

Hydrion-line, towards a Closed System for Water and Nutrients: Feedback Control of Water and Nutrients in the Drain

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Abstract

The development and market introduction of affordable ion specific sensors, like the ISFET sensor, has paved the way for completely new systems for application of fertilisers to crops in greenhouses. This paper describes the use of information feedback from flow sensors and ion specific sensors to regulate the supply of water and nutrients to a model gully. When a controller keeps the drain flow and the concentrations of the individual ions in the drain at a sufficiently high fixed value, the uptake of the plants is intrinsically compensated, i.e. the demand of the plants is exactly satisfied. Time series measurements of flow and concentration in supply and drain are used to design the controller for applying nutrients to a tomato crop in a near-practice greenhouse. Data are shown of fertiliser concentrations and flow in supply and drain during the design phase and test phase of the controller.

INTRODUCTION

Current Practise

The current practice in modern horticulture is, that a fertiliser supply unit applies nutrients in liquid form. A system of pumps, valves and irrigation capillaries delivers the mixture of water and fertiliser ions (nutrient solution) to each individual plant. The plants are grown on artificial growing media, which substitute soil (rockwool slabs, containers with perlite, peat beds). Environmental protection laws demand that growing systems are closed. For this purpose, water not used by the plants is captured in a gully. After cleaning, refilling with clean water and replenishment with additional nutrient ions it is used again (Fig. 1). Every two weeks a sample of recirculation water is sent to a laboratory, which then gives advice on adjusting the solution's recipe. Since only the EC and pH is controlled, and ions are not always taken up in the same proportions, there may be a build up of certain ions in the substrate. This forces the need for flushing the nutrient solution from time to time, leading to environmental pollution, and loss of valuable nutrient ions. Moreover, quality control of crops by manipulating the supply of individual nutrient ions is not possible. These drawbacks of the present system can be resolved if one could precisely dose each nutrient ion according to the plant's demand.

Plants, Water and Nutrient Ions

Macroscopically, the rate of change of nutrient content in the substrate is governed by (i) supply of ions and water into the growing system (ii) the drain out of the growing system, (iii) transport of ions and water from the growing medium to the root surface, and (iv) ions and water moving from the outside of the root to the inside of the root, across the root cell membranes (uptake). Physiologically, water uptake and uptake of most macronutrients by the roots are two distinct mechanisms, which are independent of each other. Water uptake is a physical process, with as driving force the water-potential [Pa], which - to a large extend - is maintained by transpiration. The rate of nutrient uptake is

determined by the demand of the plant, which depends on the growth-rate and on the status of the plant's nutrient content (Marschner, 1995). Most macronutrients are absorbed actively whilst Ca^{2+} , to a great extent, is absorbed in proportionality with water uptake (Ho et al, 1995). Active ion uptake is virtually independent of the concentration at the root surface up to very low concentrations. Such low concentrations can occur when the hydraulic resistance of the surrounding growing medium hampers transport. The question always arises whether the growing medium is able to timely deliver the nutrients at the root surface to satisfy the plant's demand. This depends upon the availability of nutrients in the inert growing medium, the porosity, the root development, and the uptake rate (De Willigen and Van Noordwijk, 1987; Heinen, 1997).

When growing conditions change, transpiration and growth rate will change. Hence, ratio of nutrient uptake and water uptake, called influx concentration, will vary due to variations in either the water uptake (transpiration driven) or the ion uptake (growth rate dependent). Water and nutrients taken up from the direct vicinity of the roots are replenished by a solute from the capillaries in the growing medium. The flow of water with nutrient ions at bulk concentration to the roots is called mass-flow. It carries the nutrient ions from the bulk substrate to the roots in a concentration equal to the bulk concentration of the substrate.

If mass flow carries a higher concentration than the actual influx concentration to the roots, nutrient ions will accumulate in the vicinity of the root surface (the boundary layer). Accumulated nutrients are flushed out to the drain in a rate dependent on the diffusion coefficient and the hydraulic resistance of the substrate. Consequently, the drainage water can have a different concentration of nutrients than the supplied water.

If mass flow carries a lower concentration than the influx concentration to the roots, all nutrients are absorbed. The direct vicinity of the roots (boundary layer) may reach depletion. The concentration gradient, which emerges in this way, enables compensation by diffusion of part of the shortage. To a great extent, the size of this contribution depends on the diffusion coefficient of the water-filled substrate and of the boundary layer. A simplified method, to calculate the conditions for which depletion and nutrient stress on crops may occur, is presented by Van Straten and Gieling (2003).

