OPTIMISING WATER USE EFFICIENCY FOR CROP PRODUCTION.

By

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

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Abstract

Poor water management and poor water use efficiency (WUE) have been identified as one of the major problems experienced by vegetable growers in most of the developing countries, including South Africa. This poor management and poor utilization of water have led to a drastic decline in the quality and quantity of available water. In South Africa agriculture uses about 50% of available water. Increasing water demand for domestic, industrial and mining uses, may decrease agriculture's share to less than the current 50%, henceforth, better utilization of this resource is imperative. Selection of a good irrigation system can limit water loss considerably. Some irrigation systems have a potential to save more water than others do.

Since irrigation systems affect the WUE of crops, care should be taken when selecting an irrigation system under conditions of limited water quantity. Ebb-and-Flood watering systems have been introduced for effective sub-irrigation and nutrient delivery within closed systems. Such a system was adapted in South Africa, to develop a vegetable production unit for use by families in rural communities, while saving substantial amounts of water. A need to further improve the WUE of this system was subsequently identified. Two studies were conducted at the experimental farm of the University of Stellenbosch (Department of Agronomy). The first trial was conducted under controlled conditions in a glasshouse, and the second under open field conditions.

In the first trial, *Beta vulgaris* (Swiss chard) and *Amaranthus spp.* ('Imbuya') were grown in two root media; gravel and pumice. In addition, an 'Ebb-and-Flood' and a 'Constant level' system were used with nutrient solutions at two electrical (EC) conductivity levels 1.80 and 3.60 mS cm^{-1}. The results of this (2x2x2x2) factorial experiment indicated that a combination of the 'Ebb-and-Flood' system with gravel as a root medium produced the best results at a low EC, when 'imbuya' was used. A high total WUE was found with 'imbuya', (7.35 g L^{-1}) at EC 1.80 mS cm^{-1}compared to a relatively low WUE of 5. 90 g L^{-1} when the 3.60 mS cm^{-1} nutrient solution was used.

In the second trial, 'Imbuya's' foliage dry mass, leaf area and WUE was evaluated under field conditions at the Stellenbosch University experimental farm, during the

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summer of 2002. The experimental farm (33°55'S, 18°52'E) is situated in the cooler coastal wine grape-producing region of South Africa with a relatively high annual winter rainfall. This trial was conducted on an alluvial soil, with clay content of 25% and a pH of 5.9 (KC*l*). A closed 'Ebb-and-Flood' system was compared with two open field irrigation systems ('Drip' and 'Flood') using nutrient solutions at two electrical conductivity levels (1.80 and 3.60 mS cm^{-1}) in all three cases. Foliage dry mass, leaf area as well as WUE was best with 'Drip' irrigation, when a nutrient solution with an electrical conductivity of 3.60 mS cm^{-1} was used. In spite of the fact that additional ground water was available for the soil grown 'Drip' and 'Flood' treatments, the 'Ebb-and-Flood' system outperformed the 'Flood' treatment, especially when the nutrient solution with an EC of 3.6 mS cm^{-1} was used. Insufficient root aeration in the flooded soil could have been a contributing factor. The fact that the 'Ebb-and-Flood' and 'Drip' systems gave the best results when the high EC solution was used to fertigate the plants, may indicate that the plants could have hardened due to the mild EC stress, better preparing them to adapt to the extreme heat that was experienced in the field.

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Uittreksel

Swak bestuur van water en 'n swak water-gebruik-doeltreffendheid (WGD) is as een van die belangrikste probleme geïdentifiseer wat deur groente produsente in die meeste ontwikkelende lande, insluitend Suid-Afrika, ervaar word. Hierdie swak bestuur en benutting van water het daartoe bygedra dat 'n drastiese afname in die kwaliteit asook in die kwantiteit van beskikbare water ervaar word. In Suid-Afrika gebruik die landbou-sektor ongeveer 50% van die beskikbare water. Toenemende water behoeftes vir huisgebruik, industrieë en die mynbou mag hierdie 50% aandeel van die landbou sektor laat krimp. Beter benutting van hierdie skaars hulpbron is dus noodsaaklik. Die keuse van goeie besproeiingsisteme mag waterverliese merkbaar beperk aangesien sekere sisteme se water-besparingspotensiaal beter as ander is.

Aangesien besproeiingstelsels die WGD van gewasse beïnvloed, is spesiale sorg nodig waar 'n besproeiingstelsel onder hierdie toestande van beperkte waterbronne gekies moet word. 'Ebb-en-Vloed' sisteme kan aangewend word om water en voedingselemente van onder in 'n wortelmedium te laat opstoot en in 'n geslote sisteem te laat terugdreineer. So 'n sisteem is in Suid-Afrika ontwikkel waarmee groente vir families in landelike gebiede geproduseer kan word terwyl water bespaar word. 'n Behoefte om die WGD van hierdie produksiesisteem verder te verbeter is egter geïdentifiseer. Twee ondersoeke is by die Universiteit van Stellenbosch se proefplaas (Departement Agronomie) gedoen. Die eerste proef is onder beheerde omgewingstoestande in 'n glashuis uitgevoer en die tweede onder veld toestande.

In die eerste proef is *Beta vulgaris* (Snybeet) en *Amaranthus spp.* ('Imbuya') in twee tipes wortelmedia; gruis en puimsteen verbou. 'n 'Ebb-en-Vloed' asoook 'n 'Konstante vlak' besproeiingsisteem is gebruik terwyl voedingsoplossings ook by twee peile van elektriese geleiding (EC) teen 1.80 en 3.60 mS cm^{-1} toegedien is. Die resultate van hierdie (2x2x2x2) fakroriaal eksperiment het aangetoon dat 'n kombinasie van die 'Ebb-en-Vloed' sisteem met gruis as 'n wortelmedium die beste resultate teen 'n lae EC lewer waar 'imbuya' gebruik is. Die WGD met 'imbuya' was hoog (7.35 g L^{-1}) by 'n EC van 1.80 mS cm^{-1}, vergeleke met 'n relatief lae WGD van 5. 90 g L^{-1} waar die 3.60 mS cm^{-1} voedingsoplossing gebruik is.

In die tweede proef is 'Imbuya' se droë blaarmassa, blaar oppervlakte en WGD onder veldtoestande op die Universiteit van Stellenbsoch se proefplaas in die somer

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van 2002 ge-evalueer. Die proefplaas (33°55'S, 18°52'E) is in die koeler kusstreke van die wyndruif produksiegebied in die winterreëngebied van Suid-Afrika geleë. Hierdie proef is op alluviale grond met 25% klei en 'n pH van 5.9 (KC*l*) uitgevoer. 'n Geslote 'Ebb-en-Vloed' sisteem is met twee veld-besproeiingsisteme vergelyk ('Drup' en 'Vloed') terwyl voedingsoplossings teen twee peile van elektriese geleiding (1.80 en 3.60 mS cm^{-1}) in al drie gevalle gebruik is. Blaar droëmassa, blaaroppervlakte asook die WGD was die beste met 'Drup' besproeiing waar die EC van die voedingsoplossing 3.60 mS cm^{-1} was. Ten spyte van die feit dat ekstra grondwater vir die 'Drup' and 'Vloed' behandelings beskikbaar was, het die 'Ebb-en-Vloed' stelsel beter as die 'Vloed' behandeling gedoen veral waar die voedingsoplossing se EC 3.6 mS cm^{-1} was. Swak wortelbelugting was waarskynlik die rede waarom vloedbesproeiing swak produksie gelewer het. Die feit dat die 'Drup' en die 'Ebb-en-Vloed' behandelings in die veldproef die beste gedoen het waar die EC hoog was, mag moontlik met die gehardheid van die plante verband hou wat aan ekstreem warm en dor toestande blootgestel was.

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'I know that happiness does not come from things, even 20th century things. It can come from work and pride in what you do' (M. Ghandi).

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Chapter 1

OPTIMIZING WATER USE EFFICIENCY FOR CROP PRODUCTION: A SUMMARY ON LITERATURE REVIEW

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Chapter 1

Optimising water use efficiency for crop production

1.Introduction

About 70% of our planet's surface is covered with water. Water is essential to life on earth. Most of the earth's water is saline and only three percent is fresh. Of this fresh water, about two percent is ice; only one percent is available for human, plant and animal use. Of this fresh water, about 97.7% occurs as ground water, 1.5% as lake water and 0.8% as surface soil water. The mechanism of the water cycle is governed by solar activity, ensuring a relatively stable distribution of water among land, ocean and atmosphere. The total balance of free water of the entire earth has probably been constant since the Precambrian era, more than 500 million years ago. Human activities over the years led to the deterioration of the quality of available water. These losses come from the increasing use of water for civil and industrial settlements, road networks and agriculture. Agriculture uses about 60% of available water throughout the world. In South Africa, however, agriculture uses about 50% of our available water (Water Research Commission, 1996; Tognoni *et al.*, 1998).

The sub-humid climate in South Africa comprises 20% of its total area. This area has a mean annual rainfall of more than 750 mm. This part of the country is characterized by mountains with high run-off, indigenous forests and timber plantations with little cultivation of land. The rest of the country has an arid to semi-arid climate, implying that rainfall in this area is 50% or less of the annual evaporative demand for optimal plant production. About 65% of the country receive less than 500 mm of rain per year. The average annual rainfall for the country is only 497 mm, well below the world average of 860 mm, with a mean annual run-off of 53 500 million m^3 by all rivers in South Africa. In the world, about 1.1 billion people are without clean water. In South Africa, more than 7 million people (17% of the total population) do not have access to adequate potable water (Dept. Water Affairs & Forestry, 1999). It is clear that there is a great demand for this limited resource in South Africa and across the world.

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2. Physical water use efficiency

Physical water use efficiency (WUE) may be measured as a ratio of dry matter produced per unit area (t ha^{-1}) per unit evapotranspiration (mm) (Jansen *et al.*, 1981). WUE can also be defined as crop yield divided by the amount of water used: WUE = Mcrop/Vwuse (Mcrop= mass of crop; Vwuse = the amount of water used). Increases in WUE can be accomplished either by increases in Mcrop relative to Vwuse or by decreases in Vwuse relative to the Mcrop. Both techniques may increase the beneficial use of water (Lamm, 1997). Water use efficiency can be improved in a number of ways. In a thorough review of crop yield response to water use, Howell *et al.,* (1990) suggested the following to increasing WUE:

- Increase the harvest index (ratio of crop economic yield to the total dry matter production).
- Reduce the transpiration ratio (ratio of transpiration to dry matter production).
- Reduce the root mass needed to initiate the first increment of economic yield.
- Increase the transpiration component (percentage of total water used) by reducing evaporation, drainage and run-off.

3. Water loss

Water loss is defined as water that is not used by the intended crops as transpiration. Water loss can be categorized as atmospheric losses, surface losses, and drainage losses.

3.1 *Atmospheric losses*

- Evaporation from open water (reservoirs, canals, and fields).
- Wind drift and spray evaporation from overhead irrigation systems.
- Evaporation from bare soil.
- Transpiration from vegetation that is not the intended crop.

3.2 *Surface losses*

- Runoff from fields.
- Flow from drainage pipes.

3.3 *Drainage to ground water*

- Seepage losses from canal pipes.
- Seepage losses from the field.

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Losses matter if:

- the loss performs no useful function;
- the lost water is not recovered downstream of the point of loss;
- the loss causes some detrimental environmental impact or
- the loss increases capital or recurrent costs.

Losses do not matter if:

- The lost water has no value.
- The lost water can be recovered downstream.

4. Water economics

The most costs effective way of increasing the productivity of irrigation water is to increase the WUE of crops. Therefore, economic water use efficiency (economic WUE) is another parameter that can be used to optimize water savings. It reflects the net income generated per unit of water consumed (R m^{-3}). When comparing the WUE of different crops the economic WUE should be taken into account. The physical WUE is necessary in analyzing the efficiency of management practices for a given crop or group of similar crops. Economic WUE of irrigated crops in South Africa varies from less than R0.20 m^{-3} to more than R10.00 m^{-3}. This depends entirely on the input costs, yield and the price of the produce. The economic WUE of grain crops is often very low. The approach of many farmers is that inexpensive inputs are not limiting. This has previously often resulted in over-irrigation with a low economic WUE as a result (Water Research Commission, 1996).

Poor water management and poor WUE has been identified as one of the major problems experienced by farmers in most of the developing countries. Most countries do not monitor the performances of irrigation systems (Hennessy, 1993). Steinburg *et al.*, (1995) estimated that re-circulation of nutrient solutions allows for 20-30% savings in water and a saving of up to 60% in mineral nutrients. Dr Baudain of the FAO goes further stating that up to ten times less water may be used per kilo of tomatoes produced under protection with soil-less production techniques, compared to flood irrigation (Personal communication, FAO, Rome, Italy).

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5. Effect of salinity

Growing systems that re-circulate nutrient solutions are attractive, due to the combined saving of water and fertilizers. However, with longer periods of re-circulation, the greater the risk that salts may accumulate. Electrical conductivity (EC) is a parameter used to measure the concentration of salts. Higher salt concentrations have a negative impact on the yield of a given crop, therefore, it is required to maintain the EC of the nutrient solution with flushing rates of up to 30% or more (Stanghellini *et al.*, 1998).

