particular range of pressures.
If the sum of all the flow rates of the emitters in the system exceeds the capacity of
the system, many of the emitters will not operate properly because the pressure
will be below the minimum needed for reliable delivery of water at the specified
rate. In this case, some emitters will not deliver any water, while others will operate
at a reduced level. Consequently, some plants will not receive sufficient amounts
of nutrient solution.

Usually, a commercial production system will include many irrigation circuits.
These do not normally operate at the same time; instead each circuit is scheduled
according to the needs of the plants. In large operations there may be hundreds of
circuits. On a hot summer day, many groups of plants may run out of water
simultaneously. In such an event, the grower must schedule irrigation so as to
ensure that no plant experiences water stress. It is important for the grower to
understand the maximum demand for water that may occur and the pumping
capacity required to accommodate this, even under a worst-case scenario. This
may be the limiting factor to how much production is possible.

It should also be noted that if every irrigation circuit is maximized with regard
to the available pumping capacity, this imposes a significant burden on the grower,
who can then irrigate only one circuit at a time. Most growers prefer to install a
pressure regulator in each circuit, which are then designed to use less than half of
the total capacity of the entire facility and function according to the pressure
regulators. This allows the grower to selectively combine circuits that are irrigated
simultaneously. Clearly it is important to group plants with similar water and
nutrient requirements into circuits.

7.5.1.2. Uniformity

Uniformity is one of the most important characteristics of irrigation systems
used in commercial greenhouse production. The reason for this is that the grower
must be able to forecast production and meet market demands. In non-uniform
systems, portions of the production may be either substandard or delayed. The
type of irrigation system affects uniformity. A high degree of nutrient application
control is the main advantage of drip irrigation, which has a large number of
emitters per unit area with a high uniformity of discharge.

Uniformity can be measured by calculating the coefficient of uniformity (Lieth
and Burger, 1989). A value of 90% can be achieved for drip systems, compared
with 60-80% for sprinklers. Pressure-compensated emitters have a coefficient of
variation of less than 5% when new, resulting in a uniformity coefficient as high as
96% (Dasberg and Or, 1999). In practice, however, growers frequently assemble
circuits that are much larger than the theoretical specifications so as to save
money on irrigation valves, filters and pressure regulators. Furthermore, uniformity
decreases over time, as some emitters become clogged. It should be noted that it
is impossible to achieve perfect uniformity, and continual servicing of the filters, valves and emitters is needed to assure the highest level of uniformity possible.

The uniformity of irrigation depends on the technical layout, which is a main condition for any control system and water efficiency. Different technical layouts depend on the crops and growing systems. Some crops, such as fruit, vegetables or roses, are grown in containers or slabs placed in rows with drip irrigation along each row. Cut flowers, such as carnations or freesia, are grown in 1-1.5 m wide beds, which are filled with substrate and drip irrigation is installed for the whole bed, not for each single plant. Plants, which grow span-wide, like lettuce or radish, need an irrigation system that covers the whole greenhouse area.

The technical layout of irrigation systems includes:

1. A water source and/or storage reservoir. For long term water storage, a rain-water reservoir is mainly used, while for short term supply, tanks with a capacity to supply all the plants for one day are satisfactory. The latter is suggested in case of a technical breakdown.

2. A delivery system. The basic equipment for delivery systems consists of a nutrient solution mixing unit with a pump, main line, sub lines, lateral lines and/or emitters. For the standard layout, the sub-lines and lateral lines are closed at the ends. The main problems are the time delay and the fall in pressure resulting from increasing distance from the pump. Comparison of the standard system with the “Tichelmann” layout (Gieling et al., 1995), which has been used in heat technology, has shown that these problems can be solved. This is very important for irrigation strategies in the event of changes in the nutrient composition or EC value depending on radiation during the day. With the “Tichelmann” layout, the new solution is supplied to each plant within seconds. So the grower and/or the irrigation control, can react much faster to control parameters, like climate conditions. This enables a quick switching over to new irrigation strategies, especially in autumn or winter when nutrient consumption is low. The system should be divided into different circuits depending on the total area and the climate gradients within the greenhouse due to the direction of radiation. For instance, when designing an irrigation system in Northern Europe it is important to take into account that the water consumption by the plants increases towards the southern and western directions.

3. In closed systems, a drainage system and reservoir is required to collect the drainage solution to be recycled.

4. The drainage water should be filtered and disinfected prior to being reused. Different water treatment technologies, like UV-treatment, heat, or slow sand filters may be involved to disinfect the drainage solution. New biological methods using beneficial microorganisms are under discussion.
7.5.2. Types of systems

Various types of irrigation systems are used in greenhouse production. Lieth (1996) grouped the systems according to a) the level of automation and b) whether the flow of irrigation solution to the plants is overhead, at the surface, or below the surface (sub-irrigation). Depending on the water supply at a particular time and place, irrigation systems can be divided into macro- and micro-systems.

In hydroponics, micro-irrigation is feasible due to the limited volume of substrate per plant. Micro-irrigation systems offer a wider variety of components than those using high pressure overhead or sprinkler irrigation. Overhead systems have some disadvantages for plant growth and quality and lead to disease problems, especially towards the end of the crop.

7.5.2.1. Overhead systems

Overhead systems apply water or nutrient solution to the aerial part of the plant in a way that causes the foliage to become wet. If the water is clean and clear, it leaves no residue, but if the water contains any solutes, these will show up as white deposits on the foliage after the water has evaporated. Apart from the potential for accumulated residues, there is also the possibility of disease developing in the water droplets on the foliage.

