SUSTAINABLE WATER USE IN PROTECTED MEDITERRANEAN HORTICULTURE

HORTIMED

Deliverable n. 8

A blueprint for optimal management of multiple-quality water-resources

IMAG

Cecilia Stanghellini & Frank Kempkes

11-07-2003

Contents

1. Definitions, notation and units

Closed system is a definition that applies to all growing systems, whereby the water drained from the root zone can be recollected and [partly] re-used for irrigation of the same crop. However, even with total re-utilisation of drain, such systems have an outlet (the water and nutrients uptake by the crop) and an inlet (the water and fertilisers that are injected to balance losses, and non useful salts that may come with the water).
Such systems differ according to the way fertilisers are added to the loop, as shown in the scheme below. The "Dutch" system (that is sometime applied in the Mediterranean region as well) requires on-line control of EC and ph, and automated injection of chemicals to meet pre-set targets of both. The "Mediterranean" system is suitable for manual operation: an amount of nutrient solution is prepared and then used to refill the system until it runs up. Either way, when the water used for refill contains salts that are not fully absorbed by the plants, these will accumulate in the substrate-mixing tank loop, and make it necessary to refresh (leaching) at some time.

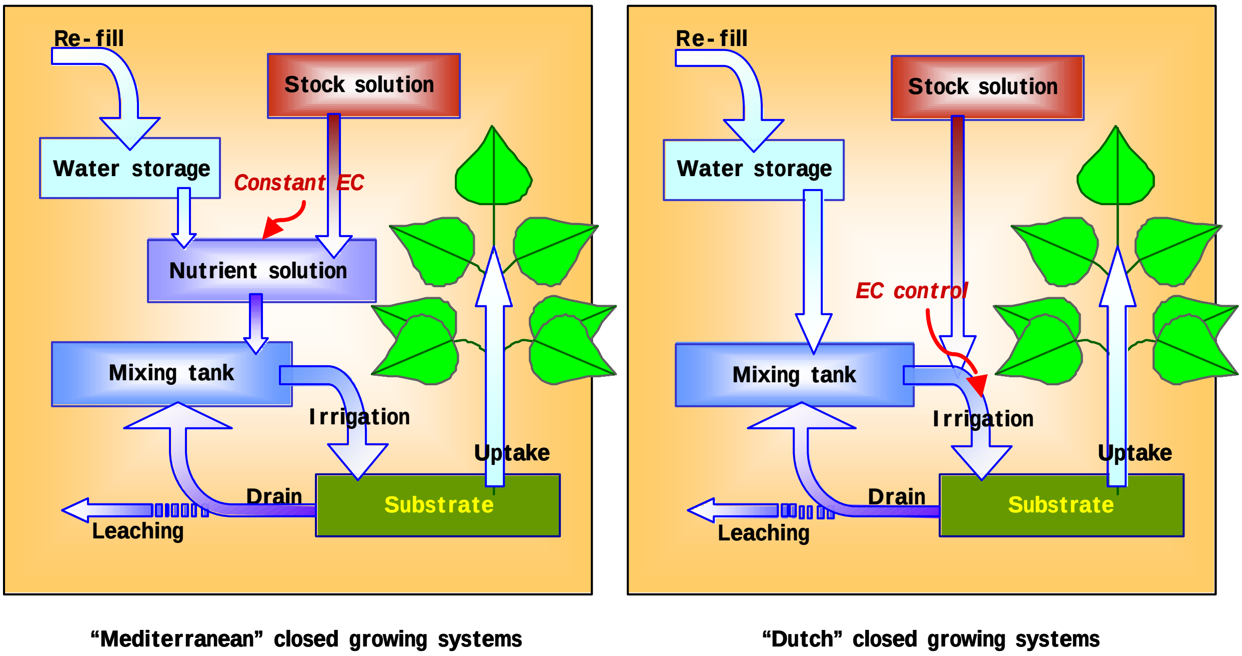

Figure 1. *Schematic definition of the storage volumes and flows in closed systems. There are two main classes, in view of the way water and nutrients are refilled into the loop. In the Mediterranean system, the nutrient solution with the desired concentration is prepared in advance and used to re-fill the mixing tank. In the Dutch system, nutrients are added directly to the water drawn from the mixing tank, whenever its EC is lower than a pre-set level.*

Volumes are represented by the capital letter V, the subscript indicating the kind of volume. Unit is m^3.

Volume *(V, m^3)* is the volume of water in the system, that is the water contained in the storage tanks, in the substrate and in the connecting pipes

Water use *(V_R, m^3)* is the amount of water that is added (re-fill) to the system during a given interval. In a "Mediterranean" system this is equal to V_{NS} that is, the amount of nutrient solution added to the mixing tank in a given interval.

Irrigation *(V_I)* is the amount of water supplied to the crop during a given interval. The word ***dose*** indicates the volume supplied during one irrigation event.

Water uptake *(V_U)* is the amount of water that is used by the crop in a given period, that is transpiration + biomass growth. Biomass growth is usually less than 10% of transpiration.

Potential evaporation *(V_{EP})* is a standard measure of the "evaporative demand" of a given climate. It estimates the water uptake by a short, full covering, well watered crop. In greenhouses it depends primarily on sun radiation, secondly on humidity and, to a minor extent, on temperature. Meteorological services provide it routinely, for field conditions.