If water and nutrients were supplied exactly in agreement with the (time-varying) influx, no drain would remain. However, in practice the substrate needs to be flushed to remove ions that are not taken up by the plants, which results in a drainage flow. Even though in an ion-specific controlled system the need for flushing is reduced, a certain amount of through flow remains necessary to ensure wash out of ions that are conservative. Moreover, in this way, sufficiently uniform conditions in the substrate are provided and crystallisation is prevented.

Control of the concentration of individual ions in the solution that feeds plants in a greenhouse is feasible when on-line analysers with ion specific sensors are available to be used by growers on a practical scale. Bailey et al. (1988) describe an ion concentration measuring system applied in a greenhouse. The system uses ISE electrodes as sensors. Gieling (2001) describes a measuring system using ISFET sensors. In a series of projects named Hydrionline, Van den Boogaard et al. (2003) describe the development of an injection system that dilutes liquid fertilisers based on of ion specific concentration measurements in a feedback control loop for each fertiliser ion. One of the products of this project, the basal controller for water and nutrients, is subject of this paper.

MATERIALS AND METHODS

Measurement of Flow and Concentration

In the Hydrion-line project, a small measuring gully with 16 tomato plants (Aromata) is used as a physical model. Placed amidst the plants in the greenhouse it mimics the whole growing system. It is equipped with sensors that measure supply flow, drainage flow, as well as concentrations of individual ions in supply and drain (Gieling, 2001). In the Hydrion-line research projects it is used in the identification and design

procedure of the control algorithms, and on-line in the actual feedback control loop. The system is shown in Fig. 2. Plants are rooted in a small rockwool block that is placed on a substrate mat on a measuring gully (size measuring gully: 8.3 m; growing medium: Rockwool, type Grodan Expert; size Rockwool mat: 7,5 x 15 x 100 [cm]; size Rockwool seedling block: 7,5 x 10 x 10 [cm]). Sixteen plants are placed on a measuring gully. Water is supplied to each plant by a dripper, and passes through the substrate to be collected by the gully. The outflow of the model gully passes through a tipping spoon flow meter, and is collected in a small sampling tank. Sampling into the analyser occurs only when sufficient water has been collected. Both supply flow and drain flow are sampled for analysis by means of a Hydrion Ion Analyser model Hydrion-10. The analyser incorporates the sensors (ISE electrodes), the sampling fluidics, the calibration fluids, the data acquisition and data mining software and software and hardware for communication. It is important to minimise the delay time between the moment of taking a fluid sample and the moment the signal is analysed. The amount of drain available per supply cycle is too small to fill up a long hose to bring the sample to an analyser outside the greenhouse compartment. Consequently, the distance between the ion analyser and the sampling point has to be small. The nutrient solution is supplied to the plants by means of a Synopta controller system with a GPS-Maximix 7140 water supply unit and a Modifeed 1220 nutrient supply unit from Hortimax B.V.

EXPERIMENTAL RESULTS AND DISCUSSION

Identification experiments were performed on the process described. A controller according to Fig. 3 controls the drain flow of the model gully at a fixed value of $1.5\text{L}\cdot\text{h}^{-1}$ (Gieling, 2001). The set values for the nutrient supply recipe were increased to a new ion composition. Using the analyser and an automatic data sampling system, a time series of the supply- and drain flow and ion concentrations was established. A closer look at the data is given in detail plots (Fig. 4 and 5), which are extracted for 3 days, starting on 4-Dec-2002 00:00. Where necessary, missing data have been interpolated, and at some places where large outliers exist, data have been removed (a short period with the EC data). The static gain of the data is of interest for comparison with expectation from theoretical models. These can be derived from the ultimate change in the response read from the data values, as in Table 1. The response data for the EC step response experiment from Fig. 5 shows roughly a second order behaviour, possibly with delay, but it is not easy to detect the delay. The output moves from about 2.5 mS to 3.7 mS, while the input changes from 2.2 mS to 3.5 mS. The signal can be approximated quite well by delay plus first order, with the following characteristics: dead time: $t_d \approx 290$ min; apparent time constant: $\tau \approx 1120$ min; static gain: $K \approx 0.85$ mS·mS⁻¹. Note that both prior and after the step excitation, the concentration at the output is higher than the concentration at the input. The concentration ratio actually depends upon the water and nutrient uptake, as can be seen from an overall mass balance. If the concentration of the input is higher than the concentration of the output, it indicates a nutrient concentration effect. This occurs when the ratio of nutrient uptake is lower in relation to water uptake. The converse may also happen. This concentration effect should not be confused with the process gain. According to the Cohen-Coon recommendations, the controller parameters for a continuous PI-controller would be:

$$K_c = \frac{1}{K} \frac{\tau}{t_d} \left(0.9 + \frac{t_d}{12\tau} \right) = 4.2 \text{ mS/mS} \quad (1)$$

$$\tau_I = t_d \frac{30 + 3t_d/\tau}{9 + 20t_d/\tau} = 630 \text{ min} \quad (2)$$