The greatest advantage of overhead sprinkler systems is the low cost of installation in comparison with other types of systems. However, this benefit has a price. Overhead sprinkler systems tend to lack uniformity. Commonly, a uniformity coefficient of 50% is achieved, which means that a substantial amount of the pumped water never reaches the root zone of the plants. This problem is particularly acute for plants in containers that are not spaced close together.

Overhead irrigation can be applied by the so called “boom systems”. A boom system consists of a rig that moves overhead, allowing plants that are arranged in a uniform pattern to be irrigated by one attendant (Lieth, 1996). Boom systems are used for pot plants and plant propagation. The uniformity of boom systems depends on the design and layout of the nozzles on the boom, the consistency of water pressure in the supply, and the uniformity of speed at which the boom travels over the plants.

Mist and fog systems are not irrigation systems. These dispense water to the air and are used for climate control rather than to supply the plants with irrigation water.
7.5.2.2. Surface systems - Drip irrigation

Drip irrigation is defined as the application of water through point or line sources (emitters) on or below the soil or substrate surface with low pressure (20-200 kPa) and a low discharge rate (1-30 l h⁻¹ per emitter). The term "trickle irrigation" is used interchangeably with "drip irrigation" (Dasberg and Or, 1999).

The most popular system used in hydroponics is low-pressure drip irrigation. If a certain low pressure is used for transport, a pressure regulator is recommended for uniformity per emitter. Numerous new drip irrigation supply systems are being developed and new watering or irrigation strategies allow increased efficiency. Drip irrigation systems are designed for the low volume delivery of water. Such systems may use ½-inch polyethylene (PE) pipes to supply a header pipe. Smaller, ¼- and 1/8-inch, vinyl pipes (spaghetti tubing) serve for all lead-in tubes and lateral lines. Buried PVC pipes are generally used for the main line to and from the nutrient solution unit in more permanent situations.

Emitters

Punch-in emitters, emitters using a membrane, or in-line emitters have been developed. These can be inserted directly into a PE-pipe after punching a hole into it, and have an inlet barb to retain the emitter in place. Some emitters have self-piercing inlet barbs to punch their own hole. Emitters come in regular and pressure-compensation forms that require a certain pressure for water release. In such systems all drip emitters start dispensing irrigation solution at the same moment (at the same pressure) and prevent drainage of the supply line after the valve is turned off. Thus, leaching at a particular spot does not occur (Van Os, 1998).

Emitters are available in a wide range of shapes and flow rates. Most modern emitters use a turbulent flow design (pressure-compensation), which keeps dirt particles in motion so that they cannot settle until they have left the emitter. This is important for the uniformity of systems supplying a long-term crop. There are four categories of emitters: porous pipes (leaking pipes), punch-in emitters, emitter lines and micro-sprinkler heads.

Porous pipes

Porous pipes are the easiest and a low-price option. They can be used in permanent locations as surface or sub-irrigation systems. A negative aspect is that due to the irregular situation of the numerous pores, internal water pressure control is not possible. As a result, porous pipes lose pressure along the length of the pipe,
and this leads to uneven water delivery and empty pipes after watering. A further disadvantage of porous pipes is that they can only be used on flat ground.

**Punch-in emitters**

Three main types of punch-in emitters exist: drip emitters, in-line drip emitters and misters. Drip emitters are the most popular. Punch-in emitters are suitable for containers, pot plants, vegetables or cut flowers (e.g., roses). They literally deliver water drop by drop, keeping the surface of the substrate almost dry but the roots moist. The flow rate is low (e.g., 2 l h⁻¹) and may vary depending on the emitter type, the number or distance of emitters, pressure, or even temperature of the material.

In-line drip emitters are a hybrid between a drip emitter and an emitter line. They are similar to punch-in emitters because they are inserted into the irrigation line wherever needed. Similar to emitter lines, they enter directly into the line and not its periphery. Most of them are designed for ¼- or ⅛-inch vinyl tubing. They have a more limited range of flow rates than drip emitters.

Misters are mostly used in specialized nurseries to grow plants requiring high air humidity. Mistral give off a fine mist that humidifies the air. Emitters designed to give larger water droplets, which form drips, serve a double purpose. They moisten the air and supply the plants with water. Because misters must be run at regular intervals during the day, but only for few minutes at a time, they should have their own circuit and control, which should be independent of other emitters.

**Emitter lines or pipes**

Emitter lines incorporate equally spaced emitters directly into plastic pipe. The pressure-compensating emitters are preinstalled at a fixed spacing and rated to dispense at specific rates. Sold in rolls, emitter lines can easily be installed and are a lower investment. Depending on the quality, emitter lines can be used for several years, or must be replaced each year with the crop. Generally plant spacing must match the spacing of the emitters along the pipe.

**Micro-sprinkler heads or spray emitters**

Micro-sprinkler heads occupy a place between micro- and overhead sprinkler irrigation. These mini-sprinklers use low pressure and narrow diameter pipes to apply water in a spray as sprinklers. They are not as efficient as drip emitters, since they lose some water due to evaporation and overspray. Emitters of various
spray patterns are available, including full circle, half-circle and quarter-circle. Most micro-sprinklers cover a small radius of 0.5 to 3 m. This system can be used for substrate benches or thin layer systems serving plants with a high plant density (e.g. cut flowers). These emitters should be placed on the substrate surface along the plant row using a horizontal spray to keep the leaves dry.