Schwarz & Kuchenbuch (1998) reported that the growth and yield of tomatoes decreased with an increasing EC. At 6 dS m^{-1}, yield was 50% less, compared to plants grown at 1 dS m^{-1}. Water uptake decreased with an increasing EC. At an EC of 9 dS m^{-1} water uptake was reduced to 60%, compared to plants grown at an EC of 1 dS m^{-1}. The reduction in water uptake was mainly due to a decrease in leaf area. At an EC of 9, the leaf area was 20% smaller, compared to plants grown at the lowest EC (1 dS m^{-1}). WUE increased at increasing EC levels when related to the total biomass and decreased when related to tomato fruit yield. Increasing the EC from 1 to 6 dS m^{-1} caused a rise of up to 50% in the dry matter content of the fruits. In contrast, it was found that the total dry matter of the vegetative parts of the plant was reduced by about 10%.

When using a nutrient solution with an EC of 6.3 dS m^{-1} or more, tomato production was unprofitable (Soria & Cuartero, 1998). They reported a negative correlation between water consumption and EC. This suggests that less water is used with an increasing EC. WUE, expressed as fruit yield per litre of water uptake per day, at EC values of 2.7, 6.3, 9.8 and 13.0 dS m^{-1}, was 2108, 2172, 1327, and 2405 g l^{-1}. Water uptake was the limiting factor for tomato fruit production under saline conditions. The amount of water that was taken up was transformed into fruit at a similar rate at the four EC treatments (Soria & Cuartero, 1998). Combrink (1998) found that the reduced tomato fruit yield with increasing salinity levels was directly related to a reduced fruit size and that salinity level did not cause any significant difference in the number of fruit harvested. Where 18.50 mmol NaCl was added to a standard nutrient solution to increase the EC from 2.2 to 3.9 mS cm^{-1}, yield was reduced by 30% and fruit mass by 33%.

According to Leornardi (1998), celery seems to be more tolerant to saline conditions than tomatoes. He reported that an increase in the EC of a nutrient solution up to 10.5 dS

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m^{-1} did not affect plant dry matter production of celery. Plant dry weight only decreased at the highest salt concentration (16 dS m^{-1}). At this high EC treatment, total N production per plant was significantly lower due to a reduction in plant weight.

Karam *et al.,* (1998) reported that tuber yield of potatoes and evapotranspiration were sensitive to both salinity and soil texture. WUE was not affected; although the tuber yield on clay soil was 30% lower than that on loam soil. Tuber dry yield equaled 1.75 and 1.52 kg m^{-2} on loam and clay soils respectively, with averages of 4.69 and 4.60 kg m^{-3} for WUE.

In any re-circulating system, pathogens may accumulate and diseases may spread when millions of spores are poured into the water. Algae may develop where nutrient solutions are exposed to light. Apart from the hazard of blocked filters, caused by the presence of algae in the re-circulating water, big vein virus can be transmitted to lettuce, causing enlargement of the vascular bundles. Most prominent pathogens in re-circulating hydroponic units are *Phytophthora cinnamomi,* and *Randopholus similis* (Van Os *et al.*, 1999).

6. **Root exudates and accumulation of ions**

Field grown crops and even crops grown in a drain-to-waste hydroponic unit, are less vulnerable to the accumulation of pathogens and diseases because excess ions as well as root exudates can be leached. When a re-circulating system is used, a build up of impurities from the water or from applied chemicals may change the original balance of nutrients. Other sources of impurities originate from the plant itself. A whole range of substances are known to be exudated from plant roots into the nutrient solution, including cytokinins (Hurd, 1978). Waechter-Kristensen *et al.*, (1999) reported that most of the organic compounds in closed hydroponic systems originate from the incoming water, the substrate, microbial activity and root exudates.

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6.1. *Incoming (feeding) water*

Water sources used for the production of crops in greenhouses include rain water, municipal or well water and natural water reservoirs. Municipal water and natural water reservoirs in the USA pose an increased risk for the accumulation of organic compounds and plant pathogenic micro-organisms. Cucumber mosaic virus and both *Erwinia carotovora* and *Erwinia chrysanthemi* were found in lakes, rivers, and reservoirs during the summer season. It was also found that the quality of the water was detrimentally affected by the presence of these organisms, releasing allelochemicals inhibiting plant root development (Waechter-Kristensen *et al.*, 1999).

6.2. *Substrate and microbial activity*

Organic compounds in nutrient solutions are monitored by measuring the total organic carbon (TOC). It reflects a complex matrix, containing different types of carbon occurring in the nutrient solution. This includes damaged roots, micro-organisms and dissolved organic compounds (DOC). TOC could be used to measure both micro-organisms and organic compounds. It was found that the DOC values in filtered (>0.22 μm) water varied between greenhouses. For five open systems containing rockwool, mean DOC varied from about 10 to 40 mg l^{-1}. For three closed systems tested, the mean DOC varied from 11 mg l^{-1}, measured at the end of the gutters for lettuce in NFT, to 53 mg l^{-1} between cucumber plants in rockwool. In a commercial tomato culture, using closed hydroponics with drip irrigation on rockwool slabs, the DOC value ranged from 10 to 40 mg l^{-1}. There is, however, little information on the TOC and DOC values for closed hydroponic systems available. The values reported here are within the range for healthy vegetable crop production in hydroponics (Waechter-Kristensen *et al.*, 1999).

6.3. *Root exudates*

Plant roots release a wide range of organic compounds. The release of organic compounds by the roots differs between species and cultivars, and depends on plant developmental stage. It also depends on external factors affecting plant growth such as light, CO_2, O_2, nutrient supply, temperature and micro-flora. Cucumber seedlings were affected by several peptides. The amount of proteinacous material was in the range of 20 to 80 μg per mg of root dry matter. The release of peroxides increased with decreasing P-supply. Besides lactic and / or acetic acid, phenol acids were also found in the nutrient

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solution of hydroponic grown tomatoes. Phenolic acids are known for their phytotoxic effects. However, they can stimulate growth at lower concentrations. In the roots of tomato plants, some chlorogenic and protocatechuic acids were found (Waechter-Kristensen *et al.*, 1999). According to Sundin *et al.*, (1997) ferulic acid found in the nutrient solution of lettuce, inhibited root hair formation, root elongation and growth. Turkey (1977) found peaks of growth substance concentrations in the solution at times when the roots were dying. It was difficult to decide whether the roots were killed by the build up of these growth substances or whether the substances were liberated by dying roots. Trials have shown no detrimental effects on tomato seedling growth or seed germination using a nutrient solution that has been circulated in tomatoes for a month when root growth was poor and dead roots occurred. It seems as if some crops, such as tomatoes, are not detrimentally affected by re-circulated nutrient solutions if the EC and pH levels are controlled.

7. **Accumulation of heavy metals in field crops**

Toxic metals can enter plant tissue from the soil, rainwater deposition and irrigation with sewage effluents. The uptake of heavy metals by plants can detrimentally affect growth and can cause health hazards to humans and animals feeding on these affected plants. The effect of any toxic element on plants depends not only on its chemical properties but also on the presence of other elements. Heavy metal contamination does not involve a single metal, but rather a combination of metals. Total plant dry weight in *Phaseolus vulgaris* decreased significantly as heavy metals increased. The dry mass of plants from a high concentration treatment was 49.5% less than the control. Plants in the high concentration treatment exhibited Zn, Cd, Ni, B, Mn and Cu toxicity symptoms as intervenous chlorosis on older leaves (Sánchez *et al.*,1999).

8. **Low cost hydroponic systems**

Low cost hydroponic systems have the potential to save water due to an improved WUE, although this has not yet been quantified. These systems are easy to operate, using minimum amounts of water, are easy to install and to maintain. However, the cost effective use of these systems is something which has not yet been evaluated.

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8.1. *The wick system*

This system is based on the property of water to rise in capillary spaces. The advantage of this principle is that the necessity for frequent watering is eliminated. Instead, a reservoir with nutrient solution has to be topped up at intervals; this nutrient solution is drawn into the growing medium from the reservoir with a wick (Harris, 1994). With this system, the root medium stays moist at all times. The risk that waterborne diseases may spread is reduced. The nutrient solution is not exposed to direct sunlight, assisting to reduce evaporation.

8.2. *Hydro-culture luwasa system*

This system is self-watering and it is used for household or indoor plants. This system works through capillary action of expanded shale (Resh, 1997). Other media, allowing capillary movement of water may be used: One such a medium is expanded clay balls (LECA= Light Expanded Clay Balls). The right amount of water is supplied to the plant roots by capillary attraction between the clay particles. At the same time, ample air spaces allow diffusion of oxygen to the respiring roots. This system uses two containers; an inner container or growing pot and an outer container as nutrient solution reservoir. A tube to measure the level of nutrient solution or to add water may be installed (Harris, 1994).

8.3. *Manual Ebb-and-Flood system*

In this system, a plant is grown in a bucket with gravel set on top of a bench. A second bucket, containing the nutrient solution, is connected to the first bucket with a hose. Irrigation is achieved by raising the bucket of nutrient solution above the one containing the plant. After sufficient nutrient solution has drained into the plant-containing bucket, the raised bucket is then lowered to allow the nutrient solution to drain back to it. This system can be adapted by using a series of buckets, each attached to a pulley, which can be used to raise and to lower the buckets during the irrigation period (Resh, 1997). Irrigation of small containers can be achieved by raising a milk bottle, used as nutrient solution reservoir, above the level of the pot. When the nutrient solution is within 12 mm from the surface of the medium, the bottle is then lowered to the ground. The nutrient

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solution will then drain back to the bottle where the topping up with nutrient solution is done (Harris, 1994).

8.4. *Gravel film technique (GFT)*

The nutrient solution in this system is stored in a reservoir under a slightly sloping tray containing plants with gravel as a medium. Nutrient solution is pumped for 24 h along the gravel surface and is re-used (Resh, 1997).

8.5. *Terrace system*

This system uses a series of beds that are made over a sloping ground, to allow fertigation through gravitational force. Each set is at a lower level than the other bed. Nutrient solution is stored in an above header tank, raised several meters above the level of the first bed. An automatic solenoid or manual valve is used to control the flow of solution from one bed to the next. The valves may be automatic or manual. The nutrient solution flows into a sump from where it is pumped back into the raised tank. Each bed must be filled completely before the solution is allowed to drain into the following bed (Harris, 1994).

8.6. *Solar powered Ebb-and-Flood system*

For this system a 12 V, 18 W solar panel and a small 12 V caravan shower pump is used. The solar panel generates electricity to drive the shower pump and also serves as a solar integrator. The irrigation frequency increases at higher levels of solar radiation, when the solar panel produces more power and more nutrient solution is pumped up from the bottom to the top reservoir. When the solution reaches an overflow level in the top reservoir, a siphon action is induced. The same process is repeated in four plant containers placed at four decreasing levels. Pots are placed in these containers to be exposed to the 'Ebb-and-Flood' type of irrigation, induced by the automatic siphoning system (Combrink & Harms, 2001).

9. WUE of several crops, using different irrigation systems

Inefficiencies in water use can no longer be ignored, because of the increasing public awareness on the responsible use of non-renewable resources (Meyer *et al.*, 1990). Increasing water needs claimed for domestic, industrial and mining uses, may decrease

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agriculture's share to less than the current 50%. Thus, better utilization of this resource is imperative. The correct selection of irrigation systems can limit water losses considerably (Wittwer & Honma, 1979; Water Research Commission, 1996). Further savings can be realized with the correct use of soilless culture (Resh, 1978; Papadopoulos, 1991). Under specific conditions, these alternatives can play a major role to save water and electricity. Stone & Nofziger (1993) reported that water might be saved by reducing evaporation from the soil surface, especially when drip irrigation is used, or by using mulches. WUE is typically higher for autumn and winter grown crops. Irrigation is often more efficient if it is done at night than during the day.

Hodgson *et al.,* (1990) reported that drip irrigation can maintain adequate levels of soil water and improve crop yield. Drip irrigation improved WUE by preventing deep percolation losses of irrigation water. WUE under drip was 16% better than with furrow irrigation, due to the channel losses and run off losses associated with furrow irrigation. Henceforth, a better water use efficiency could be achieved with furrow irrigation by having good management. This may be done by reducing losses between pump and field, reducing water logging, by reducing run-off losses and by re-circulating run-off water (Hodgson *et al.,* 1990).

Irrigation supplied to wheat during the crown root initiation and milk stages appears to increase the WUE more effectively, than using frequent irrigations. The WUE at these stages of growth were 0.83 and 0.88 kg m^{-3}, respectively (Mishra *et al.*, 1995). Kang *et al.*, (2000) concluded that alternate furrow irrigation is an effective water saving method in arid areas, specially on sandy loam soils, where maize production relies heavily on repeated irrigation. The WUE for maize was about 5.75 kg m^{-3} in 1997 and 5.16 kg m^{-3} in 1998.

WUE expressed in terms of the volume of water used per mass of dry material produced, was least on cucumber at 12°C, where 1768 ml of water was required to produce one gram of dry material. At 20°C, the WUE was about 570 ml g^{-1} (Daskalaki & Burrage 1998). Sharmasarkar *et al.,* (2001), working with dry material produced per unit of water, reported that WUE for drip irrigation on sugar beet ranged from 9.6 to 10.6 kg m^{-3}. On flood irrigated beet, it ranged from 3.8 to 5.3 kg m^{-3}.

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According to Al-Jamal *et al.*, (2001), WUE on onions increased from 0.19 to 0.9 kg m^{-3} when furrow was replaced by sprinkler irrigation. WUE can be improved by either increasing dry yield or decreasing evapo transpiration (ET). These factors can be used by crop breeders to decrease the water use of crops, while maintaining yield and quality. Dry yield is affected by the rate of photosynthesis. Exposing the crops to stress causes the stomata to close, reducing the rate of photosynthesis and lowering the yield potential. Breeding varieties that transpire less water while maintaining a higher rate of photosynthesis increased the WUE in onion (Al-Jamal *et al.*, 2001). Howell *et al.* (1996) reported that the WUE for maize ranged from 1.2 to 1.5 kg m^{-3} under USA conditions.

