‘WATERSTREAMS’: a Model for Estimation of Crop Water Demand, Water Supply, Salt Accumulation and Discharge for Soilless Crops

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Abstract

Closed growing systems are obligatory for soilless grown greenhouse crops in The Netherlands. It requires water sources of high quality as sodium (Na) accumulation is a potential risk and necessitates frequent discharge, which causes undesirable emission of nutrients and plant protection products. Rainwater as the primary water source, needs to be stored since precipitation and crop demand do not match. Large dry spells will become more frequent due to climatic changes and this necessitates the use of additional water sources, which will differ in quality and costs. The model ‘WATERSTREAMS’ was developed to estimate the total water demand and waste water flows from greenhouse crops and to optimize between options for water sources, concerning Na accumulation and nutrient emission. It describes all water flows in a greenhouse crop and the growing system. At the same time the Na concentrations in the input flows as well as the uptake are calculated, and if Na accumulates beyond a threshold value, a discharge event is programmed. The model calculations can be used to determine the total water demand from individual crops to clusters of greenhouses, as well as to optimize the size of rainwater collection tanks or the required capacity of additional water sources, using actual, historical or forecasted meteorological data. It also gives insight in the emission quantity.

INTRODUCTION

There are increasing demands of the society on water issues, since water suitable as resource for crop growing becomes more and more scarce and also environmental issues put pressure on sustainable water use in horticulture. There are two main reasons to have more insight in the crop water requirement throughout the year. In the first place, for quality reasons, rainwater is the prevailing water source in The Netherlands. As the precipitation pattern is not matching the crop demand, storage is inevitable. Since supplementary water sources of comparable quality are limited available, optimisation of the size of rainwater collection and capacities of the alternative sources is important for management and economic reasons. Secondly, regulations on the emission of nutrients and plant protection products (PPPs) to the environment force growers even more than already realised, to increase the water use efficiency (WUE).

A model describing the crop specific water demand in relation to climatic conditions and water quality aspects can be used to optimize the size of water storage and the input of supplemental water sources in relation to their dynamic availability and can be used to optimise WUE. Existing transpiration models like in INTKAM (Gijzen, 1994) are not suitable, since they need too detailed input data of crop development, which are not always available. Moreover they lack modules for other water flows in the greenhouse and the possibility of taking into account water quality aspects.

This paper describes the model WATERSTREAMS which has been developed in the last couple of years. Initially the model was developed for an approach of the total water demand of greenhouse crops. Modifications were made to obtain also dynamic changes throughout the year and to get information of daily fluctuations in water flows. In

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the last phase, the need for information about emission of nutrients and PPPs necessitated to extend the model to achieve more accurate estimations of waste water flows. As the Na concentration is the driving force for discharge, modules for salt (Na) accumulation and uptake were added. The model version described is for soilless crops and is still under development. Validation has only been performed on separate modules and so far not of the complete model.

MODEL DESCRIPTION

The model is aiming at complete covering of the major water flows in a greenhouse with soilless culture. A general description of the major water flows involved in a greenhouse is given in Figure 1. As a general approach the water balance of a greenhouse crop is considered to be closed. The boundaries of the system are the greenhouse sides, vents and the groundcover and include the area with the fertigation and water treatment equipment. Irrigation and (evapo-) transpiration are obviously the main water flows. The input is made up by the raw water flow. We consider precipitation on the greenhouse roof as input in the system. Next to rainwater the raw water may originate from various sources, each of them having their own dynamics and constraints. The output is made up by the crop water uptake, i.e for growth and for transpiration and waste-water flows: the filter cleaning, leakages and discharge of drainage water. In the Netherlands, reuse of drainage is obligatory, but discharge is taking place, mainly because of Na accumulation. Since discharge is driven by the Na concentration, the Na concentration in all water flows is also taken into account.

For some of the procedures the model makes use of earlier developed modules and partly other models are used, like KASPRO (De Zwart, 1996) for simulation of the greenhouse climate. The model can be fed with actual data from a specific greenhouse and specific climate data as well as with general data and climate databases. Internally the model calculates on hourly base, but the output is on daily basis and results are expressed as $m^3\ ha^{-1}$.