7.5.2.3. Subsurface or sub-irrigation systems

Subsurface systems involve delivery of the nutrient solution into the root zone from below. These systems include capillary mats, troughs, and ebb-flood systems. While there are advantages to using sub-irrigation, there is a tendency for salt to accumulate in the upper portion of the root zone. This occurs because the nutrient solution enters at the bottom, while water evaporates from the substrate surface. Overhead irrigation is then needed to leach out these salts. For a uniform water supply, the systems need to be perfectly level, but paradoxically, there must be a slope so that water can drain off (Lieth, 1996). On ebb/flood benches, this is achieved with built-in drainage channels. While capillary mats and troughs are mainly used for pot plants, ebb/flood systems are used for hydroponically-grown young plants, especially fruiting vegetables, using trays or benches, as well as flooded floors.

7.5.3. Layout of irrigation systems in hydroponics

Generally, hydroponic irrigation systems can be characterized as open or closed systems (Herbold, 1995). In closed systems all drainage water is captured and re-used, while in open systems the drainage water is generally discarded. Hydroponics without a substrate, like NFT or aeroponics, are closed systems. Systems where drainage water is captured (e.g. ebb-flood systems) can be either open or closed depending on whether the grower is able to clean and reuse the effluent.

7.5.3.1. Open systems

In open systems, the percentage volume of drainage solution depends on the irrigation system configuration, the type of control and the substrate. Drainage can range from low leaching fractions of 0 – 10% to as high as 90% of the supplied nutrient solution, depending on the degree of attention paid to the irrigation process (Lieth, 1996). Typically, leaching fractions of 25-35% are recommended so as to maintain the EC in the substrate at recommended levels. There are two

282
reasons for concern regarding high rates of leaching: (1) the leachate pollutes the drinking water and (2) the discarded irrigation solution represents an equivalent percentage discard of purchased fertiliser and water.

7.5.3.2. Closed systems

Closed systems were developed as a consequence of environmental pollution to enable reuse of the drainage solution in long-term crops. However, some unsolved problems still exist. Re-use of drainage water leads to an accumulation of some nutrients and ballast ions, thus resulting in alterations in the nutrient ratios. To prevent this problem, expensive systems using liquid fertiliser with ion-sensitive sensors and control units are required. Unfortunately there are currently no ion-specific sensors that can be used within a control system.

Another major problem is the potential spread of root diseases within the hydroponic system because the recirculating solution contains inoculum from any disease that has affected one or more plants grown in the system. Disinfection of the recycled nutrient solution is a must for long-term crops. Existing sterilization systems are not always applicable, mainly because of high costs, or because they affect the nutrients dissolved in the solution. Developments in disinfection equipment focus on the removal of pathogens without complete sterilization of the solution (Van Os, 1998). Currently, no possibility exists to control the root zone directly, even in the case of new root diseases.

Some studies report fewer fungal diseases in closed systems than in open ones. One explanation for this is that beneficial microorganisms present in a more natural root environment control diseases. Postma and van Elsas (2001) observed that cucumbers in rockwool after sterilization became more infected after being inoculated with *Pythium* than those grown in rockwool without sterilization. Disease suppression was associated with the presence of Actinomycetes in the drainage water. This finding suggests that it may be possible to achieve a more efficient control of soil-born diseases in hydroponics by adding beneficial microorganisms (e.g. *Bacillus subtilis*) to the root zone. In closed systems, organic compounds and microorganisms may accumulate so that biological control of the root zone is possible.

Management of microbial factors may be performed on the root surface and inside the root by plant growth-promoting organisms, in the solution by microorganisms that degrade organic compounds inhibitory to plant growth, or in an active slow sand filter. The microbial dynamics of fungi and bacteria within a recycling nutrient solution are of major interest for the stabilization of closed hydroponic systems (Waechter-Kristensen *et al.*, 1997). Future systems should include a living community of microorganisms to promote plant growth and keep closed systems in a biological balance.
According to Van Os (1998), growers of crops (tomato, cucumber, sweet pepper, roses or gerbera) which can be economically grown in closed soilless systems, frequently choose the cheapest system for the short term, preferring low investment to low annual cost. For other crops (lettuce, radish, chrysanthemum carnation, freesia) no economically feasible systems exist.

In virtually every closed system, some ion or chemical will eventually build up to an excessive level. This may be a macronutrient, sodium, chloride, or a micronutrient, such as boron. In general it is less expensive to discard such a solution than to clean it. Thus, closed systems are seldom completely closed.

7.6. Irrigation Control

Various levels of irrigation control are possible, ranging from completely manual to fully automated operation. The type of control must be matched to the production system. If, for example, only manual hand-irrigation is possible, then the substrate must have a high water holding capacity, excellent aeration and high hydraulic conductivity. The irrigation control should ensure that the supply and uptake of water, nutrients and oxygen match the requirements of the plants. Under conventional horticultural production, where irrigation is governed exclusively by the degree to which the root zone reservoir is depleted of water, this is optimized only rarely, but is adequate for most of the time.

With fully automated hydroponic systems it is possible to create optimal situations at nearly all times. This is the reason why very few commercial producers use manual irrigation control for anything other than touching-up or correcting problems.

It should be noted that the greatest impediment to efficient irrigation is a lack of uniformity in the irrigation system or in the crop. The main reason for this is that hydroponic systems are very investment-intensive and used to produce high-value crops. This means that each plant in the crop is important and growers typically want every individual plant to produce a marketable product. The emitter that delivers the least amount of water governs the duration of irrigation of the entire circuit. It is not uncommon to find irrigation systems where the emitter with the lowest flow rate is delivering water at a rate of only 30% of the emitter with the highest flow rate. Therefore, a large amount of waste will occur in such a system, irrespective of the type of irrigation control employed.

