Chapter 11

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, 95616 Davis, CA, USA

<u>Abstract:</u> ca. 300 – 400 words (please, add an abstract)

11.1. Introduction

The production systems found in modern greenhouses can be divided into two categories: **soilless** and soil-based. While soil-based production can be found in older operations, the current 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 with soil. This generally involves using little or no soil other than, perhaps, sand or gravel.

In general, hydroponic systems are **soilless** production systems. In this chapter the two terms will be used interchangeably. The public generally thinks of hydroponic systems as being water culture systems, without media; however, most hydroponic systems in commercial production use some sort of substrate to create a matrix that forms the **root zone**. The only thing that all hydroponic systems have in common is that no soil is used. Conversely, all containerized **soilless** production systems (e.g., production **of** potted flowering plant**s**) in use today are hydroponic production systems in that they create an artificial **root zone** that attempts to optimize water availability for the roots. Such production systems consist of**:** (1) the **root zone**, (2) the aerial part of the plants, (3) an irrigation system for **the supply of a** nutrient solution to the **root zone**, and (4) a drainage system for dealing with run-off from the **root zone**. While this chapter focus**es on** the irrigation system, it should be noted that this is tightly linked to the exact nature of the **root zone** and the physio-chemical environment that is maintained there.

While the substrate in such **a** system is not consumed by the plants, some of the gas and liquids are. In hydroponic systems the liquids consist of water in which ions and gases are dissolved. This liquid is termed the nutrient solution; it is the primary function of the irrigation system to deliver this solution to the plants in an optimal manner. The practice of delivering fertilizer ions along with water is termed fertigation. The formulation of such solutions is handled elsewhere in this book (**Chapter 5**).

While the term **"**nutrient solution**"** refers to the irrigation solution that is applied to the **root zone**, once this liquid reaches the **root zone** and mingles with liquids that are already present, the result is called the **"**substrate solution**"**. This solution is continually changing as the plants and microbes use portions of it and discharge compounds into it. It is, in fact, this dynamically-changing liquid that must be managed and optimized through various horticultural practices.

Many types of irrigation systems have been developed and a lot of substrates**,** like gravel, rockwool, sand, perlite, expanded clay or synthetic materials**,** are used.

Irrigation management in hydroponics is more sensitive **than in** soil-based systems. Compared to **the** soil, hydroponic systems typically have **a** much smaller root zone volume, greater water-holding capacity, more available water, lower moisture tension, greater hydraulic conductivity, and **a** higher dissolved oxygen concentration **in** the irrigation solution. Typically soil contains a multitude of **substances** that act **as a** buffer **to** chemical changes. In some hydroponics 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 **as pointed out by Sonneveld, 1981**. In the same way**,** the water and nutrient capacity **are** drastically reduced. Consequently fertigation is **probably the** most important management factor through which growers can control plant growth, yield and quality **in hydroponics** (Schroeder, 1994; Bar-Yosef, 1999; Wever et al., 2000).

Hydroponics generally requires on-demand irrigation. Plant water requirements can be determined either directly or indirectly. The most common is **an** indirect way **in which** plant status is correlated with the environment (temperature, humidity, **vapour** pressure deficit or, radiation). Direct measurements with sensors (e.g. **a** stem flow gauge) **are** now sufficiently developed and capable of successfully monitoring the plant. Future plant monitoring and control systems will combine plant features as well as its environment and provide closed–loop control (Giacomelli, 1998).

Providing the optimal amount of nutrient solution, while maintaining an ideal level of oxygen in the root zone, requires a suitable irrigation system. Such a system should operate efficiently and dependably and deliver a uniform amount of liquid to all plants so as to obtain uniformly high-quality products. The irrigation system includes distribution components which interact with the substrate and environment. The irrigation system and **its** control minimize over-watering and water stress of plants. However, optimization has not been achieved **yet** due to the inaccuracy of control systems (sensors), irrigation systems, or interactions between **the** plant and **its** environment.

The objective of this chapter is to provide principles and basic knowledge of irrigation systems and their control with respect to crop growth and production. **T**he basic strategy of irrigation, components of irrigation systems, methods for optimization of irrigation systems, and methods of controlling the system **are discussed**.

11.2. Irrigation in hydroponics

There are two points of view to irrigation in hydroponics that **provide** the foundation for making such systems work efficiently. One of these sees the root zone as a reservoir that must be refilled each time a certain level of depletion has occurred. The other viewpoint is to treat the entire system as a conduit of materials from a source to the root surface of the plants. In optimizing irrigation it is important to understand both of these two aspects of the system**.**

It is commonly understood that the **root zone** is a reservoir or storage compartment where a number of important ingredients for plant growth and survival are stored. Once any of the ingredients becomes depleted, irrigation needs to occur to re-supply this ingredient. 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. In addition to its function as a reservoir, the **root zone** must also act as **a** conduit for these same materials. Elements that are near the root surface are available to the plant**,** and the roots use active processes to move materials 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 within the root zone from **sites** of greater concentration to **those** of lower concentration. If this conduction does not work at a suitable rate, then 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 replac**e it** with **fresh,** optimally formulated nutrient solution.

It should be noted that the plant removes water and ions selectively and at different rates**,** so it is possible for more water to **be** use**d** and ions **left** behind (or vice versa). This can cause salts to build up in the root zone, and this build-up must be avoided as it is deleterious to plant growth. If low concentrations of ions are provided, then 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 in storage in the root zone and (2) they provide mass flow of such materials through the conduit. Since mass flow is much faster **in** moving materials than diffusion processes, frequent irrigation can be used to move needed elements to the root surface. In hydroponic systems this type of control is feasible since all variables can be controlled; in soil-based systems this is not **possible** since the roots would become water logged and starved of oxygen. **I**n systems where the drainage water is re-circulated, the reservoir is effectively extended into the tank where such water is collected.

The large increase of yields in hydroponics over that **in** soil are due to several factors**, of which i**rrigation management is one of the **most important**. Other factors are the higher efficiency **of** water use, because water **is** appli**ed** direct**ly** to the roots, reduced evaporation and avoidance of water stress. **However**, hydroponic irrigation management requires an accurate supply and dynamic control **because of the** low water holding capacity and restricted availability of nutrients due to the limited volume of substrates. In present horticultural practice the hydraulic circumstances in the root environment are such that plants are grown at very high pressure heads. The reason for this is that plants are grown in low volume substrates to decrease **the** cost and handling of growing medi**a, so** high irrigation frequencies are used.

Plant growth in hydroponics is related to water, nutrient and oxygen supply. Water and nutrient supply can be regulated by the nutrient solution together with the irrigation system and the irrigation frequency. In the same way**,** differences in O_2, CO_2 and ethylene in the root zone have been shown to be influenced by **the** growing medium and irrigation (Schwarz, 1995; Strojny et al., 1998).