According to Hussain & AL-Jaloud (1998), the WUE in barley could be increased by the application of 100 - 150 kg N ha^{-1}. The average WUE of a crop, based on above ground biomass, was 3.2 kg m^{-3} but when roots were included, this value increased to 4.2 kg m^{-3} (Lopez & Richards 1994). Thomas (1995) found that the WUE based on biomass per unit of ET was higher in chickpea than in barley and was higher in early maturing barley (cv. Corrette) than in a late maturing cultivar.

Karam *et al.*, (1998) reported WUE calculated as the tuber dry matter yield per unit of evapotranspiration (ET) on clay was 30% lower than on loam. The average WUE was 4.69 and 4.60 kg m^{-3} for clay and loam soils, respectively. Dinar (1993) published data for citrus from the southern San Joaquin valley, California for the period 1977-1981. It indicated average water applications of 7051, 7475, 7943 and 8171 m^3 ha^{-1} for drip, furrow with tail water re-use (TWR) sprinklers and furrow without TWR, respectively. Water savings that ranged from 5.6 to 13.7% could be achieved with drip irrigation, compared with furrow irrigation with or without TWR.

Castilla *et al.*, (1998) reported that WUE can be increased by mulching. WUE of greenhouse melons was higher when mulched. The WUE of unmulched melons ranged from 13.6 to 15.3 kg m^{-3} compared to 18.9 to 19.0 kg m^{-3} for mulched melons. Briones *et al.*, (1995) obtained a relatively low WUE of 9.1 kg m^{-3} for outdoors dripped mulched melons.

WUE for both grain crops and vegetable crops are tabulated in Table 1. Due to different moisture concentrations, the WUE of grain crops are low when compared to vegetables. In Africa as a whole, small-scale farmers are beset by varying problems, such as

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management, project planning and designing, security of tenure, size of units, farmer participation, water management, debt load, pricing policies, marketing, inputs, extension and research services, as well as mechanical and other support services (Bembridge, 1996). There are about 202 small-scale farmer irrigation schemes in South Africa involving 47 486 ha. Of the 37 198 participants, only 37% can be regarded as being commercially orientated. The remaining 63% are food-plot holders who may sometimes sell a proportion of their produce. In addition there are a large number of smaller schemes (< 2 ha) comprising of commercial gardens, food-plots and household gardens.

Table 1: Water Use Efficiency (WUE) of several crops (Water Research Commission, 1996)

Crop	WUE (kg m^{-3})
Grain crops as a group (10% moisture)	**0.15 - 1.6**
Wheat	0.8 - 1.4
Maize	0.8 - 1.6
Seed-cotton	0.4 - 0.6
Sugar-cane (sucrose at 0% moisture)	0.6 - 1.0
Vegetables as a group (70 to 90% moisture)	**0.5 - 12.0**
Tomatoes (90% moisture)	10.0-12.0
Potatoes (73% moisture)	4.0 - 7.0
Cabbage (90% moisture)	12.0-20.0
Onions (88% moisture)	8.0 -10.0

Water delivery systems must provide the desired amount of water (and dissolved oxygen and nutrients) to the root zone of the plant. This must be accomplished efficiently and uniformly in order to achieve quality crops of uniform size and maturity. Most recently Ebb-and-Flood watering systems have been utilized for effective sub-irrigation and nutrient delivery within a closed system. The benefits of sub-irrigation are improved distribution of water and nutrients, flexibility in root zone volume, plant spacing and potential to save water and nutrients (Fischer *et al.*, 1990; Fyn, 1994).

The value of water savings may provide an incentive for a transition from old to modern technologies. These savings can be higher or lower, depending on the site and location.

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Apart from water saving, technology improvement may have several other effects such as water pollution reduction and yield increase; all are assumed to increase WUE (Dinar, 1993).

The introduction of a low cost Ebb-and-Flood hydroponic unit, which is easy to operate and to maintain, can play an important role in the change of rural livelihood and in the alleviation of poverty (Combrink & Harms, 2001). A commercial Ebb-and-Flood hydroponic unit is popular for the production of potted ornamentals in Europe and it is said to be extremely efficient in saving water (Resh, 1997). Soilless plant production systems are increasingly used in Israel, Spain, Morocco, and other semi-arid areas. The need to adapt this technology to be available to resource poor farmers with little technical know how was identified and subsequent an automatic Ebb-and-Flood system was developed (Combrink & Harms, 2001). However, the WUE of this system needs further attention in order to be introduced successfully to rural communities.

Changing or improving on technological know how, include changing from one irrigation system to the best system for water savings; the use of mulch instead of bare soil; changes from open field cultivation to Controlled Environment Agriculture (CEA); the use of the closed (re-circulation) rather than an open system (drain to waste) hydroponics systems.

10. Leafy crops

Leafy crops may be classified into those that are grown commercially, those more suited to home gardens, and those that grow wild. Importance can be measured in many ways; by economic value, by frequency of use, or by contribution to the diet. Each method of classification adds useful information to the description and understanding of each type of leafy crop.

Green leaves are accepted as part of the human diet. Cultural and dietary phenomena are largely related to geography. Large numbers of species are used in Africa. It is interesting to note that many of these species are species or cultivars introduced from abroad. African people probably experimented with the edible quality of newly introduced plants, and a few may not have been tested yet. In Africa, green leaves are generally cooked into

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a stew, eaten with staple starch food. The stew offers many nutritional qualities, not present in the staple food (Martin & Rubertè, 1979).

Carotene is a series of hydrocarbons with formula $C_{40}H_{56}$, widely distributed as a yellow pigment in plants and animals, possible important in plants phototropism and in animals important as precursor for Vitamin A synthesis.

Leafy crops such as *Beta vulgaris* and *Amaranthus species* could be better used as a source of vitamin A in South Africa.

Water management and poor water use efficiency (WUE) is identified as one of the major problems experienced by vegetable growers in most of the developing countries. These inefficiencies in water use can no longer be ignored, because of the increasing pressure on the water resource and the general public awareness on the responsible use of non-renewable resources

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CHAPTER 2

Influence of hydroponic systems, root media and nutrient solutions on the water use efficiency of two leafy crops

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Influence of hydroponic systems, root media and nutrient solutions on the water use efficiency of two leafy crops.

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Abstract

Since irrigation systems affect the water use efficiency (WUE) of crops, care should be taken to select the best option under conditions of limited water quantity and quality. To save water with a closed system, the quality of water should be taken into account. In this study, conducted under controlled environmental conditions in a glasshouse, Swiss chard and 'imbuya' were grown in gravel and pumice root media. In addition, 'Ebb-and-Flood' and a 'constant level' system, as well as a nutrient solution at two electrical conductivity's (EC) 1.80 and 3.60 mS cm^{-1} were evaluated. The results of this (2x2x2x2) factorial experiment indicated that a combination of the 'Ebb-and-Flood' system with gravel as a root medium produced the best results at a low EC, when 'imbuya' was used. A high total WUE at EC 1.80 mS cm^{-1} was found with 'imbuya', (7.35 g l^{-1}) compared to a relatively low WUE of 5. 90 g l^{-1} when the 3.60 mS cm^{-1} nutrient solution was used

Keywords: Constant level, Ebb-and-Flood, imbuya, pumice, Swiss chard

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1. Introduction

About 70% of our planet's surface is covered with water. Water is essential to life on earth but 97% of the earth's water is saline. Two thirds of the remaining three percent is ice water, thus only one percent of the earth's water is available for humans, plants and animals on the continents. The water cycle is governed by solar activity, ensuring a relatively stable distribution of water among land, ocean and atmosphere. The total balance of free water of the entire earth was probably constant since the Precambrian era, more than 500 million years ago. Over the years, human activities led to the deterioration of the quality of available water. These losses come from the increasing use of water for civil and industrial settlements, road networks and agriculture. In South Africa, agriculture uses about 50% of the available water (Water Research Commission, 1996; Tognoni *et al.*, 1998).

Water management and poor water use efficiency (WUE) is one of the major problems experienced by farmers in most of the developing countries. Most of these farmers do not monitor the efficiencies of their irrigation systems (Hennessy, 1993). The most cost-effective way to increase the productivity of irrigation water is to increase the WUE of crops. Two parameters can be used to measure this. Firstly, economic WUE reflects the net income generated per unit of water consumed ($R.m^{-3}$). Economic WUE of irrigated crops in South Africa varies from less than R0.20 m^{-3} up to more than R10.00 m^{-3} (Water Research Commission, 1996). Secondly, physical WUE is necessary to analyse the efficiency of the management practices for a given crop or a group of similar crops (Water Research Commission, 1996). Jansen *et al.*, (1981) defined physical WUE as the ratio of dry matter produced per unit area (t ha^{-1}) per unit (mm) of evapotranspiration (ET), or crop yield (Mcrop) divided by the volume of water used (Vwuse). Increases in WUE can be accomplished either by increases in Mcrop relative to Vwuse or by decreases in Vwuse relative to Mcrop. Both techniques may increase the beneficial use of water (Lamm, 1997). Howell *et al.*, (1990) suggested the following to increase WUE:

- Increase the harvest index (ratio of crop economic yield to the total dry matter production).
- Reduce the transpiration ratio (ratio of transpiration to dry matter production).
- Reduce the root mass needed to initiate an increment of economic yield.

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- Increase the transpiration component of ET by reducing evaporation, drainage and run-off.

Since irrigation systems affect WUE, the selection of a specific system such as drip irrigation or sprinkler irrigation can be crucial (Wittwer & Honma, 1979). It is said that a five percent increase in irrigation efficiency in South Africa could result in water savings of up to 550 million m^3 per year (Kleynhans, 1997). Most recently, Ebb-and-Flood watering systems have been introduced for effective sub-irrigation and nutrient delivery within a closed system (Fischer *et al.*, 1990; Fyn, 1994). The benefits of using sub-irrigation are improved distribution of roots, uniformity of water and nutrient distribution, flexibility in root zone volume and plant spacing. Such a system was adapted to develop a vegetable production unit for use by families in rural communities, while saving substantial amounts of water (Combrink & Harms, 2001). A need to further improve the WUE of this system was subsequently identified and serves as motivation for this study.

2. Materials and methods

Using a factorial experimental design (2 x 2 x 2 x 2), two plant species, Swiss chard (*Beta vulgaris)* and 'imbuya', (*Amaranthus species*) were grown under controlled environmental conditions in a glasshouse. Two growing mediums, pumice (capstones) and gravel with diameters ranging from 3 to 4 mm were used as a second factor. The plants were grown using two irrigation systems; a 'constant-level' and an 'Ebb-and-Flood' system (3rd factor). As a fourth factor (salinity) the plants were subjected to two different electrical conductivity (EC) levels (standard solution with a low EC of 1.80 mS cm^{-1} and a saline solution at 3.60 mS cm^{-1}). The standard and salt solutions were prepared using the nutrient solutions given in Table 1. Micronutrients were added to both solutions as described by Combrink *et al.*, (1996). A single container with two plants was used as an experimental unit. The sixteen treatment combinations were replicated two times in a complete randomised block design.

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Table 1: Macronutrient concentrations used for a standard and a saline nutrient solution.

	Cations (me L^{-1})					Anions (me L^{-1})			
	Na^+	NH_4^+	K^+	Ca^{++}	Mg^{++}	NO_3^-	$H_2PO_4^-$	$SO_4^=$	Cl^-
Standard	0	1.00	6.5	7.00	3.5	13.00	1.00	4.00	0
Saline	18	1.00	6.5	7.00	3.5	13.00	1.00	4.00	18

For the 'Ebb-and-Flood' system, two 20 litre containers were used (Fig. 1a, Fig.1b). One was filled with 17 *l* of growth medium for two plants and the other was used as a reservoir for the nutrient solution. Plants in this system were watered by using a 12 Volt caravan shower pump to lift the nutrient solution through a rubber tube to the container with the two plants. The containers had overflow outlets at the 'flood' level, returning excess pumped solutions to the lower reservoir. After 30 minutes, the pumps stopped and the nutrient solution flowed back to the lower reservoir. Four daily irrigation cycles were conducted at 08:00, 11:00, 14:00 and 17:00.

For the 'constant level' system, one 20 *l* container was used as reservoir as well as plant container (Fig. 2a, Fig 2b). This container was filled with 17 *l* of growth medium. Plants were watered by adding nutrient solution to the bottom of the container through a vertical pipe inserted in the medium. This pipe also served as inspection hole to determine the level of the solution, using a dipstick. Solution was added to maintain a reservoir of ±5 litres (150 mm high). When the level dropped to below 1.7 litres (50 mm) it was topped up. Hence, plant roots in this system received moisture from the reservoir at the bottom or through capillary action.

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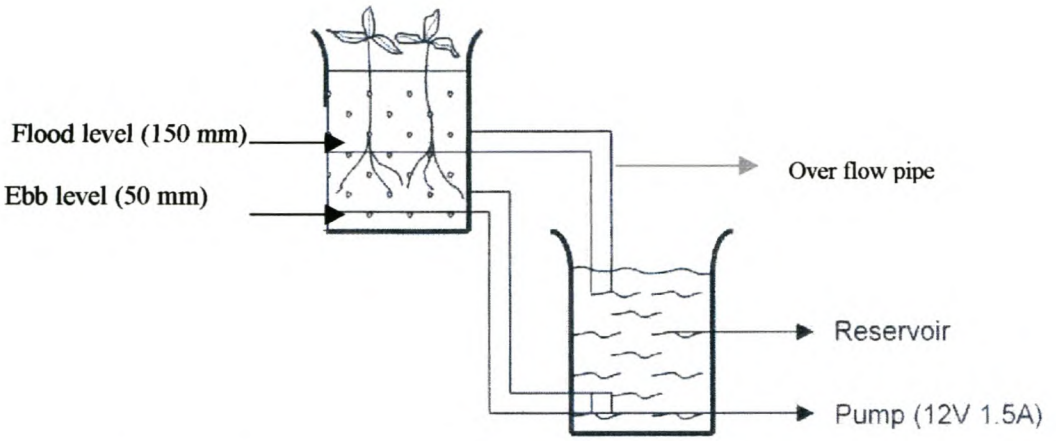

Fig. 1a: Schematic illustration of the 'Ebb-and-Flood' system with a circulating nutrient solution.