Drain *(V_D)* is the amount of water flowing out of the root zone in a given time.

Drain percentage is a common way to gauge drain. It is the fraction (%) of irrigation, that flows out of the root zone. Since in closed systems this water is at least partly reused, drain is not equal to waste, in such systems.

Leaching *(V_L)* is the amount of water flushed out of the system, in a given time interval.

Leaching fraction *($LF ? V_L / V_R$)* is the ratio between the amount of water that is flushed out of the loop for refreshing, and water use in a given period.

Leaching requirement *($LR ? V_L / V_U$)* is the ratio between the amount of water that is flushed out of the loop for refreshing, and the amount of water uptake by the crop, in a given period. Leaching requirement as defined here can well exceed 1.

Specific volumes, that is volume per unit crop area, are indicated by the small letter v, subscripts as above. Unit is m^3/m^2 or, when more practical, mm.

Time unit is hour [h]

Flow rate (that is, volume per unit time) is indicated by the capital letter Q [m^3/h] followed by the subscripts as defined above

Flux rate density (volume per unit square meter, per hour) by the small letter q [$m^3/(m^2 h)$ or mm/h]

Concentrations are represented by the capital letter C, the subscript indicating the volume it refers to. A superscript may be used to indicate the element whose concentration is considered. Unit is mmol/l.

Electrical conductivity is indicated by the symbol EC and its unit are dS/m.

EC is a measure of the amount of salts (active ions) dissolved in water. There is a link between EC and osmotic pressure of the nutrient solution. Yields are reduced by EC according to a crop-specific yield response curve.

Yield response curve normalised (fraction of yield at low EC) plot of actual yield vs EC in the root zone. It is described by two parameters: *threshold* (lowest EC at which a decrease in yield can be detected) and *slope* (steepness of the [linear] decrease thereafter). The effect of EC on yield (slope) increases with potential evaporation. This means that at a given EC there is more yield loss under high potential evaporation (Li et al., 2001).

Rules

$$V_R \; ? \; V_U \; ? \; V_L$$

$$V_U \; ? \; V_I \; ? \; V_D$$

$$V_R \; ? \; (1 \; ? \; LR) ? V_U$$

$$LR \; ? \; \frac{LF}{1 \; ? \; LF}$$

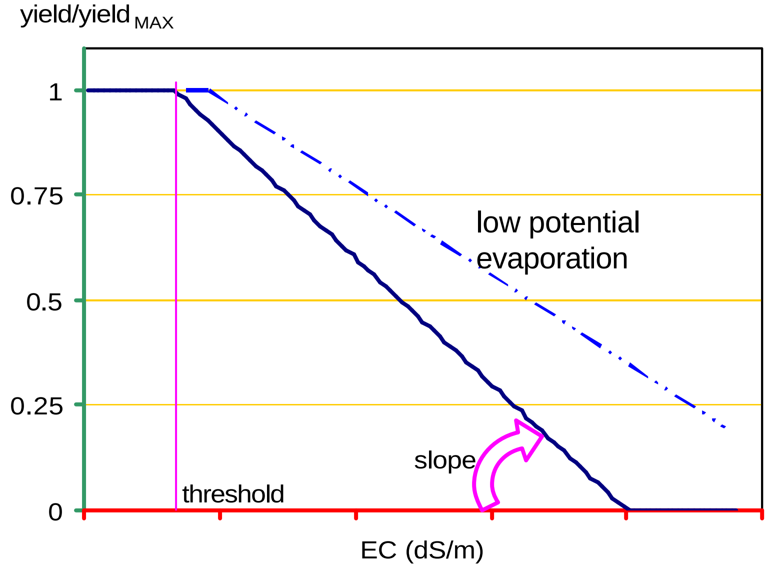

Figure 2. *Yield decrease with salinity in the root zone. The curve is usually described by the two crop-specific parameters: threshold is the lowest salinity at which a yield decrease can be observed, slope is the steepness of the decrease. Usually a low-potential evaporation environment decreases the slope*

Operating EC *(EC_O)* is the [mean] EC desired for the system

Set point EC *(EC_{SP})* is the desired EC of the irrigation in a Dutch system. Nutrients are added in the irrigation flow up to the EC_{SP}, whenever the EC in the mixing tank is lower than the set point.

Leaching EC *(EC_{MAX})* is the “ceiling” EC, that is the value beyond which the system is not allowed to go. When EC_{MAX} is reached, the system is [partly] flusched.

2. Modeling fertilisers' behaviour

As we have seen in Fig. 1, a growing system can be represented by several storage volumes, each with associated properties. The properties of a volume depend on its kind, its capacity and the flow in and out of it. Fresh water is added at one point, whereas outflow can be both uptake by the crop and possibly leaching out of the system. For instance, Figure 3 shows the main volumes and flows, for a system like the "Dutch" model in Fig. 1.