7.6.1. Irrigation scheduling

Historically, the most commonly used method for dealing with irrigation in horticulture is to schedule it. There are two aspects to this: the duration between
irrigation events and the length of the irrigation event. Typically, the interval between irrigation applications is fixed at some duration (ranging from several hours to several days) that is adjusted seasonally. The duration of the individual irrigation event is set by trial and error to ensure that each irrigation cycle delivers the amount of nutrient solution needed by the plant, plus an additional 20 to 30% leaching fraction. This surplus is in addition to any extra amounts required as a result of lack of uniformity in the irrigation system and is needed to prevent the build-up of undesirable salts in the root zone.

It should be noted that this type of irrigation control may result in sub-optimal conditions in many periods of time, although the total amount of irrigation solution supplied to the crop may be much larger than that required when irrigating according to the methods described below. In general, scheduling irrigation via some sort of time clock is better than no automation at all, but it is becoming less and less feasible as the costs of resources (water and fertiliser) and the regulatory pressures to reduce waste water increase.

7.6.1.1. Current standards

Growers who use computer-monitored devices have accurate and dynamic control over the availability of the nutrient solution. Initially, hydroponics did not involve any substrate and was based on almost continuous supply of nutrient solution to the crop (e.g. NFT) to meet the requirements of the plants by permanent flow. However, when the supply of nutrient solution was interrupted, the plants were exposed to danger of imminent damage or death because only a small amount of residual moisture could be retained in the root mat. Most hydroponic systems in use today employ some sort of substrate and intermittent irrigation applications to minimize this problem. For instance, rockwool or coconut coir are widely used in hydroponic greenhouse production. Crops grown on such growing media can tolerate overwatering since these substrates return to acceptable aeration levels soon after irrigation. Moreover, these media create a reservoir for water and nutrients. Although control of irrigation is crucial in determining crop yields, there is still some disagreement about the frequency and volume of nutrient solution to be applied, and even whether hydroponic crops should be irrigated at night (Cockshull, 1998).

Growers have to make decisions when to start and stop irrigation. Hence, they have to choose whether to give small amounts of nutrient solution many times a day, which results in less drainage and a wetter substrate (e.g. rockwool), or to supply higher amounts of nutrient solution only a few times per day, which results in more drainage and drier substrates.

While the 'optimal' irrigation schedule is still under discussion, each grower follows some basic guidelines in combination with his personal experience.
Hydroponic Production of Vegetables and Ornamentals

Research on water and nutrient supply, as well as on application strategies, focus on finding a more efficient use of water and avoiding nutrient deficiencies. Therefore, the plant requirements and all the related influencing factors must be studied and understood.

7.6.1.2. Uptake of nutrient solution

The amounts of nutrient solution taken up by plants depends on many factors, including root zone temperature. When root temperature increased from 14 to 16 °C, the daily uptake of water by tomato plants increased by 30%, with a proportional increase in nutrient uptake. The uptake of Ca and P increased by 45% and 64%, respectively, which indicates that these nutrients respond more sensitively to changes in this range of temperature than N, K and Mg, whose uptake increased by 21-24% (Adams, 1989). However, improvement in yield by root warming is rather limited when the ambient temperature is too low. For instance, when the root temperature was raised from 11 to 27 °C, with the ambient temperature maintained at about 13°C, both yield and quality of tomatoes were reduced. When the ambient temperature was 16 °C, there was a slight benefit. A root temperature of 15-18 °C was recommended for tomato before picking and 25 °C during picking (Graves, 1986). By contrast, the yield of smaller plants, such as lettuce, increased when the root temperature was raised from 8 to 17 °C even though the ambient temperature was only 8 °C.

Differences in the transpiration rates of cucumber ranging from 5 to 23% did not lead to differences in yield or quality. According to De Graaf and Esmeier (1998), there was a clear energy saving effect when crop transpiration was reduced. An irrigation model was validated for a long-season tomato crop based on solar radiation and the inside saturation deficit for rockwool and NFT. The plants used 10% more solution during April and 31% more during May, June and July. By September, the use of water by the crop exceeded the model estimate by 20%. The same trend occurred in rockwool, but the crop used 10% less water than in NFT (Hamer, 1998).

Cucumber roots grown in oxygen deficient solution showed a reduction in solution uptake that was proportional to the decrease in the oxygen level. Leaf area, fresh weight and dry matter decreased at lower oxygen availability, while stem length and leaf number were scarcely affected over 10 days. Soffer et al. (1991) showed a quantifiable relationship between the dissolved O2 level and plant growth for ficus and chrysanthemum. This suggests that the membrane permeability of root cells is reduced at lower oxygen levels through respiration-dependent processes, and growth is inhibited through leaf turgor loss (Yoshida et al., 1997).

Schröder et al. (1996) compared hydroponic systems with reference to nutrient solution uptake. The transpiration coefficient over the growing period was 334 l
kg\(^1\) and 453 l kg\(^3\) dry matter for PPH and NFT, respectively. These values are of the order of magnitude usually found in efficient crops grown in the field, but water was used more efficiently in the PPH system. It is economically relevant to know the specific amount of water consumed to produce one kg of fruit fresh weight, since the cost of water is balanced by the sale price of the product. For the production of one kg of fruit, 27.1 l and 36.7 l water had to be applied in the PPH and NFT systems, respectively. Further results showed that as water application rates are higher in NFT, the coefficient of transpiration is higher compared to PPH, which receives less water. The effect of the hydroponic systems could not be separated from the effect of water application rates, as both were different in the experiment. However, it is suggested that the efficiency of water use by the plant might be strongly influenced by either variable alone or in combination.