Fig. 1b: 'Ebb-and-Flood' system in the glasshouse

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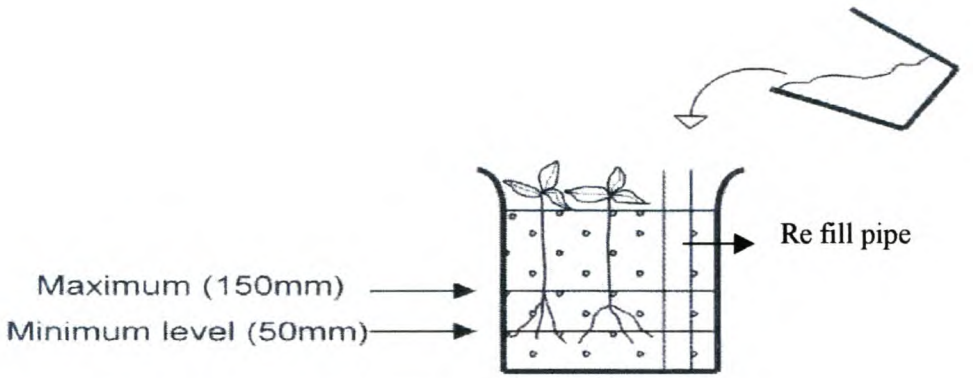

Fig. 2a: Schematic illustration of the 'Constant level' system

Fig. 2b: 'Constant' level system in a glasshouse

The volumes of added nutrient solution was recorded for both systems. The changes that occurred in the EC and pH of the nutrient solutions were measured once every second week. The foliage of 'imbuya' was harvested on plants reaching heights of ±450 mm. The plants were then cut back to 300 mm and the side shoots were trimmed back, leaving two buds for further development. Flowers and seeds were removed as soon as they developed for the duration of the experiment. Swiss chard

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was harvested every second week, once the leaves were large enough. Two Swiss chard cultivars were used, one each per container ('Lucullus' and 'Ford-hook giant'). In the same way, two 'imbuya' types were also used, *Amaranthus hypochondriatus* L and *Amaranthus tricolor* L. These cultivars were only analysed separately (split plots) where total chlorophyll and total carotene levels were evaluated. For all the other parameters, the two plants were jointly used as experimental unit. The concentration of total chlorophyll and total carotene in leaves was measured using the method of Lichtenthaler, (1984). The WUE was calculated by dividing plant dry mass by the volume of water used. For foliage-WUE, only the leaves were used and the total biomass was used to calculate the total-WUE. No diseases were observed but aphids had to be controlled with methomyl. The data was analysed with a SAS programme (SAS, 1978).

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3. Results

Table 2: Summary of the analyses of variance for the electrical conductivity (EC), taken every second week.

Source	DF	Probability (P)					
		EC Week1	EC Week3	EC Week5	EC Week7	EC Week9	EC Week11
Block	1	0.7694^{ns}	0.8438^{ns}	0.4979^{ns}	0.6214^{ns}	0.7950^{ns}	0.5738^{ns}
System (S)	1	<.0001***	0.0634^{ns}	0.0079**	0.8806^{ns}	0.6087^{ns}	0.3680^{ns}
Medium (M)	1	0.0005***	0.0259*	0.0008***	0.9162^{ns}	0.7398^{ns}	0.7890^{ns}
Conductivity (C)	1	<.0001***	<.0001***	<.0001***	<.0001***	0.0957^{ns}	<.0001***
Species (Spp)	1	1.0000^{ns}	0.9476^{ns}	0.0430*	0.0001***	0.0003***	0.0002***
S x M	1	0.5353^{ns}	0.2013^{ns}	0.0008***	0.9162^{ns}	0.7398^{ns}	0.8506^{ns}
S x C	1	**0.0116***	**0.9476^{ns}**	**0.0973^{ns}**	**0.0553^{ns}**	**0.0181***	**0.0002*****
M x C	1	0.0092**	0.0382*	0.0003***	0.4656^{ns}	0.4329^{ns}	0.6923^{ns}
S x Spp	1	0.6345^{ns}	0.9476^{ns}	0.0430*	0.1988^{ns}	0.0003***	0.0061**
C x Spp	1	0.7142^{ns}	0.6941^{ns}	0.0359*	0.2036^{ns}	0.5676^{ns}	0.7289^{ns}
M x Spp	1	0.9415^{ns}	0.5141^{ns}	0.0044**	0.1988^{ns}	0.9181^{ns}	0.0249^{ns}
S x M x C	1	0.0874^{ns}	0.4736^{ns}	0.1088^{ns}	0.6110^{ns}	0.0384*	0.6923^{ns}
Sx M x Spp	1	0.4891^{ns}	0.5565^{ns}	0.0264*	0.3222^{ns}	0.8230^{ns}	0.2804^{ns}
S x C x Spp	1	0.3656^{ns}	0.4351^{ns}	0.0102*	0.3437^{ns}	0.6425^{ns}	0.1485^{ns}
M x C x Spp	1	0.5593^{ns}	0.7429^{ns}	0.0170*	0.1758^{ns}	0.8513^{ns}	0.7364^{ns}
S x M x C x Spp	1	0.2654^{ns}	0.1296^{ns}	0.0061***	0.4393^{ns}	0.8043^{ns}	0.5540^{ns}
Error	15						
Total	31						

* = Significant at 5% ** = significant at 1% *** = significant at 0.1% ns = not significant

Bold typed values are used for discussion

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Table 3: Summary of the analyses of variance for pH measurements, taken every second week.

Source	DF	Probability (P)					
		pH Week1	pH Week3	pH Week5	pH Week7	pH Week9	pH Week11
Block	1	0.4713^{ns}	0.5824^{ns}	0.0932^{ns}	0.2247^{ns}	0.8575^{ns}	0.4355^{ns}
System (S)	1	$<.0001^{***}$	$<.0001^{***}$	$<.0001^{***}$	$<.0001^{***}$	$<.0001^{***}$	0.0008^{***}
Medium (M)	1	0.0015^{**}	0.0019^{**}	0.0014^{**}	$<.0001^{***}$	$<.0001^{***}$	0.0009^{***}
Conductivity (C)	1	0.0632^{ns}	0.2985^{ns}	0.0005^{***}	0.0407^{*}	0.6868^{ns}	0.8901^{ns}
Species (Spp)	1	0.3571^{ns}	0.1547^{ns}	0.0119^{*}	0.0443^{*}	$<.0001^{***}$	0.0090^{**}
S x M	1	**0.0038^{**}**	**$<.0001^{***}$**	**$<.0001^{***}$**	**0.1384^{ns}**	**0.0003^{***}**	**0.1625^{ns}**
S x C	1	0.1118^{ns}	0.0878^{ns}	0.8287^{ns}	0.9177^{ns}	0.3309^{ns}	0.1625^{ns}
M x C	1	0.6539^{ns}	0.2985^{ns}	0.0033^{**}	0.5274^{ns}	0.7621^{ns}	0.8466^{ns}
S x Spp	1	0.0988^{ns}	0.0035^{**}	0.1963^{ns}	0.6528^{ns}	0.0200^{*}	0.0231^{*}
C x Spp	1	0.4116^{ns}	0.3410^{ns}	0.7575^{ns}	0.2247^{ns}	0.6868^{ns}	0.0743^{ns}
M x Spp	1	0.3236^{ns}	0.0680^{ns}	0.3158^{ns}	0.9870^{ns}	0.1943^{ns}	0.6544^{ns}
S x M x C	1	0.9448^{ns}	0.0305^{*}	0.0022^{**}	0.0315^{*}	0.1943^{ns}	0.6347^{ns}
Sx M x Spp	1	0.5817^{ns}	0.0334^{*}	0.7810^{ns}	0.2405^{ns}	0.9373^{ns}	0.6299^{ns}
S x C x Spp	1	0.2925^{ns}	0.1945^{ns}	0.3925^{ns}	0.5847^{ns}	0.6868^{ns}	0.8037^{ns}
M x C x Spp	1	0.2245^{ns}	0.06794^{ns}	0.7112^{ns}	0.7081^{ns}	0.6464^{ns}	0.5964^{ns}
S x M x C x Spp	1	0.7041^{ns}	0.0120^{*}	0.9016^{ns}	0.2247^{ns}	0.5541^{ns}	0.8901^{ns}
Error	15						
Total	31						

* = Significant at 5% ** = significant at 1% *** = significant at 0.1% ns= not significant

Bold typed values used for discussion

Table 4: Summary of the analyses of variance for foliage dry mass, roots dry mass, biomass, foliage water use efficiency (WUE) and total WUE.

Source	DF	Probability (P)				
		Foliage dry mass	Roots dry mass	Biomass	Foliage WUE	Total WUE
Block	1	0.5668^{ns}	0.0769^{ns}	0.2755^{ns}	0.2808^{ns}	0.1097^{ns}
System (S)	1	$<.0001^{***}$	0.0353^{*}	$>.0001^{***}$	**0.0359^{*}**	**$<.0001^{***}$**
Medium (M)	1	0.0601^{ns}	0.3020^{ns}	0.2855^{ns}	0.2081^{ns}	**0.0011^{**}**
Conductivity (C)	1	0.1390^{ns}	0.3106^{ns}	0.1444^{ns}	0.2783^{ns}	0.0757^{ns}
Species (Spp)	1	0.9224^{ns}	$<.0001^{***}$	0.0194^{***}	0.4196^{ns}	0.0002^{***}
S x M	1	0.0180^{*}	0.0053^{**}	**0.0065^{**}**	0.0831^{ns}	0.9253^{ns}
S x C	1	0.1106^{ns}	0.6935^{ns}	0.2871^{ns}	0.1378^{ns}	0.8077^{ns}
M x C	1	0.4094^{ns}	0.5271^{ns}	0.4008^{ns}	0.9229^{ns}	0.1629^{ns}
S x Spp	1	0.0888^{ns}	0.0819^{ns}	0.0672^{ns}	0.0672^{ns}	0.7100^{ns}
C x Spp	1	0.7421^{ns}	**0.0092^{**}**	0.1978^{ns}	0.1760^{ns}	**0.0172^{*}**
M x Spp	1	**0.0433^{*}**	0.0666^{ns}	0.0324^{*}	0.3409^{ns}	0.9154^{ns}
S x M x C	1	**0.0164^{*}**	0.5222^{ns}	0.1000^{ns}	0.1254^{ns}	0.1629^{ns}
Sx M x Spp	1	0.7046^{ns}	**0.0213^{*}**	0.2371^{ns}	0.2247^{ns}	0.3485^{ns}
S x C x Spp	1	0.1721^{ns}	0.8003^{ns}	0.2669^{ns}	0.6131^{ns}	0.2240^{ns}
M x C x Spp	1	0.0893^{ns}	0.6601^{ns}	0.1528^{ns}	0.6131^{ns}	0.2344^{ns}
S x M x C x Spp	1	0.0593^{ns}	0.9663^{ns}	0.1568^{ns}	0.2247^{ns}	0.2815^{ns}
Error	15					
Total	31					

* = Significant at 5% ** = significant at 1% *** = significant at 0.1% ns = not significant

Bold typed values used for discussion

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Table 5: Summary of the analyses of variance for total chlorophyll and total carotene concentrations in the leaves.

Source	DF	Probabilty (P)	
		Chlorophyll	Carotene
Block	1	0.2860^{ns}	0.3707^{ns}
System (S)	1	0.0177^{*}	0.1387^{ns}
Medium (M)	1	0.0254^{*}	0.9367^{ns}
S x M	1	**0.0148^{*}**	0.8279^{ns}
Conductivity (C)	1	0.0586^{ns}	0.0152^{*}
S x C	1	0.6483^{ns}	0.0816^{ns}
M x C	1	0.9388^{ns}	0.3986^{ns}
S x M x C	1	0.4607^{ns}	0.6508^{ns}
Species (Spp)	1	0.0943^{ns}	0.7546^{ns}
S x Spp	1	**0.0127^{*}**	0.1017^{ns}
M x Spp	1	**0.0363^{*}**	0.1185^{ns}
S x M x Spp	1	0.1709^{ns}	0.3427^{ns}
C x Spp	1	0.3356^{ns}	0.3477^{ns}
S x C x Spp	1	0.5094^{ns}	0.7074^{ns}
M x C x Spp	1	0.7546^{ns}	0.0503^{ns}
S x Mx C x Spp	1	0.5886^{ns}	0.9672^{ns}
BLO (S x M x C x Spp)	15		
Cultivar (Cult)	2	0.0046^{***}	0.0031^{**}
S x Cult	2	0.0543^{ns}	0.1040^{ns}
M x Cult	2	**0.0239^{*}**	0.5957^{ns}
S x M x Cult	2	0.1188^{ns}	0.7467^{ns}
C x Cult	2	0.6464^{ns}	0.0436^{*}
S x C x Cult	2	0.6196^{ns}	**0.0095^{**}**
M x C x Cult	2	0.9260^{ns}	0.5252^{ns}
S x M x C x Cult	2	0.9307^{ns}	0.9411^{ns}
Error	16		
Total	63		

* = Significant at 5% ** = significant at 1% *** = significant at 0.1% ns = not significant
Bold typed values are used for discussion

3.1 Accumulation of salts

In Table 2, the most consistent trend was the interaction between irrigation systems and salinity of the nutrient solutions, as illustrated in Fig. 3. The results showed a significant increase in the accumulation of salts with both irrigation systems where a nutrient solution with a high electrical conductivity (EC=3.60 mS cm^{-1}) was used. Where a standard nutrient solution was used, a decline in the EC levels occurred, especially during the last two weeks with the nutrient solution at a 'constant level'.