Water Sources

The model is developed to apply several raw water sources as input. Beforehand the priority of the available water sources should be chosen. Rainwater (W_r) is defined as the primary water source. The total daily precipitation (P) is collected; the storage capacity is a parameter. The precipitation is corrected for direct transpiration losses and pre-wetting of the greenhouse roof and the collection system. Less than 1 mm is neglected, below 2 mm 20% is lost, from 2 mm and higher, 95% is effectively collected. If the maximum of the storage is reached, the surplus is considered as overflow. For practical technical reasons, 5% of the stored water cannot be used (G. de Jong, Haket, June 2010, pers. commun.). An additional source is desalinated water by reverse osmosis (RO) (W_{ro}), the production capacity ($m^3\ ha^{-1}\ h^{-1}$) of the installation is a parameter. The RO is turned on if the rainwater storage reaches a set minimum level and will continuously produce until a set maximum level. Another water source may be tap water (W_t). Input calculation is as with RO water, with capacity of the delivery in $m^3\ ha^{-1}\ h^{-1}$ as parameter. Other sources could be well-water or surface water (W_x) these are considered as unlimited available. Condensation water from inside the greenhouse (W_c) is optional and used prior to all external water sources. The quantity of condensation water is calculated with the model KASPRO (De Zwart, 1996). The total input of water from the various sources is described as:

$$W_{tot} = W_c + W_r + W_{ro} + W_t + W_x \quad (1)$$

Irrigation

Irrigation is driven by crop demand (evapotranspiration) (E_{tot}) and the drainage fraction (df), which is the surplus irrigation needed to prevent EC and water content differences in the substrate. The crop demand is a dynamic process and described further on, the drainage fraction is a scalable parameter. The total daily irrigation can be described as follows:

$$I = E_{tot} + E_{tot}(\frac{df}{1-df}) \tag{2}$$

where $I = W_x$ depending on the availability.

Crop Demand, Transpiration and Growth

The crop evapotranspiration (E_{tot}) is based on the empirical model by De Graaf and Van den Ende (1981), De Graaf (1988), and modifications added later (Voogt et al., 2000). Since in soilless cultivation the surface is almost completely covered, evaporation can be neglected, so transpiration is equal to the evapotranspiration. The model approaches to estimate the effect of total global radiation and the infrared radiation from the heating system received by the plant canopy. The module E_{tot} consists of two components: transpiration driven by global radiation, E_{rad} and by heating E_{heat}. Global radiation (R), measured outside the greenhouse is cumulated over time. A correction factor for light interception by the greenhouse construction is applied (*trf*). This transmission reduction factor can be determined by a specific measuring procedure (Baas and Van Rijssel, 2006) or it can be estimated from comparable greenhouses with a known *trf.* The sum of the radiation will be multiplied by an empirical crop specific transpiration factor (*cf*). This factor is derived from de Graaf (1988) and additionally trials with weighing lysimeters in research experiments and from data derived from commercial crops (Baas and Van Rijssel, 2006; Sonneveld and Voogt, 2010).

The effect of plant size and increasing LAI from start to maturity is simplified to a linear correction factor *L/S* where *L* is the actual plant length and *S* the plant height where LAI is estimated to be >3, the maximum value is 1. This factor is applied both on E_{rad} and on E_{heat}. To make the model also applicable in greenhouses with screens and artificial lighting, a screen specific factor is introduced (*sf*) representing the light reduction. In case of black-out screens the transmission reduction factor will be 100%. During the hours the screens are used (*so, sc,*) *R* will be reduced. E_{rad} is calculated as:

$$E_{rad} = \{(\sum\nolimits_{h=0}^{24} cfR10^{-3}) - (\sum\nolimits_{t=sc}^{so} sfcfR10^{-3})\}(\frac{L}{S}) \tag{3}$$

The radiation from assimilation lamps (R_{a}) consists of both PAR and infrared light, which practically have the same effect on transpiration (De Graaf and Spaans, 1998). The total radiation is calculated as a function of the installed power (P_{ass}) in W m^{-2} and corrected for a specific efficiency factor for lamps (*lf*) (Houter, 1996).

$$R_a = lfP_{ass} * .36 \tag{4}$$

The total radiation from assim. lamps is accumulated over time (lighting hours), (*ass; ase*). The lighting hours are approached by using setpoints (R^{sp}_{ass}) as the total daily global radiation level below and above which the lamps are switched on or off and taking into account also the crop specific maximum daylength (D_{max}):

$$R \geq R^{sp}_{ass}, t < D_{\max} \rightarrow E_{ass} = (\sum\nolimits_{t=ass}^{ase} cfR_a 10^{-3})(\frac{L}{S}) \tag{5}$$