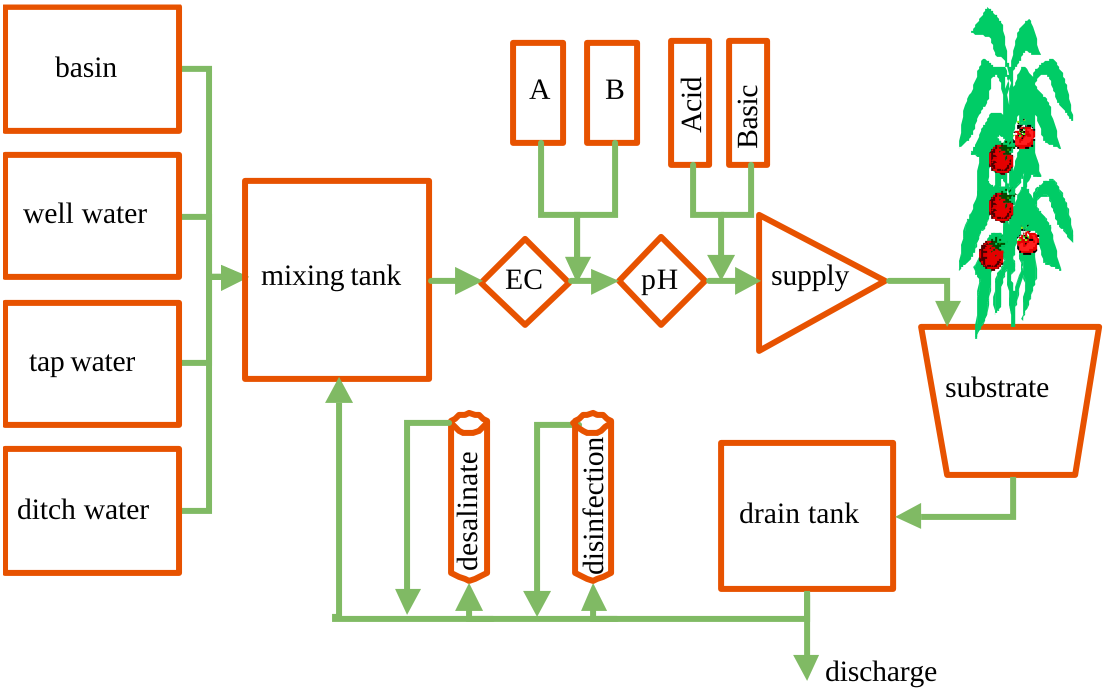

Figure 3. *Model of a closed system such as the Dutch option I of Fig. 1. Water resources are characterized by concentration of the main ions, maximal flow and maximal capacity. The storage volumes in the systems are characterized by maximal capacity and the ion concentration is calculated at each iteration, uptake of water and salts by the crop is modelled.*

In most cases the mutual dependency of all variables ensures that a simulation model can best describe such a complex system. We have implemented such a model in Mat-Lab, with a time-interval for the simulation of one hour.

The model accounts for several water sources, such as a basin, well, tap and ditch water. Each source has a capacity, a maximum flow and a quality. The quality of the resources is represented by an array giving the concentration of single ions, from which the EC is determined. The flow from the resources and the drain are combined in the mixing tank. At an irrigation event, a flow is withdrawn from the mixing tank. The EC of this supply water is controlled and if the EC is below the set point, fertilizers are added (from concentrated solutions in tanks A and B). Usually the pH is controlled and regulated afterwards.

The main farm-specific data are:

- Area of protected cultivation [m^2]
- Capacity drain water tank [m^3]
- Capacity basin (rain water) [m^3]
- Maximum capacity well [$m^3.h^{-1}$]
- Maximum capacity ditch [$m^3.h^{-1}$]
- Maximum capacity tap [$m^3.h^{-1}$]
- Capacity of the des-infection and desalinization equipment [$m^3.h^{-1}$]

For instance, the substrate is modelled as an object with a fixed maximum water retention capacity and an actual capacity (l.m^{-2}). The maximum capacity is calculated by multiplying the substrate volume with the retention capacity of this type of substrate. For rockwool slabs for instance, this is about 80 %. The actual water capacity of the substrate varies because there is an unbalanced supply and drainage. Each hour the water and ion balance of the substrate is updated. The supply of water and ions consists of supply water out of the mixing tank (via the dose unit), according to a pre-set irrigation strategy. The depletion is the sum of the water and ion uptake by the crop and the drain flow out of the substrate. There is drain flow only when the maximum capacity of the substrate is exceeded. The drain volume is then equal to the excess volume. The water balance of the substrate can be calculated by:

$$v_{S,new} \; ? \; v_{S,old} \; ? \; ?q_I \; ? \; q_U \; ??t \qquad (1)$$

where v_S indicates specific water volume in the substrate ($l\ m^{-2}$), q_I and q_U are respectively the irrigation water flow and water uptake ($l\ m^{-2} h^{-1}$) and t is the time interval. If the new actual water volume exceeds the maximum capacity $v_{S,max}$, a drain flow is calculated by:

$$q_D \; ? \; (v_{S,new} \; ? \; v_{S,max}) / t \qquad (2)$$

The concentration $C^n(mmol\ l^{-1})$ of ion n in the substrate is calculated as follows. The ion balance of the substrate is:

$$q^n_{in} \; ? \; q_I \; ?C^n_{in} \qquad\qquad q^n_{out} \; ? \; C^n_U \; ?q_U \; ? \; q_D \; ?C^n_{S,old} \qquad (3)$$

with q^n_{in} the supply of ion n ($mmol\ m\ {-2}\ h{-1}$) and q_U and C^n_U respectively the uptake water flow ($l\ m^{-2}\ h^{-1}$) and the uptake concentrtion of ion n ($mmol\ l\ {-1}$). The new ion concentration of the substrate is then:

$$C^n_{S,new} \; ? \; C^n_{S,old} \; ? \; (q^n_{in} \; ? \; q^n_{out}) \; ?t / v_{S,new} \qquad (4)$$

