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SWAP 50 years: Advances in modelling soil-water-atmosphere-plant interactions

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ABSTRACT

This paper highlights the evolution and impact of the SWAP model (Soil – Water – Atmosphere – Plant), which was initiated by R.A. Feddes and colleagues fifty years ago, in 1974. Since then, the SWAP model has played a crucial role in the advancement of agrohydrology. This paper highlights some major advances that have been made, especially focussing on the last fifteen years. The domain of the SWAP model deals with the simulation of the soil water balance in both unsaturated and saturated conditions. The model solves the Richards equation using the water retention and hydraulic conductivity functions as described by the Van Genuchten – Mualem equations. Bimodal extensions of the Van Genuchten - Mualem relationships have been implemented, as well as modifications near saturation and addressing hysteresis. An important sink term in the Richards equation is root water uptake. Crop development plays an important role in a robust simulation of root water uptake. That is why a link has been made with the dynamic crop growth model WOFOST. Instead of using a prescribed crop development, a distinction between potential and actual crop development is calculated by reducing the potential photosynthesis as a result of water or oxygen stress. Since the early days of SWAP, empirical and macroscopic concepts have been used to simulate root water uptake. Recently two process-based concepts of root water uptake and oxygen stress have also been implemented. Another important sink-source term in the Richards equation is the interaction with artificial drains. In SWAP, drainage can be simulated by either using prescribed or simulated drain heads and simulation of controlled drainage with subirrigation is possible. Finally, we briefly elaborate on three studies using SWAP: water stresses in agriculture in the Netherlands, regional water productivity in China, and controlled drainage with subirrigation. We finish discussing promising developments for the near future.

1. Introduction, history and context

Fifty years ago, R.A. Feddes and colleagues published a scientific paper on the numerical modelling of root water uptake in soils (Feddes et al., 1974). This paper marked the start of a fascinating development of numerical modelling of soil-water interactions in the Netherlands. Feddes and colleagues realized the large potential of numerical models in the biosphere, where numerous nonlinear interactions between vegetation, soil, water, and atmosphere occur under continuously changing conditions and often in scenarios with a large vertical heterogeneity. The agrohydrological model they developed combined soil water movement, crop growth, and atmospheric conditions. Initial acronyms were SWATR, SWATRE, SWACROP, and in 1997 the name SWAP was introduced: Soil – Water – Atmosphere – Plant.

It is not a coincidence that agrohydrological models are developed and maintained in The Netherlands. The country is located in the delta of large European rivers and is characterized by intensive agriculture, a high population density, deep permeable soils, large aquifers, often (very) shallow groundwater levels, and a large rainfall surplus. Shallow groundwater levels may cause flooding issues, but not always prevent drought stress (Bartholomeus et al., 2023).

Numerical modelling is very versatile in simulating the numerous

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water flow and solute transport situations occurring in the Dutch environment. Therefore, SWAP combines flow in the unsaturated and saturated zone, has extensive options for drainage and surface water management, and includes a generic crop growth model. As advocated by Jarvis et al. (2022), the SWAP developers were convinced that physical-based numerical models combining soil water flow, root water uptake, and crop growth are the most appropriate tools to address agrohydrological problems in modern society.

In any agrohydrological model, the proper simulation of root water extraction under dry, wet, and saline soil conditions plays a key role. Root water uptake was at the focus of Feddes et al. (1974) and stayed important afterward. Feddes et al. (1978) introduced a piecewise linear macroscopic root water extraction function which became the standard for several agrohydrological models worldwide (see 2.3.1). Although this function is frequently applied, more versatile microscopic root water extraction functions have become available (De Willigen, van Noordwijk, 1987; De Jong van Lier et al., 2013; see 2.3.2). Macroscopic and microscopic root water extraction functions show differences in simulations under dry conditions (De Willigen et al., 2012). Additionally, progress was made on the process-based modelling of oxygen stress and root water uptake under wet conditions (see 2.4).

In 2004, a symposium was held on progress, challenges, and applications concerning vadose zone modelling (Feddes et al., 2004). Important topics were the concepts and dimensionality in unsaturated flow modelling, system parameterization, upscaling, and observations of the soil-vegetation system. The symposium showed that in the period 1974–2004, agrohydrological models had matured, but many challenges remained (Feddes et al., 2004).

From the start, the SWAP program, its source code, and documentation were freely available (https://swap.wur.nl). Intensive SWAP courses were given in several countries around the globe. This stimulated the use of SWAP, model calibration, and concept validation in different climate zones. Currently, more than 290 scientific papers are available which show the capabilities of the program. In education, the model is used in bachelor and master courses to make students familiar with soil hydrology and its impact on vegetation and groundwater (Moene, van Dam, 2014).

Van Dam et al. (2008) described important features of SWAP concerning the numerical solution of the Richards equation, macropore flow, evapotranspiration, and vadose zone – groundwater interactions. Since then, the model has been applied in many international studies and has been developed further. In this paper, we describe advances in simulating crop-soil-water interactions, soil hydraulic properties, and root water uptake concepts. We give an overview of typical case studies and describe applications in The Netherlands and China, and one example regarding climate-adaptive drainage with subirrigation. We conclude with developments we foresee in the near future.

2. Developments in SWAP in the past 15 years

In this section, we describe some major advances in the SWAP model implemented since 2008. Detailed information can be found in the model manual (Kroes et al., 2017) and other documentation included in the download package of SWAP (https://swap.wur.nl).

The core of the SWAP-model pertains to the water balance in the unsaturated – saturated top part of the soil. It solves the well-known Richards (1931) equation here given as

$$\frac{\partial\theta(h;t)}{\partial t} = \frac{\partial}{\partial z}\left(K(h;t)\left(\frac{\partial h(t)}{\partial z}+1\right)\right) - S_{\rm r}(h;t) \pm S_{\rm d}(h;t) \quad (1)$$

where h is the pressure head with $h \geq 0$ when the soil is saturated and $h < 0$ when it is unsaturated (cm), θ is the volumetric water content (cm^3 cm^{-3}), K is the hydraulic conductivity (cm d^{-1}), z is the vertical coordinate (cm; positive upward), the term 1 accounts for gravity (cm cm^{-1}; note: 1 stands for $\partial z/\partial z$), t is the time (d), $S_{\rm r}$ is a sink term referring to root water uptake (cm^3 cm^{-3} d^{-1}), and $S_{\rm d}$ is a source or sink term referring to the interaction with drains (cm^3 cm^{-3} d^{-1}): removal of soil water via the drains is considered as a sink (-), whereas water infiltration from drains into the soil is a source (+). The Richards equation is solved numerically for specific boundary conditions at the top (determined by the atmosphere) and at the bottom, for given relationships between h, θ, and K, and for given sink-source terms $S_{\rm r}$ and $S_{\rm d}$. The numerical solution was described in detail in Van Dam et al. (2008). In the following sections details are given regarding the relationships between h, θ, and K (Section 2.1), and the sink-source terms $S_{\rm r}$ (sections 2.2, 2.3, 2.4) and $S_{\rm d}$ (section 3.3). Salinity stress is not discussed in detail in this paper. SWAP has the option to consider the piecewise linear reduction function following Maas and Hoffman (1977). Salinity stress can also be included in the process-based root water uptake models as was done by Heinen (2001) and De Jong van Lier et al. (2009). However, the latter option is not yet operational in SWAP.

2.1. Soil hydraulic properties

As indicated, the three variables h, θ, and K are related to each other. The relationship θ(h) is the water retention function and $K(h)$ or K(θ) is the hydraulic conductivity function. These functions can be determined on individual soil samples. It appears that such data can be well described by analytical expressions. Many examples of such expressions exist in the literature (e.g., Leij, et al., 1997). The most often-used relationships are those given by Van Genuchten (1980). The water retention function is given by

$$S(h) = \frac{\theta(h)-\theta_{\rm r}}{\theta_{\rm s}-\theta_{\rm r}} = \begin{cases} 1 & 0 \leq h \\ (1+|\alpha h|^{\rm n})^{-\rm m} & h < 0 \end{cases} \quad (2)$$

Based on the hydraulic conductivity theory of Mualem (1976), Van Genuchten (1980) derived the following hydraulic conductivity function (provided $m = 1 - 1/n$)

$$K(S) = K_{\rm s}S^{\lambda}\left(1-\left(1-S^{1/{\rm m}}\right)^{\rm m}\right)^2 \quad (3)$$

or

$$K(h) = \begin{cases} K_{\rm s} & 0 \leq h \\ K_{\rm s}\dfrac{\left((1+|\alpha h|^{\rm n})^{\rm m} - |\alpha h|^{\rm n-1}\right)^2}{(1+|\alpha h|^{\rm n})^{\rm m(\lambda+2)}} & h < 0 \end{cases} \quad (4)$$

In these Van Genuchten – Mualem (VGM) functions, S is the effective degree of saturation (dimensionless; [0..1]), θ_r is an asymptotic residual water content (cm^3 cm^{-3}), θ_s is θ at saturation (cm^3 cm^{-3}), K_s is K at saturation (cm d^{-1}) and α (cm^{-1}), n, m and λ (all three dimensionless) are shape parameters. These relationships have been implemented in SWAP, and the user should supply the corresponding parameters (θ_r, θ_s, K_s, α, n, λ) for each soil layer.

If no information on these parameters is available or the measured data suggests a different relationship, tabulated h-θ-K data can be provided for each soil layer. SWAP performs interpolation in these tables during the simulation. Tabulated input allows for great flexibility. However, the numerical solution of the Richards equation requires also data on the first derivative of the water retention function: $C(h) = {\rm d}\theta/{\rm d}h$ (cm^{-1}). For the Van Genuchten relationship (Eq. (2)) this can be given by the analytical expression,

$$C(h) = \begin{cases} 0 & 0 \leq h \\ (\theta_{\rm s}-\theta_{\rm r})\alpha nm|\alpha h|^{\rm n-1}(1+|\alpha h|^{\rm n})^{-1-\rm m} & h < 0 \end{cases} \quad (5)$$

whereas from the tabulated input data C can only be approximated and is likely not smooth at the input values. A non-smooth relationship for C might cause numerical problems and/or additional iterations might be needed.

For more complex soils, analytical expressions might be preferred above tabulated input data to describe these physical properties. In SWAP, the bimodal equivalent of the VGM relationships according to Durner (1994) and Priesack and Durner (2006) is available, given by

$$S(h) = \begin{cases} 1 & 0 \le h \\ \sum_{i=1}^{2} \omega_i \left(1 + |\alpha_i h|^{n_i}\right)^{-m_i} & h < 0 \end{cases} \tag{6}$$

$$K(S) = K_s \left(\sum_{i=1}^{2} \omega_i S_i\right)^{\lambda} \left[1 - \frac{\sum_{i=1}^{2} \omega_i \alpha_i \left(1 - (S_i)^{1/m_i}\right)^{m_i}}{\sum_{i=1}^{2} \omega_i \alpha_i}\right]^2 \tag{7}$$

where i is a counter for the two pore size subsystems that make up the overall hydraulic properties as a linear superposition of the underlying subsystems and ω is a dimensionless weighting factor for the two subsystems with $\omega_1 + \omega_2 = 1$. The expression for C is

$$C(h) = \begin{cases} 0 & 0 \le h \\ (\theta_s - \theta_r) \sum_{i=1}^{2} \omega_i \alpha_i n_i m_i |\alpha_i h|^{n_i - 1} \left(1 + |\alpha_i h|^{n_i}\right)^{-1-m_i} & h < 0 \end{cases} \tag{8}$$

For the bi-modal option, the user should supply the corresponding set of parameters for each soil layer (θ_r, θ_s, K_s, α_1, α_2, n_1, n_2, λ, ω_1).