The influence of the heating system is estimated by the sum of the delta T from greenhouse and heating pipe temperature in $^{\text{o}}$C times minutes. This temperature sum is multiplied by the empirical heating factor (*hf*), derived from De Graaf (1981). E_{heat} is based on an empirical approach, the data based on trials with a standard heating system using five heating pipes of ø 51 mm. However, in modern greenhouses sometimes two or three heating systems are used, with different temperature regimes. Therefore the algorithm is extended with the temperature sum for each heating grid (HP^a), with a correction factor being the circumference of the heating pipes ($HP^a{}_d$) relative to 0.801 m, the circumference of the original situation. E_{heat} can be calculated for n heating systems:

$$E_{heat} = \sum_{h=1}^{24} \left(\sum_{t=0}^{x} \left(\frac{HP_d^a}{0.801} hf (T_{pipe}^a - T_{air}) 10^{-4} \right) \right) \left(\frac{L}{S} \right) \tag{6}$$

For plant growth, which determines the crop water uptake next to transpiration, a simple approach is chosen. For fruit vegetables, the total (expected) fruit yield (Y) is taken as measure to estimate the total fresh biomass production and from there the water consumption, taking into account the different fruit/shoot ratios (*shrr*) and average dry matter fraction (*dm*), data derived from various experiments. In case no such data are available, the water uptake for growth is estimated to be 10 % from the total water uptake (De Graaf and Van den Ende, 1981):

$$G_W = \left(Y + Y\left(\frac{shrr}{1 - shrr} \right) \right) \times (1 - dm) \quad | \quad G_W = E_{tot} + E_{tot}\left(\frac{0.1}{1 - 0.1} \right) \tag{7}$$

Waste Water Flows

To prevent blocking of drip nozzles, irrigation water is filtered through sandfilters or fine filters. These filters are backwashed on a regular basis and cause a waste water flow. Backwash is done automatically, on time basis or pressure difference between in- and output flow (Van Lier, Revaho, June 2010, pers. commun.). For the model, the frequency and quantity are parameters and differ depending on the situation, water source and type of filter. The quantity of filter flush water is calculated as a fraction of the total irrigation (F_f).

Partly discharge of drainage water will be carried out for several reasons (Voogt and van Os, 2010). One obvious reason is a too high salinity in the root environment. There are several strategies for discharge (Voogt and van Os, 2010). In this model the standard procedure of discharge (D_c) is the total content of the drainage buffer (D_{bf}) storage to be drained to waste. The content of the buffer is a parameter, by default 10 m^3 ha^{-1}. Optional, three other discharge strategies may be chosen in the model. If salinity does not play a role, still discharge can be carried out. For this situation, the model can be imposed with some fixed moments or quantities with discharge actions.

Almost inevitably, some leakage will occur in commercial practice, either from the irrigation system, or from the gutters or from the drainage collection system. The quantity of leakage is unknown but cannot be neglected. Therefore a leakage rate (L_f) is added as fraction of the irrigation water, by default the value is set to 0.02 but this is not better than a best guess. The equation for total waste water is as follows:

$$W_{wst} = (F_f + L_f)I + D_c \tag{8}$$

where Dc follows form eq. 15.

Salinity

As driving force for occasional discharge of drainage water, salt accumulation is calculated. Without exceptions Na is the bottle neck element for all horticultural crops (Sonneveld, 2000) and it is therefore obvious to use this element as parameter. The model uses straightforward Na balance calculations, taking into account the total input and output of Na together with the water flows. For all water sources (W_x) the Na concentrations (Na_x) need to be defined. The model run start with the initial Na in the system resulting from the system water quantity (WQ) (substrate, piping and buffer tanks) and the concentration of the water used (Na_{syst}). At the end of each time loop Na_{syst} is reset as result of the input/output balance. The concentration in the root environment is defined as:

$$Na_{RE} = \frac{Na_{syst}}{WQ} \tag{9}$$

The Na in the input is calculated by the quantity of each source (W_x) and the Na concentration (Na_x) in the specific sources:

$$Na_w = W_r Na_r + W_{ro} Na_{ro} + W_t Na_t + W_x Na_x \tag{10}$$

Condensation water is considered to be free of Na, Na in RO water differs depending on the system, membrane age and maintenance, by default it is set to 0.15 mmol L^{-1}, a value commonly found in commercial practice and Na in tapwater differs largely depending of the source. Na in rainwater depends on the distance from the North Sea coast and the precipitation (Sonneveld et al., 1979). Based on the data of Sonneveld et al. (1979) and Ridder et al. (1981) the actual Na concentration can be described as a function of distance from the coast (*DC)* and precipitation *(P*). Alternatively, fixed average Na concentrations can be used. The contribution of other water sources is based on average Na concentrations as parameters.