Therefore, for a good prediction of the salt accumulation in the system, the uptake of nutrients by the crop must be known. Literature tells that uptake is for some ions driven by transpiration, and for others by assimilation. The model calculates transpiration and assimilation through two subroutines developed respectively by Stanghellini (1987) and Gijzen (1992), the latter based on the photosynthesis model of Farquhar and von Caemmerer (1982). Both subroutines require indoor climate to be known. Further, the user is required to give in the “crop sheet” the proportionality factor for uptake of the main nutrients and the process to which uptake is proportional. Such factors can be found for some crops in the literature (Sonneveld 2000).

Data from the experiment described above have been used to validate the model, by comparing calculations with two-weekly analyses of root extracts. Results are reported by Kempkes & Stanghellini (2002) who have shown that the model can predict rather well the evolution of most important minerals in the system, that is: N, K, P, S,

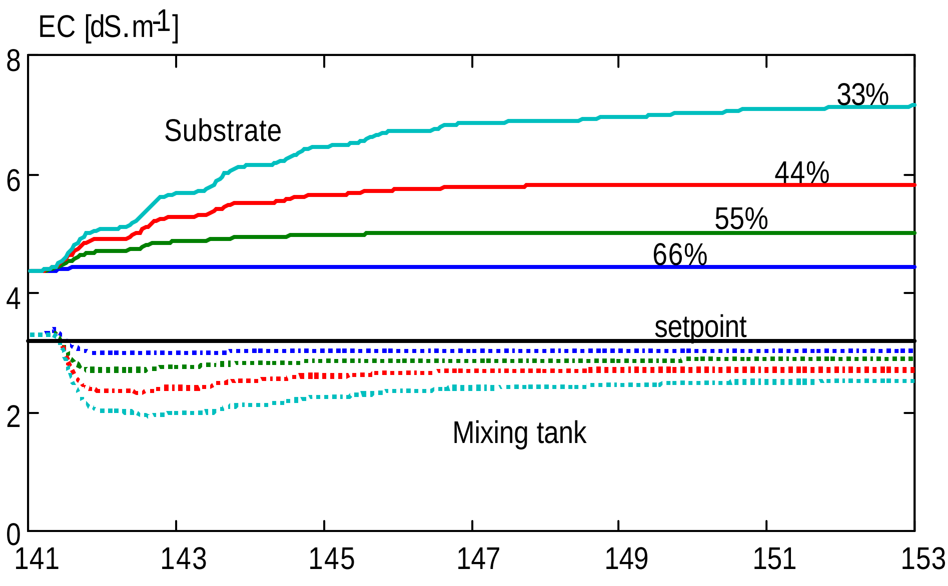

Figure 4. *Evolution of EC in the substrate and in the mixing tank of a system such as pictured in Fig. 8, calculated for various drain percentages. Water drawn from the mixing tank is brought up to the set point EC (here dS m-1). The evolution was calculated through real weather values, for the period indicated (DOY=Day Of Year)*

With a small drain fraction, unused nutrients accumulate in the substrate, resulting in a relatively higher EC there. Obviously, as the drain fraction increases, unused nutrients are brought fast back into the mixing tank, so that the EC there is closer to the set point (3.5 in this case). As a consequence of this, fewer nutrients are added to the system at each irrigation event.

2.1.2 Effect of EC-set point

Let's assume the refill water has a concentration of 20 mmoll^{-1} Na. As any crop hardly absorbs sodium, Na will accumulate. Now we analyse the effect of three different strategies on the concentration of nutrients.

1. The set-point EC of irrigation is fixed beforehand on a level of 3.5 dS.m^{-1} (Dutch system)
2. The set-point of irrigation is steadily above the EC in the mixing tank with an offset of 0.5 dS.m^{-1} (Mediterranean system).
3. The set-point of irrigation is fixed and 50 % of the system volume is leached whenever the Na level in the substrate reaches the level of 40 mmol l^{-1}.

Figure 4 displays the effect of each one of these strategies upon the evolution in time of:

a. the overall EC level in the substrate; b. the concentration of useful nutrients and c. the accumulation of sodium.

As it may be observed, the Dutch strategy (1) results in a fast depletion of nutrients, strategy 2 maintains the required concentration of nutrients but results in a fast increase of EC, and strategy 3 maintains the EC within boundaries, without depletion of nutrients. Obviously it requires more input of both water and nutrients.