Furthermore, extensions for the VGM relationships have been published by Peters (2013), Iden and Durner (2014) and Peters (2014) (the Peters-Durner-Iden model or PDI model). In the PDI-model the (capillary) water retention function is extended with an adsorption component, and the (capillary) hydraulic conductivity relationship is extended with water film transport (related to the adsorption component in the water retention extension) and optionally with water vapour transport. Both mono- and bimodal expressions are provided. Disregarding adsorption, film, and vapour transport results in the original VGM relationships. Another extension provided in the PDI-model is the possibility to scale the θ(h) such that $\theta(h_0) = 0$ (instead of the asymptotic value θ_r), with h_0 referring to oven-dry conditions ($\sim -10^{6.8}$ cm). The PDI model is implemented in SWAP; however, it has not been used extensively so far.

Modifications of the VGM model near saturation have been suggested in the literature. In SWAP, the modification as described by Ippisch et al. (2006) is implemented. This modification introduces an air-entry value h_{ae} (cm). This affects the shape of θ(h) only minimally, but the impact on K of fine-textured soils can be large. To avoid numerical instabilities of the solution scheme, the θ(h) curve in the range $-0.01 > h > 1.05h_{ae}$ is approached by a cubic spline of which the parameters preserve the continuity of θ(h) and $C(h)$. A second modification near saturation concerns K at saturation. The parameter K_s of the $K(S)$-relation is usually derived from experiments with unsaturated flow. These experiments may yield a poor estimate of K at saturated conditions where soil structure usually dominates over soil texture. However, to accurately simulate runoff conditions and drainage, a correct value of K at saturation is essential. Therefore, SWAP users may specify in addition to the parameter K_s the experimentally determined value of the K at saturation, $K_{s,exp}$ (cm d^{-1}). Close to saturation, in the range $0 > h > -2$ cm, SWAP will linearly interpolate between $K_{s,exp}$ and $K(S)$ at $h = -2$ cm.

Computers may not accurately calculate values of K at very low values of h (or S). To increase accuracy at low values of h (or S) one can approximate the Mualem expression by a power-expression. For example, Heinen (2023) suggested

$$K(h) = \begin{cases} K_s & 0 \le h \\ K_s \dfrac{\left((1 + |\alpha h|^n)^m - |\alpha h|^{n-1}\right)^2}{(1 + |\alpha h|^n)^{m(\lambda+2)}} & h_c < h < 0 \\ K_s^* m^2 |\alpha h|^{-(2+m\lambda)n} = K_c \left(\dfrac{h_c}{h}\right)^{(2+m\lambda)n} & h \le h_c \end{cases} \tag{9}$$

where h_c is the pressure head below which the power expression is valid. Heinen (2023) provides expressions from which h_c can be determined; it is dependent on the parameters α and n. Similar approximations were already proposed in the SOHYP and RETC computer codes (Van Genuchten, 1978; Van Genuchten et al., 1991).

The relationships θ(h) and $K(h)$ differ for drying and wetting processes, i.e., they are hysteretic (Miller and Miller, 1956). Topp (1969) showed experimentally that θ(h) is hysteretic and that K(θ) has negligible hysteresis. In SWAP, the scaling method of Scott et al. (1983) is implemented to account for hysteresis, but only for the monomodal version of the VGM equations. If hysteresis is to be considered in the simulation, one additional parameter needs to be supplied, the α parameter for the main wetting curve: α_w (cm^{-1}). The main drying curve is then described by the set (θ_r, θ_s, α_d, n) and the main wetting curve by the set (θ_r, θ_s, α_w, n), with $\alpha_w > \alpha_d$. Often only information regarding the main drying curve is available. If hysteresis is to be considered then one could use $\alpha_w = 2\alpha_d$ as suggested by Kool and Parker (1987).

Experience shows that the exact shape of the θ(h) and K(θ) functions have a great influence on the solution of the Richards equation. So, this information should be supplied as accurate as possible. The best information comes from measured relationships. If these are lacking, one can take data from the literature that best matches the study site under consideration. This can be done via pedotransfer functions or tabulated data that describe the VGM parameters (see, e.g., Nemes et al., 2001; Schaap et al., 2001; Tóth et al., 2014; Wösten et al., 1999). Heinen et al. (2022) described the averaged VGM parameter sets for different soil texture classes in The Netherlands. They also combined this information with the Dutch soil map, consisting of 368 standard soil profiles to derive a national soil physical units map.

2.2. *Crop growth in interaction with soil, climate and water management*

Root water uptake is a sink term in the Richards equation, important for the prediction of evapotranspiration, and generally a large component in the water balance. The amount of water extracted from the soil by roots is determined by the conditions and characteristics of the atmosphere, the plant, and the soil. To correctly simulate root water uptake, a proper estimation of the actual crop development is necessary.

In hydrological models, crop development is often simulated using a static approach, which means that crop development during the growing season is predefined and not influenced by climate conditions or unfavourable growth conditions. For the simulation of root water uptake, a dynamic crop development simulation is desirable. In SWAP, two options for dynamic crop growth modelling are available: i) WOFOST (Van Diepen et al., 1989; Boogaard et al., 2014) for arable crops and ii) an adapted version of WOFOST for the simulation of grassland (Kroes and Supit, 2011).

The dynamic crop growth model WOFOST was developed by the Centre for World Food Studies in Wageningen and has been applied for many years as part of operational crop yield forecasting systems (De Wit et al., 2019). The basic processes simulated by WOFOST are phenological development, biomass growth, partitioning over plant organs, and root growth. The most important external drivers for crop development are daily weather data and initial crop conditions. The most important internal driver is the leaf area index (LAI) which is the result of leaf area dynamics controlled by photosynthesis, allocation of biomass to leaves, leaf age, and development stage. In turn, LAI controls the daily rates of photosynthesis and evapotranspiration (Fig. 1).

The radiation energy absorbed by the canopy is a function of incoming radiation and crop leaf area. Potential photosynthesis is calculated using the absorbed radiation and taking into account photosynthetic leaf characteristics. A part of the produced carbohydrates (CH_2O) is used to provide energy for the maintenance of the living biomass (maintenance respiration). The remaining carbohydrates are converted into structural matter. In this conversion, some mass is used for growth respiration. The dry matter produced is partitioned among roots, leaves, stems, and storage organs, using partitioning factors as a function of the crop development stage. The mass partitioned to the leaves determines leaf area development and hence the capacity for light interception. This interaction of light interception and leaf area growth causes an important positive feedback in WOFOST. The dry mass of the various plant organs is determined by integrating their growth rates over time. The WOFOST model further considers that part of the living biomass dies due to senescence during crop development.

In dynamic crop growth models, as described by Boogaard et al. (2014) and Kroes et al. (2017), the distinction between potential and actual crop development is calculated by reducing the potential photosynthesis due to water, oxygen and/or salinity stress, as a function of relative transpiration (T_{act}/T_{pot}), which yields actual photosynthesis. Unlike the static approach, the reduction in root water uptake will then affect the crop development and thus the crop water demand in the remaining part of the growing season. Actual transpiration equals cumulative root water uptake over the root zone. In the next sections, we discuss the effect of drought (2.3) and oxygen stress (2.4) on root water extraction.

2.3. Drought stress: macroscopic (empirical) and microscopic (process-based) concepts

Plants take up water from the soil via their root system, almost all of which is subsequently transpired via the leaves. If the root water uptake cannot match the required atmospheric demand, plants increase the canopy resistance to vapour flow by (partly) closing their stomata, thus reducing gaseous exchanges (mainly H_2O and CO_2) via the leaves. This results in reduced metabolism and growth. Therefore, from a soil water balance and crop modelling standpoint, a good description of root water uptake, the sink term S in Eq. (1), is essential. Root water uptake is a key process in the global water cycle (Jasechko et al., 2013; Rothfuss and Javaux, 2016).

2.3.1. The macroscopic or empirical concept of Feddes

Since the early beginning of the SWAP model, root water uptake has been described by the empirical and macroscopic concept proposed by Feddes et al. (1978). According to this concept, the reduction of root water uptake due to drought and oxygen stress is described by a piecewise linear function (Fig. 2, left):

$$\alpha_{Fe} = \begin{cases} 0 & h_1 \le h \\ \dfrac{h - h_1}{h_2 - h_1} & h_2 < h < h_1 \\ 1 & h_3 \le h \le h_2 \\ \dfrac{h - h_4}{h_3 - h_4} & h_4 < h < h_3 \\ 0 & h \le h_4 \end{cases} \tag{10}$$

where α_{Fe} is the Feddes reduction function (dimensionless) and h_1, h_2, h_3, h_4 are crop-dependent input variables (cm). For $h_3 < h < h_2$ no reduction in water uptake occurs. For $h_4 < h < h_3$ a linear decrease in root water uptake occurs due to drought stress. For $h_2 < h < h_1$ a linear decrease in root water uptake occurs due to oxygen stress; an alternative for oxygen stress is discussed in section 2.4.

The total water demand (T_{pot}, cm d^{-1}) is divided over all soil layers proportional to a given root distribution. For each soil compartment, the actual water uptake is calculated based on Eq. (10). The sum uptake from all the compartments (T_{act}, cm d^{-1}) is then compared to the total demand to determine the amount of reduction (if any). Compensation, i.e., more uptake from a wet layer if one or more other layers present a reduced uptake, may be included according to Jarvis (1989); (2011), which is visualized in Fig. 2 (right). If $\alpha_{crit} \le T_{act}/T_{pot} < 1$, where α_{crit} is a user-defined value in the range [0..1] (e.g., α_{crit} = 0.7), complete

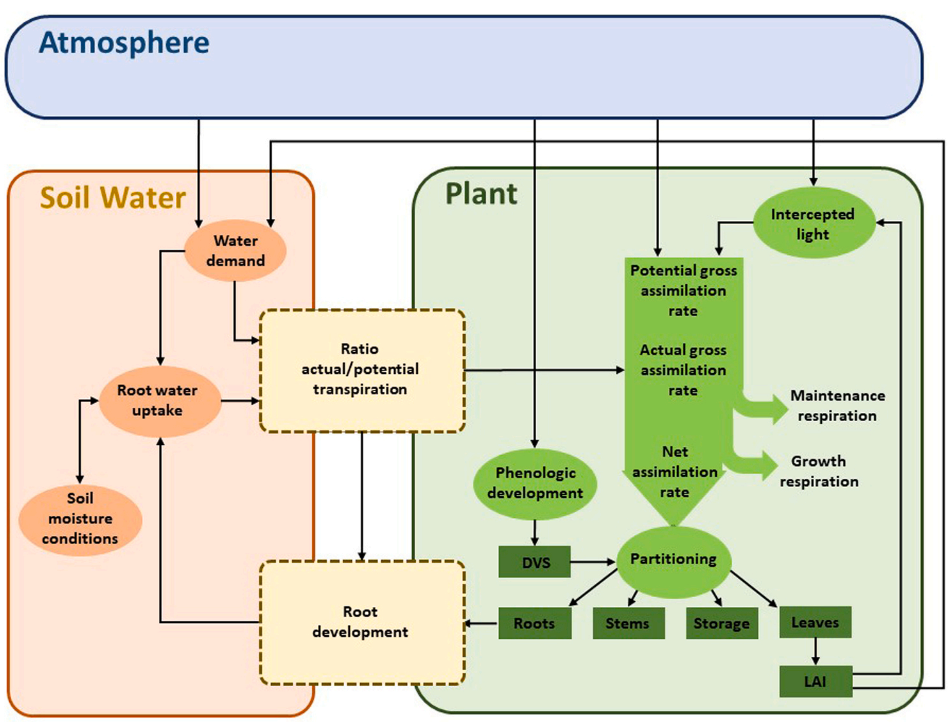

Fig. 1. Flow chart of dynamic crop growth as simulated by WOFOST (adapted from De Wit et al., 2019).