$$Na_r = P - .208\ln(DC) + 0.775 \tag{11}$$

The Na input by fertilisers (Na_f) is calculated as a default concentration of 0.055 mmol L^{-1} in input of nutrient solution (W_{ns}). This figure is based on recently obtained information from a survey on the Na content of fertilisers (Voogt, 2012). Na_f is a fixed to the EC of the fertilisers solution (EC_f) , as the dilution rate depend on the EC value of the irrigation water (EC_I), W_{ns} results from the ratio between both EC values. The total Na input (Na_{inp}) is calculated as:

$$Na_{inp} = Na_w + Na_f \left(\frac{EC_I}{EC_f}\right) W_{tot} \tag{12}$$

The plant uptake is based on the crop specific linear relationships between the concentration in the root environment (Na_{re}) and the uptake concentration, which can be described as fraction of the prevailing Na concentration (Uf_{Na}) (Voogt and Van Os, 2012):

$$U_{Na} = Uf_{Na} Na_{re} E \tag{13}$$

As there will be loss of Na by the waste water flow, which is assumed to have the same Na concentration as the root environment. The total output of Na is calculated as:

$$Na_{out} = U_{Na} + W_{waste} Na_{re} \tag{14}$$

The accumulation of Na in the root environment is calculated and based on the mass balance of all inputs and outputs. As the uptake is concentration dependent, the prevailing Na concentration is calculated stepwise based on the resulting total Na quantity and the total water volume in the system. At the end of each time loop, the resulting actual Na_{re} will be compared with Na_{max} and will result in a decision for discharge.

$$D(t, Na_{re}) : Na_{RE} \geq Na_{\max} \rightarrow D = D_{bf} \tag{15}$$

Dynamics in the Growing System

The model calculation starts from a given planting date and ends at crop termination. The water quantity of the whole growing system i.e. the substrate, irrigation system and equipment is considered as fixed, assuming no changes in the buffering. This implies that the water needed for saturation of the slabs as well as the water lost a termination are considered as balance neutral. The calculations are done on an hourly basis. As for the input data usually daily data are used, irradiation data are divided hourly over the daylight period, according to the average radiation distribution pattern.

Precipitation, if occurring, is divided over 4 hours or a maximum of 10 mm h^{-1}. The actual level in the buffer tank is reset each hour, resulting from the net precipitation and the total water demand. Buffer tank overflow is also calculated hourly, causing a pulsated flow. The irrigation follows from the accumulation of the crop demand and specific parameters as irrigation per time and the required drainage fraction. In reality growers play with drainage fraction over the day, forcing drainage early after sunrise and irrigation is stopped long before sunset. Some parameters have been added to simulate this operational settings. Some growers change the drainage rate during the growing period, dependent on the time of the year or cropping stage. These settings are not yet part of the model.

SIMULATIONS

By example, Figure 2 shows some of the model output, the simulation results of a year round, standard tomato crop. The chosen storage of 2000 m^3 ha^{-1} is in an average year not sufficient to cover the demand, so RO water is supplemented during a certain period. The quantity condensation water is limited in view of the total demand, but is significant in the winter half year. With the model, by iteration, the optimum water storage can be calculated, which results for a standard tomato crop in an average year in 2850 m^3 ha^{-1}. Simulation of a dry year results in a required storage of 4800-5000 m^3 ha^{-1}. With a storage capacity of 2000 m^3 ha^{-1}, the model calculation results for a dry year in a required RO installation with a capacity of 27 m^3 ha^{-1} day^{-1}.

In a normal year, the water quality results in very limited Na accumulation (Fig. 3) and no discharge is needed. However, by simulating a dry year, with instead of RO water tapwater as supplemental source, with on average 1.5 mmol Na L^{-1}, the accumulation rapidly increase to the maximum acceptable level and resulting in frequent discharge with a total quantity of 350 m^3 ha^{-1}.

CONCLUSION

We developed a model for quantification of the total crop water demand and the use of multiple water sources, throughout the year. The model is suitable to estimate the required collection tanks for rainwater and the capacities of supplemental water. Also the effects of wet and dry spells and expected climate change can be evaluated. With the model also Na accumulation, hence the required discharge of drainage water from closed growing systems can be estimated, making the evaluation of several water sources and crop management decisions by growers possible. Further research is necessary to validate and expand the model.