Schwarz and Kuchenbuch (1998) reported that the water uptake of tomatoes in closed systems depends on the EC-level. Tomato growth and yield decreased with increasing EC. Yield was reduced by 50% at 6 dS m\(^{-1}\) in comparison with 1 dS m\(^{-1}\). Water uptake was reduced at higher EC-levels independently of related parameters, like leaf area index (LAI). At 9 dS m\(^{-1}\), water uptake was reduced by 60% compared with 1 dS m\(^{-1}\), due to a 20% decrease in leaf area. However, changes in plant growth, leaf area and water uptake were caused by both solar radiation and EC level. The vapour pressure deficit (VPD) of the greenhouse atmosphere directly affects water uptake through its effect on transpiration. Plants grown under optimal humidity show well-developed leaves and a high LAI. Plants grown under sub-optimal, mostly high VPD for a long time show a reduced leaf size and a low LAI, which adversely affects yield and quality. In addition, the uptake of nutrient and water may be reduced because the roots are insufficiently supplied with assimilates from the leaves due to permanent VPD stress.

Root activity and/or influx of water and nutrients are important for optimal growth (Schwarz et al., 1996). Studies with cucumber showed that root dry mass was 10 times higher in rockwool than in polyester fleece. Moreover, the distribution and appearance of the roots were quite different in the two substrates. Root systems in polyester fleece were fine and had significantly whiter root tips. The differences in root mass resulted from the different physical parameters of the substrates. As no significant differences in yield and quality were detected, it was concluded that a smaller root system in polyester fleece with the same influx of water and nutrients was more efficient than that in rockwool, (Schröder and Förster, 2001).

### 7.6.1.3. Interaction between irrigation schedules and plant growth

Irrigation control ensures that the nutrient solution supply matches plant requirements at all times, but to control plant growth (e.g. generative or vegetative) other treatments are needed. Especially in long-season crops like tomato, which is a perpetually harvested crop, a physiological balance between vegetative and
generative growth should be maintained throughout the cropping period. Plant
treatments are necessary until the 15th inflorescence. For cucumber, new varieties
have been bred which are able to regulate fruit setting by themselves. A ‘sink/
source balance’ for assimilates exists for each plant between the leaves as source
and the plant apex, flowers, fruit and roots as sinks. Controlled watering contributes
to the achievement of a desirable balance between vegetative and generative
growth at different stages of plant development. For instance, the flowering of
young tomato plants under poor light conditions can be improved by intermittent
circulation in NFT (Graves and Hurd, 1983), or by restricted watering in rockwool,
which reduces the expansion of young leaves. Competition for assimilates is then
in favour of the flowers and fruits, so early yield can be improved. The same
principle has been applied to watering crops, like sweet pepper, tomato or
cucumber in rockwool systems. The nutrient solution supply is matched to the
carbon assimilation of the crops, resulting in balanced growth. Controlled watering
can also be used to regulate fruit size in tomato. For instance, when tomato plants
were watered with either 60% or 120% of the recommended amount calculated
from the solar radiation, the average tomato fruit weights were 84% and 104%,
respectively, of those supplied with the recommended dose (Adams, 1990).

Nowadays, growers follow various irrigation schedules, depending on the
type of hydroponic system, substrate or climate. Each grower has his own schedule
based on a control level and personal experience. In addition, the schedule can be
changed according to plant development, fruit setting or external influences, like
market prices, customer preference or other economic factors. For these reasons,
growers manipulate plant growth by irrigation control. This means that irrigation
may differ from the optimal water supply, which is linked to the requirements of
the plants, by employing sensors or control models. A general recipe for all plants
and hydroponics does not exist. Climate and irrigation management should be
combined when aiming at controlling the growth of the plants.

To explain the interactive effect of irrigation schedules, an example will be
given for cucumber in a substrate, particularly rockwool. Generative growth of
plants is stimulated by exposure to stress due to a difference between day and
night temperatures, a high EC value in the solution, watering with a low drainage
percentage, restriction of water and reduced irrigation before night. By contrast,
vegetative growth of plants is stimulated by low or no difference between day and
night temperature, a low EC value in the solution, watering with a high drainage
percentage, and an increase of VPD, which results in higher transpiration rates.
An example of irrigation control is given based on plant stage, time, solar radiation
and drainage. According to the plant stage, water supply is time based, e.g. two
intervals of 100 ml plant⁻¹ hour⁻¹. Differences due to high radiation are compensa-
ted for by the light sum method developed for a full canopy (Lattauschke, 2000).
The actual water consumption can be determined by the following simple
equation:
\[ W_{ac} = KR \]

where \( W_{ac} \) denotes the actual water consumption in ml m\(^{-2}\),
\( K \) is a constant, which in this example was estimated to be 0.0003 ml J\(^{-1}\)
\( R \) indicates the radiation or light sum in J m\(^{-2}\).

The start of irrigation depends on light sums which should reach values of between 40 and 60 J cm\(^{-2}\) in closed systems and 140 - 180 J cm\(^{-2}\) in open systems. This results in drainage volumes of 30% in closed and 15% in open systems, respectively.

If the water requirement is estimated at 21 per plant per day and the watering dose amounts to 100 ml per day, 20 intervals will be necessary. The EC level can be changed in response to radiation differences to optimize irrigation control (e.g. ± 0.2 dS m\(^{-1}\)). A high EC level is used for low radiation and a low EC level for high radiation. Flow rates can also be changed to control the EC and pH in the substrates.