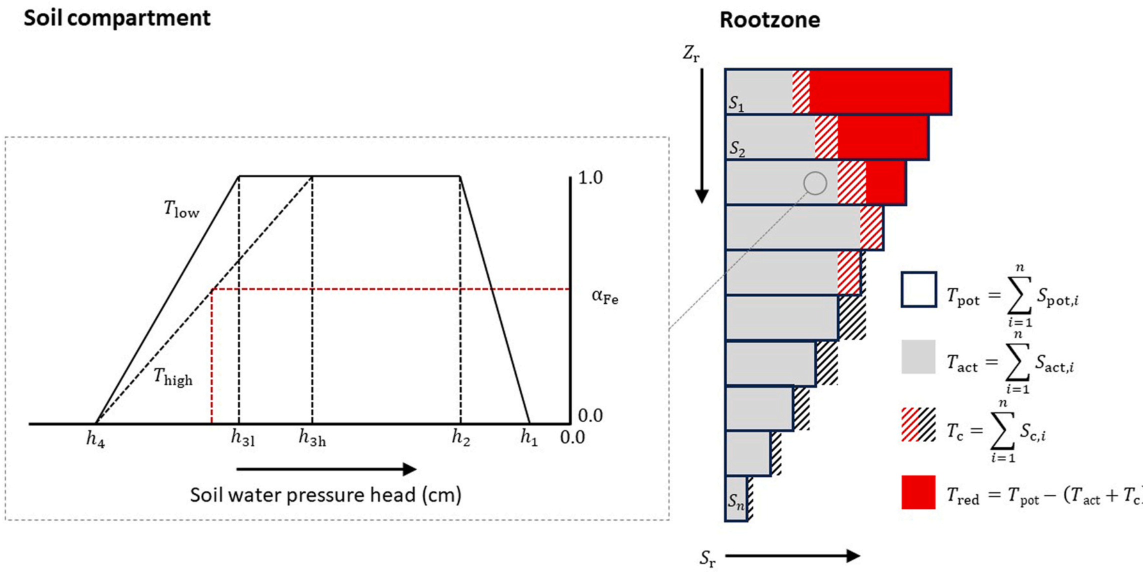

Fig. 2. Transpiration reduction factor as a function of soil water pressure head (left) and explanation on Jarvis compensation (right); see text for further explanation.

compensation is simulated and for each soil compartment the actual root water uptake is multiplied by the factor T_{pot}/T_{act}, such that $T_{act,c} = T_{pot}$ (subscript c refers to the result after applying compensation; $T_{act,c} = T_{act} + T_c$, see Fig. 2 with T_c given by the hatched area). If $T_{act}/T_{pot} < \alpha_{crit}$, partial compensation is simulated: for each compartment, the uptake is multiplied by $1/\alpha_{crit}$, which results in $T_{act,c} = T_{act}/\alpha_{crit} < T_{pot}$. The transpiration reduction is given as $T_{red} = T_{pot} - T_{act,c}$ (red area in Fig. 2).

The robustness of the Feddes model has been questioned. For example, De Melo and de Jong van Lier, (2021) stated that the number of calibrations and validations of this concept is limited. Therefore, using this concept in a wide spectrum of soil-crop-climate scenarios should be questioned.

We will refer to the Feddes-concept without compensation by Fe_0 and with compensation by Fe_1. Note that in some studies the Feddes reduction factor α also causes reduction under wet conditions. An alternative for the modelling of reduction in water uptake due to oxygen stress will be discussed in section 2.4.

2.3.2. *The microscopic or process-based concepts*

Besides the macroscopic root water uptake model by Feddes, several process-based models describing root water uptake have been developed. Two of these have recently been implemented in SWAP. De Willigen, van Noordwijk, (1987) described the process of uptake by roots; not only of water but also of oxygen and nutrients. A cylindrical soil column can be assumed around each root with root radius R_0 (cm); the radius of this soil column is inversely proportional to the root length density according to (Fig. 3; left)

$$R_1 = (\pi L_{rv})^{-0.5} \tag{11}$$

where R_1 is the radius of the soil cylinder (cm) and L_{rv} is the root length density (cm cm^{-3}). Water will flow from the outside of the cylinder toward the root in the middle due to a gradient in pressure head (h) (Fig. 3; right).

De Willigen, van Noordwijk, (1987) showed that the physical state in the soil column can be described very accurately with an analytical, steady-rate formulation. This formulation is not based on h but on the matric flux potential, $M(h)$ (cm^2 d^{-1}), defined as the integral of $K(h)$ (Raats, 1970). Any profile described in terms of M can be transformed in h or θ. The analytical solution provides an expression for the water flux q (cm^3 cm^{-2} d^{-1}) toward the root wall and can be upscaled to an entire root system. Here, De Willigen, van Noordwijk, (1991), Heinen (2001),

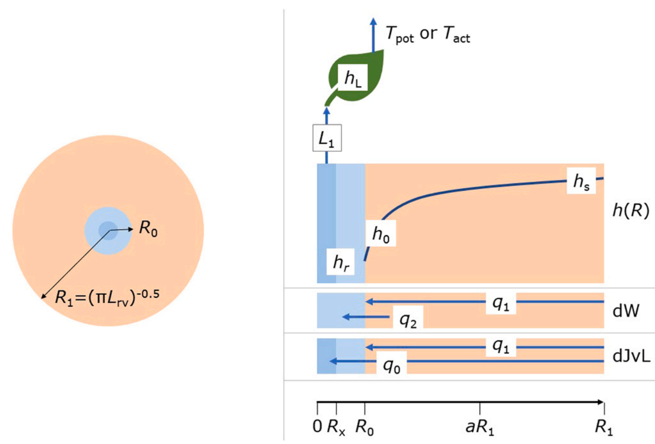

Fig. 3. Top view of a single root with radius R_0 surrounded by a cylinder of soil with R_1 given by Eq. (11) (left), and (right) vertical cross-section of the root and radial soil cylinder showing the gradient in $h(R)$ towards toe root wall and the fluxes considered in the dW and dJvL concepts (see text for further explanation).

and De Willigen et al. (2011); (2012) (further denoted as the dW concept) used two fluxes: a water flux in the soil column toward the root wall (q_1) and a water flux across the root wall (q_2) (Fig. 3). For the dW concept, the equations involved are given by

$$q_{1,j} = \Delta z_j \rho_{dW,j} \left(M_{s,j} - M_{0,j} \right) \tag{12}$$

where q_1 is the flux from the bulk soil (s) toward the root-soil interface (0) (cm d^{-1}), Δz is the thickness of the soil compartment (cm), M is the matric flux potential (cm^2 d^{-1}), j is the soil compartment sequential number, and ρ_{dW} is a geometry factor (cm^{-2}) given by

$$\rho_{dW} = \frac{r^2 - 1}{0.5 R_1^2 \left(0.25(1 - 3r^2) + r^4 \ln\left(\frac{r}{r^2 - 1} \right) \right)}, \quad \text{with} \quad r = \frac{R_1}{R_0} \tag{13}$$

The water flux across the root wall q_2 (cm d^{-1}) is given by

$$q_{2,j} = \Delta z_j L_{rv,j} K_r \left(h_{0,j} - h_r \right) \tag{14}$$

where K_r is the hydraulic conductivity of the root wall (cm d^{-1}), and h_r is the pressure head inside the root (root water potential; cm). The h_r is related to the leaf water potential h_L via a relationship taken from Zhuang et al. (2001)

$$h_L = h_r - \frac{T_{pot}}{a_0 + a_1 T_{pot}} \tag{15}$$

with $a_0 = 3.1844\ 10^{-5}$ d^{-1} and $a_1 = 1.7768\ 10^{-4}$ cm^{-1} (De Willigen et al., 2011). The transpiration reduction function is given by (Campbell, 1991)

$$T_{act} = T_{pot}\left(1 + \left(\frac{h_L}{h_{L,1/2}}\right)^p\right)^{-1} \tag{16}$$

where $h_{L,1/2}$ is h_L where $T_{act} = 0.5T_{pot}$, and p is a dimensionless curve shape parameter, usually in the range 5–10; a step function can be approximated by taking a large value for p (e.g., $p = 250$) (Fig. 4). The sum for all computational layers of all q_1 and that of all q_2 must be equal to each other and equal to the (actual) water uptake T_{act}.

De Jong van Lier et al. (2013) used the same steady-rate solution (further denoted as the dJvL concept). They defined an alternative expression for the water flux from the soil column directly into the root (q_0) which also includes q_1. For the dJvL concept, the main equation is given by

$$h_{0j} + \phi_{dJvL,j} M_{0j} = h_L + \phi_{dJvL,j} M_{s,j} + \frac{T_{act}}{L_1} \tag{17}$$

where L_1 is the conductance in the pathway root-stem-leave (d^{-1}) and ϕ_{dJvL} is a geometry factor (d cm^{-1}) given by

$$\phi_{dJvL} = \frac{R_1^2 \ln\left(\frac{R_0}{R_x}\right)}{2K_r} \rho_{dJvL} \tag{18}$$

where R_x is the radius of the xylem vessel (cm) and ρ_{dJvL} is a geometry factor (cm^{-2}) given by

$$\rho_{dJvL} = \frac{4}{\left(R_0^2 - a^2 R_1^2 + 2\left(R_0^2 + R_1^2\right)\ln\left(\frac{aR_1}{R_0}\right)\right)} \tag{19}$$

where a is a dimensionless fraction indicating where in the soil cylinder the pressure head equals the value h_s. According to de Jong van Lier et al. (2006); (2008); (2013), $a = 0.53$ is a good approach in monomodal Van Genuchten-type soils. The water flux inside the soil cylinder is given by

$$q_{1j} = \Delta z_j \rho_{dJvL,j}\left(M_{s,j} - M_{0,j}\right) \tag{20}$$

Both dW and dJvL concepts result in a set of N nonlinear equations with N unknowns, with the requirement that the sum of water uptake from all soil compartments is equal to T_{act}, the latter being a function of the additional unknown h_L. The N unknowns are h_0 (observe that M_0 is a function of h_0) and the nonlinearity is a consequence of the nonlinear functions $M(h)$ and $T_{act}(h_L)$. This equation system is solved via a double, nested iteration procedure as given in Appendix A.

For both dW and dJvL microscopic concepts, implicit compensation occurs. By simultaneously solving the system for all computational layers in the root zone, a thermodynamically most favourable distribution of water uptake is simulated: more water uptake will implicitly be simulated from zones where hydraulic conditions are more favourable, and no subsequent computational step is needed to deal with this compensation.