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Figures

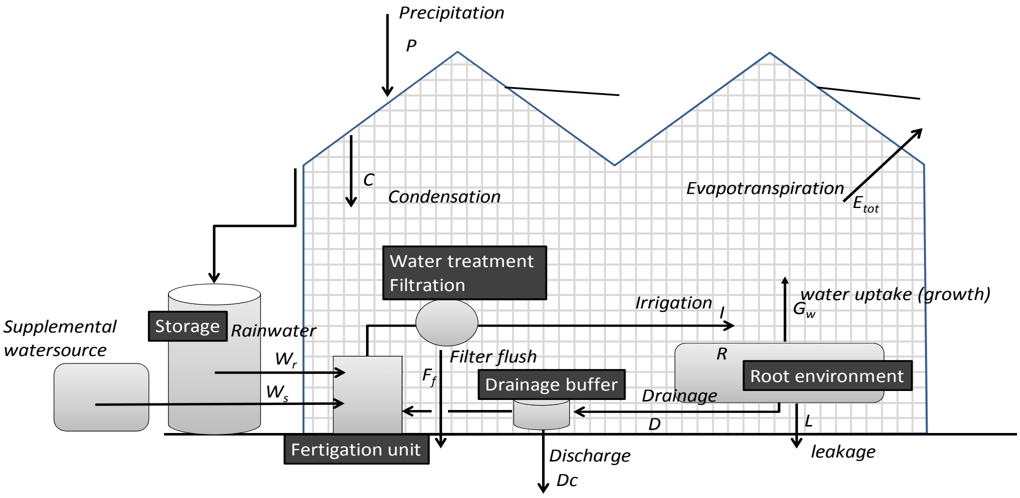

Fig. 1. Schematic picture of the water flows in a greenhouse crop.

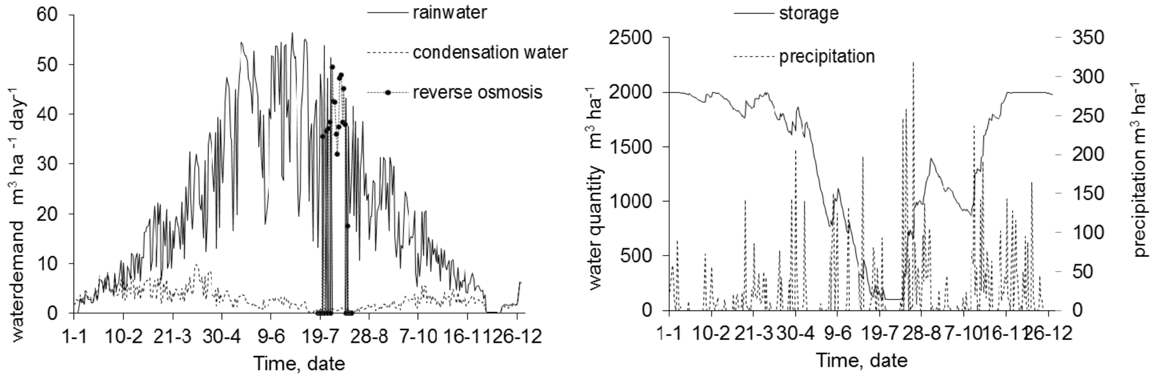

Fig. 2. Simulation results of a tomato crop with a water basin of 2000 m^3 ha^{-1}; climate data of an average year; reuse of condensation water. The demand for rain- and RO water (left) and the development of the rainwater storage and precipitation (right).

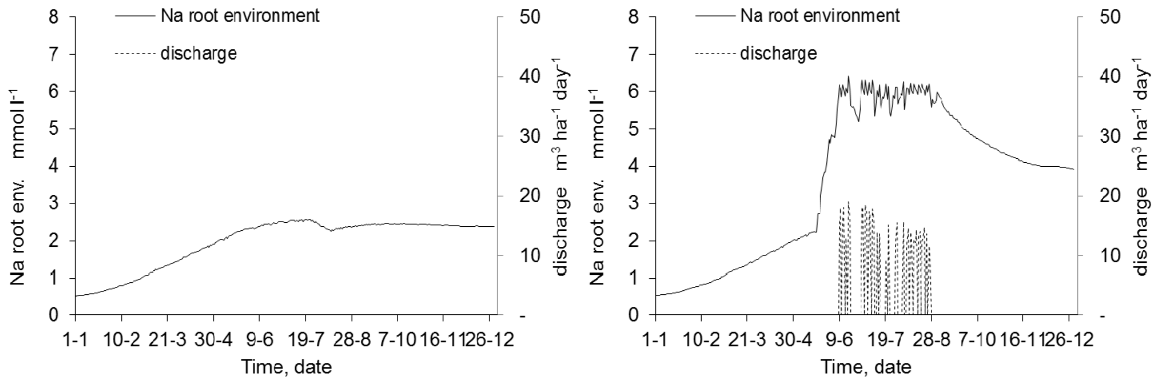

Fig. 3. Simulated Na concentration in the root environment and the required discharge of drainwater to prevent Na accumulation; in case of the tomato crop in Figure 2 (left) and the same in a dry year using tapwater as supplemental water source.