The root zone in hydroponics is created for plant growth, water, nutrient and oxygen supply only, **but** not for **the** support of **the** plants. In most hydroponics **systems**, plants need support by special devices**,** like wires, trays or nets. **T**he irrigation system should adjust **the dose a**ccording to the **requirement of the** different hydroponic systems **and** substrates. Comparable high yields can be achieved as long as irrigation and fertilization are optimized for the specific substrate.

A number of authors describe a surplus of nutrient solution **of** between 20 and 50% in practice in hydroponics. In an open irrigation system, each surplus leads to losses of water and nutrients. Closed irrigation systems reduc**e the** surplus, **but** need expensive disinfection of the solution.

Adequate aeration of the root zone is achieved. Roots need air, **particularly** oxygen, for respiration. Both porous substrate and controlled irrigation result in good air exchange **with**in the root zone. In addition, a nutrient solution enriched with dissolved oxygen can improve plant growth and the stability of the system.

In short, hydroponics needs relevant investment, higher knowledge **on the part** of the growers and improved cultural practices.

11.3. Water quantity and quality

In virtually all plant production systems, access to clean water is essential **for the** produc**tion of** high quality horticultural products. While this is always of great importance, it **may** become even more **crucial in** instances of natural or politically-imposed water shortage. This results in increasing cost**s** for water or water purification**, which i**n hydroponic production is of particular importance, **since** this type of production is not possible without it.

11.3.1. 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 on the plants. Under high humidity, low light and temperature, the rate of water usage can be almost zero. Any production system must have the irrigation system 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., summer conditions), 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 needs of the plants and will result in production losses during the summer.

Maximum water-use figures have been reported for various crops. At the low end are cool-climate cropping systems consisting of plants that are harvested once with **an** annual water **consumption** as low as 8,600 m^3 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 m^3 ha^{-1}. Other crops grown at low temperatures, and mixed crops will use 10,000 m^3 ha^{-1} **per** year. These figures are based on average transpiration rates, increas**ed by** ca. 30% for drainage. The drip irrigation system must **have the** capacity to supply the plants under the conditions that represent the highest water consumption per day plus an overcapacity of **at least** 30% for drain**age** water. The water consumption of plants is linked to **the** stage **of plant growth** (size), solar radiation, relative humidity, and air movement. **An** example **of w**ater requirement for cucumber is shown in Table 1.

11.3.2. 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 in improving 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. **W**ater 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 the main** quality parameters, **particularly** salinity, alkalinity and specific ion toxicity **due to excessive concentrations of** sodium, **sulphates** and chloride.

In irrigation systems **with** small orifices for the emission of the irrigation solution to the plants, high water quality is required so as to avoid problems **arising from** clogged emitters. For **both** open and closed systems optimal values of water quality exist (Table 2). If the water quality needs improvement**,** treatments **such as filtration** or reverse osmosis **may be** necessary.

Salinity is one of the key characteristics that are generally cited in conjunction with water quality **and represents** a measure of all the salts that are present. While 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 of greater values has been found to be beneficial. The key to this **situation** is that the ions which caus**e** high EC readings **should** be **ones** that the plant can use as nutrients, and **their concentrations** to be non-toxic. The use of saline water for hydroponics has also 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 at the expense of yield. The **utilization** of waste water (sewage) **that is** rich in nutrients has also been shown to have some promise (Schwarz, 1995). **However, there are** problem**s arising from** the organic solids **included in it**, **which pose a** potential risk for human health, particularly **when the waste water is used for** production **of edible plants**.

11.4. Root environment in hydroponics

One major objective of hydroponics is to ensure a perfect exchange of nutrient solution **i**n the root **zone** so that fresh nutrient solution and oxygen are supplied **as** needed. During summer, when plants have **a** high water consumption, the nutrient solution passes through the substrates a few times per day. In periods with low radiation (**autumn**), water consumption is low and solution exchange is limited. Increasing flow rates result in wet conditions in **the** root zone and subsequent oxygen deficiency. In addition**,** the substrate parameters change at the end of each crop. The porosity decrease**s mainly as a result of the** decomposition of organic substrates **and** increasing root mass. The following topics are focused **on in relation to** the root environment **of** different irrigation and hydroponic systems.

11.4.1. Dissolved oxygen (DO)

Oxygen deficiency 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**,** the elevated water temperatures during summer may lead to oxygen deficiency in the root zone. Oxygen is the final oxidant in a series of enzymatic oxidations, which is **releases** most of the chemical energy needed for root growth from sugars. The dissolved oxygen in **the** nutrient solution has a direct influence on root function (particularly respiration). Oxygen has to be present in the water around the roots. Any deficiency of oxygen depresses root growth and nutrient uptake. For the roots of most plants, reductions of the dissolved oxygen level below 60% **will inhibit** growth. The root tips are killed and growth is stopped if the oxygen level in the nutrient solution is below 2.5 % (Jackson, 1980).

With increasing temperature**,** the amount of oxygen in the water will drop while at the same time the plant's demand for oxygen will increase. Over the same temperature range the plant will increase its demand for oxygen **by** about 4 times. The dissolved oxygen level depends on **the** water temperature. At 10º C there will be 10.93 mg $\mathbf{l}^{-1}$ O_2, at 20º C 8.84 mg $\mathbf{l}^{-1}$ O_2, and at 30º C only 7.53 mg $\mathbf{l}^{-1}$ O_2 at saturation (Vestergaard, 1984). In addition, oxygen is consumed for other purposes such as **the** metabolism **of** micro-organisms.

Depending on the water source, the dissolved oxygen level is about between 20% to 40% of total capacity at saturation. **The oxygen content of the solution will be 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% (Schröder, 1994; Wever et al., 2000).

Generally, the only practical way **by** which oxygen can enter the water is by surface diffusion. The amount of oxygen diffusion into the water depends on the **ratio** of water or substrate surface to the 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 compressed air. More expensive methods to oxygenate the solution are to add chemicals, or pure oxygen under pressure. One of the objectives of irrigation is to stabilize the dissolved oxygen concentration in the hydroponic system.

11.4.2. Oxygen gradient

Hydroponics shows quite different oxygen gradients for design flow techniques and flow rate. Dependent on design, there are 3 different flow techniques: longitudinal, horizontal and vertical flow. To be sure that the roots have the optimal dissolved oxygen level, the oxygen exchange rate must be close to 100%.