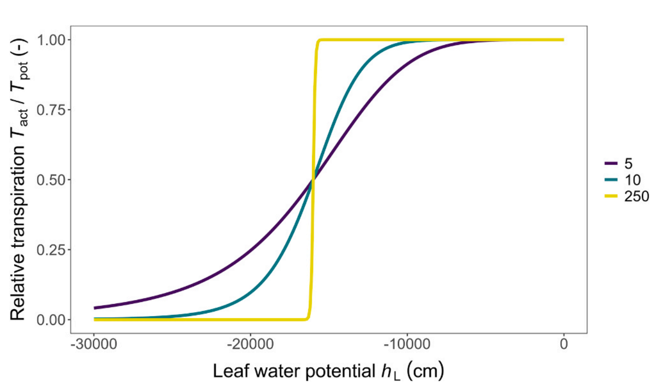

Fig. 4. Relative transpiration as a function of leaf water potential according to the Campbell (1991) function for three values of exponent p with $h_{L,1/2}$ = −16000 cm.

2.3.3. Example

SWAP-WOFOST simulations were performed for a 30-years period (1991–2020) using the root water uptake concepts Fe_0, Fe_1, dW, and dJvL. Simulations were performed for four representative Dutch soil profiles, either with a shallow groundwater level (mean highest (MHG) and mean lowest (MLG) groundwater level in ranges [27–39] and [57–71] cm below the soil surface) or with a deeper groundwater level (MHG and MLG in ranges [71–127] and [204–222] cm below soil surface). The VGM parameters for these soil profiles are given in Appendix B. The simulated reduction in grass yield is shown in Fig. 5. In general, Fe_1 results in lower yield reductions than Fe_0. The yield reductions according to dW and dJvL are very similar but lower than Fe_0 or Fe_1. This means that, according to the process-based concepts of dW and dJvL, plants experience less difficulty in taking up water from the soil. This is largely due to the implicit compensation resulting from these concepts, leading to an enhanced uptake from wetter layers, often at the bottom of the root zone (Fig. 6).

2.3.4. Discussion

While the process-based reduction functions (dW and dJvL) contain a physical description of the process of water transport, they require some additional parameters. All of these have a physical or physiological meaning and can be independently measured or their values can be retrieved from literature. Publications dealing with the concepts of dW and dJvL provided data on these parameters (including ranges). These were summarized by Heinen and Mulder (2023), including literature data collected by De Willigen, van Noordwijk, (1987).

Despite these advantages, the Feddes reduction function is by far the most popular among users of the SWAP model due to its apparent simplicity. Would it be possible to calibrate the Feddes limiting pressure heads using a process-based reduction function?

In their attempt to do so by applying the dJvL model, Dos Santos et al. (2017) were not successful. A moderate agreement could only be obtained in case there is hardly any compensation occurring in the root zone. The only simple way to compare the Fe-concept and a process-based concept is by considering a monolayer root zone. From the dW-concept, it then follows that the relationship between T_{act}/T_{pot} and h_s is nonlinear as opposed to the linear decrease according to the Feddes-concept. This nonlinearity is caused by the nonlinear $M(h)$ properties of the soil layer (Heinen and Mulder, 2023).

Since only a single root (or leaf) water potential is considered in the microscopic concepts, the implicit (intrinsic) compensation effect may be overestimated. Hydraulic redistribution of water in the soil via the root system (hydraulic lift) may also be simulated, although this is sometimes not seen as realistic. Models have been developed for the three-dimensional analysis of water flows in the soil-root system (e.g., Javaux et al., 2008), and recently an upscaled one-dimensional version of this model has been proposed by Vanderborght et al. (2023).

2.4. Oxygen stress

The metabolic processes occurring in roots require oxygen. In (near) water-saturated soil conditions, where oxygen diffusion is limited, most

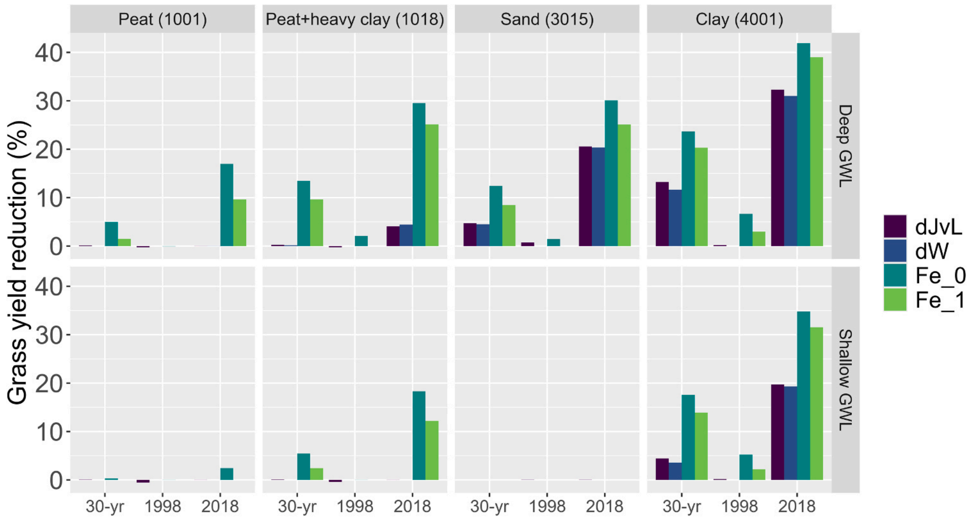

Fig. 5. Simulated grass yield reductions for four soil profiles (top panels) and two groundwater levels (GWL; right panels) according to the four concepts Fe_0, Fe_1, dW, and dJvL. Yield reductions are given as thirty-year averages (30-yr: 1991–2020) and for a wet year (1998) and a dry year (2018). The soil profile codes refer to the BOFEK soil profiles given by Heinen et al. (2022).

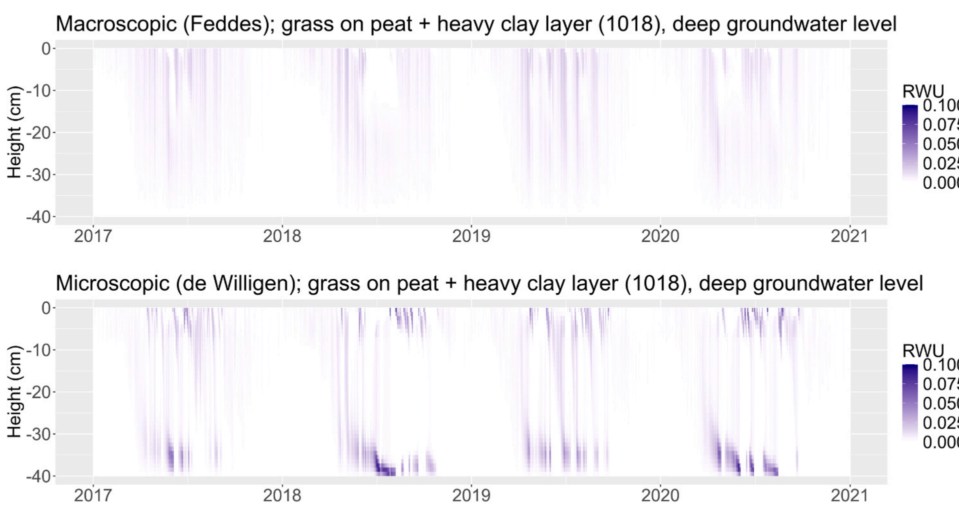

Fig. 6. Time-depth distributions of root water uptake (RWU, cm d^{-1}) for the case of grass on soil profile 1018 (peat + heavy clay layer) and a relatively deep groundwater level according to Fe_1 (top) and dW (bottom).

terrestrial plants suffer from a lack of oxygen. The effect of insufficient soil aeration on the functioning of plants has been an important field of research for a long time, e.g. in (1) agriculture, as oxygen stress reduces yields (Dasberg and Bakker, 1970), (2) ecology, since water logging affects plant species composition (Runhaar et al., 1997), and (3) hydrological modelling, as water logging reduces root water uptake (Feddes et al., 1978).

Oxygen stress depends on various abiotic and biotic factors. For many years, procedures for root water uptake simulation, including the Feddes function (Fig. 2), did not combine both plant physiological and soil physical processes to predict the reduction of root water uptake in scenarios of insufficient soil aeration. In SWAP, a more process-based approach was included.

Oxygen stress, defined as the daily respiration reduction (i.e. potential minus actual respiration) is calculated with the process-based model of Bartholomeus et al. (2008) for oxygen transport and consumption. The model combines interacting physiological processes (i.e. root respiration and microbial respiration) and physical processes (i.e. macro-scale and micro-scale oxygen diffusion) to simulate daily respiration reduction, using generally applied physiological and physical relationships. Oxygen stress occurs when the actual root respiration is lower than the potential root respiration, i.e. when the oxygen supply cannot meet the oxygen demand of plant roots. Root respiration is determined by interacting respiratory (i.e. oxygen consuming) and diffusive (i.e. oxygen providing) processes in the soil and to the roots. The model of Bartholomeus et al. (2008) is applied to all rooted soil layers of SWAP, to account for layer-specific soil physical properties, moisture contents, and temperatures. The process-based description of oxygen uptake has a great analogy with the process-based root water uptake concepts described above.

Bartholomeus et al. (2008) showed that assuming constant values for h_1 and h_2 in the Feddes-model (see Eq. (10) and Fig. 2) is inappropriate for an accurate determination of oxygen stress. Reduction of root water uptake due to oxygen stress may start already under drier conditions and it is not only crop-dependent but also depends strongly on soil type and soil temperature.

3. Case studies

Over the last five decades, the SWAP model has been used in many research projects. Van Dam et al. (2008) catalogued studies with SWAP until 2008. In addition to that, Table 1 lists studies with SWAP in recent scientific literature. Below, we briefly describe three case studies: 1. Water stresses in agriculture (Netherlands); 2. Regional water productivity (China); 3. Controlled drainage with subirrigation.

3.1. Agricultural yield reduction due to water and oxygen stress

Many of the more recent additions and improvements in SWAP are due to a large project ('Watervision Agriculture') in the Netherlands dealing with predicting agricultural yield reductions due to water and oxygen stress (Hack-ten Broeke et al., 2016; 2019). The integration of the WOFOST dynamic growth model in SWAP (Section 2.2) and the addition of oxygen stress as a driver for actual growth (section 2.4) are a result of this study. In parallel, the option of process-based root water uptake was taken into account (Section 2.3).

The main aim of this study was to develop an instrument for practitioners (policymakers, water authorities, water management engineers, drinking water companies) to allow for studies to determine the impact of regional or local hydrological interventions (e.g., changes in groundwater level management due to surface water management or activating groundwater pumping wells) or climate change on hydrological conditions and agricultural crop production. This outcome can then be used to decide on management options or (financially) compensate farmers for loss of yields due to such hydrological interventions. It appears that the impacts on yield are determined by soil profile properties such as the water retention and hydraulic conductivity functions (see Section 2.1), crop type (see Section 2.2), meteorological conditions, and groundwater dynamics. 'Watervision Agriculture' consists of three modes of usage. For the first mode, about 1 million simulation runs with SWAP-WOFOST were performed for which the simulated yield reductions were summarized by a random forest model.

Table 1
Studies with SWAP as reported in recent scientific literature.