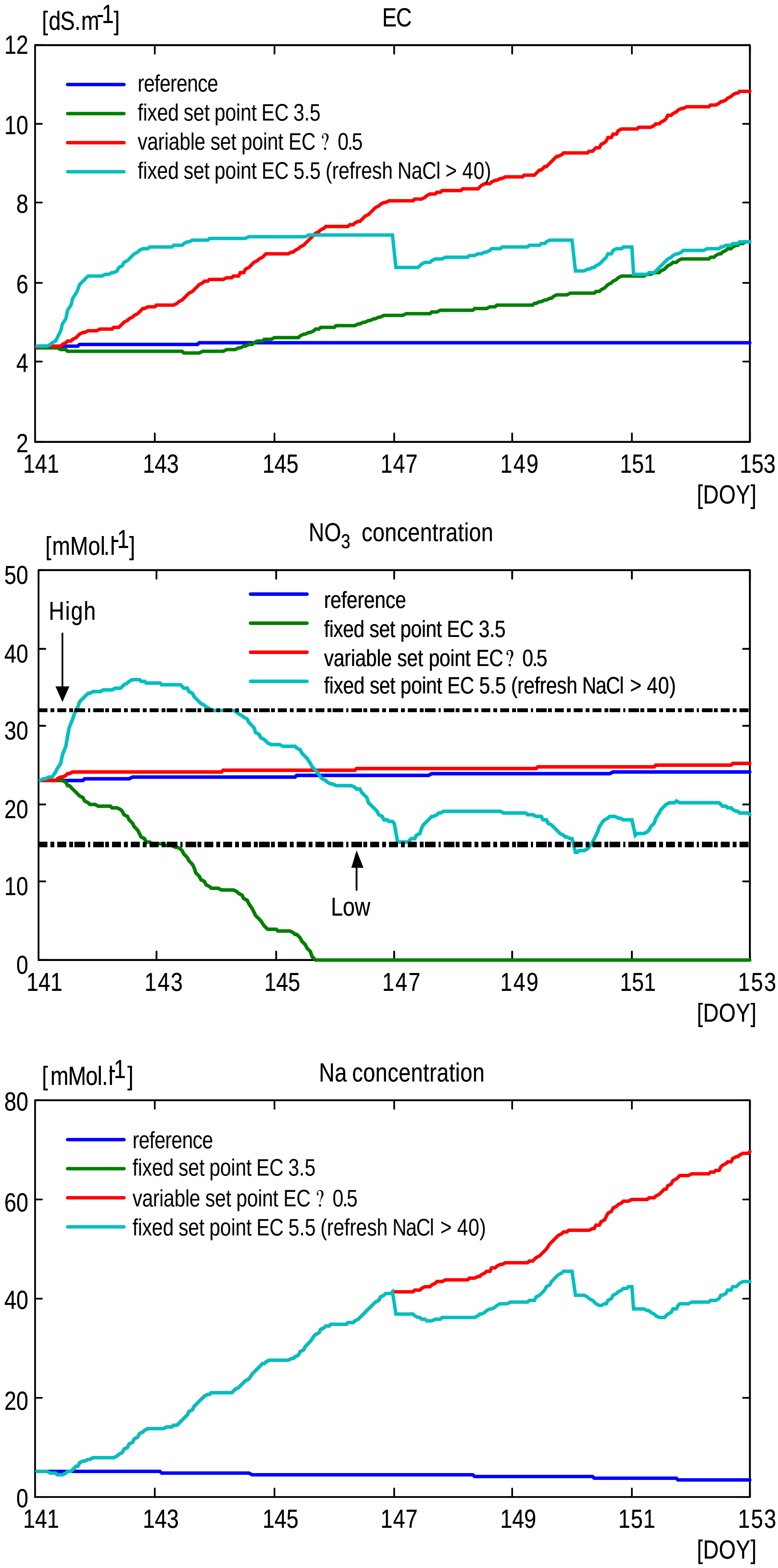

Figure 5. *Evolution in time of concentrations in a closed sytem, re-filled with water containing 20 nmmol l-1 Na, and managed according to three strategies, as indicated.*
Top: trend of EC;
Center: trend of NO_3 concentration, showing the fast depletion with a fixed EC-set point. The lines marked "high" and "low" indicate the regions where variations in NO_3 are considered acceptable (De Kreeij et al., 1999);
Bottom: trend of concentration of Sodium. The lines for the fixed set point and variable set point are coincident, since accumualtion of sodium in a system that is not refreshed is independent from the strategy (it is determined solely by water uptake).

3. Accumulation of non-useful salts

We have seen that when the water used to re-fill the system contains salts that are not necessary to the crop, since at most a very small fraction may be absorbed passively, such salts tend to accumulate in the system. The rate of accumulation (and the required leaching) may be easily estimated through a number of simplifying assumptions.

As explained at length in Deliverable 6, let's assume that the system is very well mixed and there is no buffer and no delay. This applies, for instance, to a Nutrient Film (NFT) system. Let the progression of time be represented by the dimensionless ratio V_U/V, that is the ratio between the amount of water taken up by the crop in a given time interval t, and the total volume of water in the system (Carmassi et al., 2002). Let the absorption of ion *n* be proportional to the concentration of that ion in the system:

$$p = \frac{C_U^n}{C^n} \qquad (5)$$

With $C^n{}_U$ the uptake concentration of ion n, $mol\ l^{-1}$, C^n the concentration of ion n in the system, and *p* a proportionality factor, defined by Eq(5). For most horticultural crops *p* for the non useful ions is at most 0.2 (Sonneveld, 2000). In this case, Na concentration, for instance, is described by a growth equation of the form:

$$\frac{dC^{Na}}{dt} = p\frac{V_U}{V}\left(\frac{C_R^{Na}}{p} - C^{Na}\right) \qquad (6)$$

where $C^N{}_R$ is the Na concentration of the re-fill water, $mol\ l^{-1}$. Eq (6) can be solved and yields:

$$\frac{C^{Na}}{C_R^{Na}} = \frac{1}{p} + \left(1 - \frac{1}{p}\right)\exp\left(-p\frac{V_U}{V}\right) \qquad (7)$$

This result is analysed in Figure 6, that shows that the accumulation diverges from a straight line with the ratio of uptake to volume, in the measure that *p* is large.