In aeroponics, **a** dissolved oxygen level **of almost** 100 % will be easily reached. Deep flow technique (DFT) is based upon oxygen is being dissolved in solution and brought up by circulation. The root system becomes loose, so that solution exchanges **can** take place easily. If DFT is combined with vertical flow**, it** giv**es excellent** control of the root zone, not only for oxygen, but also for **the** transport of waste products (CO_2) away from the roots. The nutrient film technique (NFT) us**es** flow techniques **in** a system with a very thin nutrient film. As the roots grow in**to** the channel**, they** form a mat**, which** function**s as** a barrier **to** the film **making the** flow **a** few centimeters high. Many authors have described (Gisler∅d and Kempton, 1983; Vestergaard, 1984; Goto et al., 1996; Yoshida et al. 1997) a dramatic oxygen gradient along the NFT channel. Dissolved oxygen level**s** drop to 60 % **or** less **by** the end of each channel. The modified "Super NFT" using nozzles for spraying the solution along the channel **ameliorates** this problem.

For most hydroponic **systems** using substrates**,** the oxygen supply chang**es to** a wide **degree** depending on **various** substrate parameters, e.g., **the** water holding capacity**,** porosity and irrigation schedule. Baas et al. (1997) tested growing media **in a** rose **crop**, especially **with respect to** oxygen availability. Roses were propagated in rockwool blocks 6.5 cm high. They found that oxygen stress is minimal and rooting is optimal at a volumetric air content **in** the media **of** between 20 and 25% in the lower 2,75 cm of the rockwool. This corresponds to a volumetric air content **of** between 37 and 42% in the whole block. Rose cuttings rooted and grown in aerated water culture and rockwool under different oxygen conditions have shown significant differences in shoot growth.

Low oxygen conditions have **been shown to** increase root porosity and alcohol dehydrogenase (ADH) activity. By changing plants from aerated to **non**-aerated solution**s,** the ADH activity increased. After 9 days, the ADH **of these** plants **was lower than in those** which has been in **no**n-aerated solution all **the** time. This indicates **that** roses are able to adapt to **unfavourable** oxygen conditions for a short time. **A**t the same time**,** root growth was reduced by 50% while shoot growth was little affected. Plants formed more primary roots and less seminal roots under oxygen deficiency (Gislerød et al., 1997). This is in agreement with other results where plants formed more secondary and adventitious roots. In addition the nutrient uptake of N, K and Ca is significantly lower **in** plants grown under oxygen stress, which can influence shoot growth and **the** quality of products as well. Cucumber grown **for** 10 days under low oxygen conditions did not **exhibit a** difference in shoot growth (Yos**h**ida et al., 1997)

However, it can be **p**resumed that suboptimal irrigation or irrigation control**,** with high drain**age** values or high water capacities 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) describe**d** plant plane hydroponic**s** (PPH) as a thin layer system with fleece mats as substrate. The oxygen level determined in solution increased **by** up to 95% (on average 80%) along the horizontal flow due to the good surface diffusion of oxygen.

11.4.3. Gas exchange

Wever et al. (2000) measured gas composition in growing media, focussing mainly on oxygen (O_2), carbon dioxide (CO_2) and ethylene (C_2H_4). The model system consisted of a cylinder of 0.20 m height filled with ca. 3.5 l growing medium. O_2 levels as low as 5.4 %, CO_2 as high as 8.7 % and C_2H_4 as high as 8.3 x 10^{-5} % were measured. From the top **of the cylinder** to the bottom**,** the O_2 concentration decreased and the CO_2 and C_2H_4 concentrations increased. The gradients for O_2 and CO_2 concentrations over the height of the **cylinder** were less then 0 - 0.6 % for most media, except rockwool where an average difference of 4 % O_2 was found between top and bottom. For C_2H_4, the differences between top and bottom were relatively more extreme (up to 0.9 x 10^{-5} % C_2H_4), **and even higher in** rockwool (0.9 to 2.5 x 10^{-5} % C_2H_4). O_2 contents were lowest and the CO_2 and C_2H_4 were highest **in** peat and **in the** bottom layer of rockwool. There appears to be a relation**ship** 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 show**n** similar high CO_2-concentration in the gas of the root zone**, a**n average CO_2 concentration of 2800 ppm **being** measured for cucumber and 2700 ppm for tomato (Schroeder, 1994**)**. The peaks of 6900 ppm and 6000 ppm are explained by higher biological activity due to higher temperature and PAR during this grow**th** period. Because roots of plants and micro-organisms consume O_2 and produce CO_2, the root zone must be **regarded** as a living community.

Carbon dioxide varies considerably. Concentrations occurring in the soil atmosphere range from 1**,**000 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. Similar values of CO_2, produced by microbial activity, differ from 50 to 80% (Trolldendier, 1972; Martin, 1977; Schröder, 1994). Root reactions to large concentrations of CO_2 are less definable than for a low concentration of oxygen. CO_2 concentration**s** that ha**ve** been **reported to** inhibit root growth differ greatly, and it is difficult to compare the experimental findings with field conditions. High concentration of CO_2 (10**,**000 ppm) can partially inhibit while 1000 ppm alone may stimulate root growth (Geisler, 1963; Radin and Loomis, 1969).

In applying these findings, it must be realized that the methods available for determining CO_2 do not allow measurement of concentrations at the immediate root surface, but mainly present concentrations **in** the pores or air in 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 **too high** CO_2 concentration**s can be better** tolerated by roots in hydroponics if **sufficient dissolved** oxygen is available at the same time (Jackson, 1980).

Besides water, oxygen and carbon dioxide may be considered **to be** modifying factors, **since** they are correlated with the water content. Increasing **the** water content **of** soil and substrates cause**s** increasing CO_2 and decreasing oxygen **concentrations**.

Adequate substrate aeration is of **crucial** importance for plants grown in media. This indicates the need to obtain quantitative information on **the** gas composition **of the** media in order to be able to relate plant performance to determined concentrations. To do **this**, a good testing method must be developed to measure gas composition in growing media. Apart from differences in O_2, CO_2 and ethylene **concentrations** have been shown to be influenced by growing medi**a** and irrigation (Strojny **et al.**, 1998). **S**imple, accurate and inexpensive systems are **required with** which the gas composition in **the** growing media can be measured and the determined gas composition **can be related** to water content of the media and root function. Oxygen supply**,** however**,** is considered to be mainly determined by the physical characteristics of the grow**th** medium. The volumetric air content is important, since it is expected to be directly related to oxygen diffusion rates (Bunt, 1991).

In substrates**,** effective transport of water is important to provide roots with water and nutrients. Insufficient transport of water due to unsaturated hydraulic conductivity and hysteresis may lead to dry areas and reduced use of substrates by the roots (Wever et al., 1997). This is important for sub-irrigation. Furthermore the water capacity of the substrate must be known. In **the** case of a high water capacity and no consumption by **the** plants, the solution cannot be changed in the root zone **as** desired. Then**,** only with a fresh solution **can** the values be changed, but in this case, any supply **of** solution leads directly to over-watering and oxygen shortage.

11.5. Irrigation systems

Generally, irrigation systems deliver water to the plants. Hydroponic irrigation systems **in particular, deliver** nutrient solution to the growing media, if used, or direct to the roots of **the** plants. Thus, in the NFT system, plants are placed in sloped troughs where nutrient solution continuously flows down the troughs in a thin film passing **over** the roots. Various types of irrigation system exist and are used in greenhouse production.