7.6.1.4. Example of an irrigation schedule

Irrigation scheduling involves the selection of particular irrigation patterns for various parts of the crop production period. For example, in greenhouse cucumber production, between transplanting and flowering irrigation should be scheduled so as to induce slight water stress and increase root growth. All fruits should be removed for up to 50 cm of shoot length to increase vegetative growth. An example of an irrigation schedule for cucumber is shown in Table 3.

Tomatoes should be stressed longer after transplanting (i.e. for about 3 weeks) in order to set the first and second trusses. Otherwise the plants will grow more vegetatively under low light conditions. An example for the calculation of the amount of solution per day based on time and radiation is given in Table 4. Solution supply follows the higher plant demand due to higher light conditions. On the other hand, the water capacity or substrate moisture (%) can influence plant growth. For rockwool culture, there are some target values for the control of moisture in the substrate, and special sensors have been developed for substrate moisture control. For example, the hand-held Grodan Water Content Meter (WCM-H) has been specially developed to measure water content, EC and temperature in rockwool. Using an electrical field, the WCM-H measures the average water content across the slab (Anonymous, 1999). For the spring crop of cucumber, a 60% moisture content was advised. At this moisture level, the early yield was higher by 40% and the root systems showed more fine roots and white root tips. If the radiation during the day is very high, the plants need much more water even in
### Table 3. Irrigation schedule for cucumber grown in rockwool based on time and radiation in North Europe (intervals can change between 30 ml to 100 ml solution).

<table>
<thead>
<tr>
<th>Plant stage</th>
<th>Irrigation time/ Radiation level</th>
<th>Low radiation (Spring)</th>
<th>High radiation (Summer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>before transplanting</td>
<td>filling all slabs</td>
<td>100 % saturation</td>
<td>100 % saturation</td>
</tr>
<tr>
<td>after transplanting</td>
<td>2 h after sunrise to</td>
<td>1 interval/h</td>
<td>2 intervals/h</td>
</tr>
<tr>
<td></td>
<td>2 h before sunset</td>
<td>1 start/60 min</td>
<td>1 start/30 min</td>
</tr>
<tr>
<td>3 days after</td>
<td>no irrigation</td>
<td>no irrigation</td>
<td>1 interval in the morning</td>
</tr>
<tr>
<td>transplanting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cucumber fruits on</td>
<td>8-9 a.m.</td>
<td>1 interval/10 min</td>
<td></td>
</tr>
<tr>
<td>primary shoot</td>
<td>9-10 a.m.</td>
<td>1 interval/5 min</td>
<td></td>
</tr>
<tr>
<td>11 a.m. 6 p.m.</td>
<td>1 start/30 min</td>
<td>2 starts/30 min</td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>+ 1 interval</td>
<td>+ 1 start</td>
<td></td>
</tr>
<tr>
<td>&gt; 100 W m(^2)</td>
<td>= 2 interval/30 min</td>
<td>= 3 starts/30 min</td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>+2 starts</td>
<td>+2 starts</td>
<td></td>
</tr>
<tr>
<td>&gt; 250 W m(^2)</td>
<td>= 3 starts/30 min</td>
<td>= 4 starts/30 min</td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>+3 starts</td>
<td>+3 starts</td>
<td></td>
</tr>
<tr>
<td>&gt; 400 W m(^2)</td>
<td>= 4 starts/30 min</td>
<td>= 5 starts/30 min</td>
<td></td>
</tr>
<tr>
<td>main growth</td>
<td>1-9 p.m.</td>
<td>1 interval/30 min</td>
<td></td>
</tr>
<tr>
<td>generative and</td>
<td>start at 7 a.m.</td>
<td>+1 interval = 2 starts/30 min</td>
<td></td>
</tr>
<tr>
<td>vegetative growth</td>
<td>radiation &gt; 100 W m(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at the same time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>end of crop (autumn)</td>
<td>9-11 a.m.</td>
<td>1 interval/5 min</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Calculation of the amount of nutrient solution.

<table>
<thead>
<tr>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of schedule:</td>
</tr>
<tr>
<td>Stop of schedule:</td>
</tr>
<tr>
<td>Total time:</td>
</tr>
<tr>
<td>Time based start:</td>
</tr>
<tr>
<td>Total starts by time:</td>
</tr>
<tr>
<td>Amount of solution by time:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light sum:</td>
</tr>
<tr>
<td>Light start set point:</td>
</tr>
<tr>
<td>Light starts:</td>
</tr>
<tr>
<td>Amount of solution by radiation:</td>
</tr>
<tr>
<td>Total amount of solution:</td>
</tr>
</tbody>
</table>
the early night, between 6-11 p.m. If no irrigation is applied during that time, this could result in decreasing substrate moisture during the night. The growth of fruit is stimulated by high moisture contents during the evening and drainage should be prevented during the night. Irrigation at night is advised if the moisture content of the substrate has fallen below 8-10% the previous morning. A lower moisture content leads to lower fruit quality, or even cracking and drying of roots in the upper substrate layers. The moisture content decreases much faster in a small substrate volume than in a high one. High moisture content in the morning leads to O₂ deficiency and root death, resulting in water stress, which leads to more generative growth. Thus, irrigation control is necessary under low light conditions. A typical radiation graph for a day shows peaks between 12 midday and 3 p.m. whereas the temperature peaks are observed between 2 and 5 p.m. The set point for light sum depending irrigation starts should be high (e.g., 150 J cm⁻²). The drainage percentage should be about 15% after 3 p.m. and solution volume higher (120 to 180 ml per emitter and plant), but at fewer intervals. During autumn, when light decreases, the moisture content should follow the light reduction (Lattauschke, 2000).