Digital Controller Implementation

Let c_k be the controller output at control instant t_k , and $e_k = y_{sp} - y_k$, the error between actual process output y_k at sample time t_k and the desired set-point y_{sp} , then the digital PI controller in velocity form is given by Eq.3.

$$\Delta c_k = K_c \left(1 + \frac{T}{\tau_I} \right) e_k - K_c e_{k-1} \quad (3)$$

$$c_k = c_{k-1} + \Delta c_k$$

where T is the sampling interval. As a rule of thumb, in digital control systems the sampling time should be less than 10 to 20 % of the dominant time constant or the dead time, whichever is smaller. It means that the sampling time should be less than 30 min. So, the actual controller interval of 33.33 minutes (2000 s) is just appropriate. Using the Cohen-Coon parameters obtained, and $T = 2000$ s the following result is obtained:

$$\Delta c_k = 4.42e_k - 4.2e_{k-1} \quad (4)$$

$$c_k = c_{k-1} + \Delta c_k$$

This result indicates the following. Once an error occurs, an input change of about four times the error should be implemented. If at the next sampling time the error persists, only small further changes are made, thus preventing over-reaction. This controller behaviour can be totally attributed to the dead time.

The result can also be put in linear discrete state space form with the control movement Δc as output as follows:

$$x_{k+1} = e_k; \quad \Delta c_k = -K_c x_k + K_c \left(1 + \frac{T}{\tau_I} \right) e_k \quad (5)$$

$$\text{discrete } A, B, C, D \text{ matrices: } A = [0], B = [1], C = [-K_c], D = \left[K_c \left(1 + \frac{T}{\tau_I} \right) \right] \quad (6)$$

$$\text{and substituted numbers : } A = [0], B = [1], C = [-4.2], D = [4.42] \quad (7)$$

The number 4.42 can be reduced to reduce overshoot, but it should not be lower than 4.2. Setting the second state equal to the (uncontrolled) steady input best initialises the controller. In Fig.6 results are shown from a preliminary test with a controlled system for nutrient supply in a greenhouse with a real crop (Wouters, 2002). In the system the set values of 3 nutrients are kept at a fixed value: NO_3^- at $10\text{mM}\cdot\text{L}^{-1}$, K^+ and Ca^{2+} $5\text{mM}\cdot\text{L}^{-1}$. Fig.6 shows that the controller is able to keep the ion concentration in the drain reasonably well at the set values. From the K^+ graph it can be seen that the settling time is quite long with these controller parameters. Some of the measured data points in the "reliable data" area show an unexpected deviation. These outliers disturb the controller actions. Outside the window of reliable data, the analyser had problems with its sampling valves, leading to unreliable data, and consequently to erroneous control commands, stressing the need for automatic fault detection procedures in future equipment. Even so, after the analyser produces reliable data again, the controller tries to return to its set value.

CONCLUSIONS AND PERSPECTIVES

The feedback system as described automatically ensures that the nutrient demand of the plants is satisfied. One of the practical advances, apart from reducing pollution and preventing unnecessary pollution loss, is that it saves the cost of chemical analysis of samples taken by hand by the grower. This development was possible only thanks to the

advent of ISE and ISFET ion-specific sensors. Yet, a number of practical difficulties still needs to be resolved, in particular the stability and robustness of the measuring system, and the life expectation of the sensors. The feedback control strategy is part of a strategy with a wider scope, where nutrient supply is based upon crop growth and development models. In such a model-based system it would be possible to actually control the nutrient uptake of the plants, with the perspective of controlling crop quality. This, however, is still a dream for the future, hopefully within reach in the Hydrionline III project.