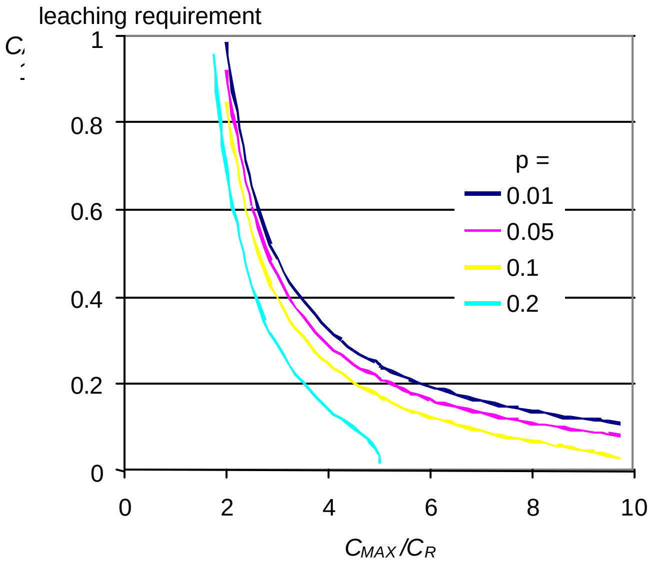

Figure 7. *Leaching requirement (fraction of water uptake) vs the ratio between the concentration at which the system is flushed and the concentration of the water resources. Uptake concentration is assumed to be proportional to the prevailing concentration, through the factor p*

As Fig. 2 shows, yield decreases with the concentration of salts in the system. At a given concentration yield is so much decreased that the culture is not profitable anymore. Let's stick to Na and call this concentration C^{Na}_{MAX}. Let's also assume that when this concentration is reached, the grower is able to flush the whole volume of water in the system and start again. Eq(7) can be rearranged to calculate the leaching requirement as a function of the ratio of the maximum concentration to the re-fill concentration:

$$LR \;?\; \frac{V}{V_U} \;?\; ?\, \frac{p}{\ln\left(1 \;?\; p\,\frac{C^{Na}_{MAX}}{C^{Na}_{R}}\right) \;?\; \ln(1 \;?\; p)} \qquad (8)$$

Figure 7 shows how *p* and the maximum allowed concentration affect the leaching requirement. A more practical example is in Figure 8, where the leaching requirement can be estimated as a function of the concentration of the refill water, for various maximum concentrations, indicated at right, and two values of the factor *p*. It may be gathered from Fig. 8 that the effect of *p* in reducing leaching requirement is most evident at relatively low concentrations of the refill water. At higher values (that is, $C^{Na}_{R} \;?\; pC^{Na}_{MAX}$) the leaching requirement may be roughly estimated through:

$$LR \;?\; \frac{C^{Na}_{R}}{C^{Na}_{MAX}}\left(\frac{C^{Na}_{R}}{C^{Na}_{MAX}} \;?\; 1\right) \Big/ \left(1 \;?\; \frac{p}{2}\left(\frac{C^{Na}_{d}}{C^{Na}_{MAX}} \;?\; 1\right)\right) \qquad (9)$$

Although both Eq(8) and (9) may seem of little practical use, there is a very important conclusion to be drawn here, and it is that the leaching requirement with a water source containing non useful salts, is determined solely by the concentration of the water source and the maximum concentration allowed in the system. The effect of any affinity of the crop with the salt, that is the crop absorbs a fraction of it, is of secondary importance.