7.6.2. Sensor-based irrigation control

The best approach to irrigation control is to measure the pertinent root zone variables and to use this information to make irrigation decisions. The reason for this is that we directly measure the variables which need to be controlled as part of the irrigation process.

All available moisture sensors relate some sort of electrical, physical, or chemical phenomenon to the amount of moisture that is present in the root zone. The simplest of these consists of a matrix of porous material in which two electrodes are embedded in a precise configuration. The electrical conductivity in the sensors is related to the level of moisture. Unfortunately, it is also related to the EC of the liquid. While such sensors are frequently used in field crop production, they are not particularly useful when a nutrient solution is applied during irrigation.

Tensiometers are sensors that are not affected by salinity. These devices consist of a tube with a ceramic tip at the lower end and a pressure-sensing device at the other end. The tube is filled with water and the ceramic is allowed to become wet. Then the device is sealed and the ceramic end is embedded in the root zone substrate. The substrate has a particular moisture tension and the ceramic comes into equilibrium with this. As it does so, it gives up or takes in water until the tension within the tube and in the media surrounding the ceramic are equal. If the tube is equipped with either a tension gauge or pressure transducer, it is possible to measure the tension inside the tube (which is equal to the moisture tension in the substrate). By using a moisture release curve, it is possible to determine the moisture content.
Hydroponic Production of Vegetables and Ornamentals

When using sensors to measure aspects of the root environment for control purposes, it is important to have the right amount of information and this information to be completely reliable. It is pointless to have multiple sensors for the same variable since most control systems are unable to use more than one signal to drive a particular device. With irrigation systems one typically uses one sensor per valve. The grower moves this sensor around in the crop so that it is always in a location that is representative of the type of control that the grower wishes to see. For a grower, who wishes to see no crop losses due to water stress, this would mean placing the sensor in the root zone of one of the larger plants, in a location exposed to more sun and air movement than the other plants (i.e. at the aisle). Moreover, the emitter of this plant should preferably deliver water at a slightly lower rate than the other ones. Other sensors are also available, but those employing electrical properties are frequently affected by ions (fertiliser) and are thus useless in hydroponics.

On the whole, sensor technology is not particularly advanced. This is an area where research is needed to find a better sensor. The tensiometer is satisfactory, but requires attention and servicing; virtually all other sensors are either too expensive or relatively useless. This leaves the door open for model-based systems, as described below.

It should be noted that all types of sensors that are currently available treat the root zone as a reservoir; sensors measuring any characteristic of the root zone related to its role as a conduit are currently not available. This is an area where future innovation would prove very useful, since this is a key area in which hydroponics differ from other agricultural systems. One exception is the possibility to relate the hydraulic conductivity to moisture tension (Raviv et al., 2001), but this requires calibration for each substrate. Although this might be a burden, it could be useful in modifying irrigation tension set-points. For example, Lieth and Burger (1989) showed that ideal high and low tension set-points for various media are 5 and 1 kPa. Recently, Raviv et al. (2001) showed that differences in the hydraulic conductivity of two different systems suggest that the set-points should be shifted to different values so as to keep the hydraulic conductivity at functionally feasible (more optimal) levels.

It should be noted that tensiometers have found widespread use in irrigation control in a variety of soil-based systems. In such systems, tensiometers are used to start irrigation based on a high-tension (dryness level) set-point. Hydroponic systems tend to respond very rapidly to changes in moisture status and thus a high-flow model must be used (Oki et al., 2001). Using such a tensiometer it is possible to trigger off the start of irrigation and, assuming the water application rate is slow, to determine when an adequate amount of irrigation water has been applied. This allows for the implementation of the following sensor-based control. Assuming that the sensor is located in the root zone of a plant that is representative of the entire crop, the system continually monitors the moisture tension and turns on the
irrigation system once a high-tension set-point has been reached. For soilless substrate systems this is typically 5 kPa. As irrigation occurs, the system continues to monitor the tension. Once a low-tension set-point is reached, the system turns off the irrigation valve either immediately or after a specified additional time to allow for leaching. Implementation via an electronic controller or computer control would include the following additional safety checks: maximum irrigation duration, minimum irrigation duration, minimum length of time between irrigation events, maximum length of time between irrigation events, and tension readings that trigger alarms.

It should be noted that one should not attempt to hold a particular fixed tension set-point. Kiehl et al. (1992) reported that the best crop results were found if the tension was allowed to fluctuate between a moderately dry level and wet conditions. Suitable high and low tension set-points for container media were found to be 5 and 1 kPa. (Lieth and Burger, 1989; Kiehl et al., 1992). Raviv et al. (2001) noted that saturation in some media results in sub-optimal conditions that are not manifested by visible symptoms, suggesting that for such media, long periods at low tensions are not ideal. They also showed that low hydraulic conductivity can be a problem if the high-tension set-point is too high.

### 7.6.3. Model-based irrigation control

The use of mathematical models in horticulture has increased substantially in recent years and a lot of effort has gone into developing models that can be used to calculate the water status of plants with the aim of using this information for irrigation management. Models that are suitable for use in irrigation management involve calculation of the amount of water that is lost from the root zone as the sum of that which evaporates from the root zone and that which is transpired from the aerial parts of the plant (evapotranspiration). Most of such models use either a version or a combination of the models originally developed by Pennman and Monteith to calculate the instantaneous rate of evapotranspiration; this is then summed or integrated over time to estimate the total amount of water lost since a starting time. Once a particular amount is estimated to have been lost, an irrigation event is initiated.