11.5.1. 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 such systems use 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** a number of plants **within each** group **is** irrigated at the same time. Each circuit must be designed to **meet** the following criteria.

11.5.1.1. Capacity

A fundamental criterion for an irrigation circuit is that it must have the capacity to handle the demand placed upon it. Typically**,** each emitter has a particular flow rate that it is designed to deliver. If the sum of all the flow rates of the emitters in the system exceed the capacity of the system, then many of the emitters will not operate properly. In the **instance**, some emitters will not deliver any water**,** while others will operate at **a** reduced level. The result is that some plants will not receive **sufficient amounts of** nutrient solution.

It should be noted that **the operation of** all circuits simultaneously is generally not **necessary**. However, in large operations there may be hundreds of circuits and on a hot summer day, many may need to operate simultaneously. It is important for the grower to understand the maximum demand **for** water that may occur and the pumping capacity **required** to accomplish this, even under **a** worst-case scenario.

It should also be noted that if each irrigation circuit is so large as to **saturate** the level that is technically feasible in terms of capacity, then this imposes a significant burden on the grower**, who** can **therefore** irrigate only one circuit at a time. Most growers prefer to install a pressure regulator at each circuit and design each circuit to be smaller (sized according to the pressure regulator). This then allows the grower to selectively combine circuits that are irrigated simultaneously.

11.5.1.2. Uniformity

In commercial production, uniformity is one of the most important characteristics. 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 are either substandard or delayed. The type of irrigation system affects uniformity. The high degree of nutrient application control is the main advantage **of** drip irrigation, due to the large number of emitters per area with **a** high uniformity **of** discharge. **An** application efficiency of 90% can easily be achieved**,** compared with 60-80% for sprinklers. The manufacturing variation of new emitters has a coefficient of variation **of** less than 5%, resulting in a uniformity coefficient of more than 96% (Dasberg and Or, 1999). These figures **apply only to** new emitters and installations. In **practice,** uniformity decreas**es** over time. Even nutrient solution distribution around each emitter is not uniform depending on **the** substrate, system and other parameters. It should be noted that it is impossible to achieve perfect uniformity.

The uniformity of irrigation depends on the technical layout**, which** is a main condition for any control system and water efficiency. **D**ifferent technical layout**s** depend on **the** crops and growing systems. Some crops are grown in rows in containers or slabs**,** such as fruit**,** vegetables or roses. The drip irrigation is situated along each single row. Other plants**,** like cut flowers such as carnations or freesia**,** are grown in beds (1 - 1.5 m wide) Beds are filled with substrate **and** the drip irrigation is installed for the whole bed**,** not for each single plant. Plants, which grow span-wide, like lettuce or radish, need a system covering the whole greenhouse area to which the irrigation system must be adapted.

Technical layout of irrigation systems include**:**

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

(2) **the delivery system**. Basic equipment of delivery systems consist 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 end. The main problems are the time delay and the fall in pressure resulting from increasing distance from the pump. Compari**son of** the standard system with the "Tichelmann" layout (Gieling et al., 1995), which has been used for heat technology, has shown that these problems c**an** be solved. This is very important for irrigation strategies in **the event** of chang**es in** the nutrient composition or EC value depending on radiation during the day. With the "Tichelmann" layout**,** the new solution is supplied **within** seconds **to** each plant. So the grower, and/or the irrigation control, can react much faster to control parameters, like

climate conditions. This allow**s** 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 climate gradients **within** the greenhouse, due to direction radiation, e.g., in Northern Europe there is a higher water consumption by plants in the south and west directions.

(3) In closed systems, a drainage system and reservoir is required to collect the drain**age** solution for recirculation. Drain**age** water should be disinfected and filtered before reuse.

(4) Different water treatment technologies, like UV-treatment, heat, or slow sand filters are common. New biological methods using beneficial micro-organisms are **under** discussion.

11.5.2. Type of system

Various types of irrigation systems are used in greenhouse production. Lieth (1996) grouped the system**s** by level of automation and **whether** the flow of irrigation solution to the plants **is** in overhead, surface, subsurface or sub-irrigation systems. 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 necessary due to the limited volume of substrate. 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.

Mist and fog systems dispense water to the air and should be used for climate control and not for water supply **to the** plants. High-pressure fog systems dispense small water droplets that evaporate in the air before reaching the plant.

Boom systems consist **of** a rig that moves overhead above the plants allowing uniform irrigation (Lieth, 1996). Boom systems are used for pot plants and for plant propagation.

11.5.2.1. 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) at a low discharge rate (1-30 l h^{-1} per emitter). In the literature, "trickle" is used interchangeably with "drip" (Dasberg and Or, 1999).

The most popular system used in hydroponics is low-pressure drip irrigation. I**f 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 water efficiency. Drip irrigation systems are designed for low volume delivery of water. All systems use 1/2-inch polyethylene (PE) pipes to supply a header pipe. Smaller pipe**s** of ¼-**,** and 1/8-inch vinyl pipes (spaghetti tubing)**,** serve for all lead-in tubes and lateral lines. For the main line to and from the nutrient solution unit **in** more permanent situations**,** buried PVC pipes **are** generally use**d**.

Emitters.

New emitters**,** like punch–in emitters, emitters using a membrane, or in-line emitters**,** have been developed. The emitters can be inserted directly in a PE-pipe after punching a whole into it. They have an inlet barb at their base so that they won't pop back out. Some emitters have self-piercing inlet barbs to punch their own hole. Emitters come in regular and pressure compensation forms (**they** need a certain pressure for water release) to provide leaks. The effect is that all drippers start at the same moment (at the same pressure) and **stop on** the emptying of the pipe end. Leaching at one spot does **not** take place (Van Os, 1998).

Emitters are available in a wide range of shapes and capacities. Most modern emitters use turbulent flow design (pressure-compensation), and keep dirt particles in motion so **that** they cannot settle until they **have left** the emitter. Th**is** 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 are the easiest and a low-price option. They can be used for permanent locations as surface or sub-irrigation systems. **A** negative **aspect** is **that** due to the numerous pores situated irregularly, inner water pressure control is not possible. As **a** result, porous pipes lose pressure towards the end of each length, and this leads to uneven water delivery and empty pipes after watering. Also, **they** can be used only on flat ground.

Punch-in emitters

Three main types 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**,** keep**ing** the surface of the substrate almost dry and **the** roots moist. The flow rate (e.g., 2 l h^{-1}) can be changed by different types, 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. Like punch-in emitters, they are inserted into the water line according to need, like emitter lines because the**y enter** right into the line and not its periphery. Most are designed for 1/4-inch tubing or 1/8-inch vinyl tubing. They have a more limited range of flow rates than drip emitters.