Citation	*Location*	*Primary study objective*	*Special feature used*
Bonten et al. (2012)	Netherlands	Transport heavy metals	Lateral drainage options
Bonfante et al. (2017)	Lebanon	Agricultural production	Soil heterogeneity
Kroes et al. (2018)	Netherlands	Soil water recirculation	Upward and downward flow
Mokhtari et al. (2018)	Iran	Crop yield prediction	Assimilation satellite data
Pinto et al. (2019)	Brazil	Intercropping competition	Interaction 2 SWAP columns
Bonfante et al. (2019)	Italy	Soil quality and health	Surface runoff
Taufik et al. (2019)	Indonesia	Peatland management	Extensive drainage options
Hack-ten Broeke et al. (2019)	Netherlands	Water stress in agriculture	Crop-soil-water interaction
Kroes et al. (2019)	Argentina	Land use change	Distributed modelling
Li, Ren, (2019a), Li, Ren, (2019b))	China	Crop water productivity	Irrigation options
Da Silva et al. (2020)	Brazil	Irrigation management	Soil hydraulic properties
Eberhard et al. (2020)	Germany	Salinization marshland	Water and salt interaction
Maleki Tirabadi et al. (2022)	Iran	Regional salinization	Combination with SWAT
Pinheiro and Nunes (2023)	Brazil	Soil tillage effects	Dynamic maize growth
De Melo et al. (2023)	New Zealand	Land and water productivity	Microscopic root water uptake
De Wit et al. (2024)	Netherlands	Drainage with subirrigation	Extensive drainage options
De Jong van Lier et al. (2024)	Brazil	Water balance components	Stochastic interface

The user can access these tabulated data for combinations of soil type, crop type, weather station (historic data or climate prediction) and classified groundwater level information. The second mode allows the user to select one specific SWAP-WOFOST simulation run out of the 1 million that were used to generate the tabulated data of the first mode. The user can than tailor the input data to the conditions at hand. The third mode refers to the possibility to run multiple SWAP-WOFOST simulations for a specific region to allow regional-specific simulations. The second and third modes use the SWAP-WOFOST model directly, making it possible to analyze the simulated crop yield in detail. Examples can be found in Hack-ten Broeke et al. (2019).

3.2. Regional water productivity in the North China Plain

The North China Plain (NCP) is sometimes denoted as the breadbasket of China as it produces a large part of all Chinese wheat and maize. However, the widespread wheat-maize rotation in NCP consumes 700–1000 mm yr^{-1}, much more than the annual average rainfall of 500–600 mm. The extraction of groundwater for irrigation has caused a groundwater table decline of nearly 1 m yr^{-1} during the past forty years (Yang et al., 2022). This groundwater decline has a huge detrimental impact on the environment. Therefore, in NCP no longer land productivity (crop yield/land surface area, kg ha^{-1}) is a main goal, but water productivity (crop yield/water consumed, kg m^{-3}). A higher water productivity is urgently needed to decrease groundwater mining in NCP and might be achieved by more effective irrigation and crop diversification.

Li, Ren, (2019a) applied SWAP-WOFOST in a distributed way in NCP for evaluating agrohydrological cycles and irrigation strategies. They started with a global sensitivity analysis to identify the most important calibration parameters. These parameters were calibrated and validated using experimental data from six stations spread over NCP. For regional simulation, they overlayed 12 maps for regional simulations involving meteorology, soil, crops, land use, water resources, and administrative divisions. The simulated yields of winter wheat and summer maize were consistent with statistical values, and the simulated evapotranspiration matched the remote sensing data. Li, Ren, (2019b) used the calibrated models to evaluate 11 limited irrigation scenarios and their effect on land and water productivity. Li and Ren (2023) further extended the water productivity analysis with differences between sprinkler irrigation and surface irrigation.

The diversification of the traditional monoculture of wheat and maize in NCP with cash crops (e.g. potato) and legumes (peanut and soybean) can be beneficial for farmers, society, and the environment. For instance, crop diversification may increase the equivalent yield, reduce N_2O emissions, and stimulate soil microbial activities (Yang et al., 2024). Investigations on the water productivity of alternative cropping systems in NCP using SWAP-WOFOST are ongoing.

3.3. Controlled drainage with subirrigation

In Eq. (1) a sink-source term was used for the interaction with drains (drain pipes, ditches, or other open water bodies). Traditionally drains are regarded as sinks for soil water in the saturated part of the soil and the drain flux is set equal to the difference in soil water pressure head and the drain level (depth) divided by a drain resistance. In SWAP, this option is extended via the possibility of using a time-variable drain head. Outflow only occurs when the soil water head exceeds that inside the drain. By adjusting the drain head, one can also allow water to flow from the drain into the soil in case the soil head is less than that inside the drain (infiltration from drains or subirrigation). Here we describe a recent study on controlled drainage with subirrigation.

Controlled drainage with subirrigation (CD-SI) could be an appropriate measure to address the imbalance in water demand and supply in groundwater dependent regions. CD-SI has the potential to anticipate both dry and wet weather extremes, as it can i) retain, ii) recharge and

iii) discharge groundwater (De Wit et al., 2024). De Wit et al. (2024) showed that the implementation of CD-SI systems may alter several water balance components (Fig. 7). The groundwater level may rise, and depending on both soil physical conditions determining capillary rise, and crop rooting depth, crop water availability and crop yield may increase.

A challenge in modelling the hydrological effects of CD-SI systems is the dynamic modelling of both the water level in the control pit and the water supply rate, rather than considering these as constants. As these factors depend on the drainage threshold in the control pit, groundwater level, maximum available external water supply, drainage resistance and infiltration resistance, dynamic modelling is required for correct insights in the water balance components and effective implementation of subirrigation (Evans, 2008).

CD-SI systems can be modelled in SWAP via either the basic or the extended drainage module. Basic drainage is used when the water level in the control pit is fixed or given as input from measurements. The extended drainage option in SWAP allows for the dynamic simulation of the water level in the control pit, using the controlled drainage system as the 'secondary drainage system' of the extended drainage module.

SWAP simulations for four experimental CD-SI fields in the Netherlands (De Wit et al., 2024) showed that the use of CD-SI systems leads to an important increase in actual plant transpiration only in dry years. Corresponding results for one site (their site A) are shown in Fig. 8. For meteorologically average and wet years the differences between subirrigation and no subirrigation are less pronounced or even negligible. A comparison of the four experimental fields also showed that hydraulic resistance to downward seepage is needed to prevent excessive downward seepage. Together with drainage towards surface water, these losses significantly increase the required water supply. However, ditch drainage losses can be limited by adapting the surface water level to the groundwater level.

Field experiments combined with process-based model simulations are required to understand the real-world situation better, leading to better models in terms of schematization, modelled processes, and parameter values. The calibration of SWAP by inverse modelling using the PEST software (Doherty, 2010) allowed to reproduce the data of the field experiments with CD-SI systems (De Wit et al., 2024). Both the required water supply and the water level in the control pit of the CD-SI system were simulated dynamically, which appeared to be a key element in understanding the functioning of CD-SI systems. Process-based modelling led to insight into the water balance components, also those components that can hardly be measured in the field, or occur in conditions that were not part of the experimental periods, like extremely dry or wet meteorological conditions. The SWAP-modelling procedure can support the design of CD-SI systems for a range of geohydrological settings, including quantification of required water supply rates for different management strategies of CD-SI systems, crop characteristics, and meteorological conditions.

4. Promising developments in the near future

The SWAP model described in this paper is a research model that is often used for studies on the effects of climatic or hydrological changes in agriculture. As a research model, its main relevance relates to increasing the process-based understanding of soil-water-plant-atmosphere interactions. Scientific advances in modelling the flow of energy and matter in the soil-plant-atmosphere continuum help to understand these interactions. In this paper, several examples of scientific improvements were presented, including the process-based modelling of root water uptake and oxygen stress. Working on these improvements and additions showed that a more precise simulation of root growth is needed to correctly simulate the root response to the soil-water conditions. This includes adaptive root growth simulation, planned to be included in SWAP shortly.

Climate change results in higher temperatures, and more pronounced weather extremes resulting in severe drought, water excess, and prolonged heat waves. The cumulative effects of these extreme conditions on crops are not well known and the development of model features to address these issues is needed.

Soil subsidence and salinization are becoming a growing threat to society, especially in delta areas and areas with peat soils. Underlying processes are only slightly part of the SWAP model as yet, but with the increasing relevance of these issues, the required model development seems obvious. The combination of physical soil processes resulting in subsidence and the effect of sometimes temporal salinity due to seepage or irrigation with saline or brackish water on root development and crop response should receive attention in the near future.

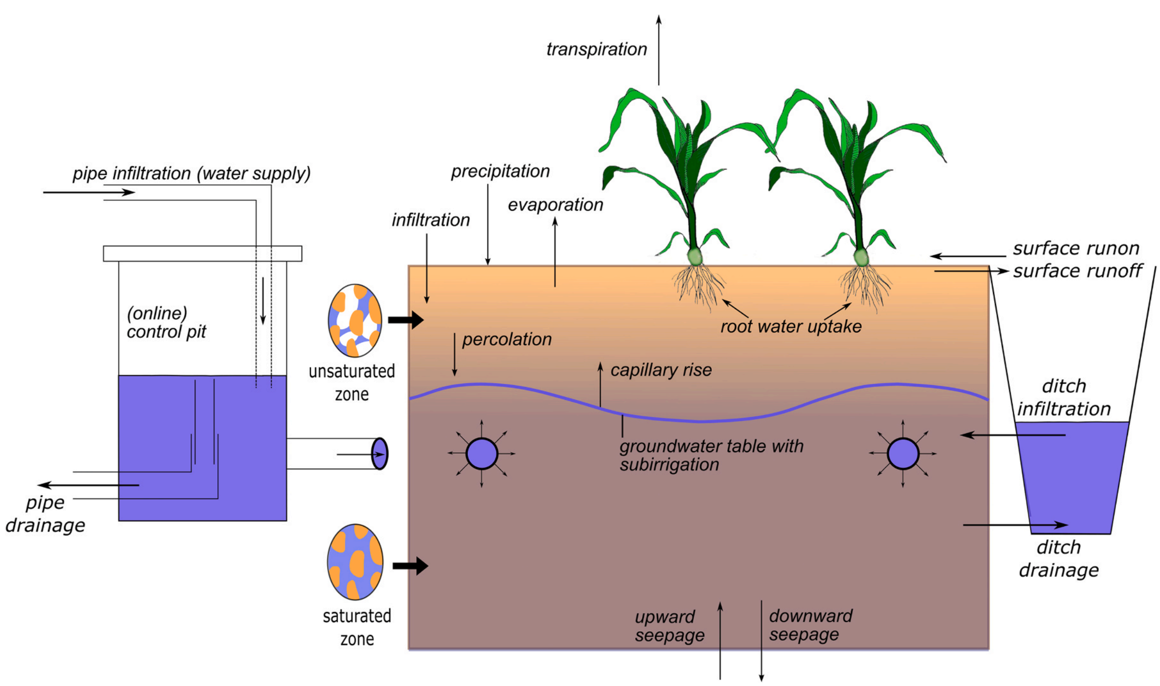

Fig. 7. The soil water column at field scale with the water balance components in the (un)saturated zone (source: De Wit et al#, 2022).