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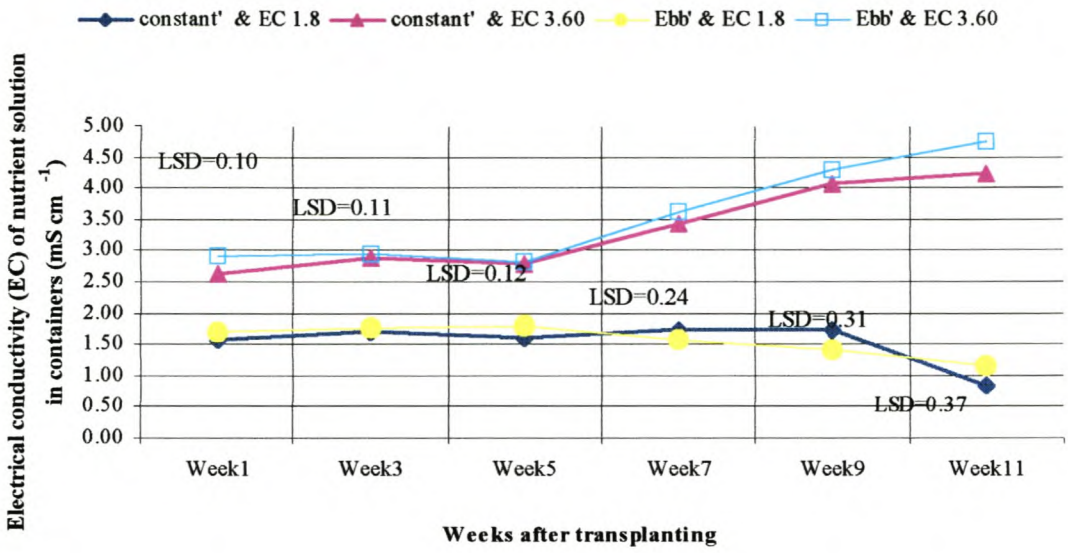

Fig. 3: Accumulation of salts affected by an interaction between the conductivity of applied nutrient solutions and irrigation systems ('Ebb'= Ebb-and-Flood; 'constant'=constant level used as a reservoir).

3.2 pH of the nutrient solution

As seen in Table 3, changes in pH were significantly affected by an interaction between root media and irrigation systems. This seems to be the most consistent trend and it was therefore used in Fig. 4. The results indicated that only with the 'Ebb-and-Flood' system where pumice was used as a root medium, a significant decline in pH occurred over time, reaching a level of 5 at week seven. Although significant differences were found between other treatments, these were less consistent over time.

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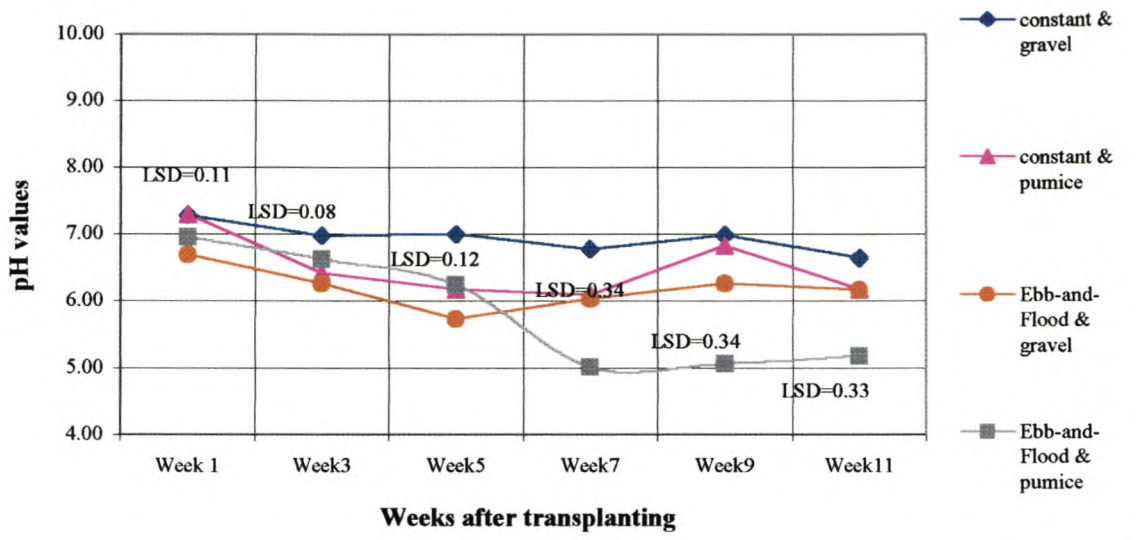

Fig. 4: Changes in pH levels of the nutrient solutions affected by an interaction between irrigation systems and root growth media.

3.3 Foliage dry mass.

Two interactions affected foliage dry mass, as shown in Table 4 (M x Spp and S x M x C). Fig. 5 illustrates how the interaction between conductivity levels, irrigation systems and root media, affected foliage dry mass. Foliage dry mass was notably better using the 'Ebb-and-Food' system, but by comparing the performances of gravel and pumice at the two EC levels with this irrigation system, gravel gave the best results only at the low EC.

The significant interaction between root media and crops is illustrated in Fig. 6. When gravel was used as root medium Swiss chard was the best yielder but on pumice, 'imbuya' out performed Swiss chard.

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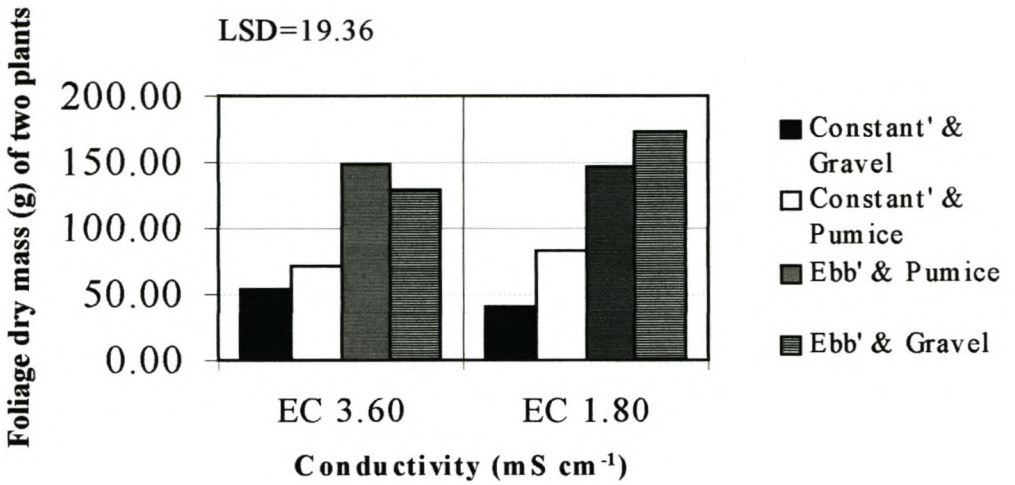

Fig. 5: Foliage dry mass affected by an interaction between conductivity of the nutrient solution, irrigation systems ('Ebb=Ebb-and-Flood; 'Constant'= constant level as reservoir) and root media (Pumice and Gravel).

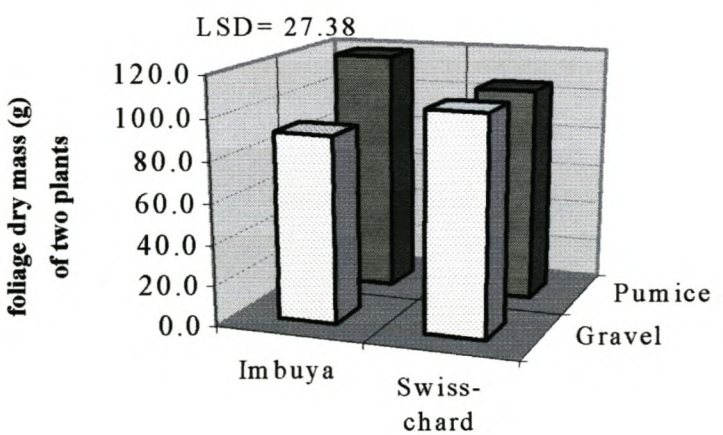

Fig. 6: Foliage dry mass affected by an interaction between species and root media.

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3.4 Root dry mass.

Root dry mass was affected by an interaction between irrigation systems, plant species and root media (Table 4, Fig. 7), as well as an interaction between the EC of the nutrient solution and plant species (Fig. 8).

Root production by 'imbuya' in gravel (Fig. 7) increased significantly by switching from the 'constant level' to the 'Ebb-and-Flood' irrigation system. This positive effect with the 'Ebb-and-Flood' system was not found with Swiss chard or where pumice was used as root medium.

In Fig. 8, it can be seen that 'imbuya' produced more roots than Swiss chard, but this effect was much bigger where a standard nutrient solution was used.

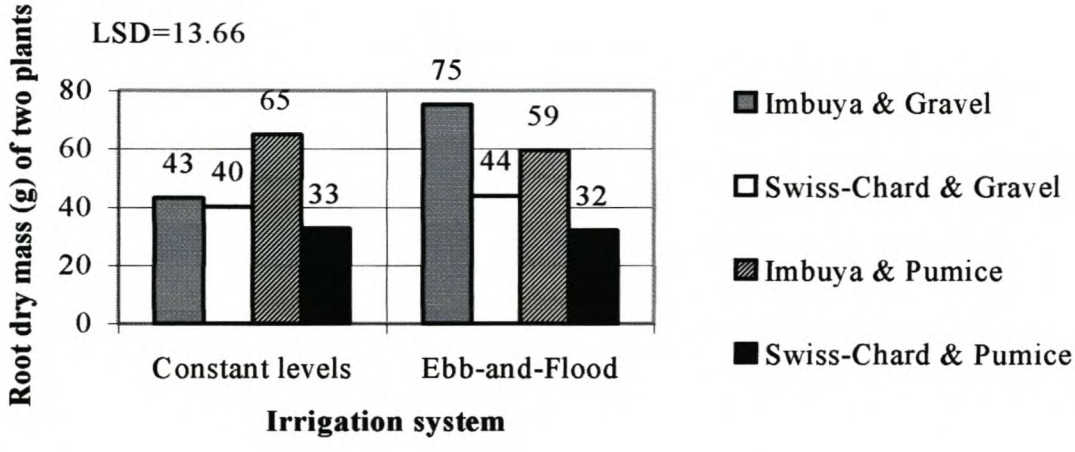

Fig. 7: Root dry mass affected by an interaction between irrigation systems, plant species and root media.

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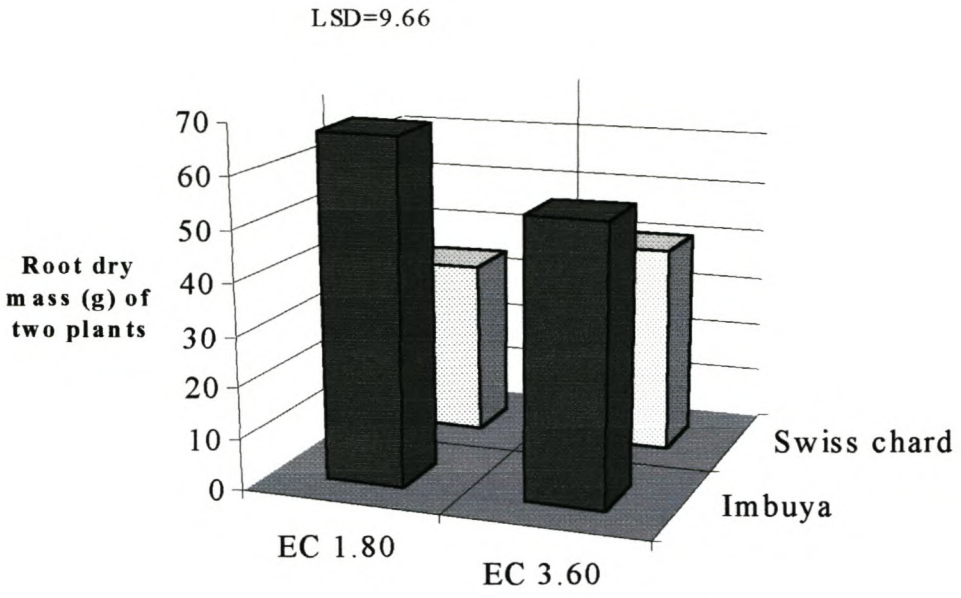

Fig. 8: Root dry mass affected by an interaction between the conductivity of nutrient solutions and two crops.

3.5 Total biomass

Total biomass was significantly affected by an interaction (P=0.01) between irrigation systems and the root media.