Misters are most**ly** used for specialized nurseries growing high humidity plants. Misters 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 separate from other emitters.

Emitter lines or pipes

Emitter lines incorporate equally space**d** emitters directly into ½-inch pipe. Water runs through the lines **and** some drips out. The emitters are preinstalled, e.g., at 15, 20, 25 or 30 cm spacing and are rated to dispense different volumes of water. Emitter lines should be use**d with** pressure-compensating emitters using the turbulent flow design described, especially for a long line (20 - 200 m), and even a small slope. Sold in rolls, emitter lines can be easily 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.

Micro-sprinkler heads or spray emitters

Micro sprinkler heads **occupy a** place between micro and sprinkler irrigation. These mini-sprinklers use low pressure and narrow diameter pipes to apply water in a spray as sprinklers. They are not so efficient as drip emitters, since they lose some water **due** to evaporation. They can spray a full circle or increments of it. Most 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 leaves dry.

11.5.2.2. Subsurface or sub-irrigation systems

Subsurface systems bring 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 build up in the upper portion of the root zone. This occurs because the nutrient solution enters at the bottom, and water evaporates from the substrate surface. Overhead irrigation is needed for leaching the salts **and** to prevent root damage. 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). While capillary mats and troughs are mainly used for pot plants, ebb/flood systems are used for hydroponically- grown young plant**s**, especially fruit vegetables using trays or benches, as well as flooded floors.

11.5.3. Layout of irrigation systems in hydroponics

Generally, hydroponic irrigation systems are grouped in**to** open, semi-closed, and closed fertigation systems (Herbold, 1995). Hydroponics without **a** substrate**,** like NFT, **a**eroponic**s**, or ebb-flood systems**,** are closed systems.

11.5.3.1. Open systems

Open systems are hydroponics without recirculation of drain**age** water. The **percent** volume of drain**age solution** depends on the irrigation system used, irrigation control, and **the** substrate buffer. Drain**age** can **amount to** between 0 and 50% of **the** supplied nutrient solution. Maintaining the EC in substrates or solution within boundaries requires drain**age** rates of 30% or more. **However**, environmental pollution **due to** the leaching of water **and** fertilizer**s is** of concern.

11.5.3.2. Closed systems

Closed systems were developed **a**s a consequence of environmental pollution **because they enable** reuse **of** the drain**age** solution **in** long-term crop**s. However,** some unsolved problems **still** exist. Re-use of drain**age** water leads to **an** accumulation of nutrients, other ions, and **hence**

to **a** changing nutrient ratio. To prevent this problem, expensive **systems** using liquid fertilizer with ion-sensitive sensors and control units are necessary. **Currently,** one of the main problem**s** is the spread of root diseases **via the** recirculat**ing** solution. **D**isinfection of the re-circulating nutrient solution is a must for long-term crops to avoid an outbreak of root diseases. Existing sterilization systems are not always appli**cable**, mainly because of high cost**s**. Developments in disinfection equipment focus on the removal of pathogens without complete sterilization of the solution (Van Os, 1998). Nevertheless, only the pathogen of the drain**age** solution can be removed. Currently, no possibility exists to control the root zone directly, even in **the** case of new root diseases. The closed system is in front of and behind the disinfection **device** in-sterile.

On the other hand, many growers use their substrates for several years without any disinfection, or decline **in** successive crops due to diseases. Other studies describe **fewer** fungal diseases in closed systems than in open **ones**. One explanation is that in a more natural root environment, diseases are controlled by beneficial micro-organisms.

Postma and van Elsas (2000) observed that cucumbers in rockwool after sterilization, **became** sicker after being inoculated with *Pythium* than **those grown in** rockwool without sterilization. Disease suppression was associated with the presence of Actinomycetes in the drain**age** water. This suggest**s** that there may be a possibility of adding beneficial micro-organisms **(**like *Bacillus subtilis* products**)** to the root zone**.** In closed systems, organic compounds and micro-organism**s** 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, **or** in the solution by micro-organisms **which** degrad**e** plant growth-inhibitory organic compounds, **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 present a living community of micro-organisms promoting plant growth and keeping closed systems in a biological balance.

Van Os (1998) recognized, growers who grow crops (tomato, cucumber, sweet pepper, roses or gerbera) which can be economically grown on (closed) soilless systems, choose the cheapest system for a short term, preferring the low investments to low annual cost. For the other crops (lettuce, radish, chrysanthemum carnation, freesia) there are no economically feasible system.

11.5.3.3. Semi-closed systems

Semi-closed systems are technically closed systems**, which** are opened on occasion to flush out the drain**age** solution, or to change the entire solution in the system. For existing problems in closed systems, this is a step to decrease water and nutrient leaching, but not to prevent. Zero-leach**ing** systems are used to indicated no, or very minimal drainage from a container after irrigation. Irrigation control via tensiometers allows saturation of substrates without leaching**, but a** high volume **and uniformity** of substrate **is required**. This is achieved by placing tensiometers in representative pots or places in the system. Otherwise, this system results in increased soluble salts in the substrate.

11.6. 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 be carefully optimized to allow **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**,** yet may be adequate 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 to touch-up or to correct 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 to have every individual plant result in **a** marketable product. Thus the emitter that delivers the least amount of water governs the irrigation duration of the entire circuit. It is not uncommon to find irrigation systems where the slowest emitter is delivering water at **a rate of only** 30% of the fastest emitter. This means that a large amount of waste must occur in such a system, regardless of the type of irrigation control that is used.

11.6.1. 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 **intervals** between irrigation **applications** are fixed at some duration (e.g. one day or one hour) that is adjusted seasonally. The duration of the individual irrigation event is set by trial-and error to **ensure** that **each** irrigation **circle** delivers the **necessary** amount of nutrient solution**,** plus an additional 20 to 30%. 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 results in many periods of time whe**n** the plants are at sub-optimal conditions**,** while at the same time using much larger amounts of irrigation solution than 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 fertilizer) and the regulatory pressures to reduce waste water increase.

Scheduled irrigation generally considers the following two variables: **(a)** frequency of irrigation (a.k.a. number of irrigation **applications** per day/week) **and (b) the** duration of each irrigation event.

11.6.1.1. Current standards

Growers **who use** computer-monitored devices have accurate and dynamic control over the availability of the nutrient solution. Initially, hydroponics was without substrate and had continuous irrigation, e.g., **by** NFT**, to** ensure the requirements of plants by permanent flow rates. In this case, only the root mat contains a small amount of residual moisture should the flow of solution be interrupted. More recently, however, hydroponics uses substrates and **intermittent** irrigation **applications**. **For instance, the use of** rockwool has been widely adopted for **the cultivation of greenhouse** crops. Crops **can** tolerate being over watered, there is generally a reservoir of water and nutrients **which** depends on the **physical properties of the** substrate**,** and the system can readily be controlled. Although control of irrigation is crucial in determining crop yields**, t**here is still some disagreement about **the** frequency and volume of nutrient solution to be applied**,** and even whether tomato plants grown in rockwool should be irrigated at night (Cockshull, 1998).