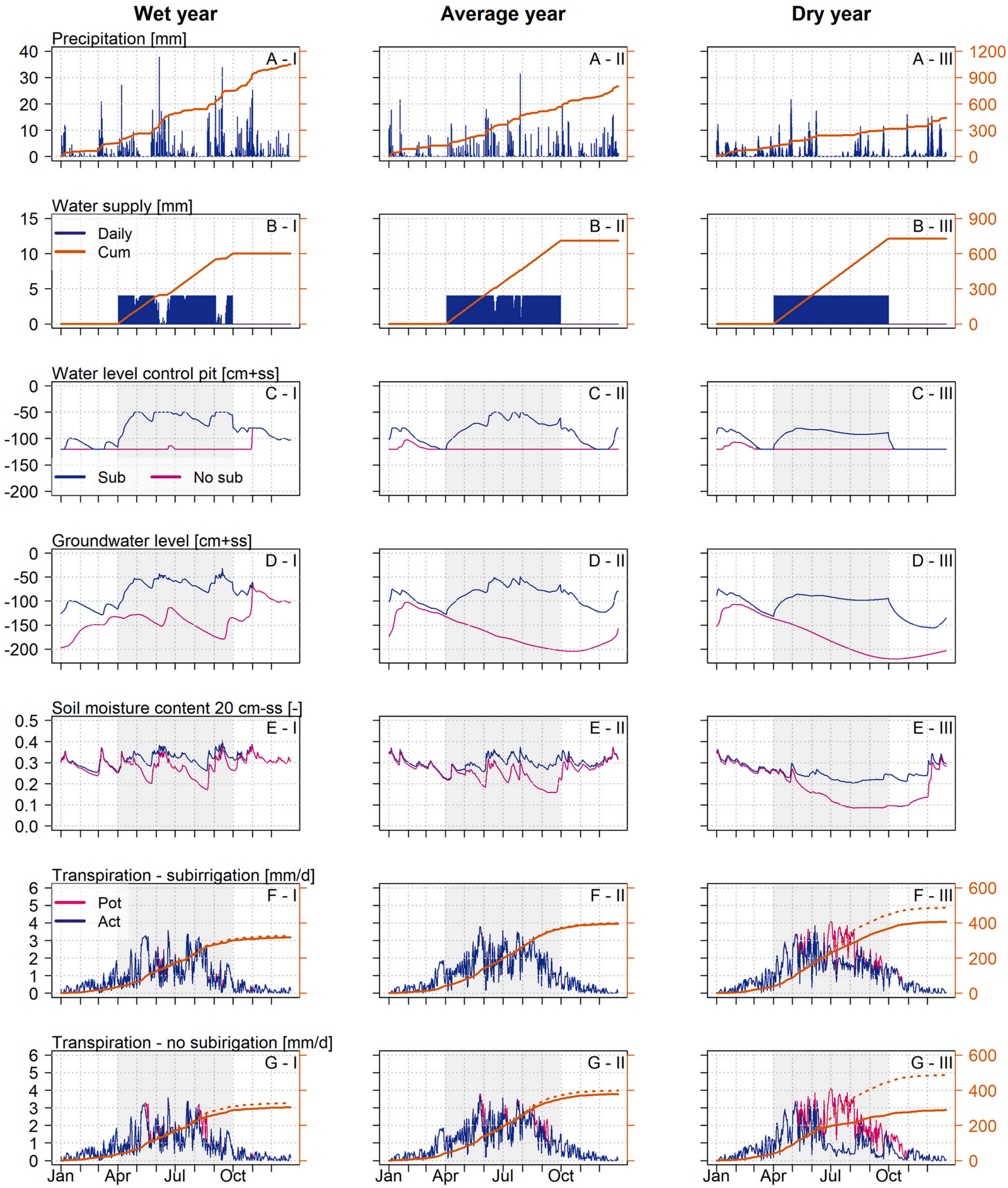

Fig. 8. Hydrological consequences of controlled drainage with subirrigation for a wet year 1998 (I, left side), an average year 2012 (II, middle) and a dry year 2018 (III, right side), as modelled with SWAP for field site A from De Wit et al., (2024). Precipitation (input, A), water supply (modelled, B), water level in the control pit (modelled, C), groundwater level (modelled, D), soil moisture content at 20 cm-ss (modelled, E), and potential and actual transpiration for a field with subirrigation (modelled, F) and a field without subirrigation (modelled, G). Precipitation and water supply are given on daily ('Daily') base and cumulative ('cum') amounts. Transpiration is given as cumulative potential transpiration (dotted, orange lines) and cumulative actual transpiration (solid, orange lines). Water level in the control pit, groundwater level, and soil moisture content at 20 cm-ss are given for a situation without subirrigation ('no sub') and with subirrigation ('sub'). The grey blocks represent the subirrigation period (1st April 30th September) (source: De Wit et al., 2024)).

This topic also links to the not well-incorporated processes of temporal variation of soil conditions. Ploughing, wetting and drying, freezing and thawing, harvesting, subsoiling, temperature changes etc. all affect soil physical conditions during the year. These processes are addressed in SWAP in a limited way and the response of root and crop development to these temporally variable conditions is also not considered.

Another type of improvement is linked to the applied studies in which SWAP is used. Case studies as presented in the previous sections as examples of the applicability of SWAP for societal challenges require easy access and user-friendliness. This then requires another type of development allowing for future changes to be considered, such as transitions in agriculture, extreme weather events, and land use changes. Traditionally SWAP is used for simulating soil hydrological processes with a single crop. Agricultural developments will require modelling situations with mixed or multiple crops and even agroforestry, with growing winter crops or intertwined areas with agriculture and nature areas within one field.

It is also important to allow for more extensive types of agriculture involving not only water-related crop growth but also nutrient-related crop growth. Taking possible nutrient shortages into account will result in more realistic modelling of agricultural yields. At present, a simple N balance can already be simulated by SWAP. This is intended as a pre-processor for the detailed nitrogen dynamics model ANIMO (Groenendijk et al., 2005) which can be run separately after a SWAP simulation run. We understand that the importance of N availability (or more generally: nutrient availability) in the complex soil-water-atmosphere-plant system will become more evident and needed in the near future. Extending the current solute transport function in SWAP with N source (e.g. mineralization, fertilization) and sink (e.g. denitrification) functions will extend the SWAP-WOFOST applicability to situations with N limitations and will allow the study of water-nitrogen interactions.

When these future developments have been realized we believe that the model will increase in applicability for land evaluation studies, scenario studies involving hydrological management options, studies on climate impact and possible climate adaptation, and also in studies involving the design of resilient soil-water-land use systems for the future.

CRediT authorship contribution statement

Marius Heinen: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Mulder:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jos van Dam:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruud Bartholomeus:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Quirijn de Jong van Lier:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Janine de Wit:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Allard de Wit:** Writing – review & editing, Writing – original draft, Conceptualization. **Mirjam Hack-ten Broeke:** Writing – review & editing, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Solution procedure process-based root water uptake models

The equation systems for both the dW and dJvL concepts are solved via a double, nested iteration procedure. First, two estimates for h_L are searched for such that

$$F(h_L) = U(h_L) - T_{act}(h_L) \tag{A.1}$$

results in a positive and a negative value for the function F. Then the final value for h_L can be found such that $F = 0$ (or less than some small convergence criterion). The function $U(h_L)$ is the solution of the inner iteration loop in which the set of N equations with N unknowns is solved. For the concept of dW it is given by

$$\begin{aligned} u_1 &= Q_1(x_1 - h_L) - S_1(M_{s,1} - M_{0,1}) = 0 \\ u_2 &= Q_2(x_2 - h_L) - S_2(M_{s,2} - M_{0,2}) = 0 \\ &\dots \\ u_N &= Q_N(x_N - h_L) - S_N(M_{s,N} - M_{0,N}) = 0 \end{aligned} \tag{A.2}$$

where $x = h_0$ and $Q = \Delta z L_{rv} K_r$ (d^{-1}) and $S = \Delta z \rho_{dW}$ (cm^{-1}). In matrix notation this is given by $\mathbf{U}(\mathbf{x}) = 0$. For the concept of dJvL it is given by

$$u_1 = h_L - x_1 + SS_1(M_{s,1} - M_{0,1}) + \frac{T_a}{L_1} = 0$$
$$u_2 = h_L - x_2 + SS_2(M_{s,2} - M_{0,2}) + \frac{T_a}{L_1} = 0 \tag{A.3}$$
$$\ldots$$
$$u_N = h_L - x_N + SS_N(M_{s,N} - M_{0,N}) + \frac{T_a}{L_1} = 0$$

Where $x = h_0$ and $SS = \phi_{dJvL}$ (d cm^{-1}). In matrix notation this is given by $\mathbf{U}(\mathbf{x}) = 0$. So, for both concepts the solutions are found in a similar way.

Following a Newton-Raphson method (Press et al., 1992) the problem $\mathbf{U}(\mathbf{x}) = 0$ is rewritten based on a Taylor expansion as

$$\mathbf{U}(\mathbf{x} + \delta\mathbf{x}) = \mathbf{U}(\mathbf{x}) + \mathbf{J}\cdot\delta\mathbf{x} + O(\delta\mathbf{x}^2) \tag{A.4}$$

Disregarding the second-order term on the right-hand side and requiring that $\mathbf{U}(\mathbf{x}+\delta\mathbf{x}) = 0$, the problem reduces to

$$\mathbf{J}\cdot\delta\mathbf{x} = -\mathbf{U} \tag{A.5}$$

This matrix problem can be solved and the estimate for $\mathbf{x}$ can be updated as

$$\mathbf{x}_{new} = \mathbf{x}_{old} + \delta\mathbf{x} \tag{A.6}$$

This continues iteratively until $\delta\mathbf{x} \to 0$, or the sum of all $|\delta x|$ is less than a convergence criterion. The Jacobian $\mathbf{J}$ contains the derivatives du/dx. For the concept of dW this is given as (note: $dM/dh = K$)

$$\mathbf{J} = \begin{vmatrix} Q_1 + S_1K_1 & 0 & \ldots & 0 \\ 0 & Q_2 + S_2K_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & Q_N + S_NK_N \end{vmatrix} \tag{A.7}$$

Similarly, for the concept of dJvL this is given by

$$\mathbf{J} = \begin{vmatrix} -1 - SS_1K_1 & 0 & \ldots & 0 \\ 0 & -1 - SS_2K_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & -1 - SS_NK_N \end{vmatrix} \tag{A.8}$$

Since $\mathbf{J}$ only contains non-zero entries on the main diagonal, its inverse can be obtained directly. All diagonal elements of $\mathbf{J}^{-1}$ are equal to the reciprocal of the diagonal elements of $\mathbf{J}$. Thus, Eq. (A.5) can be solved directly: $\delta\mathbf{x} = -\mathbf{J}^{-1}\cdot\mathbf{U}$.

Appendix B. Soil hydraulic properties of soil profiles used in 2.3.2

In section 2.3.2 simulation results are given for four soil profiles. Each soil profile consists of 2 or 3 soil layers for which the VGM parameters are listed Table B-1.