In Fig. 9 it can be seen that the 'Ebb-and-Flood' system produced more biomass on both root mediums, but gravel seemed to benefit more with fluctuating nutrient solution levels. Although an overall low biomass production was found using a 'constant level' for both media, pumice seemed to be a better option without fluctuations in nutrient solution levels.

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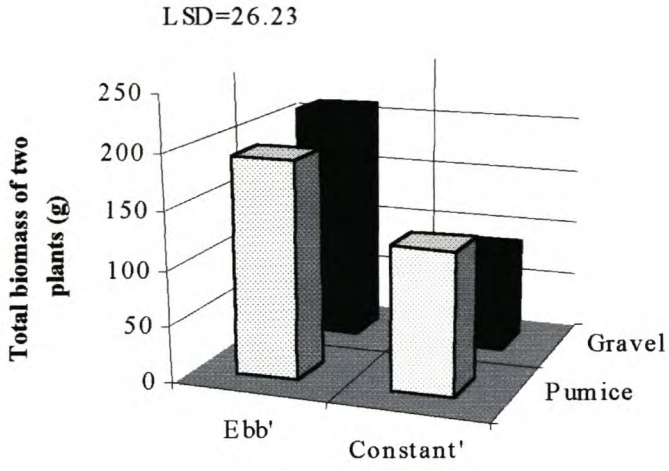

Fig. 9: Total biomass affected by an interaction between irrigation systems and root media ('constant'= constant level as a reservoir; 'Ebb'=Ebb-and-Flood).

3.6 Water use efficiency (WUE)

Foliage WUE was only affected by irrigation systems (Table 4). An average leaf production of 3.95 g l^{1} was found with the 'constant level' system, significantly (P=0.04) better than the 3.49 g l^{-1} found with the Ebb-and-Flood system.

As can be seen in Table 4, total WUE was significantly affected by two main effects; irrigation systems (P=0.0001) and root media (P=0.01) as well as an interaction C x Spp. The 'constant level' system produced a total-WUE of 7.11 g l^{1}, significantly more than the 4.75 g l^{-1} found with the Ebb-and-Flood system. Where gravel was used as a root medium, the average total-WUE was 6.52 g l^{-1}, compared to 5.33 g l^{-1} for pumice.

Total-WUE as affected by an interaction between plant species and nutrient solution concentrations is illustrated in Fig. 10. 'Imbuya' seems to use water more efficiently than Swiss chard, especially when produced at a low conductivity level.

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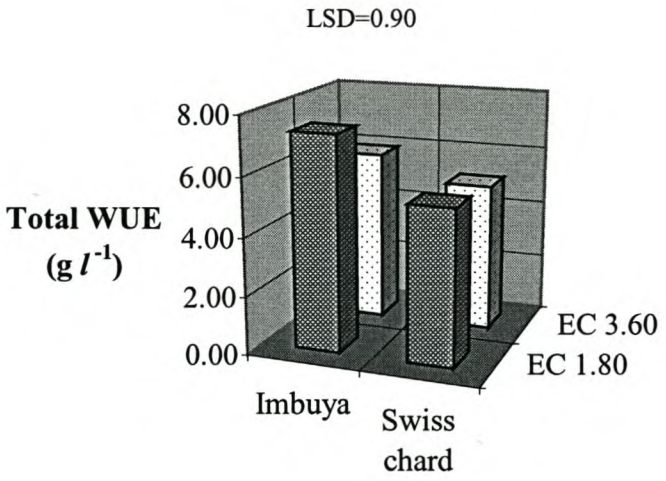

Fig. 10: Total water use efficiency (Total-WUE) affected by an interaction between conductivity levels of the applied nutrient solution and plant species.

3.7 Chlorophyll

Table 5 indicates that total chlorophyll levels were influenced by four interactions involving two factors each (S x M; S x Spp; M x Spp; M x Cult). Far less chlorophyll occurred in the leaves of plants with the 'constant level' irrigation system, only where gravel was used as a root medium (Fig. 11). Henceforth, chlorophyll levels were also affected by an interaction between species and root media (Fig. 12). Chlorophyll levels in Swiss chard leaves were lower than in 'imbuya' leaves, but only where gravel was used as a root medium. In Fig. 13, a very low chlorophyll content is shown in 'imbuya' leaves but only where a 'constant level' irrigation system was used. The last interaction that affected chlorophyll concentrations in leaves is illustrated in Fig. 14. Here it can be seen that the poor performance of Swiss chard on gravel (Fig. 12) was due to the poor performance of Lucullus where gravel was used as a root medium.

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3.8 Carotene

Total carotene concentrations in plant leaves were affected by an interaction involving three factors (S x C x Cult) (Table 5). In Fig. 15, the highest carotene concentration was found in the Swiss chard cultivar 'Ford-hook giant', when it was produced with the 'constant level' irrigation system at an EC of 3.6 mS cm^{-1}.

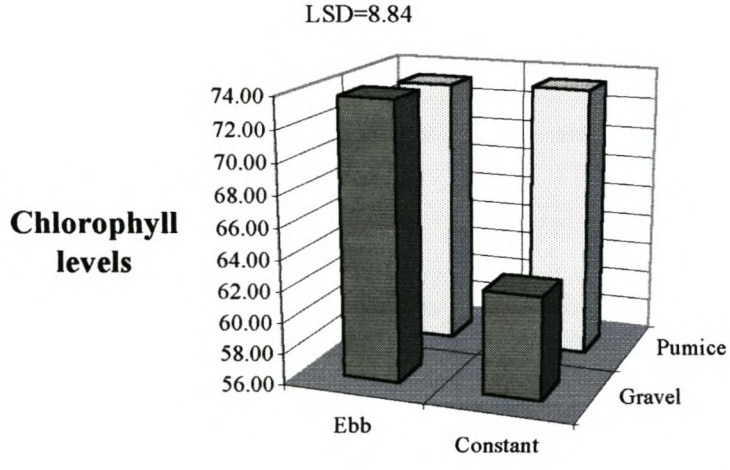

Fig. 11: Chlorophyll ($\mu g\ g^{-1}$) levels affected by an interaction between root medium and hydroponic systems (Ebb= Ebb-and-Flood; Constant= constant level used as a reservoir.

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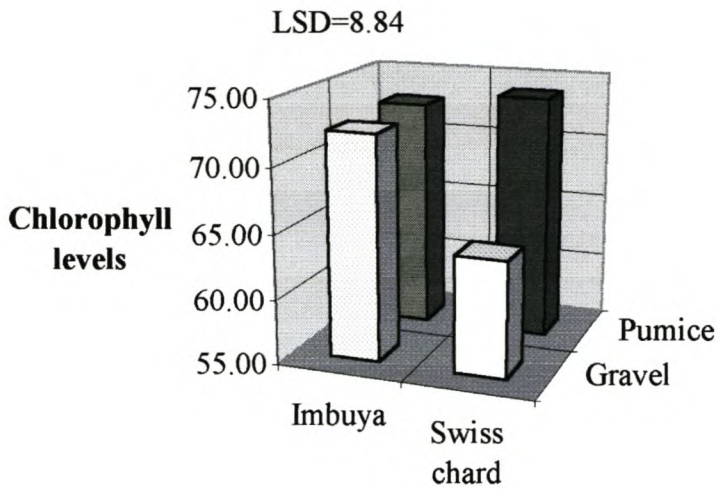

Fig. 12: Chlorophyll levels (μg g^{-1}) affected by an interaction between species and root media.

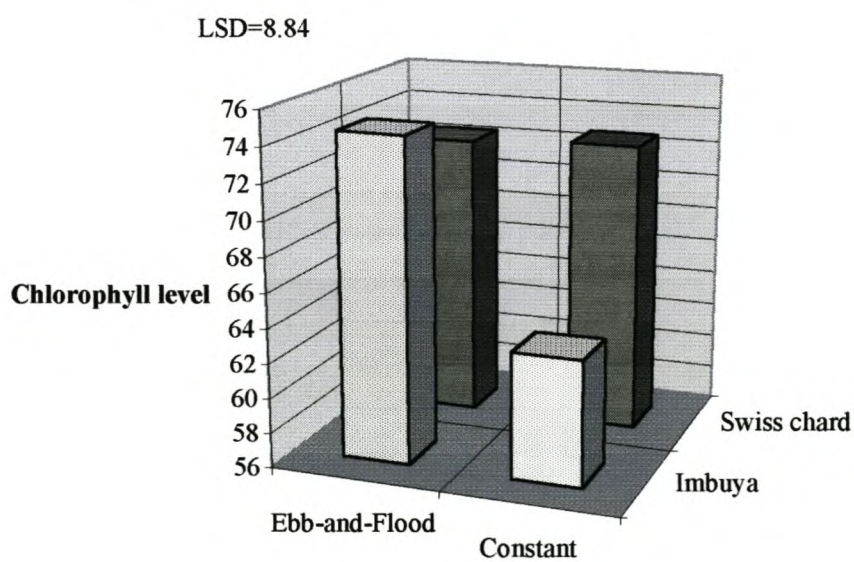

Fig. 13: Chlorophyll levels (μg g^{-1}) affected by an interaction between irrigation systems and plant species ('Constant'=Constant level used as a reservoir).

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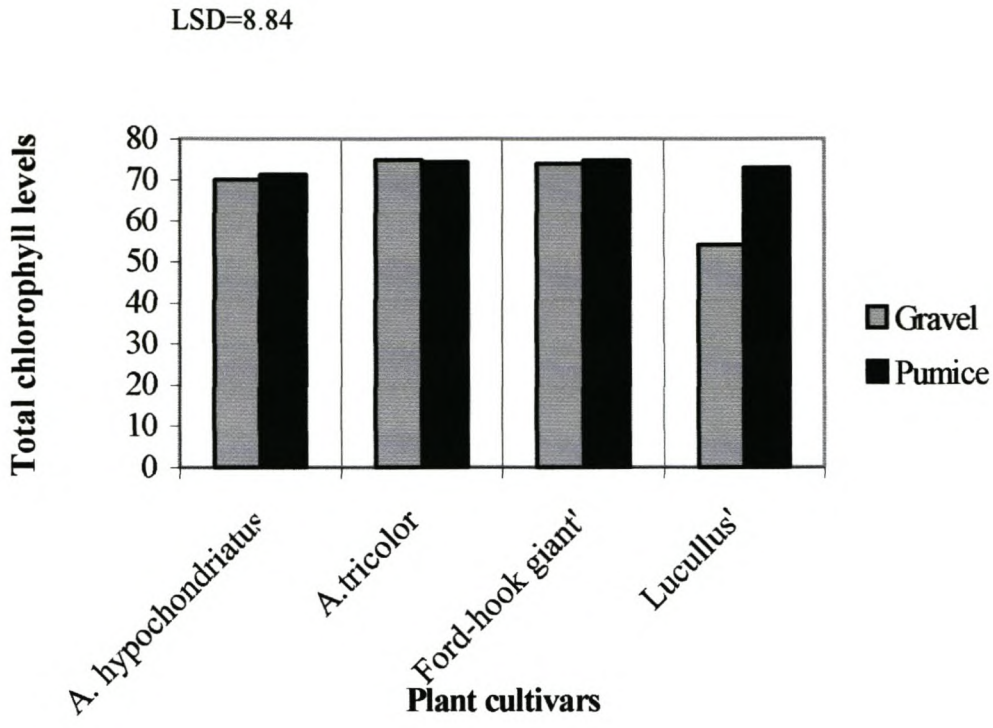

Fig. 14: Chlorophyll levels (μg g^{-1}) affected by the interaction between cultivars and root mediums.

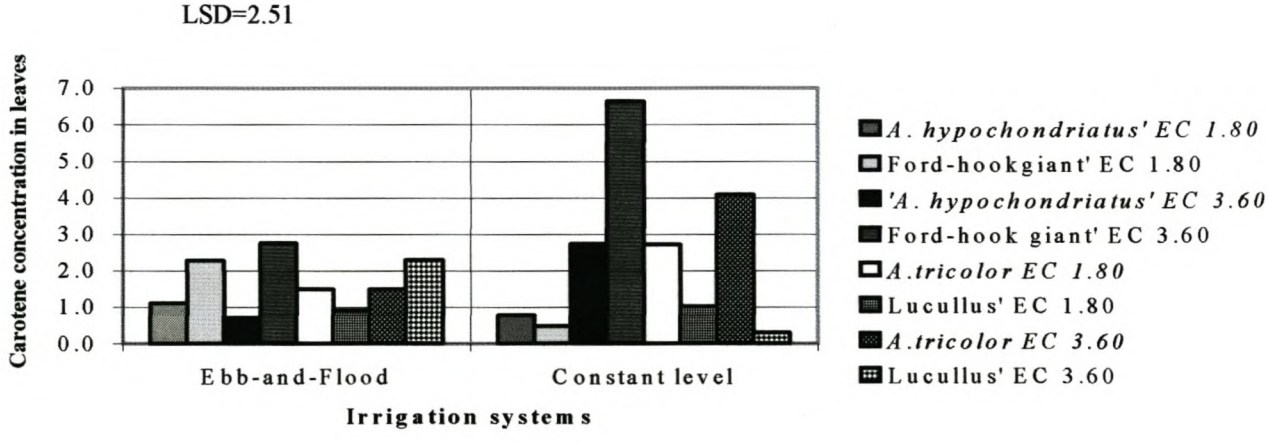

Fig. 15: Carotene levels (μg g^{-1}) affected by an interaction between irrigation systems, plant cultivars and conductivity levels of the nutrient solution.