Growers have to make decisions when to start and stop irrigation. **Hence**, they have to **choose** either **to** give small amounts of nutrient solutions 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** result**s** in more drainage and drier substrates. Descriptions range from wet, medium, to dry regimes.

The ‘optimal’ irrigation schedule is still **under** discussion and each grower follow**s** some basic knowledge **in combination with his personal** experience. Research on water and nutrient supply, **as well as on** the strategies **involved in it,** focus on **a** more efficient use of water and the avoidance of nutrient losses. Therefore, the plant requirements and all **the related** influencing factors must be studied and understood.

In practice, growers control the supply of nutrient solution **using suitable** computer **programs** by calculating the amount of water needed for transpiration rates. Irrigation intervals depend on the integration of solar radiation plus an extra amount for drainage (e.g. 30%). The drain**age** is needed to flush excessive nutrients through the substrate and to compensate for variations in water supply, **which** depend on the uniformity level of the system (emitters) and/or **differences in** nutrient solution uptake **by** each single plant **due to variability of** transpiration **rates** within the greenhouse.

11.6.1.2. Uptake of nutrient solution

The results of numerous authors show th**at** differences in nutrient solution uptake by the plant depend on many factors**, including for example t**emperature in the root zone**.** When root temperature increased from 14 to 16º C, the daily uptake of water by a tomato plant increased by 30%**,** with a proportional increase **in** Ca **uptake**. In comparison, to N, K and Mg (21 -24% increase), the uptake of Ca and P (45% and 64%) was more sensitive to changes in this range of temperature (Adams, 1989). However, improvement of the 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 27º C**,** with the ambient temperature **maintained** at about 13º C, both yield and quality of tomatoes was reduced. **When** the ambient temperature **was** 16º C, there was a slight benefit. A root temperature of 15 -18º C was recommended before picking**,** and 25º C during picking**,** for tomato (Graves, 1986). On the other hand, when root temperature increased from 8 to 17º C **in crops of** smaller plants like lettuce**,** the yield increased, even when the ambient temperature was only 8º C.

Differences in **the** transpiration rates **of** cucumber, rang**ing** 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** reduc**ed**.

An irrigation model was validated for **a** long-season tomato crop based on solar radiation and inside saturation deficit for the rockwool system and NFT. The plants used 10% more solution during April **and** 31 % more during May, June and July. By September, crop water use exceeded the model estimate by 20%. The same trend occurred in rockwool**,** but the crop used 10 % less water than **in** NFT grown crops (Hamer, 1998).

Cucumber roots grown in oxygen deficient solution showed a **reduction in** solution uptake **that** was proportion**al** to **the** decrease in oxygen. Leaf area, fresh weight and dry matter decreased at lower oxygen availability, while stem length and number of leaves were scarcely affected **over** 10 days. These facts suggest that **the** membrane permeability of root cells is reduced at lower oxygen level 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^{-1} dry matter for PPH and NFT, respectively. These values are in 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** economical**ly relevant to know the** specific amount of water consumed to produce one kg of fruit fresh weight**,** since the cost for water is balanced by the money obtained for the product. For **the** production of one kg of fruit**,** 27.1 l and 36.7 l **of water** had to be applied in the PPH and NFT system**s**, respectively. Further results showed that as water application rates are higher in NFT, the coefficient of transpiration is higher compared to PPH**, which** receiv**es** less water. The effects of the hydroponic system**s could not** be separated from the effect of water application rates, as both were different in the experiment. However, the differences measured suggest that the efficiency of water use by the plant might be strongly influenced depending on either variable or **a** combination of both.

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-level. At 6 dS m^{-1}**,** yield was reduced **by** 50% compared with **that obtained at** 1 dS m^{-1}. Water uptake was also reduced **at** higher EC-level**s** independentl**y** of related parameters**,** like leaf area index. At 9 dS m^{-1}**,** water uptake was reduced **by** 60% compared with 1 dS m^{-1}, due to 20% less 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 has a direct effect o**n** water uptake due to **the** transpiration rates of plants. Plants grown under optimal humidity conditions show well-developed leaves and consequently a high LAI. Plants grown under sub-optimal, mostly high VPD for a long time have **a** reduce**d** lea**f** size and a low LAI, a response that adversely affects yield and quality**.** In addition, the roots will be insufficiently supplied with assimilates **from the leaves,** due to permanent VPD stress**, and c**onsequently roots show a lower nutrient and water uptake.

Nevertheless, root activity and/or influx of water and nutrients are important (Schwarz et al. 1996). Studies **with** cucumbers in rockwool and polyester fleece substrates showed that root dry mass was 10 times higher in rockwool than in polyester fleece. Even the root distribution and **appearance of the root** system **were** quite different in the **two** substrates. It was observed that root systems in polyester fleece were fine and had **significantly** more white root tips. The differences in root mass result from different physical parameters of **the** substrates. It can be concluded, that a smaller root system in polyester fleece with the same influx of water and nutrients is more efficient than in rockwool, **since** no significant differences in yield and quality **were detected** (Schröder and Förster, 2000).

11.6.1.3. Interaction between irrigation schedules and plant growth

Irrigation control ensures that the nutrient solution supply matches plant requirements at all times**, b**ut **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, **there has to be a** physiological balance between vegetative and generative growth. Plant treatments are necessary until the 15^{th} 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 sinks**,** like plant **apex**, flower, fruit and finally roots. Controlled watering **contributes to the** achieve**ment of a** desirable balance between the 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**,** to reduce the expansion of young leaves. Competition for assimilates is then in **favour** of the flower**s** and the 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. **T**he nutrient solution supply is matched **to** the carbon assimilation or growth 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 **treated with the** recommended watering **dosage** (Adams, 1990).

Nowadays, **professional** growers follow various irrigation schedules, depending on **the** type of hydroponic system, substrate or climate. At the least, each grower has his own schedule based on **a** control level and **personal** experience. In addition**,** the schedule can be changed depending on plant development, fruit setting or external influences like market prices, customer behavior or **other** economical **factors**. For these reasons**, professional** growers have to manipulate plant growth by irrigation control. **This** means th**at** 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 and **cannot** be given. Climate and irrigation control must work together for plant control.