Table B-1
Values for the Van Genuchten – Mualem parameters θ_r, θ_s, α, n, λ and K_s for four soil profiles for the indicated soil layers (depth)

Profile	Depth (cm)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (-)	λ (-)	K_s (cm d^{-1})
1001	0–15	0.0	0.7186	0.01906	1.1367	0.0001	4.4837
	15+	0.01	0.8486	0.01193	1.2715	-1.2493	3.4020
1018	0–7	0.0	0.7186	0.01906	1.1367	0.0001	4.4837
	7–35	0.01	0.5733	0.02785	1.0800	-6.0913	9.6893
	35+	0.01	0.8486	0.01193	1.2715	-1.2493	3.4020
3015	0–25	0.02	0.4339	0.02165	1.3488	7.2021	83.2416
	25–60	0.02	0.3871	0.01608	1.5244	2.4397	22.7618
	60+	0.01	0.3658	0.01599	2.1628	2.8680	22.3222
4001	0–20	0.01	0.4481	0.01283	1.1353	4.5805	3.8323
	20–40	0.0	0.4436	0.01432	1.1260	2.3571	2.1224
	40+	0.01	0.5607	0.00881	1.1581	-3.1723	1.0797

References

Bartholomeus, R.P., van der Wiel, K., van Loon, A.F., van Huijgevoort, M.H.J., van Vliet, M.T.H., Mens, M., Muurling-van Geffen, S., Wanders, N., Pot, W., 2023. Managing water across the flood–drought spectrum: experiences from and challenges for the Netherlands. e2 Camb. Prism.: Water 1. https://doi.org/10.1017/wat.2023.4.

Bartholomeus, R.P., Witte, J.P.M., van Bodegom, P.M., van Dam, J.C., Aerts, R., 2008. Critical soil conditions for oxygen stress to plant roots: substituting the Feddes-function by a process-based model. J. Hydrol. 360, 147–165. https://doi.org/10.1016/j.jhydrol.2008.07.029.

Bonfante, A., Sellami, M.H., Abi Saab, M.T., Albrizio, R., Basile, A., Fahed, S., Giorio, P., Langella, G., Monaco, E., Bouma, J., 2017. The role of soils in the analysis of potential agricultural production: a case study in Lebanon. Agric. Syst. 156, 67–75. https://doi.org/10.1016/j.agsy.2017.05.018.

Bonfante, A., Terribile, F., Bouma, J., 2019. Refining physical aspects of soil quality and soil health when exploring the effects of soil degradation and climate change on biomass production: an Italian case study. Soil 5, 1–14. https://doi.org/10.5194/soil-5-1-2019.

Bonten, L.T.C., Kroes, J.G., Groenendijk, P., van der Grift, B., 2012. Modeling diffusive Cd and Zn contaminant emissions from soils to surface waters. J. Contam. Hydrol. 138–139, 113–122. https://doi.org/10.1016/j.jconhyd.2012.06.008.

Boogaard, H.L., de Wit, A.J.W., te Roller, J.A., van Diepen, C.A., 2014. WOFOST Control Centre 2.1 and WOFOST 7.1.7. User's guide for the WOFOST Control Centre 2.1 and WOFOST 7.1.7 crop growth simulation model. Update of Technical Document 52. Alterra, WUR, Wageningen, The Netherlands. Available at: https://www.wur.nl/en/research-results/research-institutes/environmental-research/facilities-tools/

software-models-and-databases/wofost/documentation-wofost.htm (validated: 12-mar-2024).
Campbell, G.S., 1991. Simulation of water uptake by plant roots. In: Hanks, J., Ritchie, J. T. (Eds.), Modeling Plant and Soil Systems, Agronomy Monograph 31. ASA CSSA SSSA, Madison, WI, pp. 273–285.
Da Silva, A.J.P., Pinheiro, E.A.R., de Jong van Lier, Q., 2020. Determination of soil hydraulic properties and its implications for mechanistic simulations and irrigation management. Irrig. Sci. 38 (3), 223–234. https://doi.org/10.1007/s00271-020-00664-5.
Dasberg, S., Bakker, J.W., 1970. Characterizing soil aeration under changing soil moisture conditions for bean growth. Agron. J. 62, 689–692. https://doi.org/10.2134/agronj1970.00021962006200060001x.
De, Jong, van Lier, Q., Metselaar, K., van Dam, J.C., 2006. Root water extraction and limiting soil hydraulic conditions estimated by numerical simulation. Vadose Zone J. 5, 1264–1277. https://doi.org/10.2136/vzj2006.0056.
De Jong van Lier, Q., van Dam, J.C., Metselaar, K., 2009. Root water extraction under combined water and osmotic stress. Soil Sci. Soc. Am. J. 73, 862–875. https://doi.org/10.2136/sssaj2008.0157.
De Jong van Lier, Q., van Dam, J.C., Durigon, A., dos Santos, M.A., Metselaar, K., 2013. Modeling water potentials and flows in the soil–plant system comparing hydraulic resistances and transpiration reduction functions. Vadose Zone J. https://doi.org/10.2136/vzj2013.02.0039.
De Jong van Lier, Q., van Dam, J.C., Metselaar, K., de Jong, R., Duijnisveld, W.H.M., 2008. Macroscopic root water uptake distribution using a matric flux potential approach. Vadose Zone J. 7 (3), 1065–1078. https://doi.org/10.2136/vzj2007.0083.
De Jong van Lier, Q., de Melo, M.L.A., Pinheiro, E.A.R., 2024. Stochastic analysis of plant available water estimates and soil water balance components simulated by a hydrological model. e20306 Vadose Zone J.. https://doi.org/10.1002/vzj2.20306.
De Melo, M.L.A., de Jong van Lier, Q., 2021. Revisiting the Feddes reduction function for modeling root water uptake and crop transpiration. J. Hydrol. 603, 126952 https://doi.org/10.1016/j.jhydrol.2021.126952.
De Melo, M.L.A., de Jong van Lier, Q., Cichota, R., Pollacco, J.A.P., Fernández-Gálvez, J., Pahlow, M., 2023. Sensitivity analysis of land and water productivities predicted with an empirical and a process-based root water uptake function. J. Hydrol. 626, 130241 https://doi.org/10.1016/j.jhydrol.2023.130241.
De Willigen P., van Dam, J.C., Javaux, M., Heinen, M., 2011. Comparison of the root water uptake term of four simulation models. Alterra-rapport 2206. Alterra, Wageningen, the Netherlands. Available at: https://edepot.wur.nl/183284 (validated: 12-mar-2024).
De Willigen, P., van Dam, J.C., Javaux, M., Heinen, M., 2012. Root water uptake as simulated by three soil water flow models. Vadose Zone J. https://doi.org/10.2136/vzj2012.0018.
De Willigen, P., van Noordwijk, M., 1987. Roots, plant production and nutrient use efficiency. Ph.D. Thesis. Wageningen Agricultural Univ., Wageningen, the Netherlands. Available at: https://edepot.wur.nl/202228 (validated: 12-mar-2024).
De Willigen, P., van Noordwijk, M., 1991. Modelling nutrient uptake: from single roots to complete root systems. In: Penning de Vries, F.W.T., van Laar, H.H., Kropff, M.J. (Eds.), Simulation and systems analysis for rice production (SARP): Selected papers presented at workshops on crop simulation of a network of national and international research centres of several Asian countries and the Netherlands, 1990–1991. PUDOC, Wageningen, the Netherlands, pp. 277–295. Available at https://edepot.wur.nl/327786 (validated 12-mar-2024).
De Wit, A., Boogaard, H., Fumagalli, D., Janssen, S., Knapen, R., van Kraalingen, D., Supit, I., van der Wijngaart, R., van Diepen, K., 2019. 25 years of the WOFOST cropping systems model. Agric. Syst. 168, 154–167. https://doi.org/10.1016/j.agsy.2018.06.018.
De Wit, J.A., van Huijgevoort, M.H.J., van Dam, J.C., van den Eertwegh, G.A.P.H., van Deijl, D., Ritsema, C.J., Bartholomeus, R.P., 2024. Hydrological consequences of controlled drainage with subirrigation. J. Hydrol. 628, 130432 https://doi.org/10.1016/j.jhydrol.2023.130432.
De Wit, J.A., Ritsema, C.J., van Dam, J.C., van den Eertwegh, G.A.P.H., Bartholomeus, R. P., 2022. Development of subsurface drainage systems: discharge – retention – recharge. Agric. Water Manag. 269, 107677 https://doi.org/10.1016/j.agwat.2022.107677.
Doherty, J., 2010. PEST: Model independent parameter estimation. Watermark Numerical Computing, Brisbane, Queensland, Australia. https://pesthomepage.org/.
Dos Santos, M.A., de Jong van Lier, Q., van Dam, J.C., Bezerra, A.H.F., 2017. Benchmarking test of empirical root water uptake models. Hydrol. Earth Syst. Sci. 21, 473–493. https://doi.org/10.5194/hess-21-473-2017.
Durner, W., 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resour. Res. 30, 211–223. https://doi.org/10.1029/93WR02676.
Eberhard, J., van Schaik, N.L.M.B., Schibalski, A., Gräff, T., 2020. Simulating future salinity dynamics in a coastal marshland under different climate scenarios. Vadose Zone J. 19 (1), e20008 https://doi.org/10.1002/vzj2.20008.
Evans, R.O., 2008. Drainage: controlled. Taylor and Francis.
Feddes, R.A., Bresler, E., Neuman, S.P., 1974. Field test of a modified numerical model for water uptake by root systems. Water Resour. Res. 10 (6), 1199–1206. https://doi.org/10.1029/WR010i006p01199.
Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc. Wageningen. https://edepot.wur.nl/168026 (validated: 12-mar-2024).
Feddes, R.A., de Rooij, G.H. van Dam, J.C. (Eds.), 2004. Unsaturated zone modeling. Progress, challenges and applications. Wageningen UR Frontis Series, volume 6. Kluwer academic publishers, Dordrecht, the Netherlands, 364 p. Available at: https://library.wur.nl/WebQuery/edepot/137470 (validated: 12-mar-2024).
Groenendijk, P., Renaud, L.V., Roelsma, J., 2005. Prediction of Nitrogen and Phosphorus leaching to groundwater and surface waters; Process descriptions of the Animo 4.0 model. Wageningen. Alter. –Rep. 983. Available at: https://edepot.wur.nl/35121 (validated: 12-mar-2024).
Hack-ten Broeke, M.J.D., Kroes, J.G., Bartholomeus, R.P., van Dam, J.C., de Wit, A.J.W., Supit, I., Walvoort, D.J.J., van Bakel, P.J.T., Ruijtenberg, R., 2016. Quantification of the impact of hydrology on agricultural production as a result of too dry, too wet or too saline conditions. Soil 2, 391–402. https://doi.org/10.5194/soil-2-391-2016.
Hack-ten Broeke, M.J.D., Mulder, H.M., Bartholomeus, R.P., van Dam, J.C., Holshof, G., Hoving, I.E., Walvoort, D.J.J., Heinen, M., Kroes, J.G., van Bakel, P.J.T., Supit, I., de Wit, A.J.W., Ruijtenberg, R., 2019. Quantitative land evaluation implemented in Dutch water management. Geoderma 338, 536–545. https://doi.org/10.1016/j.geoderma.2018.11.002.
Heinen, M., 2001. FUSSIM2: Brief description of the simulation model and application to fertigation scenarios. Agronomie 21, 285–296. https://doi.org/10.1051/agro:2001124.
Heinen, M., 2023. Modified expression for hydraulic conductivity according to Mualem–van Genuchten to allow proper computations allow-pressure heads. Vadose Zone J., e20279 https://doi.org/10.1002/vzj2.20279.
Heinen, M., Mulder, M., 2023. Microscopische wateropnamemodellen en dynamische wortelverdeling in SWAP (in Dutch). Report 3230, Wageningen Environmental Research, Wageningen, the Netherlands. https://doi.org/10.18174/583541.
Heinen, M., Mulder, H.M., Bakker, G., Wösten, J.H.M., Brouwer, F., Teuling, K., Walvoort, D.J.J., 2022. The Dutch soil physical units map: BOFEK. Geoderma 427, 116123. https://doi.org/10.1016/j.geoderma.2022.116123.
Iden, S., Durner, W., 2014. Comment to "Simple consistent models for water retention and hydraulic conductivity in the complete moisture range" by A. Peters. Water Resour. Res. 50, 7530–7534. https://doi.org/10.1002/2014WR015937.
Ippisch, O., Vogel, H.-J., Bastian, P., 2006. Validity limits for the van Genuchten – Mualem model and implications for parameter estimation and numerical simulation. Adv. Water Resour. 29, 1780–1789. https://doi.org/10.1016/j.advwatres.2005.12.011.
Jarvis, N.J., 1989. A simple empirical model of root water uptake. J. Hydrol. 107, 57–72. https://doi.org/10.1016/0022-1694(89)90050-4.
Jarvis, N.J., 2011. Simple physics-based models of compensatory plant water uptake: concepts and eco-hydrological consequences. Hydrol. Earth Syst. Sci. 15, 3431–3446. https://doi.org/10.5194/hess-15-3431-2011.
Jarvis, N., Larsbo, M., Lewan, E., Garré, S., 2022. Improved descriptions of soil hydrology in crop models: The elephant in the room? Agric. Syst. 202, 103477 https://doi.org/10.1016/j.agsy.2022.103477.
Jasechko, S., Sharp, Z.D., Gibson, J.J., Birks, S.J., Yi, Y., Fawcett, P.J., 2013. Terrestrial water fluxes dominated by transpiration. Nature 496, 347–350. https://doi.org/10.1038/nature11983.
Javaux, M., Schröder, T., Vanderborght, J., Vereecken, H., 2008. Use of a three-dimensional detailed modeling approach for predicting root water uptake. Vadose Zone J. 7 (3), 1079–1088 https://doi.org/10.2136/vzj2007.011.
Kool, J.B., Parker, J.C., 1987. Development and evaluation of closed-form expressions for hysteretic soil hydraulic properties. Water Resour. Res. 23, 105–114. https://doi.org/10.1029/WR023i001p00105.
Kroes, J.G., van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R. F.A., Mulder, H.M., Supit, I., van Walsum, P.E.V., 2017. SWAP version 4. Theory description and user manual. Report 2780, Wageningen Environmental Research, Wageningen, the Netherlands. Available at: https://edepot.wur.nl/416321 (validated: 12-mar-2024).
Kroes, J., van Dam, J., Supit, I., de Abelleyra, D., Verón, S., de Wit, A., Boogaard, H., Angelini, M., Damiano, F., Groenendijk, P., Wesseling, J., Veldhuizen, A., 2019. Agrohydrological analysis of groundwater recharge and land use changes in the Pampas of Argentina. Agric. Water Manag. 213, 843–857. https://doi.org/10.1016/j.agwat.2018.12.008.
Kroes, J.G., Supit, I., 2011. Impact analysis of drought, water excess and salinity on grass production in the Netherlands using historical and future climate data. Agric. Ecosyst. Environ. 144 (1), 370–381. https://doi.org/10.1016/j.agee.2011.09.008.
Kroes, J., Supit, I., van Dam, J., van Walsum, P., Mulder, M., 2018. Impact of capillary rise and recirculation on simulated crop yields. Hydrol. Earth Syst. Sci. 1–31 https://doi.org/10.5194/hess-2017-223.
Leij, F.J., Russell, W.B., Lesch, S.M., 1997. Closed-form expressions for water retention and conductivity data. Ground Water 35 (5), 848–858. https://doi.org/10.1111/j.1745-6584.1997.tb00153.x.
Li, P., Ren, L., 2019a. Evaluating the effects of limited irrigation on crop water productivity and reducing deep groundwater exploitation in the North China Plain using an agro-hydrological model: I. Parameter sensitivity analysis, calibration and model validation. J. Hydrol. 574 (2)), 497–516. https://doi.org/10.1016/j.jhydrol.2019.04.053.
Li, P., Ren, L., 2019b. Evaluating the effects of limited irrigation on crop water productivity and reducing deep groundwater exploitation in the North China Plain using an agro-hydrological model: II. Scenario simulation and analysis. J. Hydrol. 574 (2)), 715–732. https://doi.org/10.1016/j.jhydrol.2019.03.034.
Li, P., Ren, L., 2023. Evaluating the differences in irrigation methods for winter wheat under limited irrigation quotas in the water-food-economy nexus in the North China Plain. Agric. Water Manag. 289, 108497 https://doi.org/10.1016/j.agwat.2023.108497.
Maleki Tirabadi, M.S., Banihabib, M.E., Randhir, T.O., 2022. An integrated framework for simultaneously modeling primary and secondary salinity at a watershed scale. J. Hydrol. 612, 128171 https://doi.org/10.1016/j.jhydrol.2022.128171.
Miller, E.E., Miller, R.D., 1956. Physical theory for capillary flow phenomena. J. Appl. Phys. 27, 324–332. https://doi.org/10.1063/1.1722370.