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Literature Cited

- Bailey, B.J., Haggett, B.G.D., Hunter, A., Albery, W.J. and Svanberg, L.R. 1988. Monitoring nutrient film solutions using ion selective electrodes. *J.Ag.Eng.Res.*, 40 (1988) 2, p. 129-142.
- De Rijck, G. and Schrevens, E. 1994. Application of mixture-theory for the optimisation of the composition of the nutrient solution. *Acta Hort.* 401
- De Willigen P. and Van Noordwijk, M. 1987. Roots, plant production and nutrient use efficiency. PhD Thesis Wageningen University, 279p.
- Gielsing, Th.H. 2001. Control of water supply and specific nutrient application in closed growing systems. PhD thesis Wageningen University, ISBN 90-5808-525-2, 2001.
- Heinen M. 1997. Dynamics of water and nutrients in closed, recirculating cropping systems in glasshouse horticulture. PhD thesis Wageningen University.
- Ho, L.C. Adams, P., Shen, H., Andrews, J. and Xu, Z.H. 1995. Responses of Ca-efficient and Ca-inefficient tomato cultivars to salinity in plant growth, calcium accumulation and blossom-end rot. *J.Hort.Sci.* 70, 909-.
- Marschner, H. 1995. Mineral nutrition of higher plants. Second Edition. Academic Press. ISBN 0-12-473542-8918.
- Schrevens, E. and Cornel, J.A. 1990. Design and analysis of mixture systems, Applications in hydroponic plant nutritional research. *Plant and Soil* 154, p.45-52.
- Van den Boogaard, H.A.G.M., Marcelis, L.F.M. and Gielsing, Th.H. 2003. Hydrionline III: On-line monitoring and control system for process water in closed growing systems in greenhouse industry. (Min. Economic Affairs).
- Van Straten, G. and Gielsing, Th. H. 2003. Controller settings for closed system ion control in greenhouses, 2002 ASAE Annual International Meeting/ CIGR XVth World Congress Chicago, cd-rom proceedings, paper no. 023031, pp.9.
- Wouters, H. 2002. Het regelen van de voorziening van water en specifieke nutriënten op een gemiddelde constante drain in een gesloten teeltsysteem. Graduation Thesis (in Dutch) Wageningen University.

Tables

Table 1. Static gain of EC [mS], K⁺, NO₃⁻ [mMol·L⁻¹].

	Output			Input			Static gain
	ultimate	initial	difference	ultimate	initial	difference	
EC	3.8	2.5	1.3	4.0	2.25	1.75	0.74
K ⁺	6.5	4.2	2.3	6.8	4.5	2.3	1.0
NO ₃ ⁻	26	16	10	25	13	12	0.83

Figures

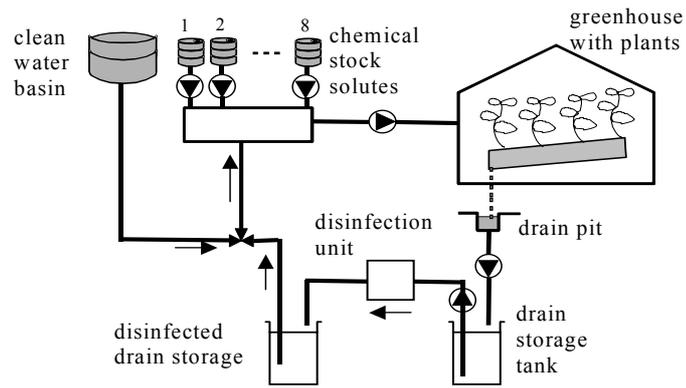


Fig. 1. Nutrient injection, with storage tanks and disinfecting unit

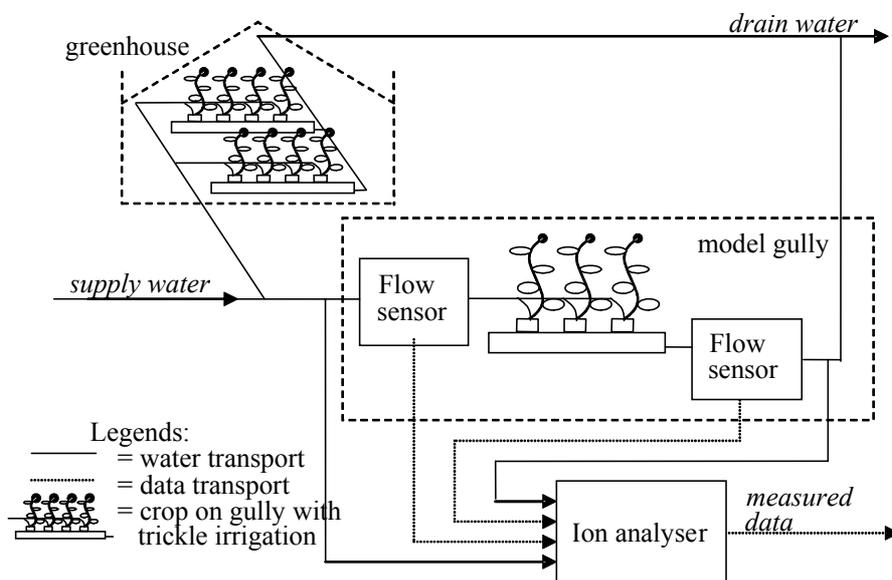


Fig. 2. Schematic representation of the instruments in the greenhouse.