To explain the interactive effect of irrigation schedules**,** an example will be given for cucumber in a substrate, **particularly in** 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 drain**age 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 drain**age percentage**, and **an** increase of VPD **which results in** higher transpiration rates. An example for irrigation control is given based on plant stage, time, solar radiation and drain**age**. According **to** the plant stage, water supply is time based, e.g., on two intervals of 100 ml **per** plant **per** hour. Differences due to high radiation will be compensated **for** by the light sum method, developed for **a** full canopy (Lattauschke, 2000). The actual water consumption can be determine**d** 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 0.0003 ml J^{-1} and

R indicates the radiation or light sum in J m^{-2}

The start of irrigation depend**s** on light sums **of** between 40 and 60 J cm^{-2} **in** closed systems and 140 - 180 J cm^{-2} **in** open systems. This results in drain**age** volume**s** of 30% in closed and 15% in open systems, respectively.

If the water requirement **is estimated at** 2 l per plant **per** day, 20 intervals are necessary **if the watering dose amounts to 100 ml**. Even manual starts are advised for irrigation control. **The** EC level can change **in response** to radiation **differences** to optimize the irrigation control (e.g. ± 0.2 dS m^{-1}). **A h**igh EC level is used for low radiation and **a** low EC level for high radiation. Even flow rates can change to control the EC and pH in the substrates.

11.6.1.4. Example of an irrigation schedule

The irrigation of cucumbers should be sub-optimal (water stress) after transplanting **in order to** increase root growth until flower**ing** and fruit set. All fruits should be **removed for** up to 50 cm **so as 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 week**s)** **in order** to set the first and **second** inflorescence**s, o**therwise **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. **S**olution supply follow**s** the higher plant demand due to higher light conditions. Extra irrigation starts over night depend on **the** moisture content of **the** substrate in the morning. 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 s**pecial 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. **T**he early yield was higher by 40 % **and t**he root systems show**ed** more fine roots and **white** root tips. Irrigation during the night depends on the moisture content in the morning. If the radiation during the day is very high, the plants need much more water even in the early night**,** between 6 - 11 p.m. **Thus, 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 d**rainage should be prevented during the night. Irrigation **at** night is advised if the moisture **content of the substrate falls** below 8-10 % in the morning. **A l**ower moisture content leads to quality losses of fruits, or even cracking and drying of roots in the upper substrate layers, otherwise new root growth will be stimulated. But the substrate parameters must be known. **With a** small substrate volume**,** the moisture content decreases much faster than **with** high volume substrates. High moisture content in the morning leads to oxygen deficiency and root death**, r**esulting **in** water stress, **which** leads to more generative growth. **Thus,** irrigation control is necessary under low light conditions. A usually radiation graph for a day shows peaks between 12 a.m. and 3 p.m. The temperature graph shows peaks between 2 and 5 p.m. **The s**et point for light sum starts should b**e** high (e.g., 150 J cm^{-2})**. D**rainage **should be** about 15% after 3 p.m. and **solution volume** higher, but **at fewer** intervals **and levels** of 120 to 180 ml/emitter and plant. During **autumn**, when light **decreases,** the moisture content should follow the light reduc**tion** (Lattauschke, 2000)

11.6.2. 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 that we need to control through irrigation.

All available 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 consist 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 where the applied irrigation solution consists of a nutrient solution.

Tensiometers are sensors that do not have this disadvantage. These devices consist of a tube with a ceramic tip at the lower end and a pressure-sensing device at the other end. They can be used to measure the moisture tension at some location in the root zone. (Some more information on the operation principle of tensiometers, or at least a reference to another literature source would be welcome).

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 generally 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 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 losses due to water stress, this would mean placing the sensor **into the root zone of** one of the larger plants, in a location **exposed to** more sun and air movement**s** 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** that use electrical properties are frequently affected by ions (fertilizer) 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 system**s**.

It should be noted that of the sensors that are **currently** available all deal with the root zone as a reservoir and none measure any aspect of its role as a conduit. This is an area where future innovation would prove very useful to hydroponics**,** since this is a key area **in which** hydroponcis differ from other agricultural systems. One exception is that it is possible to relate the hydraulic conductivity to moisture tension (Raviv et al., 2000)**, b**ut this requires calibration for each substrate. Although this might be a burden, it could be useful in modifying irrigation tension set-points. For example, while Lieth et al. (please complete) have shown that ideal high and low tension set-points for various media are 5 and 1 kPa, recent work by Raviv et al. (2000) showed that differences in **the** hydraulic conductivity of two different systems suggested that the set-points should be shifted to different values so as to keep the hydraulic conductivity at functionally feasible levels.

With the above information one can implement a sensor-based irrigation system as follows**,** assum**ing** that the irrigation controller is capable of sensor-based control.

The first step is to survey an irrigation circuit to locate plants **that** are representative of the entire crop. Typically the crop is not perfectly uniform and it is important to know where the plants are **located that receive the** least amount of water. Many irrigation circuits require a long time to charge the lines, so that some plants do not **receive** water until long after the first set of plants**.**

As a second step, the following information should be introduced into the sensor system:

high-tension set-point

low-tension set-point

maximum irrigation duration

minimum irrigation duration

supplemental 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. (Lit?) Raviv et al. (2000) noted that saturat**ion** conditions in some media can result in sub-optimal conditions that are not manifested in visible symptoms, suggesting that for such media, low tensions are not ideal. They also showed that hydraulic conductivity can be a problem if the high-tension set-point is too high.

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 idea that this information can be used in irrigation management.

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

Numerous models and mathematical equations have been developed **in this respect**. While it is beyond the scope of this chapter to include the**m** here, it is important to understand some 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 only sensors to measure the environment. Without measurements of the plants, one can at best calculate a potential amount of water consum**ption**. Various researchers are currently developing models that can use the environmental sensor data to calculate changes in leaf area index, but none of these are as yet available for use in commercial settings.

This means that the implementation of model-based methods requires the grower **to** relate an actual irrigation rate to some sort of 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. Thus**,** most greenhouse computer systems do not have such a routine, **but** instead provid**e** 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 provide automatic seasonal adjustment.

In general one needs to be wary of whether one can trust 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** bas**is** o**f** such calculations**,** these particular data would be the last as the plants would suffer severe damage from insufficient irrigation at that one event. 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.

11.6.4. Modeling nutrient solution uptake

A number of models have been developed for **the** transport of water and nutrients in the soil. Despite better control opportunities in **hydroponic systems**, the control of moisture content **in** substrates is far less understood than **in the** soil. This is a consequence of the small root volume, the high frequency **of** watering, and **a** lack of knowledge of the hydraulic properties of the numerous substrates.

Water and nutrients share the **same** transport path in the substrate and in the plants. Water uptake is mainly a passive process. The evaporation power of the environment (temperature, VPD, radiation) cause water to transpire from plant surfaces and results in water flow into the roots and plant.

Nutrient uptake is mainly an active process against a gradient in concentration, so the plants have to spend energy to take up nutrients. Dissolved nutrients in the water stream in turn become part of the water flow potential **driven** by osmosis. The theoretical foundations of these processes are well understood**,** but not the microscopic mechanisms **that occur** in cell membranes from the root to the leaf.