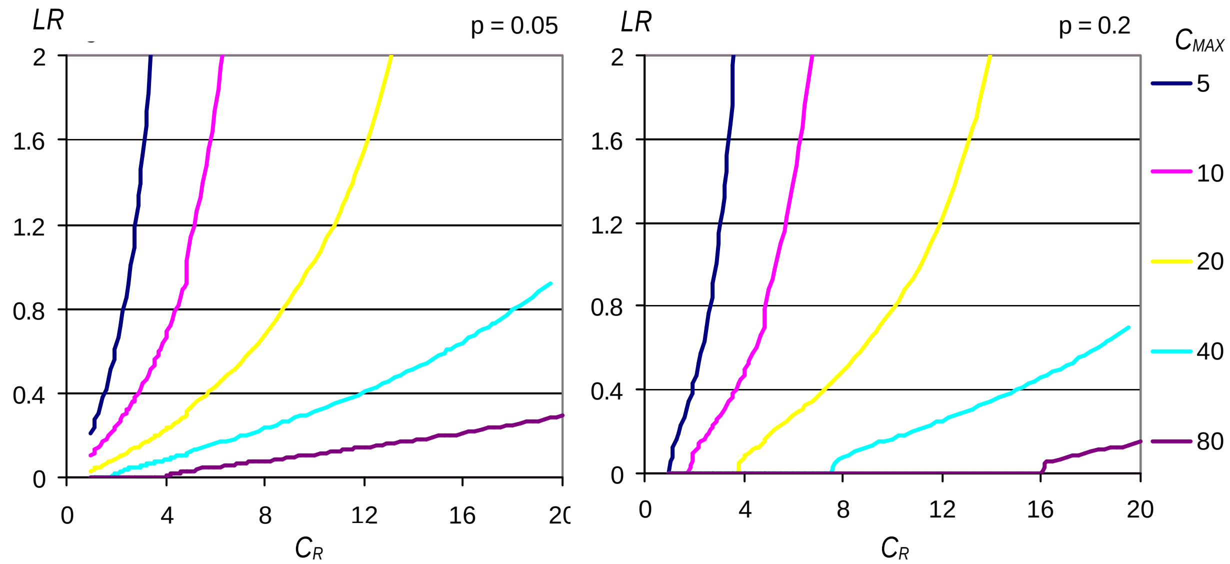

Figure 8. *Leaching requirement vs the concentration of the re-fill water, depending on the concentration at which the system is flushed (C_{MAX} , indicated at right). Left for p= 0.05 and right for p=0.2.*

3.1 Experimental validation

We checked this theory in an experiment where two systems where compared: a Dutch system, refilled with very good quality water (control), and a Mediterranean one, refilled with water containing 12 mmol l^{-1} of Na (brackish). In both cases rockwool slabs were used as substrate, with overabundant irrigation, to create conditions for the hypotheses above to be valid, as described by Stanghellini et al. (2002).
The control treatment was refilled with water containing 0.8 mmol·l-1 Na. Irrigation water was automatically brought up (when necessary) to an EC of 3.5 dS/m by injection of concentrated nutrient solutions (A & B system). The other treatment simulated a water source containing 12 mmol·l-1 Na, used to refill a basic solution of 1.6 dS/m. No EC control took place at water gift and whenever (manually-measured) EC in the slabs exceeded 9 dS/m, equivalent to about 45 mmol Na in the mixing tank, the latter was emptied and the slabs were drained. As it turns out, only about 50% of the volume of the system could be refreshed each time, given the large buffer of water remaining in the slabs. The evolution of EC in the substrate is shown in Figure 9 for both treatments.

Amount and EC of drain was determined both by tipping-buckets on 8-plant sections of a row (two per treatment) and by measuring flow pumped out the two underground re-collection tanks. Water uptake was determined as the difference between the two. The amount of water flushed each time out of the system was recorded as well. Table 1 gives the mean values over the treatment period of the controlled parameters, and the total water balance.

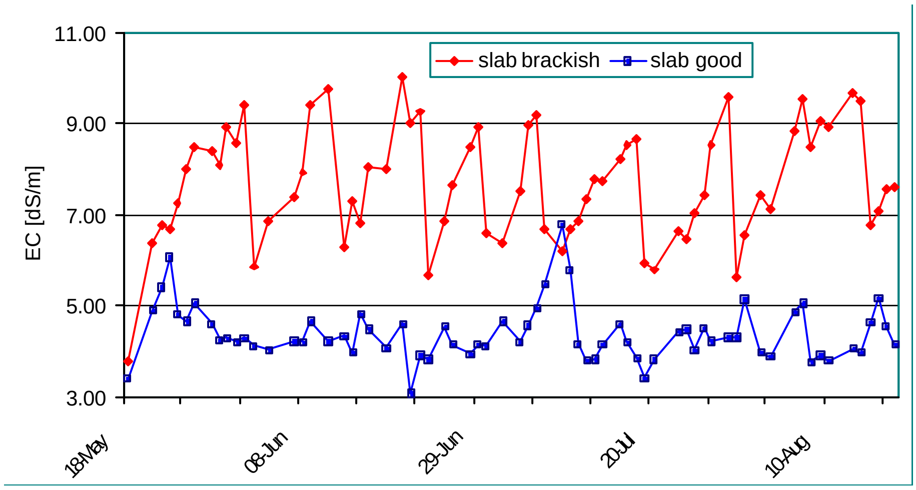

Figure 9. *Evolution of EC in the slabs for the two treatments. The one re-filled with brackish water was flushed anytime EC exceeded 9 dS/m.*

Round tomato	Re-fill good	Re-fill brackish	% of control
Mean EC irrigation *dS/m*	3.8	6.9	182
Mean EC slab & drain *dS/m*	4.4	7.6	173
Water gift *l/plant*	463	463	100
Water use *l/plant*	152	153	101
Leaching fraction	0.04	0.22	500
Water uptake *l/plant*	145.8	125.9	86
Transpiration *l/plant*	136.4	118.1	87
Mean LAI	2.1	1.8	86
Biomass (no roots) *kg/plant*	9.4	7.8	83
Yield *kg/plant*	7.8	6.5	83

Table 1. *EC of irrigation water, in the slabs and drain (mean values over the treatment period); total water fluxes and fresh weight. LAI is shown for reference.*

Figure 10 (a re-drawing of Fig. 7) shows that the leaching fraction we had is compatible with a p around 0.2. Similarly, a factor 0.2 can be deduced from experiments by the Pisa team, described by Malorgio et al. (2001) also with tomato and refill water containing 6, 12 and 24 mmol l^{-1}, and in Deliverable 6 with refill water of 10 eand 20 mmol l^{-1} and various C^{Na}_{MAX}.