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4. **Discussion**

The high EC nutrient solution had a tendency to further increase the salinity levels on the re-used nutrient solution (Fig. 3). Stanghellini *et al.*, (1998) reported that an 'Ebb-and-Flood' system may increase salinity. In this trial, however, this only happened when the high EC solution was used. Salinity levels with the 'Ebb-and-Flood' system, using saline water, increased from 3.60 to 4.74 mS cm^{-1} at the end of the experiment. With the 'constant level' system, the salinity levels only increased to 4.24 mS cm^{-1}, using the same nutrient solution. This was possibly due to slightly lower evaporation losses. The results indicate that the use of poor quality water to prepare a nutrient solution for re-circulation may increase the EC of the nutrient solution over a certain period of time, regardless of the type of irrigation system used. Similar results were reported in soils where poor quality water was used for irrigation (Rhoades, 1974; Adiku *et al.*, 2001).

pH levels were not influenced by the interaction between conductivity of the nutrient solution and the irrigation systems, as was the case with EC levels. However, a significant variation in pH resulted due to an interaction between irrigation systems and root media. The use of an 'Ebb and Flood' lowered the pH of the nutrient solution, only with pumice as substrate. This may indicate that some sort of acidification processes resulted due to the wetting and drying of pumice with the 'Ebb-and-Flood' system

The interaction affecting the foliage dry weight of the combined crops (Fig. 5), indicates that the 'Ebb-and-Flood' irrigation system generally outperformed the 'constant level' system. A possible explanation for the overall positive effect of 'Ebb-and-Flood' may be the associated forced movement of air with the rising and falling of water levels. The increased availability of oxygen and air exchange to the respiring roots could have contributed to improve plant development (Resh, 1997). The reason why this effect was smaller on pumice may be related to the porous nature of this medium with better gas exchange properties. If this is the case, the interaction illustrated in Fig. 6, shows that 'imbuya' responded better with the better-aerated root medium.

Root growth of 'imbuya' responded well to the 'Ebb-and-Flood' irrigation system with gravel as root medium (Fig. 7). The roots yielded about 75 g compared to 43 g

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with a 'constant level'. This might also be related to the good aeration and flexibility in root zone volume after the flooding stage (Combrink & Harms, 2001; Fischer *et al.*, 1990; Fyn, 1994). The best medium for the 'constant level' system was pumice where a root mass of 65 g was obtained with 'imbuya'. This may also be an indication that 'imbuya' performs better on the well-aerated pumice root medium, compared to Swiss chard.

Total biomass production with the 'Ebb-and-Flood' irrigation system did not seem to be affected by the two root mediums, as can be seen in Fig. 9. With a 'constant level' nutrient solution, however, a lower total biomass was found on both root mediums (gravel and pumice), but gravel yielded significantly less with only 89 g against 126 g with pumice. This better biomass production on the porous medium (pumice), only when the 'constant level' system was used, may indicate that root aeration was a limiting factor where the nutrient solution level was not fluctuated.

Total WUE with the 'constant level' production unit was higher than that of the 'Ebb-and-Flood' system as measured by the total biomass divided by the volume of water used. Plants grown on the 'Ebb-and-Flood' system were much bigger than those from the 'constant level' system as can be seen in the foliage dry mass (Fig. 5) and the total biomass (Fig. 9). Therefore these bigger plants used more water. This affected the results, indicating that the 'constant level' system has a better WUE than the 'Ebb-and-Flood' system. The high foliage WUE obtained with the 'constant level' system was not associated with a better foliage yield. Crop production should not only focus on how much water can be saved, but also on how much yield can be produced per volume of water consumed (Jansen *et al.*, 1981) or by increasing the harvest index or ratio of crop economic yield to the total dry matter production, while reducing the amount of water used (Howell *et al.*, 1990; Al-Jamal *et al.*, 2001). Total WUE was better on gravel, possibly due to pumice, being more porous than gravel, which might have enhanced the loss of water through capillary movement to the surface, enhancing evaporation. Root production of 'imbuya' decreased at the higher salinity levels, compared to Swiss chard, where the best yield was found at the high conductivity level (Fig. 8). This may indicate that 'imbuya' is less tolerant to saline conditions than Swiss chard. This is also visible in Fig. 10 where 'imbuya' benefited most where a low EC was used. A high total WUE was found with 'imbuya' at an EC of 1.80 mS

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cm^{-1}. The total WUE at this conductivity level was 7.35 g l^{-1} compared to 5. 90 g l^{-1} obtained at 3.60 mS cm^{-1}.

Where gravel was used as a root medium with the 'constant level' system, a low production of chlorophyll was found (Fig. 11). Swiss chard seemed to be responsible for this, producing very low concentrations of chlorophyll with gravel as a root medium (Fig. 12). When comparing Fig. 12 with Fig. 6, it can be seen that the leaf yield, with this same treatment combination, was relatively good. It seems as if the type of irrigation system had no influence on the chlorophyll concentration of crops except in Swiss chard, compared to a significant lower chlorophyll concentration with a 'constant level' where 'imbuya' was grown (Fig. 13). This can be attributed to the low concentration of chlorophyll in the 'Lucullus' cultivar with a gravel medium (Fig. 14).

Carotene is a series of hydrocarbons with formula $C_{40}H_{56}$, widely distributed as a yellow pigment in plants. This pigment is a precursor for vitamin A. The cultivar 'Ford-hook giant', grown at 3.6 mS cm^{-1} with the 'constant level' production system, had a carotene level of more than double that was found where it was grown with the 'Ebb-and-Flood' system (Fig. 15).

5. **Conclusion**

'Imbuya' had an overall better total biomass production than Swiss chard at a low conductivity and its total biomass production was also better on pumice. This specie seems to be less tolerant to saline conditions than Swiss chard and may also need a better aerated root medium.

The 'Ebb-and-Flood' irrigation system stimulated root development and biomass production, compared to the 'constant level' system. Henceforth, WUE on the 'Ebb-and-Flood' system was depressed, due to the fast growth of crops on this system.

Although the 'Ebb-and-Flood' system had a low WUE when compared with the 'constant level' system, it remains possible to overcome some shortcomings. Since the WUE was significantly higher on gravel, only this medium should be used for the 'Ebb-and-Flood' system. Gravel is cheaper than pumice and it is easily accessible.

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CHAPTER 3

Leaf yield of *Amaranthus hypochondriatus* L ('imbuya') affected by irrigation systems and water quality.

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Leaf yield of *Amaranthus hypochondriatus* L. ('imbuya'), affected by irrigation systems and water quality

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Abstract

'Imbuya's' foliage dry mass, leaf area index and foliage water use efficiency (WUE) was evaluated under field conditions at the Stellenbosch University experimental farm, during the summer of 2002. The University of Stellenbosch farm (33°55'S, 18°52'E) is situated in the cooler coastal wine grape-producing region of South Africa. This trial was conducted on an alluvial soil, having clay content of 25% and a pH of 5.9 (KC*l*). Three irrigation systems ('Drip', 'Ebb-and-Flood', and 'Flood') were evaluated using nutrient solutions at two electrical conductivity levels (1.80 and 3.60 mS cm^{-1}). Foliage dry mass, leaf area as well as water use efficiency was best with 'Drip' irrigation, when a nutrient solution with an electrical conductivity of 3.60 mS cm^{-1} was used. In spite of the fact that additional ground water was available for the 'Drip' and 'Flood' treatments, the 'Ebb-and-Flood' system outperformed the 'Flood' treatment, using nutrient solution with high EC, probable due to insufficient root aeration in the flooded soil. The fact that the 'Ébb-and-Flood' system gave poor results, with the low EC solution, may indicate that 'Flood' and 'Drip' treatments could have benefited from the available soil nutrients.

Keywords: Drip, Flood, leaf area, WUE

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1. Introduction

Growing plants with re-circulating water is attractive due to its water and nutrient saving potential (Stanghellini *et al.*, 1998). Further savings can be obtained by application of soilless culture techniques (Resh, 1978; Papadopoulos, 1991). Irrigation is one of the oldest and most widely known practices used in agriculture, dating back to ancient Egypt in about 5000 B.C., the Tigris-Euphrates Valley in about 3500 B.C., and India and China in about 3000 BC (Kleynhans, 1997).

The demand for water can be expected to escalate. After serving the increasing needs for domestic, industrial and mining uses, it is most likely that agriculture's share of the available water resources will be reduced to less than the current 50%. Thus, better utilisation of this resource is imperative. The selection of irrigation systems such as drip irrigation, sub-irrigation and sprinkler irrigation can affect water losses considerably (Wittwer & Honma, 1979; Water Research Commission, 1996). The correct choice of an irrigation system for specific conditions can be instrumental to substantial savings in water and electricity. Howell (2001) proposed different ways to enhance the water use efficiency (WUE) in irrigated agriculture: Increase the output per unit of water consumed, reduce water losses to unusable sinks, reduce water degradation, and to reallocate water to higher priority uses. Stone & Nofziger (1993) reported water savings by reducing evaporation from the soil surface by using mulches, especially when drip irrigation was used, and by interval timing between irrigations. Castilla *et al.*, (1998) reported that the WUE of greenhouse melons was higher with mulching. WUE is typically higher for autumn and winter grown crops compared to summer crops. Irrigation is often more efficient if it is done at night than during the day due to limited evaporation.

This field trial was done to compare the yield of 'imbuya', using water of different qualities and different irrigation systems.

2. Materials and methods

Three irrigation systems using nutrient solutions at two electrical conductivity (EC) levels, were factorially (3x2) arranged in a completely randomised block design with six replications. Plants were fertigated with nutrient solutions at EC levels of 1.80 and 3.60 mS cm^{-1}. The low and high EC solutions were prepared in the same way as described in Chapter 2 (Table 1 & 2). Micronutrients were added to both solutions as described by Combrink *et al.,* (1996). WUE and leaf area of 'imbuya' (*Amaranthus hypochondriatus)* was evaluated on an open field at the experimental farm of Stellenbosch University. The

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Stellenbosch University farm (33°55'S, 18°52'E) is situated at an altitude of 0177m above the sea level, in the cooler coastal wine grape producing region of South Africa, which have a relatively high annual winter rainfall. The trial was conducted during a relatively dry period of the year from 8 February until 15 March 2002. An alluvial soil with a pH of 5.9 (KC*l*) and clay content of 25% was used. The average weekly rainfall recorded was 0.85 mm, 0.00 mm, 0.29 mm, 0.03 mm, and 0.51mm. Average weekly maximum temperatures were 22.66 °C, 34.35 °C, 34.34 °C, 34.93 °C, 30.91 °C, and 30.27 °C. Meanwhile, the average weekly relative humidity was 69.00%, 55.80%, 64.00%, and 73.65%.

2.1 Ebb-and-Flood ('E & F')

This system was described in Chapter 2 (Fig. 1). Gravel (3 to 4 mm) was used as root medium in the top container. The other container on ground level contained the nutrient solution. Plants were watered using a 12 Volt caravan shower pump to lift the nutrient solution from the lower container through a rubber tubing to the top plant containing container. This closed system was fertigated five times a day for periods of 10 min each at 08h00, 10h00, 12h00, 14h00 and 19h00. Although the soil was not used as growth medium, the 'E & F' treatments were allocated to plots (3 m x 4 m) where the containers were placed and the plants were exposed to the same environmental conditions as the plants on the soil-grown treatments.

2.2 *Drip irrigation ('Drip')*

Plot sizes were 1.2 m^2 with 12 plants per plot, three (40 cm apart) rows with four plants each (30 cm apart). Drippers with an application rate of 2 *l* hr^{-1} were used. Plastic mulch (black at the bottom and white on top) was used to cover the drippers. Plants were watered from a 20 *l* container, used as a reservoir and raised to 1 m above the ground level to allow the water to flow through gravitational force. A measured volume of nutrient solution, the same volume used by the 'E & F' system the preceding week, was applied weekly.

2.3 Flood irrigation ('Flood')

The same plot size and plant spacing as for 'Drip' was used with 12 plants per plot (three rows with four plants in each row). Ridges (15 cm high) were formed on the four sides of the plot. Plants were irrigated weekly by applying the same volume as was used for 'Drip' on to the surface of the soil.

'Imbuya' (Amaranthus hypochondriatus L.*)* seedlings were used. Two seedlings of about 150 mm were transplanted on the 8th of February into each one of the 'E & F' experimental units, four weeks after sowing on the 11th of January 2002. These were both harvested on 15 March and the two plants from the centre of the middle rows of the 'Drip' and 'Flood'

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experimental units were harvested. The average volume of water used by plants on the 'E & F' system was calculated for each week after transplanting, for the two EC treatments separately. The volume of water used per plant in the 'E & F system was multiplied by the number of plants on the 'Drip' and 'Flood' experimental units (12) to determine the volume to be applied.

The above ground part of the plant was harvested five weeks after transplanting. Fresh and dry mass (60°C for 72 h) was measured and the leaf area of the plants was determined. A leaf area meter from LI-COR. Inc. Liconly, Nebraska (USA Model LI- 3100) was used. Foliage WUE was calculated by dividing the foliage dry mass by the volume of water used. The data was analysed with a SAS programme (SAS, 1978).

3. **Results**

3.1 Foliage dry mass

Table 1 shows a significant (P=0.0196) interaction between irrigation systems and conductivity, as illustrated in Figure 1. A 'Drip' system performed the best, especially when a nutrient solution with a high conductivity was used. Poor yields with no difference between the two nutrient solutions were found where 'Flood' irrigation was used. By comparing the 'E & F' system with 'Flood', the 'E & F' system outperformed 'Flood', only when the high EC nutrient solution was used (Fig. 1).

Table 1: Analysis of variance for foliage dry mass.