Willigen and Heinen (1998) us**ed** a two-dimensional model of water and nutrient transport in**,** and uptake from**,** a rooting medium **in** a lettuce crop. The main conclusion was that the osmotic effect on water uptake is not important. Crop models for simulation uptake and nutritional effects on growth and development are still in an early phase. Some models already integrate the nitrogen balance in their structure. Although knowledge is limited, it is sufficiently advanced to permit accurate modeling and use model output**s** to manage water application for greenhouse crops.

Climate control operations modify the transpiration of plants **and the inclusion of** these effects is one step **towards the introduction of** models. There is a difference between the amount of water that plants take up and the amount of water providing the highest yield or quality. Application of existing knowledge to irrigation management in greenhouses remains rudimentary. This is an area where simple modeling would considerably improve the control that growers can exert on the plant water status and the concentration of nutrients in the root zone.

Crop transpiration is the main component of the water requirements of plants. Estimation of transpiration **under** variable **c**limate**s** can be used for irrigation control **and** prediction **of** short-term water demands.

Analytical evapotranspiration models have been proposed for crops such as tomato (Stanghellini, 1987), cucumber (Yang et al., 1990), rose and other ornamentals (Baille et al., 1994). They are based on climatic parameters (PAR, VPD, temperature) and crop and physiological parameters (LAI and stomata resistance). The following multiple regression function derived from the Penman-Monteith equation can be used to calculate the evapotranspiration of crops:

$$\mathbf{E} = A\,[1-\exp(-\mathbf{K}\,LAI)]\,\mathbf{G} + B\,LAI\,\mathbf{D}$$

E = crop evapotranspiration

G = inside solar radiation, J $m^{-2}s^{-1}$

D = inside air **vapour** pressure deficit, kPa

K = light attenuation coefficient, related to LAI and radiation

A, B = values of equation parameters which correspond to the statistical fit of experimental data from vegetative growth (A dimensionless, B J $m^{-2}s^{-1}$ kPa^{-1})

The simplified model can be implemented for substrate irrigation control. However its application through**out** the whole crop requires re-calibration of the coefficients at the different stages **of** plant development. Furthermore the model needs validations for each crop.

A water supply calculation model of De Graaf and Esmeier **(**1998) watered the plant**s** according to **their** needs, in accordance **with** commercial practice to leach about 30% of the total supply. The model **was** used to regulate the water supply and calculate the daily water consumption. The basis of the water supply model is **a** simple equation which computes the actual transpiration integrated over time T (mm) according to**:**

$$\mathbf{T = (a_T R + b_T DM)s}$$

R = outside global radiation (J cm^{-2})

DM = "degree minutes" (K min^{-1}), **the** difference between heating pipeline temperature and greenhouse air temperature during a span of one minute integrated over time

s = plant size factor, defined as actual length of the mature plant

a_T = empirical factor (mm cm^{-2} J^{-1})

b_T = empirical factor (mm min K^{-1})

The empirical crop factors may be different for different crops, for cucumber

$a_T = 2.00*10^{-3}$ mm cm^2 J^{-1} and $b_T = 2.2*10^{-5}$ mm min k^{-1}.

The water gifts composed 3 parts according to

Gift = transpiration part + leaching part + correction part

One of the essential characteristics of this control **method** is the measurement of the amount of drain**age** water after each **irrigation cycle**. Every deviation **in** the drain**age** water measured from the desired amount of drainage water (set point) is corrected in the subsequent watering. The amount of drain**age** is measured **in** a cylindrical collection container provided with two electrodes. The distance between the electrodes determine**s** the amount of drain**age** water to be reached before the container **is** emptied. The number of times the container **is** emptied **is** regist**ered** by a pulse-counter. The aim of this model is **to save** energy by minimizing crop transpiration without reducing **quantitative** or qualitative yield.

The management of the root zone can benefit from crop models **concerning** water and nutrient uptake**; moreover,** the efficacy of control **could be also improved** through models **that** can manage the changing requirement**s** of plants.

The development of suitable sensors of water and nutrient status for feedback is necessary.

11.7. 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. Basically**,** hydroponic systems strive to simultaneously optimize the numerous root zone variables. We have not yet achieved this level and further research is needed to develop systems that are more **efficient**.

Two areas that are ripe for innovation are sensor technology and emitter technology.

In the area of sensor technology we hope to have improved sensors for O_2, CO_2, ethylene **and certain** chemical properties (EC, pH)**,** including **the** concentrations of various ions. Currently many of these sensors require frequent calibration or maintenance. **The m**easur**ement 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. **I**n the future**, i**t should be possible to have emitters that provide customized control over the amount and timing of 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 such a unit can even communicate with a central computer system to identify and **sound an** alarm for particular problems that may occur. The effect will be to 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** produc**ed in large numbers.** At first such devices would **principally** be used with 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.

Another area where improved sensor technology can result in great advances in hydroponic irrigation is in sensors to measure all particular ions that may occur in the root zone due to fertilization. Currently, such selective-ion sensors are expensive**,** unreliable **in** the long run **and** requir**e** frequent calibration. In the future we may well have a single sensor package that allows the grower to simultaneously determine the presen**ce** of nitrate, ammonium, potassium and phosphate as well as total salinity and pH. 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.

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Table1: Water consumption **by** cucumber (1.4 plants m^{-2}) in hydroponics (Göhler and Drews, 1989).

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

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

Parameter	**Units**	**Open system**	**Closed system**
EC	dS m^{-1}	< 1.0	< 0.4
pH		5-6	5-6
Total salt content	mg l^{-1}	< 500	<250
HCO3-	mmol l^{-1}	< 10	< 5
Na	mmol l^{-1}	< 3	< 1.3
Cl	mmol l^{-1}	< 2.8	< 1
$S0_4$-S	mmol l^{-1}	< 4.65	< 1.55
Zn	µmol l^{-1}	< 10	< 5
Fe	µmol l^{-1}	< 17.9	< 8
Cu	µmol l^{-1}	-	< 4
Mn	µmol l^{-1}	< 20	< 6
B	µmol l^{-1}	< 40	< 23
Br*	µmol l^{-1}	< 15	< 5

* Bromide sources from former use of methyl bromide

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).

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

Table. 4: Calculation of the amount of nutrient solution

Time	
Start of schedule:	6 a.m. (1 h after sunrise)
Stop of schedule:	8 p.m. (sunset)
Total time:	14 h (840 min)
Time based start:	each 50 min
Total starts by time:	840 min : 50 min = 16.8 (ca. 17 starts)
Amount of solution by time:	17 x 100 ml = 1700 ml per emitter and plant
Radiation:	
Light sum:	300 J cm^2
Light start set point:	60 J cm^2
Light starts:	300 : 60 = 5 starts
Amount of solution by radiation:	5 x 100 ml = 500 ml
Total amount of solution:	1700 + 500 = 2200 ml per emitter (plant) and day