Moene, A.F., van Dam, J.C., 2014. Transport in the Atmosphere-Vegetation-Soil Continuum. Cambridge University Press, New York. Available at: https://library.wur.nl/WebQuery/wurpubs/452475 (validated: 12-mar-2024).

Mokhtari, A., Noory, H., Vazifedoust, M., 2018. Improving crop yield estimation by assimilating LAI and inputting satellite-based surface incoming solar radiation into SWAP model. Agric. For. Meteor. 250–251, 159–170. https://doi.org/10.1016/j.agrformet.2017.12.250.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12, 513–522. https://doi.org/10.1029/WR012i003p00513.

Nemes, A., Schaap, M.G., Leij, F.J., Wösten, J.H.M., 2001. Description of the unsaturated soil hydraulic database UNSODA version 2.0. J. Hydrol. 251, 151–162. https://doi.org/10.1016/S0022-1694(01)00465-6.

Peters, A., 2013. Simple consistent models for water retention and hydraulic conductivity in the complete moisture range. Water Resour. Res. 49, 6765–6780. https://doi.org/10.1002/wrcr.20548.

Peters, A., 2014. Reply to comment by S. Iden and W. Durner on Simple consistent models for water retention and hydraulic conductivity in the complete moisture range. Water Resour. Res. 50, 7535–7539. https://doi.org/10.1002/2014WR016107.

Pinheiro, E.A.R., Nunes, M.R., 2023. Long-term agro-hydrological simulations of soil water dynamic and maize yield in a tillage chronosequence under subtropical climate conditions. Soil Tillage Res 229, 105654. https://doi.org/10.1016/j.still.2023.105654.

Pinto, V.M., van Dam, J.C., de Jong van Lier, Q., Reichardt, K., 2019. Intercropping simulation using the SWAP model: Development of a 2×1D algorithm. Agriculture 9 (6). https://doi.org/10.3390/agriculture9060126.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., 1992. Numerical Recipes in Fortran 77. The Art of Scientific Computing, second edition. Cambridge University Press.

Priesack, E., Durner, W., 2006. Closed-form expression for the multi-modal unsaturated conductivity function. Vadose Zone J. 5, 121–124. https://doi.org/10.2136/vzj2005.0066.

Raats, P.A.C., 1970. Steady infiltration from line sources and furrows. Soil Sci. Soc. Am. Proc. 34, 709–714. https://doi.org/10.2136/sssaj1970.03615995003400050015x.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics 1, 318–333. https://doi.org/10.1063/1.1745010.

Rothfuss, Y., Javaux, M., 2016. Isotopic approaches to quantifying root water uptake and redistribution: a review and comparison of methods. Biogeosciences Discussion. https://doi.org/10.5194/bg-2016-410.

Runhaar, J., Witte, J.P.M., Verburg, P.H., 1997. Ground-water level, moisture supply, and vegetation in the Netherlands. Wetlands 17 (4), 528–538. https://doi.org/10.1007/BF03161519.

Schaap, M.G., Leij, F.J., van Genuchten, M.T., 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251, 163–176. https://doi.org/10.1016/S0022-1694(01)00466-8.

Scott, P.S., Farquhar, G.J., Kouwen, N., 1983. Hysteretic effects on net infiltration. in: Advances in Infiltration, National Conference on Advances in Infiltration, Chicago, IL. Am. Soc. Agric. Eng., St. Joseph, Mich, pp. 163-170.

Taufik, M., Veldhuizen, A.A., Wösten, J.H.M., van Lanen, H.A.J., 2019. Exploration of the importance of physical properties of Indonesian peatlands to assess critical groundwater table depths, associated drought and fire hazard. Geoderma 347, 160–169. https://doi.org/10.1016/j.geoderma.2019.04.001.

Topp, G.C., 1969. Soil-water hysteresis measured in a sandy loam and compared with the hysteretic domain model. Soil Sci. Soc. Am. Proc. 33, 645–651. https://doi.org/10.2136/sssaj1969.03615995003300050011x.

Tóth, B., Weynants, M., Nemes, A., Makó, A., Bilas, G., Tóth, G., 2014. New generation of hydraulic pedotransfer functions for Europe. Eur. J. Soil Sci. https://doi.org/10.1111/ejss.12192.

Van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Kroes, J.G., 2008. Advances of modeling water flow in variably saturated soils with SWAP. Vadose Zone J. 7, 640–653. https://doi.org/10.2136/vzj2007.0060.

Van Diepen, C.A., Wolf, J., van Keulen, H., Rappoldt, C., 1989. WOFOST: a simulation model of crop production. Soil Use Manag 5, 16–24. https://doi.org/10.1111/j.1475-2743.1989.tb00755.x.

Van Genuchten, M.Th, 1978. Calculating the unsaturated hydraulic conductivity with a new closed-form analytical model. Report 78-WR-08, Department of Civil Engineering, Princeton University, Princeton, New Jersey. Available at: https://www.nrc.gov/docs/ML0330/ML033070005.pdf (validated: 12-mar_2024).

Van Genuchten, M.Th, 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44 (3), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

Van Genuchten, M.Th., Leij, F.J. Yates, S.R., 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. Report EPA/600/2-91/065, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma. Available at: https://www.pc-progress.com/Documents/programs/retc.pdf (validated: 12-mar-2024).

Vanderborght, J., Leitner, D., Schnepf, A., Couvreur, V., Vereecken, H., Javaux, M., 2023. Combining root and soil hydraulics in macroscopic representations of root water uptake. Vadose Zone J., e20273 https://doi.org/10.1002/vzj2.20273.

Wösten, J.H.M., Lilly, A., Nemes, A., Bas, C.L., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169–185. https://doi.org/10.1016/S0016-7061(98)00132-3.

Yang, X., Wang, G., Chen, Y., Sui, P., Pacenka, S., Steenhuis, T.S., Siddique, K.H.M., 2022. Reduced groundwater use and increased grain production by optimized irrigation scheduling in winter wheat–summer maize double cropping system—a 16-year field study in North China Plain. Field Crops Res, 108364. https://doi.org/10.1016/j.fcr.2021.108364.

Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., Xia, L., Shen, Y., Pacenka, S., Steenhuis, T.S., Siddique, K.H.M., Kang, S., Butterbach-Bahl, K., 2024. Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. Nat. communic 15, 198. https://doi.org/10.1038/s41467-023-44464-9.

Zhuang, J., Nakayama, K., Yu, G.-R., Urusjisaki, T., 2001. Estimation of root water uptake of maize: an ecological perspective. Field Crops Res 69, 201–213. https://doi.org/10.1016/S0378-4290(00)00142-8.