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Blocks	5	354.9	70.9	0.15	0.9783^{ns}
Irrigation (I)	2	6273.6	3136.8	6.61	0.0049 ***
Conductivity (C)	1	12844.4	12844.4	27.1	<. 0001***
I X C	2	4384.2	2192.1	4.6	0.0196*
Error	25	11855.2	474.2		
Total	**35**				

* = Significant at 5% ** = significant at 1% *** = significant at 0.1% ns = not significant
CV% = 2.20 %

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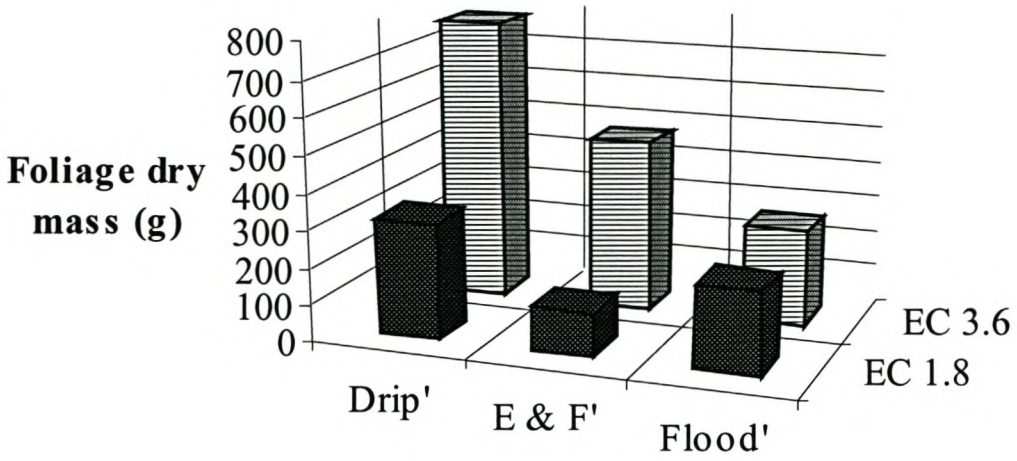

Fig. 1: Foliage dry mass influenced by the interaction between irrigation systems and conductivity of the nutrient solution ('drip= Drip irrigation; 'E & F'= Ebb-and-Flood irrigation system; 'Flood'= Flood irrigation system).

3.2 *Leaf area*

As was found with foliage dry mass, a significant interaction between irrigation treatments and EC levels was found (Table 2). This is illustrated in Figure 2. The leaf area was also significantly better when the high EC nutrient solution was used, only with the 'Drip' and 'E & F' treatments (Fig. 2). An increased EC did not have a significant effect when 'Flood' irrigation was used.

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Table 2: Analysis of variance for leaf area

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Blocks	5	112744.92	22549.0	1.4	0.2749^{ns}
Irrigation (I)	2	92468461.0	46234230.3	2777.0	0.0001***
Conductivity (C)	1	90417911.4	90417911.4	5429.9	0.0001***
I X C	2	26994461.0	13497230.4	810.6	0.0001***
Error	25	416297.3	16652.0		
Total	**35**				

* = Significant at 5% **= significant at 1% *** = significant at 0.1% ns = not significant
CV% = 3.94

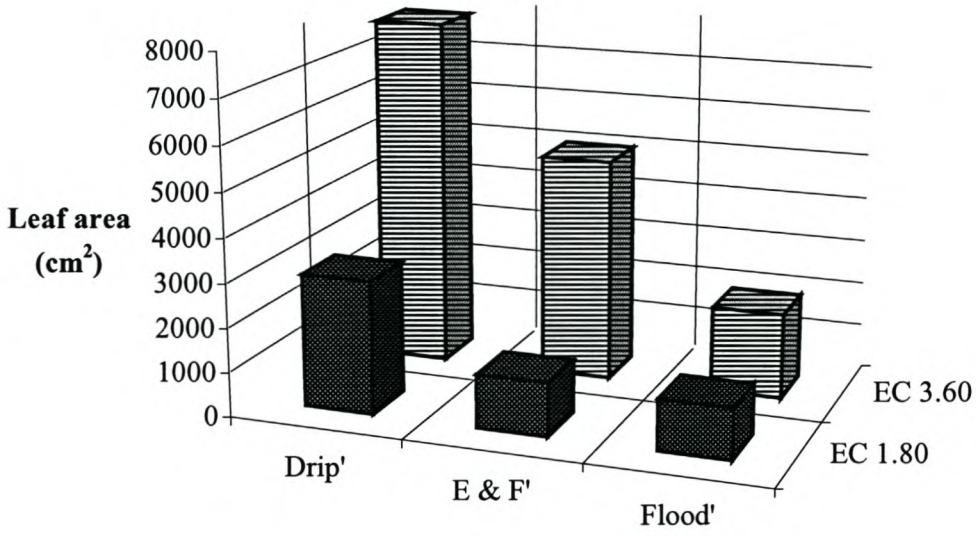

Fig. 2: Leaf area affected by an interaction between irrigation systems and electrical conductivity (EC) of the nutrient solution ('Drip' = Drip irrigation; 'E & F'= Ebb-and-Flood irrigation system; 'Flood'= Flood irrigation system).

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3.3 *Water use efficiency (WUE*

Foliage WUE was significantly (P=0.0001) affected by an interaction between irrigation systems and the conductivity levels of the nutrient solutions (Table 3). This interaction indicates that the foliage WUE was better at EC 3.60 mS cm^{-1}, only where 'Drip' and 'E & F' systems were used. The foliage WUE obtained with these irrigation systems were 80 g l^{-1} and 60 g l^{-1}, respectively. At EC 1.80 mS cm^{-1}, the 'E & F' system produced the lowest foliage WUE, lower than that of the 'Drip' and 'Flood' irrigation systems (Fig. 3).

Table 3 Analyses of variance for foliage-WUE (Water use efficiency).

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Blocks	5	44.9	9.0	0.4	0.8258^{ns}
Irrigation (I)	2	7956.1	3978.1	189.1	0.0001^{***}
Conductivity (C)	1	3733.2	3733.2	178.0	0.0001^{***}
I X C	2	2973.9	1487.0	71.0	0.0001^{***}
Error	25	525.8	21.0		
Total	**35**				

* = Significant at 5% **= significant at 1% *** = significant at 0.1% ns= not significant
CV% = 10.94

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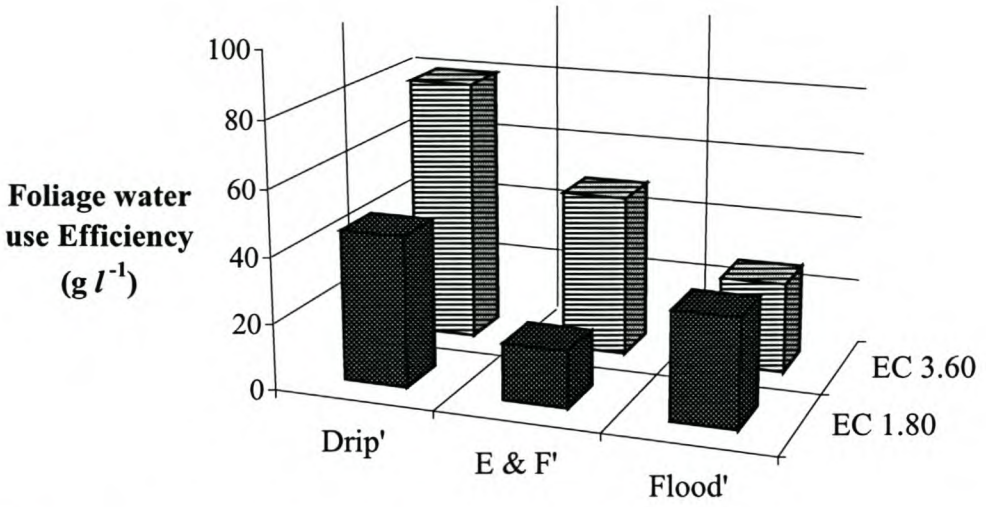

Fig. 3: Foliage water use efficiency is affected by an interaction between irrigation systems and conductivity of the nutrient solution.

4. **Discussion**

High salinity levels lower the yield of most crops (Stanghellini *et al.*, 1998). Reduced yields of tomatoes due to salinity were reported in numerous studies (Combrink, 1998; Soria & Cuartero, 1998; Schwarz & Kuchenbuch 1998;). Potato tuber yields are also said to be sensitive to salinity (Karam *et al.,* 1998). However, the results obtained in this study indicate that a nutrient solution with an EC of 3.60 mS cm^{-1} did not negatively affect foliage dry mass, the leaf area or the foliage WUE of 'imbuya'.' Imbuya' produced significantly better where poor quality water (EC 3.60) was used for 'Drip' and 'E & F' irrigation systems (Fig. 1; Fig. 2). This may indicate that 'imbuya' prefer high EC conditions to be able to withstand extreme heat or summer conditions. It is also possible that Na is an essential nutrient for 'imbuya', as is the case with other C4 plants (Brownell & Crossland, 1972). The results obtained in the greenhouse (Chapter 2), where low EC of 1.8 mS cm^{-1} gave the best yields was conducted under mild conditions. Temperature (25/12 ^{o}C), wind, relative humidity (40-90%) and solar radiation was controlled in the glasshouse. The field trial was conducted at varying and extreme summer temperatures (Day maximum 27-39 ^{o}C) in the field.

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The better leaf area and better foliage dry mass found with 'Drip', compared to 'E & F' may be associated with the use of a soil mulch. The use of drip with a plastic mulch resulted in a high yield probably due to a better utilisation of the nutrient solution. This improved used of water might have been caused by the reduction of evaporation from the soil surface Castilla *et al.*, (1998) and Stone & Nofziger, (1993). Numerous studies indicate that 'Drip' systems ensure a high WUE, when compared with other open field irrigation systems (Dinar, 1993). The poor performance of 'Flood' can probably be related to poor root aeration. To be able to judge the relatively poor performance of the 'E & F' system, it should be mentioned that unexpected rain was received only two weeks before the planting date. This allowed the soil to reach field capacity and water from the subsoil probably benefited the 'Drip' and 'Flood' treatments. In addition, it should be noted that the 'Ebb-and-Flood' system produced a better foliage yield than the 'Flood' treatment, only where the high EC nutrient solution was used. Extra nutrients from the soil could have benefited the 'Drip' and 'Flood' treatments where the low EC solution was used, as can be seen in Fig. 1. Another possible explanation for the beneficial effect of the high EC treatment on the 'E & F' and 'Drip' irrigation systems under summer conditions may be related to hardening of the seedlings. The mild water stress induced by high EC treatment, could have triggered ABA production (Wilson, 1976) that could have increased the plant's tolerance to the heat stress that occurred 19 days after transplanting. Temperatures went to up to 39.00 ^{o}C, far above the weekly average maximum temperatures of 34.34 ^{o}C. The 'Flood' treatments were probable stressed due to insufficient root aeration explaining their lack of reaction to the EC induced stress. However more work is needed to test this theory.

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Chapter 4

SUMMARY

Invention and innovation of agricultural technologies, involves the changing from old practices (cultivation; irrigation) to new and improved technologies. Improved technologies have been observed to have a better chance of increasing water use efficiency (WUE) of a particular crop. With the increasing world population, reaching approximately six billion, and the increasing demand for water by agricultural, domestic and industrial use, this has created a major problem to most of the developing countries. Poor management and poor utilization of water has led to a drastic decline in the quality and quantity of water resources. The need was identified to develop a cheap vegetable production unit, using the absolute minimum of water, while maintaining a high production.

Two trials were conducted, the first trial under controlled conditions and the second under open field conditions. In the first trial, Swiss chard and 'imbuya' were grown in gravel and pumice as root media. In addition, 'Ebb-and-Flood' and a 'constant level' system, as well as a nutrient solution at two electrical conductivity levels (EC) 1.80 and 3.60 mS cm^{-1} were evaluated. The results of this (2x2x2x2) factorial experiment showed that 'imbuya' had an overall better total biomass production than Swiss chard at a low conductivity and its total biomass production was also better on pumice. 'Imbuya' seems to be less tolerant to saline conditions under controlled environmental conditions than Swiss chard and may also require a better aerated root medium. The 'Ebb-and-Flood' irrigation system stimulated root development and biomass production, compared to the 'constant level' system. Henceforth, the WUE with the 'Ebb-and-Flood' system was relatively poor due to the fast growth of crops with this irrigation system. A combination of the 'Ebb-and-Flood' ('E & F') system with gravel as a root medium produced the best results at a low EC, when 'imbuya' was used. This promising combination was chosen to be compared with 'Flood' and Drip' irrigation systems in an open field trial.

In the field trial three irrigation systems ('Drip', 'Ebb-and-Flood' and 'Flood'), were evaluated using nutrient solutions at two electrical conductivity levels 1.80 and 3.60 mS cm^{-1}. Foliage dry mass, leaf area as well as WUE were the best with 'Drip' irrigation, when a nutrient solution with an electrical conductivity of 3.60 mS cm^{-1} was used. 'Ímbuya' showed significant better yields where poor quality water (EC

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3.60) was used for 'drip' and 'E & F' systems. This may indicate that 'imbuya' prefer saline water under extreme hot conditions. It is possible that Na is an essential nutrient for 'imbuya', as is the case with other C4 plants as was reported elsewhere. The fact that the plants performed better with a high EC nutrient solution in the field, compared to the greenhouse trial, may be related to the contrasting climatic conditions and a possibility that the high EC helped to harden the plants. The use of drip with a plastic soil cover mulch gave a high yield due to better utilisation of the nutrient solution. The use of a plastic mulch on the 'Ebb-and-Flood' system to lower evaporation or the temperature of the root medium need further investigation.