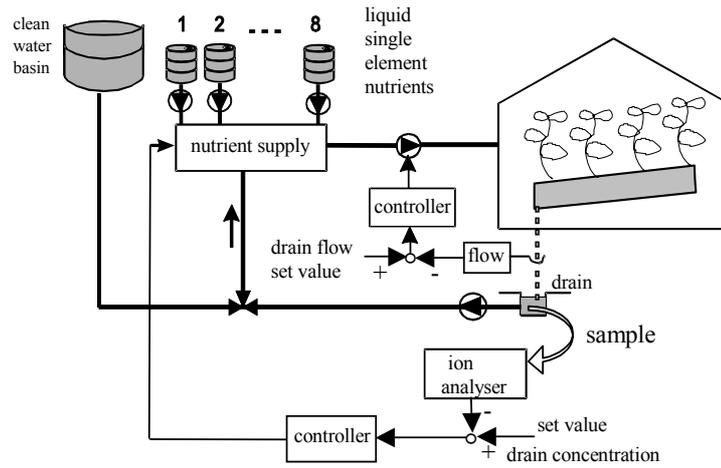


Fig. 3. Diagram of a controlled system.

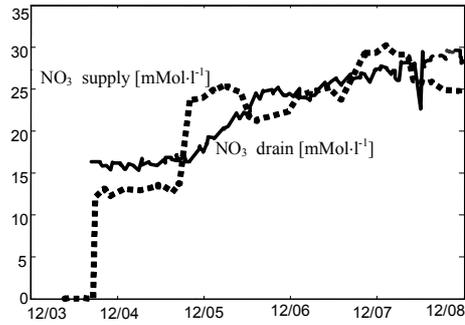


Fig. 4. NO₃ values observed in drain and supply during the step experiment.

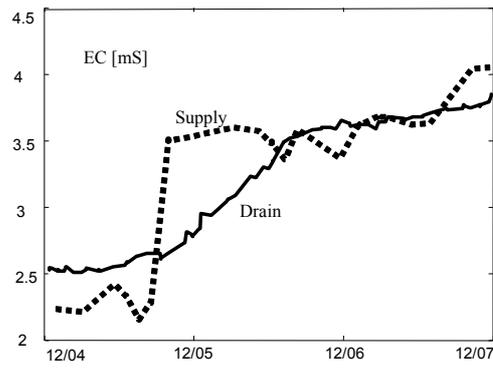


Fig. 5. EC values observed in drain and supply during the step experiment.

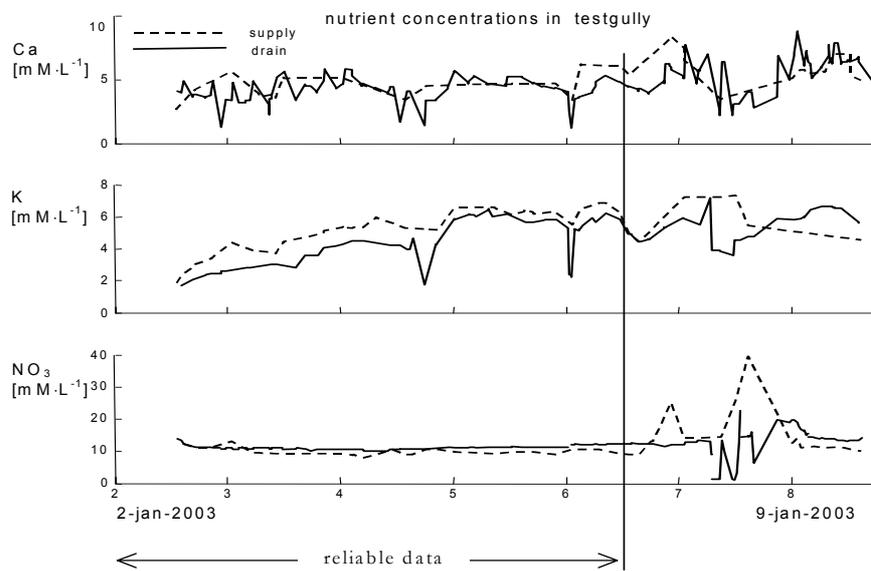


Fig. 6. Results of controller actions on Ca^{2+} , K^+ and NO_3^- supplied in a greenhouse from 2 till 9 January 2003. Set values: $\text{NO}_3^- = 10\text{mM}\cdot\text{L}^{-1}$, K^+ and $\text{Ca}^{2+} = 5\text{mM}\cdot\text{L}^{-1}$.