4. Rules of thumb

? IF nutrients are added downstream to the mixing tank (system I), a high drain percentage minimises input of salts.

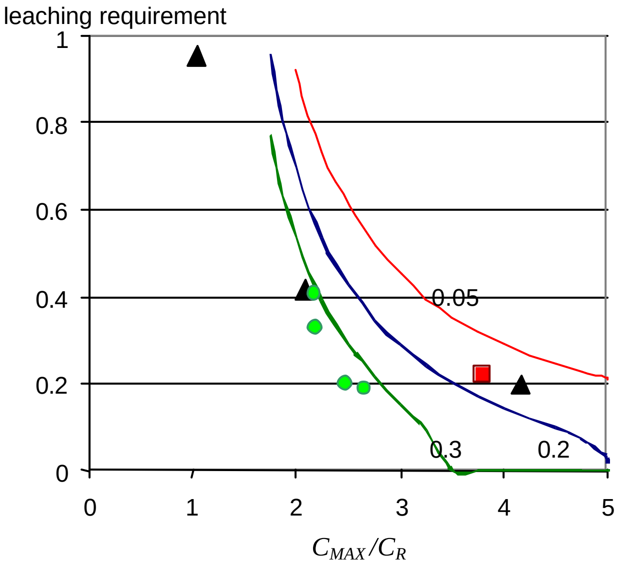

Figure Fig 10. *Experimental values of leaching requirement for round tomato. Triangles are from the Pisa team (Malorgio et al., 2001); circles are from Pisa team (deliverable 6) and square is from our Wageningen experiment. The three lines are the leaching requirement calculated through Eq(8), with values of p as indicated.*

? At a given EC of the water in the loop, high drain percentage minimises accumulation of salts in the root zone and minimises yield loss.

? The leaching fraction is independent from the volumes and flows in the system. It is determined only by: salinity of the refill water, level of salinity at which the system is flushed and, to a lesser extent, affinity of the crop with a given salt.

- The leaching fraction increases fairly linearly with the salinity of the re-fill water and decreases exponentially as the concentration in the system is allowed to get higher. The ratio between the concentration of the refill water and the concentration at which the system is flushed is a good estimate of the leaching fraction.
- Passive absorption by the crop of unuseful salts reduces significantly the leaching fraction only when the concentration at which the system is flushed is large with respect to the concentration of the re-fill water.
- The rate at which the system is flushed does not affect the leaching ratio. That is, water and nutrient requirement are the same whether the whole system is flushed at once or in smaller steps.
- If one suspects some non-linearity in the yield response to salinity, therefore, it may be better crop management to calculate beforehand the required leaching fraction and "bleed" that amount daily (for instance, before re-filling).
- IF there is a [limited] choice among water resources for re-fill, the best one should be saved until the period of highest potential evaporation.
- In order to lower salinity under high potential evaporation, the concentration at which the system is flushed, should decrease with increasing water use.

References

Carmassi G., L. Incrocci, M. Malorgio, F. Tognoni & A. Pardossi, 2002. A simple model for salt accumulation in closed-loop hydroponics. Acta Horticulturae: Protected cultivation in mild winter climate, in press.

De Kreij, C.; Voogt, W.; Bos, van den, A.L.; Baas, R. Bemestings Adviesbasis Substraten. PBG Naaldwijk. ISSN 1387-2427. Mei 1999. (in Dutch)

Farquhar, G.D. & S. von Caemmerer, 1982. Modelling of photosynthetic response to environmental conditions. In: Water Relations and Photosynthetic productivity. Springer Verlag, Berlin: 549-587.

Gijzen, H. 1992. Simulation of photosynthesis and dry matter production of greenhouse crops. CABO simulation report 28: 69 pp & 10 Annexes.

Kempkes, F.L.K. & C. Stanghellini, 2002. Modelling salt accumulation in a closed system: a tool for management with irrigation water of poor quality. Acta Horticulturae: Protected cultivation in mild winter climate, in press.

Li, Y.L., C. Stanghellini & H. Challa, 2001. Effect of electrical conductivity and transpiration on production of greenhouse tomato. Scientia Horticulturae, 88(1): 11-29.

Malorgio, F., Incrocci, L., Carmassi, G., Pardossi, A. & Tognoni, F., 2001. Accumulo di sali (NaCl) e consumo minerale in pomodoro coltivato in systemi idroponici a ciclo chiuso. Italus Hortus, 8(6): 43-48.

Sonneveld, C. 2000. Effects of salinity on substrate grown vegetables and ornamentals in greenhouse horticulture. PhD dissertation, Agricultural University, Wageningen, 151 pp.

Stanghellini, C., 1987. Transpiration of greenhouse c rops: an aid to climate management. PhD dissertation, Agricultural University, Wageningen, 150 pp.

Stanghellini, C., F.L.K. Kempkes, E. Heuvelink, A. Bonasia & A. Karas, 2002. Water and nutrient uptake of sweet pepper and tomato as (un)affected by watering regime and salinity. Acta Horticulturae: Protected cultivation in mild winter climate, in press.