Such models generally use one or more of the following four environmental variables in the calculation: light integral, average air temperature, wind speed (air movement) and relative humidity (or vapour pressure deficit). It should be noted that the best that one can do with these environmental variables is to estimate potential evapotranspiration. To determine actual evapotranspiration requires the inclusion of plant or crop variables in the equation. The most common variable used for this purpose is the leaf area index.

A variety of relevant evapotranspiration and water-use models have been developed for crops such as tomato (Stanghellini, 1987), cucumber (Yang et al.,
1990), rose and ornamentals (Baille et al., 1994). For example, the following equation was derived from the Penman-Monteith equation to calculate the evapotranspiration (E) of crops:

\[ E = A \left[1 - \exp(-K \text{LAI})\right] G + B \text{LAI} D \]

where
- \(G\) is solar radiation,
- \(D\) is the vapour pressure deficit of the air,
- \(K\) is a light attenuation coefficient related to the reduction of light in the canopy with LAI
- \(A\) and \(B\) are parameters which must be calibrated for any particular situation.

This simplified model can be implemented for irrigation control, but its application throughout the whole crop cycle requires re-calibration of the coefficients at the different stages of plant development. Furthermore the model needs validation for each crop.

Although it is beyond the scope of this chapter to discuss them here, it is important to understand the key aspects since some of these models have been incorporated into some of the computer control systems that are available and in use.

The most basic issue is that environmental control systems typically have sensors only to measure environment variables. Without the measurement of variables related to the plants, one can at best calculate a potential amount of water consumption. Various researchers are currently developing models that can use the environmental sensor data to calculate changes in leaf area index, but these are not yet available for commercial application. This means that the implementation of model-based methods requires the grower to relate an actual irrigation rate to a number calculated by the control system. In general, the implementation of a model that includes all four environmental variables is very difficult, if not impossible. Most greenhouse computer systems do not possess this capability, but provide model-based methods that include only one or two variables.

It should be noted that the main advantage of using model-based irrigation control systems is that they offer automatic seasonal adjustment, since the influence of season is expressed through the four environmental variables.

In general one needs to be wary of trusting a model to correctly calculate the plant's actual water usage at every instance. Occasionally, research is published that shows data on water requirement calculations, and one usually finds one or two data points where the water use is greatly underestimated. If a grower were to water on the basis of such calculations, there would very likely be instances where the plants would suffer severe damage from insufficient irrigation. The lesson
here is that model based calculations can be used as guidelines, but should not be used solely as an indicator of how much water to deliver.

7.6.4. Modeling nutrient solution uptake

Application of existing modeling information to irrigation management in greenhouses remains rudimentary. Decision support tools based on models could considerably improve the control that growers can exert on the plant water status and the concentration of nutrients in the root zone. Such tools would be particularly useful if they could provide an estimation of productivity in relation to water status. Furthermore, the current lack of ion-selective sensors can be overcome by the involvement of models enabling prediction of the ionic concentration in the irrigation effluent. This allows dynamic adjustment of fertiliser injectors to modify this solution with the exact amount of each fertiliser needed to create an optimal irrigation solution.

7.7. Future irrigation perspectives

In the same way that irrigation strategies are tied to particular technologies, irrigation systems are likely to change as new hydroponic systems are developed. While current hydroponic systems implement root zone conditions that have water, oxygen and nutrition at adequate levels, in the future such systems will strive to simultaneously optimize all root zone variables. Considerable research on the effects of each variable as well as on their interactions is needed. Currently all irrigation systems dynamically control water status; in the future we should be able to simultaneously control oxygen and nutrient contents as well.

Another area that is ripe for innovation is sensor technology to automatically monitor the root zone content of O₂, CO₂, ethylene and certain chemical properties (EC, pH). Furthermore, we need sensors to measure the concentrations of specific ions (e.g. nitrate); the currently available selective ion electrodes are not suitable for dynamic in-situ control since they have to be recalibrated frequently. The measurement of moisture content should become less expensive and require less maintenance.

Many emitters have been developed for a large variety of situations. It is anticipated that there will continue to be innovations, particularly in customization and miniaturization. In the future, it should be possible to have emitters that provide customized control over the amount and timing of the irrigation solution provided to individual plants. By combining miniature electronic packages with sensors and emitters, it may be possible for the emitter to provide exactly the required amount of irrigation solution to each plant. The technology is already
available to equip such units with radio transmission capability so that they can communicate with a central computer system to identify and sound an alarm for particular problems that may occur. This will also reduce the large amount of waste due to the lack of uniformity that is currently associated with most systems.

While it could be argued that such a sensor/emitter/control package would be very expensive, it should be noted that the price of such units falls dramatically when they are produced in large numbers. At first, such devices would principally be used to grow large expensive specimen plants, followed by plants that are in production for long periods of time (e.g., roses, cucumbers, tomatoes). As millions of such units are mass produced, the price would decline so as to be affordable to virtually all growers, who would in turn use even more.

In the future we may well have a single sensor package that allows the grower to simultaneously determine the presence of nitrate, ammonium, potassium and phosphate, as well as total salinity, pH and moisture tension. Such a sensor would allow the fine-tuning of irrigation systems to optimize both the water and nutrient availability. By miniaturizing such a sensor and combining it with the electronic emitter/sensor unit described above, it would be possible to optimize all irrigation variables for each individual plant in a hydroponically grown crop.

References


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Iera Odos 286, 122 43 Egaleo
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Tel./F.: +30 10-53 150 12
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